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Effects of Urban Form on Ambient Air Filter Noise Exposure in Open Areas

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Abstract: Although ambient air filters are commonly used to improve air quality in urban areas, their operation often produces significant noise levels. In this study, we investigated and addressed the issue of ambient air filter noise exposure in open areas of Chinese cities, with a focus on various typical urban forms. Firstly, fifteen common urban blocks with different forms and of 250 × 250 m each were chosen as sample sites, for which urban form indices and noise distribution indices were defined. Then noise mapping was conducted to investigate air filter noise exposure in open areas and the effects of urban form indices on noise distribution indices. Results show that urban form has considerable effects on filter noise exposure in open areas. Among the six urban form indices examined, the distance between the first-row building and the air filter was found to be the most critical factor affecting noise levels with the highest correlation coefficient (R = 0.754). The orientation of the first-row building shows the significant resisting effect on both average and background noise levels. Furthermore, the resisting effect of first-row buildings can create a maximum reduction of 12.0 dB (A) for peak noise. These indices could be profiled and used as an "a priori" tool for urban sound environment planning.

Keywords: ambient air filter; urban form; urban sound environment; noise mapping; building acoustics

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1. Introduction

Environmental noise [1], such as road traffic noise, railway noise, and aircraft noise, is considered as one of the environmental pollution sources in cities that have a negative impact on public health [2–5]. Acoustic environmental quality has become a critical factor for improving urban sustainability, and it is a growing concern among both the general public and policy makers all over the world. Social-economic factors [6,7], urban built environment [8,9], and urban form [10–12] influence noise evaluation. Among these, urban form encompasses the spatial distribution of human activities at a specific moment in time, encompassing the arrangement, appearance, and functionality of buildings and the utilization of urban space [13]. A range of urban form indices have been developed and employed in various environmental studies [14–17] to evaluate the concept and usage of urban space. A thorough understanding of the correlations between urban form and environmental noise would enable more accurate predictions, analyses, and prevention of noise pollution through the efficient design of urban planning.

Studies examining the correlations between urban form and environmental noise have commonly employed noise mapping as a primary tool for analyzing the acoustic conditions of urban areas. The effect of urban morphology on road traffic noise is a widely studied and topical issue, as evidenced by numerous investigations [18–20]. Hao et al. [21] investigated the relationship between traffic noise resistance and urban morphology in low-density residential areas. Results showed that the complete aspect ratio and the building frontal area index exhibited the most significant influence on average spatial noise levels, and decreasing the distance between the first-row buildings and a traffic road led to a reduction in noisy open areas. Margaritis and Kang [22] studied the relationship between features of urban morphology related to green spaces, roads or buildings, and traffic noise distribution in urban areas, and found that an increase in internal road connectivity contributed to higher traffic noise. In addition, it was found that the average sound level in an urban area decreased with increasing building density [17], and carefully designing building façades and geometry in street canyons could improve the sound climate for people living and walking along busy urban streets [23]. An investigation [24] conducted in Hong Kong also verified that a less disruptive noisescape was associated with urban forms with lower road and building densities. Analysis of various building types with consistent building density and small flats revealed that perimeter blocks with closed inner yards, slightly open yards, and U-shaped buildings exhibited better resistance to road traffic noise when compared to I-shaped, L-shaped, and point buildings [25].

Research on the relationships between urban morphology and various forms of environmental noise, including but not limited to aircraft noise, wind turbine noise, and leisure noise, has also been conducted. Flores et al. [26] explored the impact of street topologies and building forms on aircraft noise, and found that front façades, U topologies, and greater line-of-sight angles resulted in higher levels on the façade. In a study by Hao and Kang [27], the impact of urban morphology on the spatial noise level attenuation of flyover aircraft in low-density built-up areas was investigated. The study found that spatial noise attenuation was primarily associated with the building frontal area index and the horizontal distance between the first-row building and the flight path. A study of wind turbine noise [28] revealed that the morphology of the built environment had a significant impact on the ability of buildings to resist noise exposure, with the potential to create a quiet façade with a difference of up to 13 dB(A) compared to the most exposed facade. Furthermore, the study found that building orientation was the most effective factor in resisting noise exposure on building façades. A study [29] revealed the screening effect of balconies on talking noise and the benefits of the application of sound-absorbing material on the noise reduction over the façade. Additional research on the relationships between urban morphology and overall noise pollution [12,30] or birdsong loudness [31] has likewise demonstrated the significant effect of urban forms, including street morphology, building geometry, urban density, and green spaces. Furthermore, people's noise complaints were also correlated with urban form, in terms of their relation to transport network, land use, and building morphology [32,33].

The literature review reveals that urban morphology, at various scales including urban, individual building, and source building, has a significant impact on environmental noise exposure both in open areas and on building façades. Road traffic noise is the most commonly recognized environmental noise concern, while other sources of noise such as aircraft noise, wind turbine noise, and leisure noise are also being increasingly acknowledged. Furthermore, certain urban form indices exhibit similar effects on multiple types of noise. For instance, indices associated with noise resistance, such as building density and complete aspect ratio, demonstrate a significant correlation with noise exposure in open areas [17,21,29]. Additionally, certain indices can have varying effects on the soundscape, as demonstrated by research on the impact of green areas on birdsong [31] and the influence of building orientation on wind turbine noise exposure for building façades [28]. The results may be influenced by factors such as the height of the source, sound power level, and spectrum. Therefore, examining the effects of noise on urban soundscapes and identifying key urban morphology indices that influence noise exposure in open areas and on building façades is crucial for informing urban sound planning and mitigating negative impacts on the urban environment.

An ambient air filter is a kind of facility for mitigating outdoor pollutant concentrations and increasing wind ventilation by fan blowers, and it is thus widely utilized in urban areas [34,35]. Nevertheless, the generation of high-level noise, both mechanical and aerodynamic, during operation inevitably has a negative impact on work performance, social activities, human health, and the urban soundscape. Urban forms may also influence the propagation of sound and noise exposure of air filters in open areas within a city. For instance, sound propagation in high-density megacities may differ from that in low-density cities due to multiple reflections. Additionally, comprehending the correlation between urban morphology and ambient air filter noise exposure is crucial, given the distinct noise characteristics of air filters compared to other noise sources. Published works [34,35], however, mainly focus on the efficiency of decreasing urban pollutant concentrations.

This study aimed to investigate how urban form influences ambient air filter noise exposure in open areas and to identify the key factors affecting noise levels. Specifically, the reliability of the acoustic virtual model of the air filter noise was systematically verified by comparing between the measured and predicted noise levels of the air filter. Then, fifteen common urban blocks with different forms were first chosen as sample sites, and urban form indices and noise distribution indices were defined. Acoustic virtual models of these sites were built and noise mapping was then conducted to compare noise levels and area exposure in open areas among the fifteen sites, and correlations between noise distribution indices and urban form indices were further investigated.

2. Methodology

2.1. Measurement and Simulation of Ambient Air Filter Noise

The ambient air filter examined in this study is a pentagonal prism with a height of 5.35 m, and each side of the pentagonal plane has a length of 1.1 m, as shown in Figure 1a. The air flows through the inlet to be purified in the filter chamber, and the purified air, driven by fan blowers, flows through the circular outlet towards urban areas. High-level noise emitting from the fan blower chamber propagates towards the surrounding environment. To investigate the impact of urban form on air filter noise exposure in open areas through noise mapping, it is essential to verify the acoustic parameters and reliability of the virtual model of the air filter noise by comparing the predicted noise levels with the measured ones.

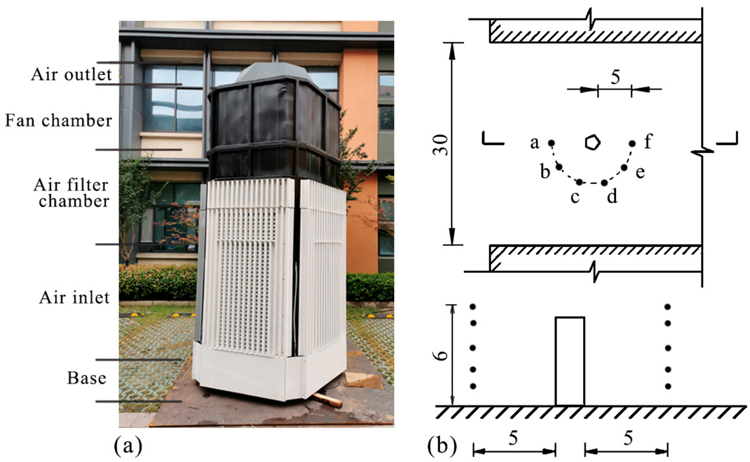


Figure 1. (**a**) A photograph of the ambient air filter examined in this study; (**b**) schematic diagrams of noise measurements of the filter tower (unit: m).

2.1.1. Noise Measurement

The air filter was positioned on outdoor flat hard ground between two buildings, 220 m away from the vehicle road, and operated at its maximum fan blade speed of 1780 r/min, as shown in Figure 1a. To ensure that the noise levels were solely produced by the air filter and not by other sources (mainly traffic noise), noise measurements were conducted after rush hour at approximately 18:00. As shown in Figure 1b, measurements were conducted at five different heights (1.2, 2.2, 3.5, 5, and 6 m) above the ground, and 6 microphone positions were evenly arranged at each height in a semicircular pattern, 5 m away from the exterior wall of the air filter to obtain the sound power level of the air filter noise [36,37].

A portable sound level meter (type 01 dB Fusion, ACOEM, France) was utilized to record sound pressure level (SPL) at 1/3 octave bands and A-weighted SPL ($L_{A,eq}$). A recording time of 20 min was chosen for each microphone position to ensure accuracy and consistency in the measurements. In addition, immediately after the noise of the filter tower was measured, the background noise was also recorded at each microphone position over the same measurement time interval.

2.1.2. Noise Simulation

As shown in Figure 1, SPLs and $L_{A,eq}$ in the study site were predicted with a commonly used noise mapping package, Raynoise 3.0 by LMS International. This uses advanced beam tracing methods to predict the sound field produced by sources at any locations in closed, open, or partially open spaces [38–40]. The 3D model of the site was first built in AutoCAD, and then it was imported to Raynoise. To model the source of the air filter in this study, point source and plane source, respectively, were selected and compared, and the sound power levels, L_W [36,37], are given Table 1. Three point sources were positioned at the geometric center of the fan chamber, 4.8 m above the ground, whereas a plane source, whose size was equal to that of the air filter plane, was placed horizontally 4.8 m above the ground. In addition, background noise, in accordance with the measured values, was also considered in noise mapping and is given in Table 1. Ground and building envelope surfaces were considered as acoustic boundaries with specific sound-absorption coefficients. The sound-absorbing properties of the materials of the virtual model, which were initially set in accordance to the values in Raynoise and the literature [41,42], were adjusted so as to decrease the differences between the predicted SPLs by noise mapping and measurement at microphone positions. The final absorption coefficients of different materials used in noise mapping are listed in Table 1. In addition, effects of sound diffraction on building edges were also considered. The air temperature was set to 25 °C, and relative humidity to 60% for atmospheric absorption. The number of rays was 4000 and the reflection order was set as 5.

Table 1. Acoustic parameter settings of the virtual model in noise mapping.

	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz
Sound power level of the source/dB	83.8	92.7	85.8	81.2	78.9	74.2
SPLs of background noise/dB	43.9	38.0	35.2	36.7	37.1	34.6
Sound-absorption coefficients of ground	0.10	0.08	0.09	0.15	0.05	0.07
Sound-absorption coefficients of building envelope	0.07	0.15	0.19	0.19	0.10	0.12

2.1.3. Comparison between the Measured and Predicted Results

Comparisons of SPLs between the measured and predicted values at different microphone positions, a, b, and c, are shown in Figure 2. A difference of approximately 4 dB at the frequency range of 63–500 Hz between the measured and predicted results was found, and the difference was up to 5 dB over 1000 Hz. However, predicted noise spectra were equal to those obtained by measurement. In Table 2, smaller differences for $L_{A,eq}$ within 2.3 dB (A) are shown. It should be mentioned that $L_{A,eq}$ was utilized to describe the noise level of air filter in the present work and to discuss the effect of urban forms on air filter noise exposure in open areas. Additionally, results predicted by point source and plane source show good agreement within a difference of 1 dB, as shown in Figure 2 and Table 2, and point source was finally utilized in this study.

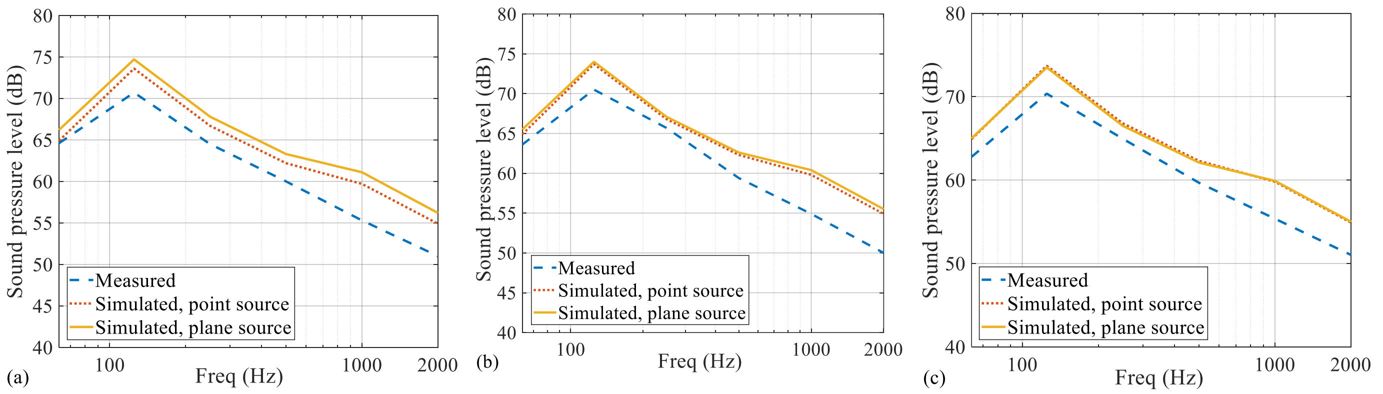


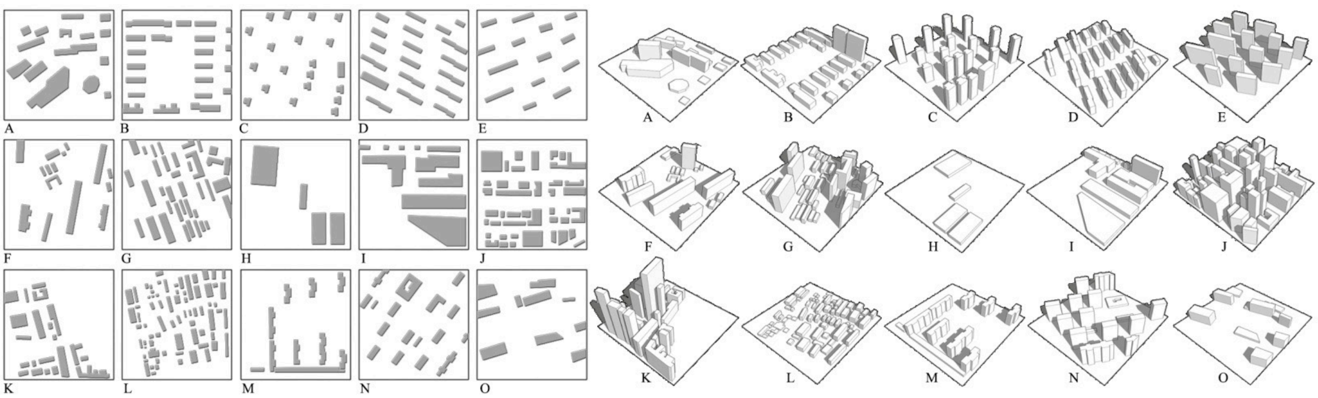
Figure 2. Measured and simulated SPLs at microphone positions, (**a**) a, (**b**) b, and (**c**) c, 1.2 m above the ground.

Table 2. Comparisons of $L_{A,eq}$ between the measurement and simulation.

	a	b	c
Measured	67.6 dB (A)	66.9 dB (A)	67.2 dB (A)
Simulated, point source	65.3 dB (A)	65.4 dB (A)	65.4 dB (A)
Simulated, plane source	66.6 dB (A)	65.8 dB (A)	65.3 dB (A)

2.2. Urban Form Selection

Fifteen urban blocks in China were chosen as study sites, based on various urban forms including land use (residential areas, commercial areas, industrial clusters, and mixed-use land), building forms (layout, height, and length), building coverage, and density. Figure 3 presents the figure-ground diagrams and 3D models of the selected sites. For example, Site B, C, D, E and M were chosen from residential areas with different building forms, orientation, density, and layout, while Site H, I, and O were areas with large industrial buildings. Commercial areas with high-density urban blocks and deep street canyons were illustrated in Site J and K. A 250 × 250 m grid was selected for each site, taking into account both computational efficiency and the potential impact of air filter noise. This grid size was deemed appropriate for accurately predicting environmental noise exposure across different urban forms [21,27,31].



(**a**) (**b**)

Figure 3. (**a**) Plans and (**b**) 3D models of the fifteen selected sites with different urban forms, each of 250 m × 250 m, where buildings are in grey, and open areas are in white (medical treatment areas: Site A; residential areas: Site B, C, D, E and M; industrial areas: Site H, I and O; commercial areas: Site J, K and L; mixed in different functional areas: F, G, and N).

2.3. Urban Form Indices

A large number of quantitative urban form indices have been explored, developed, and studied from the perspectives of environmental performance, landscape, land use, and atmospheric and wind environment [14,16,43] to make the diverse urban form quantitatively comparable. Numerous indices that were developed in previous studies, such as porosity [13,30,43], building coverage [17,30,43], floor area ratio [32], complete aspect ratio [27], and height-to-width ratio [27], have been employed in studies on the effects of urban form on environmental noise. These indices were filtered in this work with the purpose of choosing the least number of indices that were simple and adjustable for design and practice.

Six urban form indices were chosen and defined in this study, including building plan area fraction (BPAF) [27,31,44], spacing index [28], compactness index [13,28], first-row building orientation [28], distance of first-row building to the ambient air filter (DFBAAF) [21,31], and building frontal area index (BFAI) [21,27]. The first three indices are independent from the source condition, whereas the other three are related to sound source locations. The definition and calculation formula of each index is given in Table 3.

Table 3. Definitions and calculations of the six urban form indices used in this study.

Parameters	Definitions and Notes	Formula
Building Plan Area Fraction (BPAF)	The ratio of the plan area of buildings at ground level (A_P) to the total surface area of the study region (A_T).	$\mathrm{BPAF} = \frac{A_P}{A_T}$
Spacing Index (SI)	The averaged spacing from the target building to the adjacent building units on both sides. $S_{1,i}$, $S_{2,i}$, respectively, are the distances from the target building to the adjacent buildings on both sides; $\mathrm{n_{SI}}$ is the number of target buildings in the study region.	$\mathrm{SI} = \frac{1}{\mathrm{n_{SI}}} \sum_{i=1}^{\mathrm{n_{SI}}} \frac{S_{1,i}+S_{2,i}}{2}$
Compactness Index (CI)	The ratio between the source-receiver distance ($D_{S\text{-}R,i}$) and the distance from the nearest building at the front along the incidence wave ($D_{1,i}$); $\mathrm{n_{CI}}$ is the number of target buildings in the study region.	$\mathrm{CI} = \frac{1}{\mathrm{n_{CI}}} \sum_{i=1}^{\mathrm{n_{CI}}} \frac{D_{S-R,i}}{D_{1,i}}$
First-row Building Orientation (FBO)	The angle (A_i) between the connection line of air filters and the longer façade of the first-row building. $\mathrm{n_1}$ is the number of the target buildings in the first row.	$\mathrm{FBO} = \frac{1}{\mathrm{n_1}} \sum_{i=1}^{\mathrm{n_1}} A_i$
Distance of First-row Building to the Ambient Air Filter (DFBAAF)	The mean of the distances (d_i) from the frontal façades of the first-row buildings to the air filter.	$\mathrm{DFBAAF} = \frac{1}{\mathrm{n_1}} \sum_{i=1}^{\mathrm{n_1}} d_i$
Building Frontal Area Index (BFAI)	The ratio of the total area of the projected façade areas parallel with the connection line of air filters (A_{pro}) to the total surface area of the study region (A_T).	$\mathrm{BFAI} = \frac{A_{pro}}{A_T}$

Note: the unit of spacing index and DFBAAF is meter (m), and that for first-row building orientation is degree (°).

2.4. Noise Mapping

Investigations of noise exposure in open areas of air filters in each site and effects of urban form indices on noise exposure were conducted by noise mapping. Air filters are typically installed at specific intervals along roads [34]. To investigate the effects of different numbers of air filters on noise exposure, this study assumed different numbers of filters installed along one side of a site to simulate a basic situation where only a road is adjacent to an urban block. For example, air filters are evenly distributed along one side of Site A (see Figure 4), with two, four, and six filters installed for analysis. Virtual models of the selected sites were thus built as described in Section 2.1.

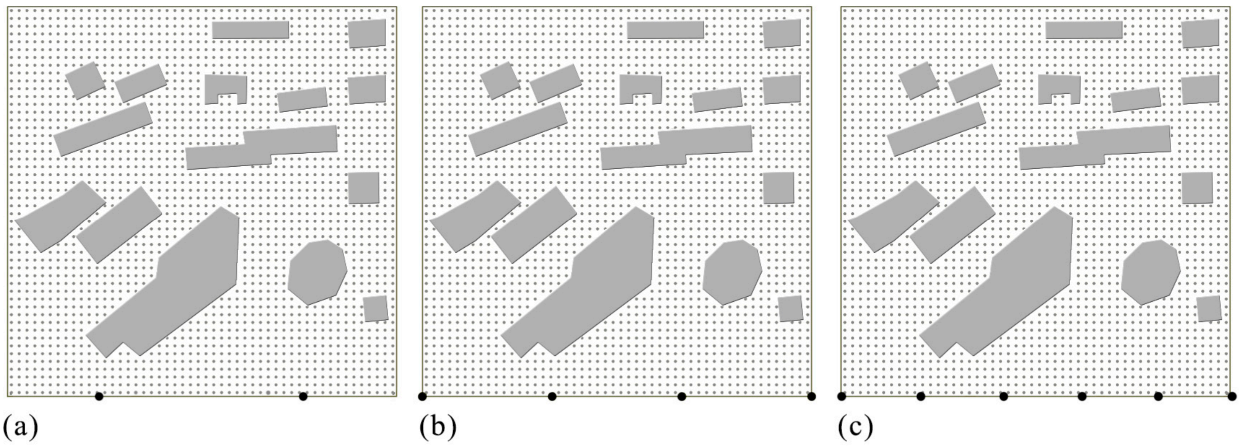


Figure 4. Illustrations of the calculation of noise distribution indices in noise mapping with (**a**) two, (**b**) four and (**c**) six ambient air filters (black dots and grey dots, respectively, denote air filters and receiver points; grey blocks represent buildings in the site).

The study investigated both noise exposure maps and noise distribution indices in open areas for each site. Noise exposure maps were generated using calculation grids with a size of 10 × 10 m, located 1.2 m above the ground, with finer grids used at corners of the buildings. For noise distribution indices, receiver points were determined in open areas of each site, spaced at 5 × 5 m intervals and represented by grey dots in Figure 4. The numbers of receiver points for the fifteen sites from A to O are 414, 448, 513, 456, 503, 477, 415, 469, 359, 405, 473, 428, 496, 474, and 488, respectively. $L_{A,eq}$ at each receiver point was then calculated in Raynoise. It is important to note that in this study, the statistical noise levels are spatial, rather than temporal, as conventionally defined. Specifically, the calculated $L_{A,eq}$ at all receiver points were arranged in descending order to obtain the noise distribution indices, L_n [43]. n of L_n specifies one certain sound level value, in dB (A), at the position of n% in all of the descending values. For example, L_{10} is the value located at the top 10% in the rankings of all the spatial noise level values. L_{10}, L_{20}, L_{40}, L_{60}, and L_{80} were finally utilized as noise distribution indices to investigate noise spatial distributions, where L_{10} and L_{20}, and L_{40} and L_{60}, indicate the spatial peak noise level and spatial average noise level, while L_{80} presents the spatial background noise level.

3. Results and Discussions

3.1. Results of Urban Form Indices and L_n

The calculated results of urban form indices for the fifteen selected sites are presented in Table 4, revealing significant variations in the values of each index across sites. In Table 5, noise distribution indices (L_n) are provided for different numbers of ambient air filters.

Table 4. Values of urban form indices of the fifteen selected sites.

	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**	**M**	**N**	**O**
BPAF	0.23	0.21	0.10	0.19	0.12	0.16	0.26	0.18	0.36	0.33	0.18	0.24	0.14	0.16	0.15
SI/m	16.5	46.1	39.0	34.2	39.6	58.0	17.2	0	23.3	9.3	11.4	7.2	72.5	29.8	40.2
CI	12.3	6.6	2.5	6.1	3.0	5.8	15.2	0	16.4	9.1	5.2	19.8	4.6	6.4	3.7
FBO/°	41.0	0	80.0	27.0	21.0	78.0	70.0	90.0	34.0	9.3	51.7	67.0	0	53.0	14.0
DFBAAF/m	55.0	13.4	39.0	32.9	45.2	34.0	24.3	64.5	70.1	12.0	7.1	38.6	16.5	29.4	60.1
BFAI	0.17	0.29	0.39	0.38	0.63	0.15	0.33	0.02	0.20	0.94	0.58	0.12	0.09	0.38	0.14

Table 5. Noise distribution indices, L_n, of the fifteen selected sites with different number of ambient air filters (unit: dB (A)).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	#
Two ambient air filters																
L_{10}	56.1	53.6	56.1	55.2	56.4	55.9	56.2	54.7	56.3	45.5	45.5	55.3	49.8	55.7	56.2	56.0
L_{20}	54.6	48.9	53.4	48.1	53.6	53.5	51.9	51.4	54.2	45.5	45.5	52.7	47.2	51.2	54.5	53.7
L_{40}	47.5	46.7	49.3	45.5	47.1	49.1	46.9	48.9	49.5	45.5	45.5	45.5	45.5	47.2	48.3	50.4
L_{60}	45.5	45.5	47.2	45.5	45.5	46.6	45.5	46.6	45.9	45.5	45.5	45.5	45.5	45.5	46.9	48.6
L_{80}	45.5	45.5	45.9	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	45.5	47.6
Four ambient air filters																
L_{10}	58.9	54.3	57.7	58.5	58.6	58.3	58.7	57.6	58.7	51.2	52.4	58.1	50.3	58.2	58.5	58.3
L_{20}	57.1	49.2	54.5	53.7	55.8	55.1	53.9	54.6	56.1	47.8	49.3	55.5	48.1	54.6	56.5	55.5
L_{40}	49.6	46.8	49.5	48.1	49.2	50.3	49.0	51.3	51.1	45.5	47.5	49.4	45.7	49.7	50.0	52.2
L_{60}	45.5	45.5	47.6	45.9	46.9	48.5	46.4	47.7	46.5	45.5	46.7	46.4	45.7	47.5	47.6	50.0
L_{80}	45.5	45.5	46.4	45.5	45.5	46.8	45.5	46.3	45.5	45.5	45.5	45.5	45.7	45.9	45.5	48.9
Six ambient air filters																
L_{10}	61.9	57.6	60.4	60.8	60.8	61.2	61.2	60.1	61.5	53.6	52.4	61.2	52.4	61.0	61.3	60.0
L_{20}	58.9	51.3	57.0	54.7	57.8	57.1	56.5	57.1	58.4	48.1	49.2	58.0	48.9	56.5	58.7	57.4
L_{40}	51.0	49.1	51.7	47.8	49.7	51.9	49.6	53.2	52.5	45.5	47.2	50.5	45.8	50.7	51.5	53.8
L_{60}	45.5	46.6	48.8	45.8	46.9	49.3	46.8	49.0	46.9	45.5	46.5	46.6	45.5	48.1	48.2	51.4
L_{80}	45.5	45.5	47.4	45.5	45.5	47.6	45.5	47.7	45.5	45.5	45.5	45.5	45.5	46.2	46.2	49.9

Note: # denotes the noise levels in open areas without buildings in the site.

3.2. Comparisons of Noise Exposure among Different Sites

Noise distribution indices, L_n, of each site under different numbers of air filters are presented in Figure 5 according to the results in Table 5. Totally different distributions of noise levels among sites are clearly observed. For example, the overall noise levels in Sites A and I are higher than those in the other sites, while the lowest noise levels, of only 45.5 dB (A), are found in Sites J and K with two air filters. The distance of the first-row building to the air filter in these two sites is less than that of any others, and the resisting effect of the first-row building on noise exposure in open areas may contribute to the low noise levels of noise indices. L_{10} and L_{20} in Site I are 10 dB (A) approximately larger than that in Site J, and the differences among sites is smaller for the value of L_{60} and L_{80}, which indicates the significant effects of urban form on peak noise (L_{10}, L_{20}). Furthermore, the number of air filters mainly influences the level of peak noise (L_{10}, L_{20}) and average noise (L_{40}, L_{60}), and there is an increase of 2 dB (A) when two more air filters are situated in the site.

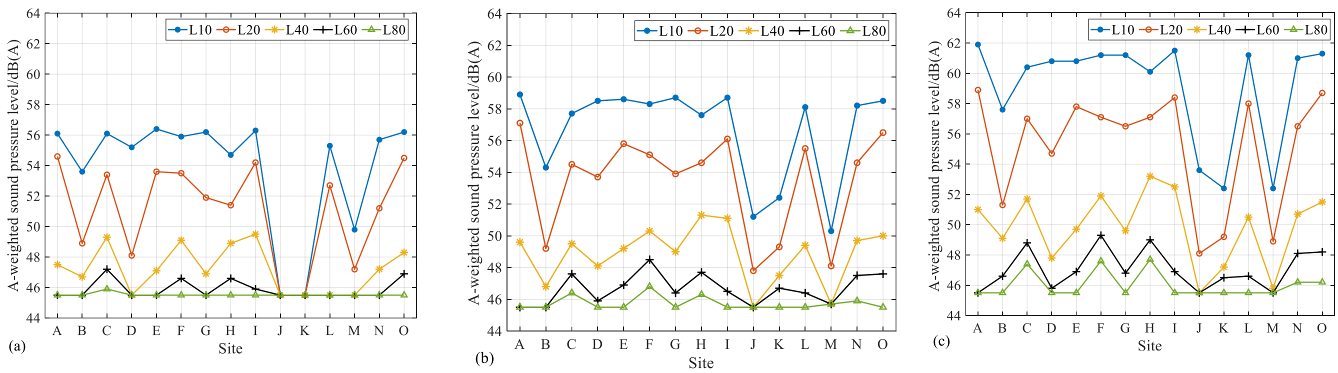


Figure 5. Noise distribution indices, L_n, of the fifteen sites under different numbers of air filters ((**a**) two air filters; (**b**) four air filters; (**c**) six air filters).

It can be seen from Table 5 that noise levels in open areas without buildings, in most cases, are higher than those of the condition with buildings, indicating the effect of buildings on the reduction in noise exposure. The degree of noise reduction differs from the sites with buildings, which may be related to the urban form indices. Furthermore, it is interesting to find that L_{10} and L_{20} in Site A, Site I, and Site O with buildings are slightly higher than the values without buildings due to the reflection in the open areas in front of the air filters.

In order to examine the noise distribution characteristics of each site, this study defined area exposure as the ratio between the number of receiver points within a specific noise level range and the total number of receiver points in the site, and Figure 6 shows the area exposure proportions of noise levels, $L_{A,eq}$, for the fifteen sites under different numbers of air filters. The results indicate a significant increase in area exposure proportions of noise levels above 50 dB (A) with an increase in the number of air filters. However, a substantial portion of open areas still experience low noise levels below 50 dB (A), and exposure areas with noise levels exceeding 60 dB (A) constitute less than 10% of the site, as shown in Figure 6a, b. It is interesting to find the lowest noise levels in Site J and Site K, and high noise levels in Site I, based on the area exposure, which is in accordance with the obtained results in Figure 5.

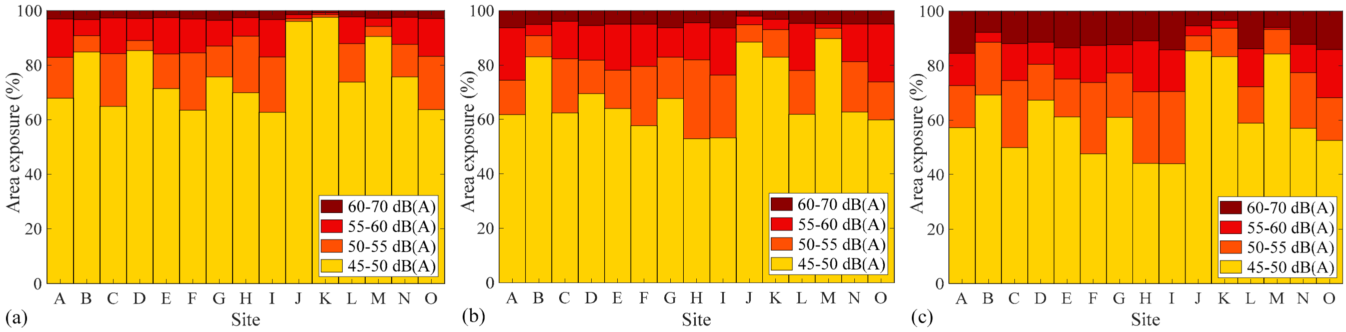


Figure 6. Area exposure proportions of noise levels, $L_{A,eq}$, for the fifteen sites under different numbers of air filters ((**a**) two air filters; (**b**) four air filters; (**c**) six air filters).

Figure 7 further shows noise levels and area exposure in the open areas of Site A, I, J, and K when four ambient air filters are situated. High noise levels exceeding 60 dB (A) are prominently observed in the vicinity of the air filter, gradually diminishing as the distance between the source and receiver increases. The emergence of lower noise level shadow zones, as depicted by the dotted line in Site K, highlights the significant impact of buildings on sound resistance, as sound waves are hindered during propagation. Site J exhibits low area exposure due to the obstruction caused by first-row buildings, whereas Sites A and I have a high incidence of noise exposure exceeding 55 dB (A). It is conjectured that urban form indices play a role in determining noise levels and area exposure in open spaces. Further analysis is required to investigate this relationship.

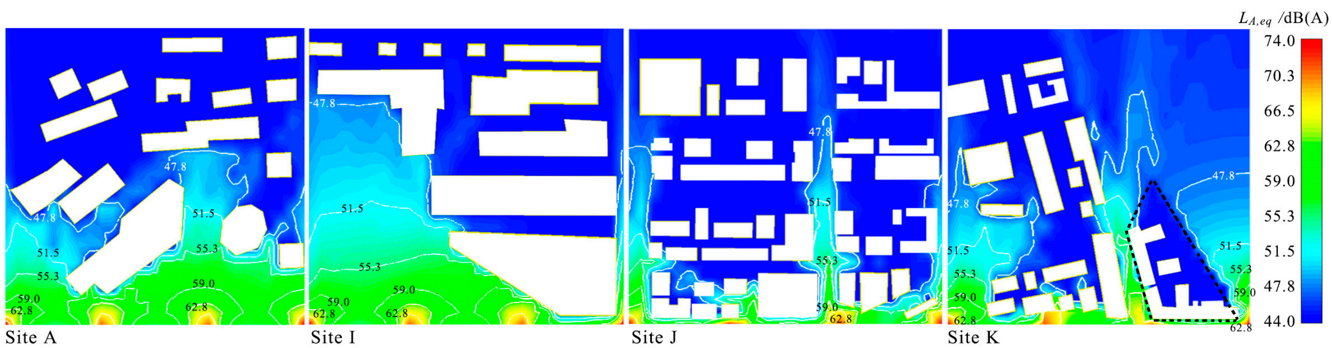


Figure 7. Noise exposure maps in open areas 1.2 m above the ground with four air filters in Sites A, I, J, and K (the dotted line in Site K represents the shadow zone created by the resistance effect of buildings).

3.3. Correlations between Noise and Urban Form Indices

By carrying out the Spearman rank correlation test using the SPSS statistics software, the correlations between urban form indices and noise indices, L_n, were examined, as given in Table 6, where 2-tailed correlations are included, and all the correlations with significance levels of $p < 0.05$ and $p < 0.01$, are highlighted with the symbols * and **, respectively. It can be seen from Table 6 that there are significant positive correlations between L_n and DFBAAF. Significant correlations between L_n and first-row building orientation (positive correlation), compactness index (negative correlation), and BPAF (negative correlation) are also observed when four and six air filters are situated on the site, which means that noise indices become larger with the decrease in BPAF and compactness index or the increase in first-row building orientation and DFBAAF. However, there is no significant correlation between L_n and spacing index or BFAI. In addition, the absolute value of correlation between DFBAAF and L_n is larger than that of any others in Table 6. Furthermore, it is interesting to find that BPAF, compactness index, and first-row building orientation mainly influence the average noise and background noise level based on the significant correlations between these urban morphological indices and L_{60} and L_{80}. DFBAAF influences the peak noise and average noise (see the correlations between DFBAAF and L_{10}, L_{20}, and L_{40}).

Table 6. Correlations between noise indices and urban form indices.

		Building Plan Area Fraction	Spacing Index	Compactness Index	First-Row Building Orientation	Distance of First-Row Building to the Ambient Air Filter	Building Frontal Area Index
Two air filters	L_{10}	−0.12	0.201	0.05	0.206	0.697 **	−0.013
	L_{20}	−0.107	0.134	0.048	0.229	0.828 **	−0.293
	L_{40}	−0.215	0.145	−0.233	0.468	0.742 **	−0.222
	L_{60}	−0.383	0.172	−0.485	0.433	0.605 *	−0.304
	L_{80}	−0.433	0.124	−0.371	0.371	0.124	0.247
Four air filters	L_{10}	0.202	−0.011	0.317	0.197	0.601 *	−0.009
	L_{20}	−0.055	−0.059	0.075	0.275	0.844 **	−0.324
	L_{40}	−0.114	−0.111	−0.139	0.599 *	0.832 **	−0.464
	L_{60}	−0.564 *	0.101	−0.585 *	0.638 *	0.447	−0.176
	L_{80}	−0.578 *	0.255	−0.523 *	0.546 *	0.115	−0.285
Six air filters	L_{10}	0.262	−0.045	0.442	0.245	0.666 **	−0.284
	L_{20}	−0.013	−0.091	0.089	0.301	0.882 **	−0.399
	L_{40}	−0.15	−0.057	−0.175	0.62 *	0.843 **	−0.45
	L_{60}	−0.429	0.16	−0.438	0.612 *	0.51	−0.212
	L_{80}	−0.526*	0.1	−0.588 *	0.605 *	0.383	−0.315

Note: * $p < 0.05$ level (2-tailed) in bivariate correlation; ** $p < 0.01$ level (2-tailed) in bivariate correlation.

Table 6 also reveals the effects of the number of air filters on noise exposure. It is interesting to find that, when two air filters are situated in the site, there is no statistically significant correlation between noise distribution indices (L_{60}, L_{80}) and urban form indices (BPAF, compactness index, first-row building orientation). However, significant correlations between these parameters are found at the $p < 0.05$ level, when four or six air filters applied. This is because the low sound power level of only two point sources leads to the very close noise level of L_{60} or L_{80} among different sites with the value of 45.5 dB (A).

To further illustrate the general effect of urban form indices on noise indices in open areas, the correlations between L_n and the four urban form indices are illustrated in Figure 8. Negative correlations between L_n and BPAF and compactness index are observed in Figures 8a and 8b, respectively, indicating the reduction in noise level with the increase in BPAF and compactness index. The slope of the regression line in Figure 8a,b suggests that BPAF and compactness index exert a greater impact on L_{60} than on L_{80}. Conversely, Figure 8c,d demonstrate a positive correlation between L_n and first-row building orientation and DFBAAF. Comparison of the regression line slopes indicates that changes in first-row building orientation and DFBAAF have a more pronounced impact on peak noise (L_{10}) than on average and background noise levels.

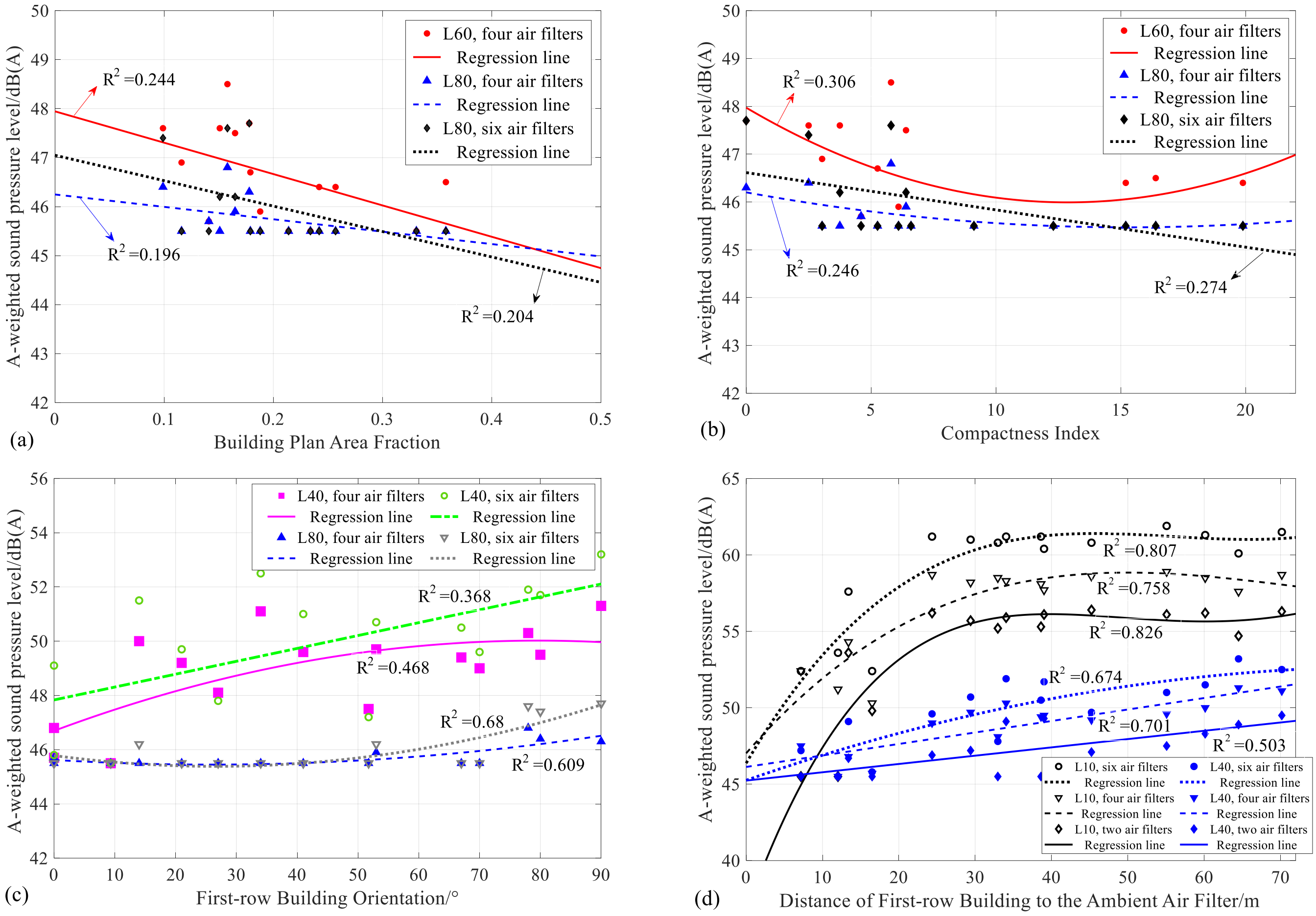


Figure 8. Correlations between noise indices and urban form indices ((**a**) Building Plan Area Fraction; (**b**) Compactness Index; (**c**) First-row Building Orientation; (**d**) Distance of First-row Building to the Ambient Air Filter).

Moreover, the regression lines in Figure 8 facilitate the estimation of noise level attenuation. Figure 8d illustrates that, depending on the distance from air filters, the first-row buildings can generate a maximum peak noise (L_{10}) reduction of 12.0 dB (A) in open areas. When the distance between the first-row buildings and air filters exceeds 35 m, peak noise levels (L_{10}) remain constant, whereas average noise (L_{40}) levels continue to increase gradually. In Figure 8c, a maximum attenuation of 3.8 dB (A) can be achieved in average noise levels (L_{40}) within open areas when the longer façade of the first-row building is parallel to the air filters. These urban form indices, therefore, could be profiled and used as an “a priori” tool for urban planning with sound environment considerations.

4. Conclusions

This study investigated how ambient air filter noise exposure in city open areas is influenced by urban form, and analyzed the key urban form indices affecting noise level. Fifteen sample sites with different urban forms, such as land use, building forms, building coverage, and density, were first chosen, for which urban form indices and noise distribution indices were defined. Subsequently, noise mapping was performed using the beam-tracing method to analyze the noise levels and area exposure ratios of air filters in open areas at each site. Correlations between noise and urban form indices were then calculated to assess the impact of urban form on noise exposure. Results show that urban form has considerable effects on noise exposure in open areas. The distance of the first-row building to the air filter was found to be the key factor affecting noise levels and showed the highest positive correlation with peak noise (R = 0.754) and average noise (R = 0.756) in open areas. The first-row buildings exert a resisting effect that can lead to a maximum peak noise reduction of 12.0 Db (A). Furthermore, the orientation of the first-row building's longer facade exhibited a significant impact (R = 0.617) on average noise levels, with a maximum attenuation of 3.8 dB (A) observed when the longer facade is parallel to the air filters. Both compactness index (R = −0.556) and building plan area fraction of sites (R = −0.552) showed noticeable negative correlations with background noise.

Although differences in the air filter noise level of the virtual model between the predicted and measured results were found, noise tonalities by prediction were equal to those found by measurement, and are still suitable for investigation of the effect of urban forms on air filter noise exposure in open areas. This study did not encompass all potential urban forms, but it can still be deemed a valuable design technique for urban planning that prioritizes acoustic environment considerations. Furthermore, controlling the urban form indices was proven to be an effective means of reducing noise levels in open areas of cities. Future work may systematically consider more sample sites with different urban forms across the world. Additionally, to decrease the noise impact of the air filters, it would be better to reduce air pollution by reducing car traffic and other sources of air pollution in metropolises.

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