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Investigation on multiple traffic noise near an airport and their effect on nearby residents

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This study investigates the impact of the noise radiated from airplanes, urban rail transit, high-speed railways, and urban roads on residents near an airport. The results showed that all respondents near the airport were highly annoyed with airplane noise, and some remain annoyed with the noise from the urban rail transit and high-speed railway connecting to the airport. The most detrimental aspect of transportation noise was sleeping disturbance. Transportation noise from 19:00 to 24:00 primarily caused the annoyance of surrounding residents. Airplane noise is the largest source of sound pollution in residences in the region adjacent to the elevated urban rail transit and airport. The insertion loss of vertical sound barrier with a height of 2.4 m at the points 25 m away from the track centerline is 6.9–8.6 dB, but the sound pressure level below 40 Hz is amplified owing to the structure-borne noise radiating from the barrier itself. The presence of sound barriers can reduce the high annoyance level from 24 to 8.2%.

Keywords Airplane noise, Railway noise, Road noise, Noise annoyance, Vertical sound barrier

Multimodal transportation hubs that integrate railways, roadways, and aviation can facilitate the travel of passengers and movement of goods and improve the efficiency of transportation. As the scale of transportation demand and the corresponding infrastructure continue to expand worldwide, multimodal transportation hubs are becoming increasingly common. However, noise pollution caused by transportation around such hubs threatens the lives of nearby residents. The World Health Organization estimated that at least 100 million people in the EU are affected by road traffic noise, and in Western Europe alone at least 1.6 million healthy years of life are lost as a result of road traffic noise based on the assessment threshold specified in the Environmental Noise Directive of the European Union (EU)[1]. In the US, 7.8 million (2.4%) individuals were highly annoyed with aviation noise, while 5.2 million (1.6%) and 7.9 million (2.4%) were highly annoyed with rail and roadway noise, respectively, in 2020[2]. Data from the annual reports of the Ministry of Ecology and Environment of the People's Republic of China show that the number of complaints about traffic noise in China increased markedly from 9,140 in 2014 to 195,000 in 2022. Noise pollution from traffic is an important environmental determinant of the health of the population[3,4]. Traffic noise, as an important source of noise pollution, has become a hot topic of government and public concerns[5–8].

Traffic noise has a significant negative impact on health and well-being of citizens, including physical ailments and psychological problems. Many attempts have been made to explore the relationship between traffic noise and negative effects. Based on the meta-analysis it is found that road traffic noise was positively correlated with hypertension, and people exposed to traffic noise had a higher risk of cardiovascular disease[9]. The correlation between the exposure to road traffic noise and hypertension is quite strong when residents live in a house without triple-glazed windows, an old house and the bedroom window facing a street[10]. Additionally, long-term exposure to road traffic noise would significantly increase the risk of stroke and heart failure[11]. Railway noise can also have adverse effects on cardiovascular disease[12]. In Pisa of Italy and the Gyeonggi province of South Korea, railway noise was found to be more likely to cause fluctuations in blood pressure than road traffic noise[13,14]. The impact of airplane noise at night on cardiovascular disease included the rise in blood pressure, the increase of stress hormone, and the impairing of endothelial function[15]. The combination of different types of noises exacerbates the adverse effect on health. The combined exposure to airplane, road, and railway traffic noise results in the higher risk of depression than any of the separate traffic noise[16].

In addition, prolonged exposure to transportation noise can cause sleep disturbances in people, and do harm to students' ability to learn. It is reported that more and more residents are suffering from the sleep disturbance by

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the road traffic noise induced by urbanization[17]. Railway noise will improve the likelihood of sleep disruption[18]. The chronic sleep debt caused by long-term exposure to nocturnal railway noise deteriorates the cognitive performance for residents living along rail tracks[19]. The high-speed railway noise has caused some interference to students' learning[20]. Students chronically exposed to airplane noise exhibited lower performance in reading comprehension[21]. The exposure to airplane noise increases the residents' heart rates during the sleeping[22]. It is found that the airplane noise is the biggest threat to a sleep, followed by railway noise, and then road traffic noise[23].

Noise annoyance can be considered an early warning sign of serious health risks because it has a much shorter developmental time than somatic diseases[24]. Therefore, the annoyance level experienced by people under the influence of noise must be accurately characterized. Typically, the annoyance level of people owing to traffic noise is described by exposure–response curves[25]. Many studies have focused on annoyance response under long- and short-term noise exposure conditions[26–29]. Brink et al.[24] built a mapping relationship between noise exposure and percentage highly annoyed under various individual noise sources (road, rail, or aviation) using a questionnaire survey and then characterized the exposure characteristics of noise by utilizing the intermittent ratio, suggesting that longer pauses are positive in reducing annoyance. The dose–response relationship suggests that higher levels of a type noise exposure, railway noise, induce higher levels of annoyance[26,27]. The road traffic noise in combination with rail traffic noise leads to an increase of the annoyance effect[28]. Noise caused by railway operations may exacerbate the annoyance level of residents[27,28,30]. Sociodemographic, psychosocial, and contextual factors also influence the annoyance level of affected individuals[31].

The precise evaluation, assessment and monitoring of noise exposure are the prerequisite to reduce its adverse impact. Typically, this evaluation involves long-term average noise levels obtained through advanced measurement or simulation techniques[32]. Noise maps, as an effective tool for providing noise exposure in specific areas, have been widely applied and developed. Compared with the expensive method of obtaining noise maps through measurements in a regular grid of points, noise propagation models has been selected due to its economic advantage[33]. Changes in noise levels during long period and temporary variations in environmental noise[34] have highlighted the disadvantages of traditional "static" noise maps, and then dynamic noise maps have emerged. The dynamic noise map allows real-time monitoring on the impact of noise sources[35]. Tao et al.[36] investigate how different locations that individuals visited in their daily lives were associated with varying noise exposure and psychological responses from dynamic perspective. The internet of things has promoted the dynamic noise map through the development of wireless acoustic sensor networks[37,38]. However, noise monitoring requires the use of high-quality equipment[39], and the cost remains high. The use of low-cost cameras and machine learning opens up a new possibility for the realization of noise maps over time[40]. Based on the large amount of data obtained from monitoring, the deep learning or artificial intelligence was used to predict the noise level[41,42].

The measures to mitigate the impact of transportation noise can be taken on the source, path, or receiver. The control of source and transmission path are the widely used measures in transportation noise so far. The European Directive 2002/49/EC has been constructed as a policy instrument to assess and manage environmental noise[43]. Electric vehicles provide an opportunity for a reduction in environmental noise from vehicles[44], which have reduced engine noise in the low speed range[45]. Low-noise pavement[46], silent tires[47] and speed limit are used to mitigate the noise exposure level of road traffic. However, the aging or damage of tires and road surfaces will inevitably increase noise[48]. The reduction of running speed may cause the traffic congestion and low operational efficiency. As is well known, the higher speed of vehicle means the larger noise, especially for the wheel-rail noise[49] and aerodynamic noise[50] in railway systems. Therefore, the method to control noise in the propagation path is alternative when noise reduction at the source fails to achieve the desired goal or is difficult to deal with. The sound barrier has become the most effective measure used in the suppression of transportation noise[51].

The sound pressure level like the day-evening-night level[52] has been used to evaluate human physiological or psychological responses to traffic noise. The psychoacoustic and noise indices from the sound pressure level of transportation noise were proposed for noise evaluation on environmental noise exposure[53]. Nevertheless, sometimes the increase in the sound pressure level plays an important role in influencing people's perceptions[54]. The spectral characteristic of noise is also crucial to analyze human responses[55,56]. Recently, the scientific community also has moved its attention towards realizing a broader spectrum of sound exposure features, and not only the annual average. Peak level and variation over time, impulsivity of events, frequency distribution, psycho-acoustics parameters can all have a significant influence on nuisance perception, and citizens are known to complain more about single high levels rather than average exposure[57]. Therefore, the variation in the human exposure–response induced by the diverse spectral characteristics of various traffic noises is still worthy of discussion.

The objective of the present study is to investigate the annoyance and spectral characteristics of airplanes, high-speed railways, elevated urban rail transit noise, and exposure of different noise sources. Additionally, the ability of sound barriers to mitigate noise from urban rail transit viaducts was elucidated, and the relationship between the sound barriers and the annoyance response of residents along the viaduct was demonstrated. This paper is structured as follows. Section 2 presents the survey, and noise tests which consists of the testing instrument, the description of measuring point layout, and the noise evaluation method. Section 3 analyzed the results of the survey and noise test. The annoyance levels, time periods, and activities of residents affected by airplane, urban rail transit, high-speed railway, and urban road noises are demonstrated. The sound source characteristics and dose-response relationships of four sound sources are given. The effects of sound barriers in reducing noise and high annoyance are also quantified. Finally, Section 4 gives the conclusions.

Survey and field tests

Survey on the impact of noise on residents

A questionnaire survey is one of the most commonly used methods for assessing the subjective experiences of residents affected by transportation noises. In this study, a questionnaire survey was conducted to evaluate the annoyance responses of neighboring residents influenced by traffic noise. The design of the questionnaire was based on the best practice guidelines for noise annoyance developed by the International Commission on the Biological Effects of Noise[58], guidelines from ISO/TS 15,666: 2021[59], and the Chinese Standard GB/T 42,473 – 2023[60]. Owing to questionnaire length and cost constraints, and to make it easier to use, a 5-point scale, which corresponds to an 11-point numeric scale, was used to indicate the annoyance level[61]. Factors affecting the annoyance rate, such as different types of transportation noise sources, distance from the noise source, sound barriers, and life pressures, were considered in the questionnaire. Gender, age, education level, and noise sensitivity related to annoyance level[62–66] were also included. The questionnaire is shown in Table S1.

This questionnaire investigated the relationship between traffic noise and the annoyance responses of residents near airports and urban railway transit/urban roads. The airplane noise is a particular nuisance on take-off and landing[67], which seriously impacts nearby residents. Residents reacted strongly to disturbances in airplane noise. Simultaneously, the residential areas near the international airport also receive the noise from the urban rail transit and high-speed railway. Therefore, the questionnaire was used to investigate the degree of annoyance among residents under the influence of multiple transportation noise sources. The questionnaire survey was conducted during on-site visits. After checking and eliminating invalid questionnaires, 200 valid questionnaires were obtained. Photographs of the onsite questionnaire survey are shown in Fig. 1.

Noise test

Test 1 is used to determine the characteristics of several noise sources and it is located in Village 1 near an airport in China, where the residents are plagued by airport, urban rail transit, and high-speed railway noise. Test 2 and Test 3 are used to evaluate the reduction performance of upright sound barriers on urban rail transit noise. Test 2 and Test 3 are located in a section with sound barriers and without vertical sound barriers in an elevated urban rail transit line. The locations of the three tests are shown in Fig. 2. It should be noted that this test plan is determined based on the ISO 3095: 2013[68] and the Chinese Standard GB 12525-90[69].

Testing instrument

The testing equipment included a 24-channel data acquisition device and free-field microphones which were calibrated before the test. When the equivalent continuous sound pressure level during the duration of transportation noise was calculated, the integration time of airplane, urban rail transit, and high-speed railway noise was 7.6 s, 8.7 s, and 20 s, respectively. The sampling frequency range is 25,000 Hz.

Measuring point layout

Assessing people's actual responses to noise from either outdoor or indoor noise levels is unreasonable[71]. Therefore, Test 1 was conducted to simultaneously obtain actual noise levels inside and outside a residence and

Fig. 1. Photos of questionnaire survey.

Fig. 2. Satellite map[70] of measurement point locations and surrounding noise sources (Baidu Maps (Version: V19.1.0) [Web Application Software]. URL: https://map.baidu.com. (2023)).

assess the difference between indoor and outdoor noise. The spectra and overall sound pressure levels of multiple transportation noises were obtained during this field test.

As shown in Fig. 3, measurement points NP1 to NP5, located outside the residential sites and close to the urban rail transit viaduct in Location 1, were used to assess outdoor transportation noise. Additionally, five measurement points were arranged at Location 2, inside and outside the residence, to measure the sound pressure levels of indoor and outdoor noise. The second-floor height of the residence is 3.3 m. Measurement points N1 and N2 were located on the first floor of the residence, 1.2 m above the outdoor and indoor floors, and N3 (outdoor) and N4 (indoor) were located 1.2 m above the second floor of the residence. N5 was located at a distance of 7.8 m above the ground level and was used to assess the outdoor airplane noise. Microphones N5 and NP5 were fixed vertically to the fiber rods to obtain the sound pressure of the airplane noise. Windows and door were closed during the tests. The test photographs are shown in Fig. 4.

The layouts of the noise measurement points of the viaduct sections with and without sound barriers were identical in Test 2 and Test 3, as shown in Figs. 5 and 6. The running speed was 73 km/h when six-car B-type subway trains passed through both test sections. Because the noise of elevated urban rail transit is dominated by wheel-rail noise and bridge structure-borne noise, measurement points N1 to N3 were arranged in the cable support next to the rail to acquire the wheel-rail noise. N5 to N6 were placed beneath the box girder bottom plate to measure the bridge structure-borne noise. To collect the comprehensive noise of the urban rail transit viaduct and study its diffusion, noise measurement points N7 to N11 and N12 to N16 were arranged at 7.5 m and 25 m away from the track centerline, respectively.

The viaduct contains 30 m simply supported concrete box-girders, with a deck slab width of 9.3 m, bottom slab width of 4.0 m, and girder height of 1.8 m; the spacing of the track centerlines of the double-track viaduct is 4.0 m. The height of the bottom of the girder for the vertical sound barrier section was 2.4 m from the ground, whereas that of the section without a sound barrier was 3.8 m. The height of the vertical sound barrier was 2.4 m, the thickness of the polycarbonate board (PC board) was 10 mm, and the thickness of the sound-absorbing board was 128 mm. Photographs of the field tests are shown in Fig. 7.

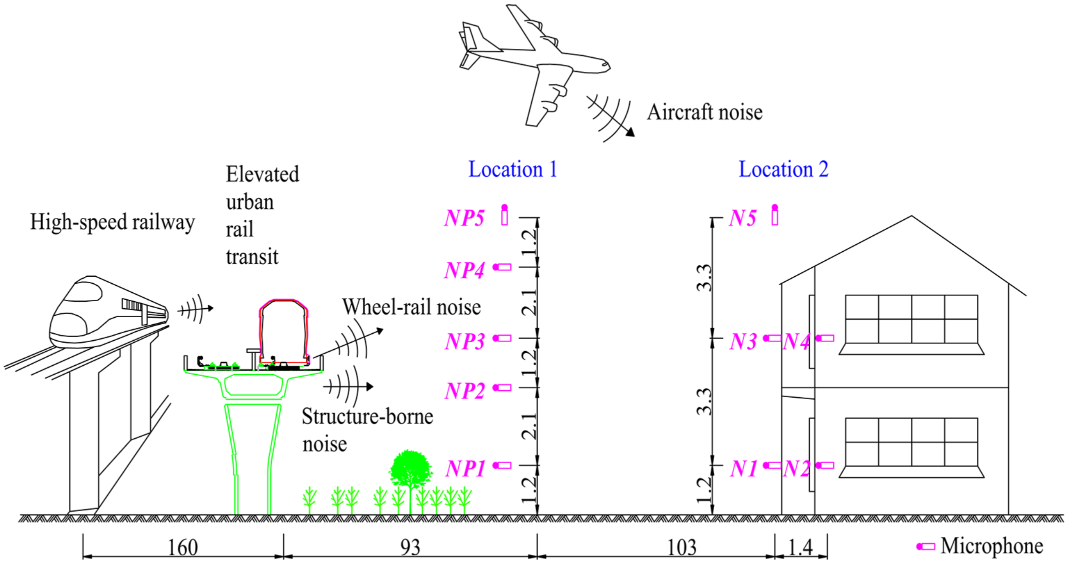

Fig. 3. Layout of noise measuring points in a residential area (unit: m).

Fig. 4. Field test in residential areas.

Noise evaluation method
The sound pressure data during the train passing time *t* is extracted for the calculation of equivalent continuous sound pressure level[68], as shown in Eq. (1).

$$L_{\mathrm{pAeq,T}} = 10\lg\left(\frac{1}{T}\int_0^T \frac{{p_{\mathrm{A}}}^2(t)}{{p_0}^2}dt\right) \tag{1}$$

where, $L_{\mathrm{pAeq,\ T}}$ is the A-weighted equivalent continuous sound pressure level in dB; T is the measurement time interval; p_{A}(t) is the A-weighted instantaneous sound pressure at running time t in Pa; p_0 is the reference sound pressure; $p_0 = 20$ μPa.

Results analysis
Noise annoyance assessment
The sample distribution of the samples from the 200 valid responses is listed in Table S2. Residents in the vicinity of airports and elevated urban rail transit suffer from airplane, elevated urban rail transit, high-speed railway, and urban road noise. Because of the large overlap between residents near the urban rail transit viaduct and urban roads, the two sources are assumed to share identical samples.

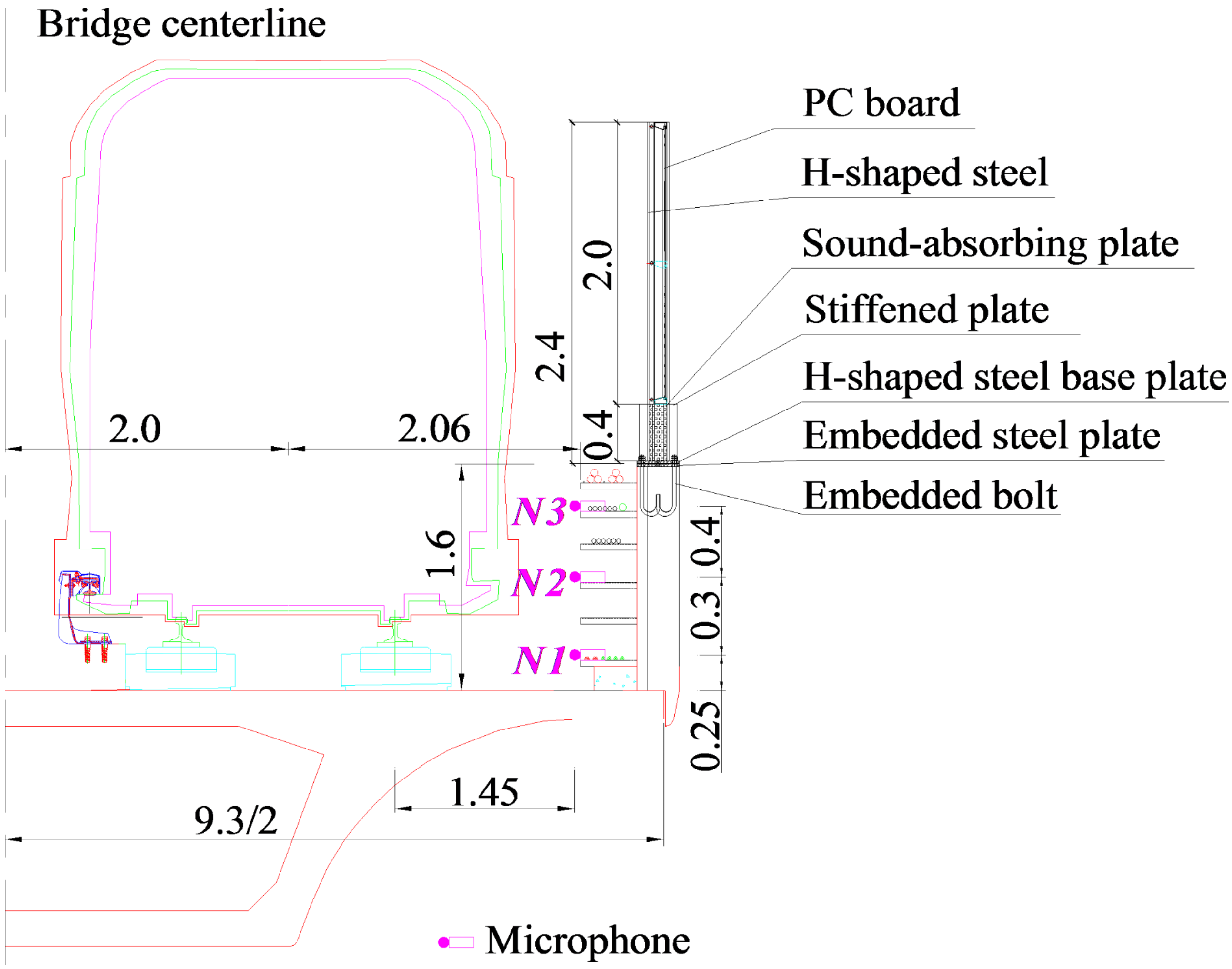

Fig. 5. Noise measurement points above the bridge deck (unit: m).

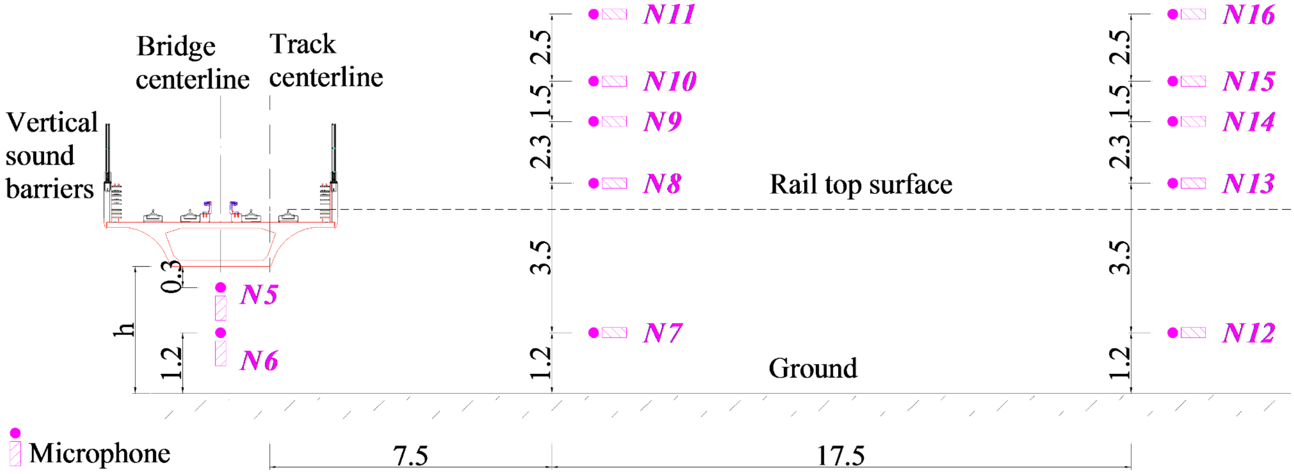

Fig. 6. Layout of noise measurement points for the urban rail transit viaduct (unit: m).

The impacts of airplanes, urban rail transit, high-speed railway, and urban road noise on residents near the airport are shown in Fig. 8. The "Very" and "Extremely" annoyed people accounted for the "highly annoyed" number[59]. Airplane noise had the greatest impact on the interviewed residents, and 100% of the residents involved in the survey experienced a high level of annoyance. Urban rail transit and high-speed railway noise

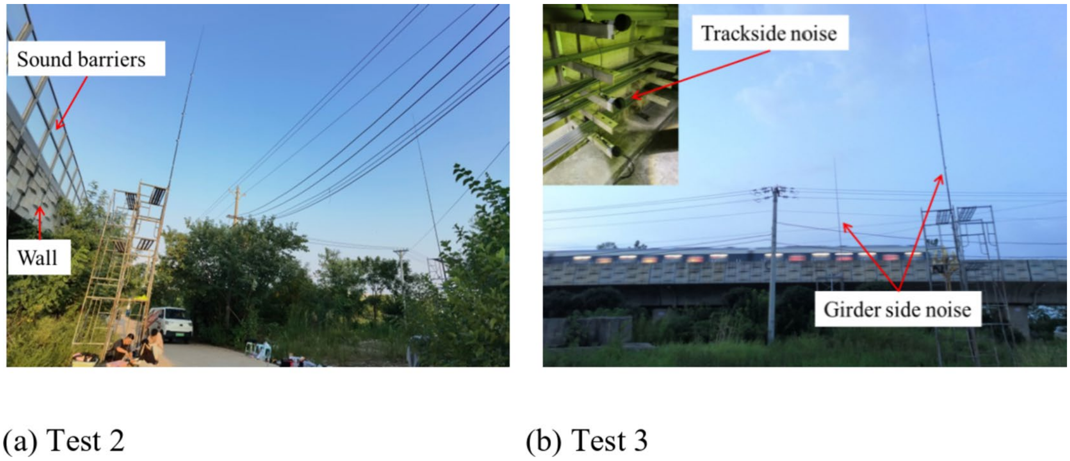

Fig. 7. Noise measurement points on the box-girder side. (a) Test 2 (b) Test 3.

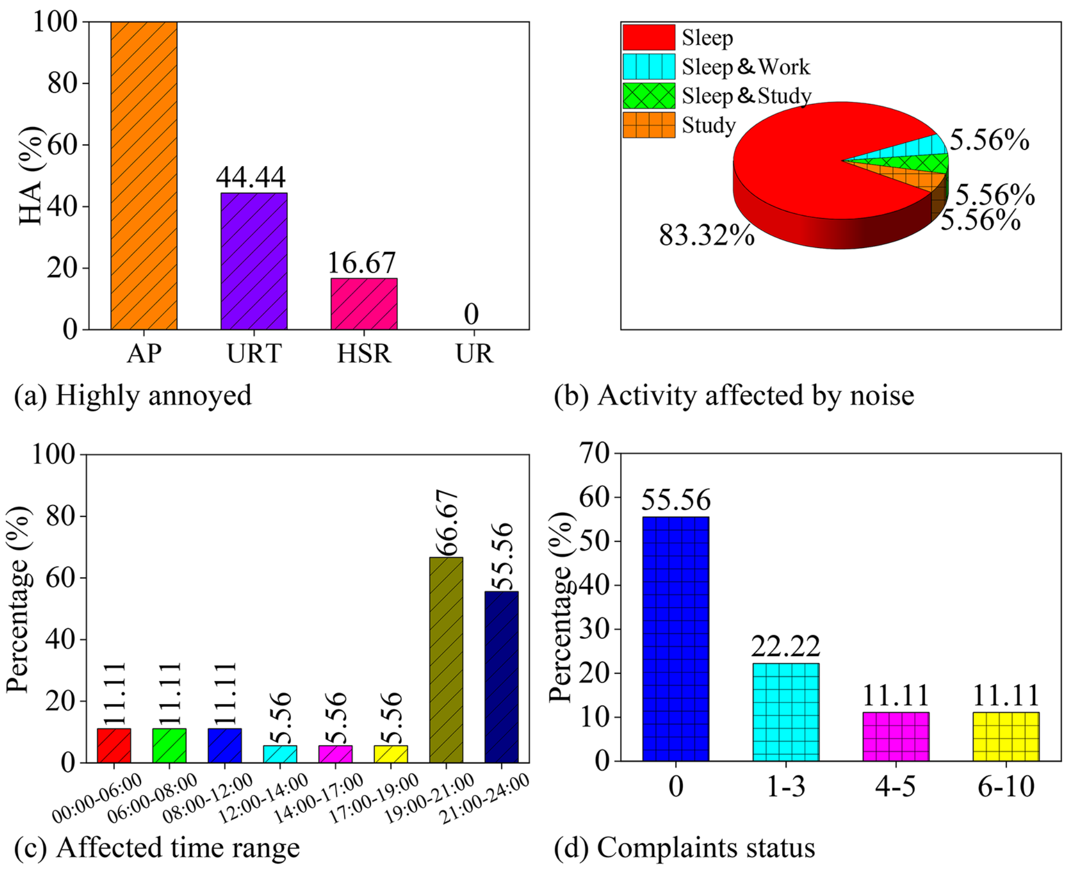

Fig. 8. Responses of the residents near the airport to multiple transportation noise. AP: Airplane, URT: Urban rail transit, HSR: High-speed railway, UR: Urban road.

also had a significant impact on the residents who completed the questionnaire, and the percentages of residents corresponding to a high annoyance degree were 44.44% and 16.67%, respectively. According to the survey, urban road noise has little impact on residents near airports. Thus, airplane noise was considered the dominant noise pollution source for residents near airports.

Of the respondents, 94.44% reported that their sleep was disturbed by the airplane noise. Sleep was the most disturbed activity, followed by studying and work. Most respondents indicated that the period of annoyance was the evening, among which 66.67% of the respondents were annoyed from 19:00 to 21:00 and 55.56% from 21:00 to 24:00. Some residents near the airport were disturbed by noise at other times of day. Due to the residents' annoyance of multiple sources, 44.44% of the respondents near the airport complained about transportation noise, with 22.22% complaining at least four times. Furthermore, according to the feedback, 72.22% of the respondents think that government-sponsored residential relocation is the best solution to the noise problem in the region close to the airport.

For residents near urban rail transit viaducts, the noise induced by trains running on the viaduct and cars running on urban roads have the greatest impact on their lives. Figure 9 shows that the residents near the elevated urban rail transit were the least annoyed with airplane and high-speed railway noise because these two sources are sufficiently far from the respondents. Therefore, urban rail transit viaducts and roads were their primary sources of noise. The percentage of respondents who were highly annoyed or annoyed with urban rail transit viaduct noise reached 53.30%. In addition, 46.70% of the respondents said that they were annoyed with urban road noise.

Sleep was also the most interrupted aspect of transportation noise, as reported by 50.56% of the respondents. Unlike the circumstances in regions near airports, residents near viaducts are affected by transportation noise in many ways, including sleep, study, mental state, and conversations. The reason for this phenomenon may be that the effects of airplane noise on talking, studying, and mood are negligible when sleep is deeply disturbed by airplane noise. The main period of transportation noise that annoyed the residents near the viaduct was also from 19:00 to 24:00. Because the sound pressure level of elevated urban rail transit and urban road noise beside the viaduct is lower than airplane noise near the airport, the proportion of residents' complaints was significantly reduced. However, the number of resident complaints was also considerable because of the high density of residents living near urban rail transit viaducts. To guide the design and implementation of noise reduction measures for urban rail transit viaducts, the factors affecting the annoyance of residents were clarified. The correlations between the factors and annoyance levels were determined using logistic regression[28]. The dependent variable produced either high annoyance or not under the influence of these factors. Therefore, a binary logistic regression analysis was used to investigate the relationship between these factors and high annoyance. The sign of the regression coefficient determines the positive or negative correlation between the annoyance level and the independent variable. If the regression coefficient is positive, an increase in the factor increases the proportion of high annoyance in the population, and vice versa. The odds ratio, as an estimation of risk[29], is the exponential power of the regression coefficient, and indicates the corresponding magnitude of change in the dependent variable when the independent variable increases by one unit. The significance level in hypothesis testing refers to the probability or risk that the original hypothesis will be rejected if correct. This

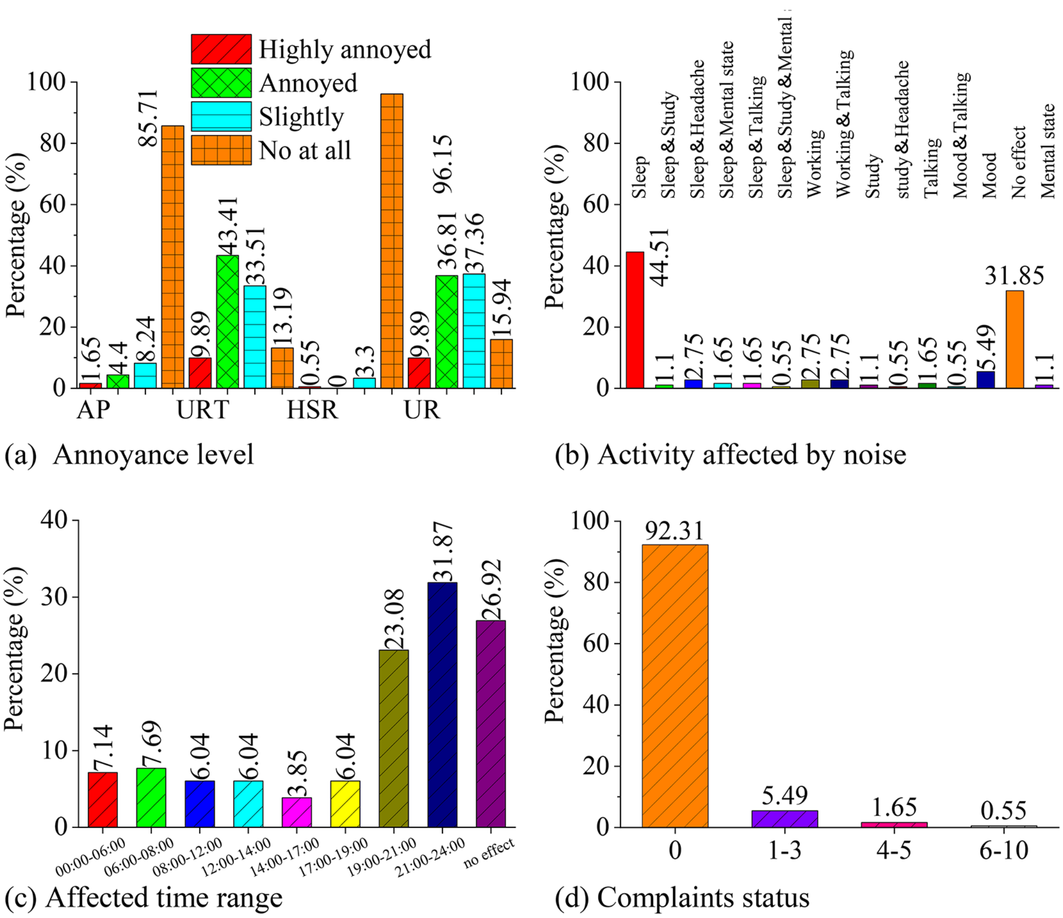

Fig. 9. Responses of the residents near the urban rail transit viaduct to multiple transportation noise.

Considerations	Gender	Age	BMI	Education	Occupation	Life pressure	Distance	Noise sensitivity	Sound barrier
Regression coefficient	0.698	−0.010	0.770	−0.439	−0.121	−0.171	−0.034	0.410	−2.328
Significance level	0.354	0.743	0.297	0.263	0.859	0.344	0.003	0.024	0.002
Odds ratio	2.009	0.990	2.160	0.644	0.886	0.843	0.966	1.506	0.097

Table 1. Correlation analysis on factors and urban rail transit viaduct noise.

Considerations	Gender	Age	BMI	Education	Occupation	Life pressure	Distance	Noise sensitivity
Regression coefficient	0.150	0.020	1.365	0.287	0.934	0.443	−0.012	0.446
Significance level	0.821	0.514	0.074	0.401	0.201	0.037	0.046	0.006
Odds ratio	1.162	1.020	3.917	1.332	2.545	1.557	0.988	1.562

Table 2. Correlation analysis on factors and urban road noise.

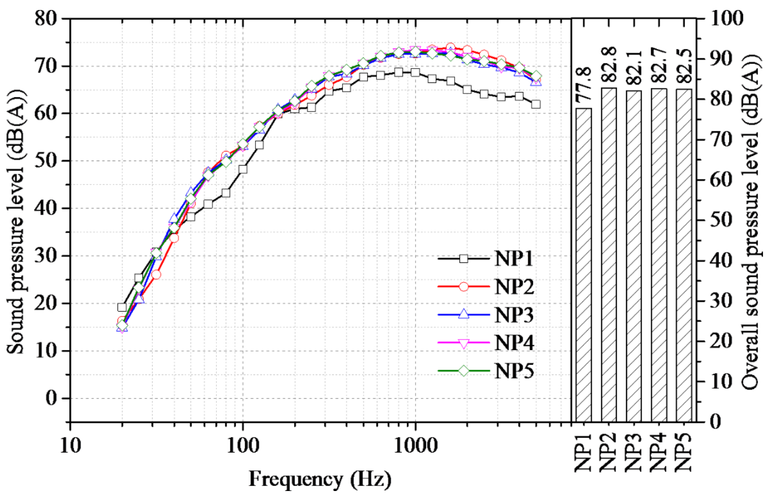

Fig. 10. Outdoor noise at Location 1 (near the viaduct) from an airplane.

value is frequently considered as 0.05, indicating that the probability of being correct is 95% when the original hypothesis is accepted.

Through binary logistic regression analysis, the correlation level of each factor with a high annoyance level under a confidence interval of 95% was obtained, as shown in Table 1. The distance from the residence to the viaduct, the residents' sensitivity to noise, and sound barriers had a significant correlation with the high annoyance level because their significance level was <0.05. In contrast, the annoyance level was not sensitive to other factors. Similarly, for urban road noise, the distance between the residence and the road, residents' sensitivity to noise, and life pressure were correlated with a high annoyance level under a confidence interval of 95%, while the other factors did not change the annoyance level significantly, as shown in Table 2.

Noise investigation of multiple sources

Due to the involvement of noise source superposition in multi-source mixed testing scenes, this section discusses independent sound sources and combined noise sources separately.

Independent sound source

By analyzing the data of Test 1, the A-weighted spectral characteristics and overall sound pressure levels of multiple transportation noises were obtained; Figs. 10 and 11 show the airplane noise. The overall sound pressure levels at N1 and NP1, which were 1.2 m above the ground, reached 77.2 and 77.8 dB(A), respectively, and were less than those at the other outdoor points due to the shielding of the ground building and plants to the airplane noise. For NP2–NP5 at Location 1, the peak value in the frequency domain was approximately 73 dB(A) and the dominant frequency ranged from 500 to 3000 Hz. The overall sound pressure levels at these points exceeded 80 dB(A). Furthermore, the overall sound pressure levels of indoor noise on the first and second floors were 62 (N2) and 63.8 dB(A) (N4), respectively. Due to the shielding effect of the walls and windows of the houses, a reduction of 15.3 and 16.3 dB(A), respectively, were achieved compared with the outdoor measurement points at the same height. From the outdoor airplane noise test results for N5 and NP5, the airplane noise spectra at Locations 1 and 2 exhibited the same trend.

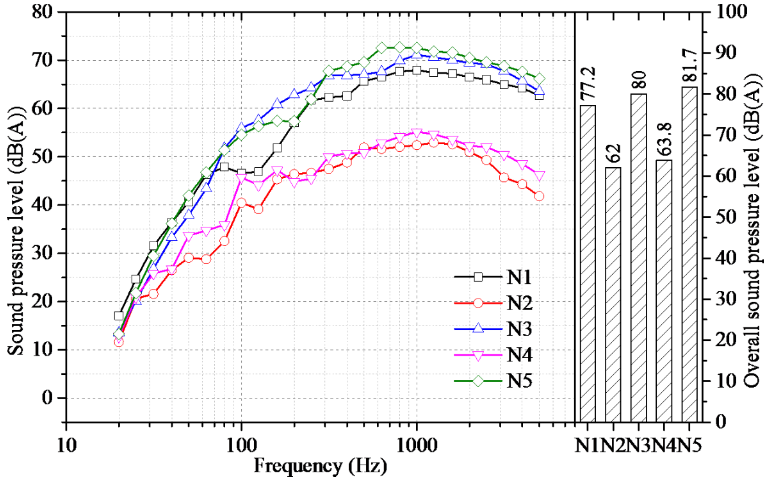

Fig. 11. Indoor and outdoor noise at Location 2 from an airplane.

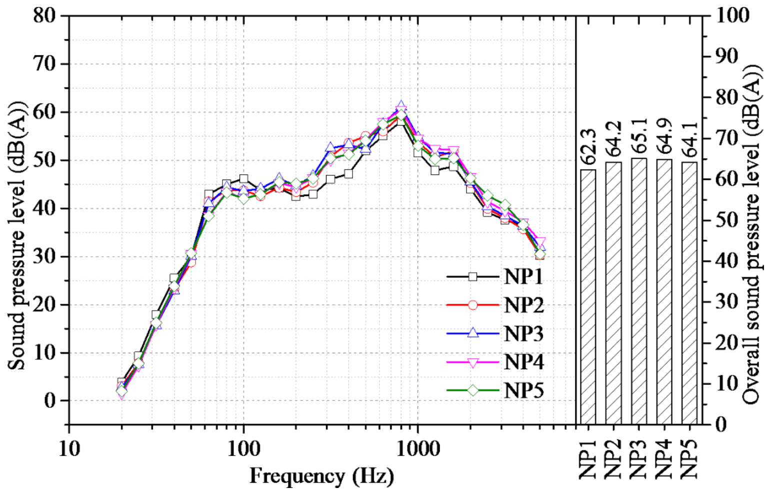

Fig. 12. Outdoor noise from the urban rail transit induced by a train running through the nearer track.

The spectra and overall sound pressure levels of the urban rail transit viaduct noise at Locations 1 and 2 are shown in Figs. 12, 13, 14 and 15. The frequency of the noise peak generated by the elevated urban rail transit system was approximately 800 Hz. The peak sound pressure levels at the measurement points approximately 93 m from the viaduct were 58–60 dB(A), and the peak of the outdoor noise at Location 2, which was 196 m from the urban rail transit, was 46–47 dB(A) in the frequency domain. The difference between the radiated noise of the elevated urban rail transit induced by a train running in two directions was less than 1.3 dB(A). The indoor noise was 12.7–15.5 dB(A) less than the corresponding outdoor noise in Location 2 owing to the shielding of walls and windows. The indoor noise at N4 on the second floor was 2.8–4.8 dB(A) larger than that at N2 on the first floor due to the shielding of ground building to the high-frequency noise.

The indoor and outdoor background noises at N1–N5 in Location 2 are shown in Fig. 16. A comparison of Figs. 14 and 16 shows that the indoor and outdoor noise of the residence increased by 4.5–6.3 dB(A) owing to the noise of the elevated urban rail transit. The inside and outside environments of the residence at Location 2 were polluted by urban rail transit noise.

Figures 17 and 18 show the spectra and overall sound pressure levels of the high-speed railway noise at both locations. The peak frequency of the high-speed railway noise at these points was approximately 630 Hz and the peak sound pressure level reached 70 dB(A). The sound pressure level of high-speed railway noise in the range of 500–630 Hz was much greater than that in other frequency bands. The overall sound pressure level of outdoor noise at Location 1 near the viaduct reached 59.5–72.2 dB(A). The overall sound pressure levels of the indoor noise at N2 and N4 were 51.4 and 50.9 dB(A), respectively, which are 10.8 and 16.1 dB(A) lower than those of the outdoor noise near the residence, respectively.

The test results of the airplane, urban rail transit, and high-speed railway noise at N3 and N4 in Location 2 of Test 1 are shown in Fig. 19, where the shaded portion is the envelope of all test results and the solid line is the mean value of the measured sound pressure level. The sound pressure level of the airplane noise was the highest.

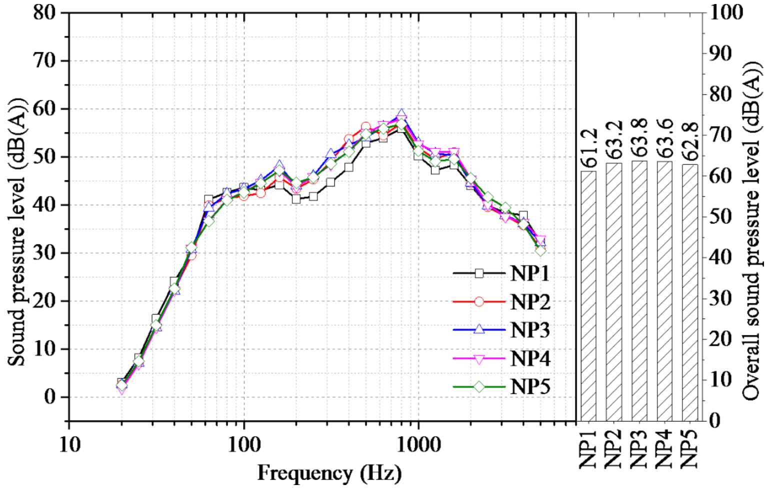

Fig. 13. Outdoor noise from the urban rail transit induced by a train running through the farther track.

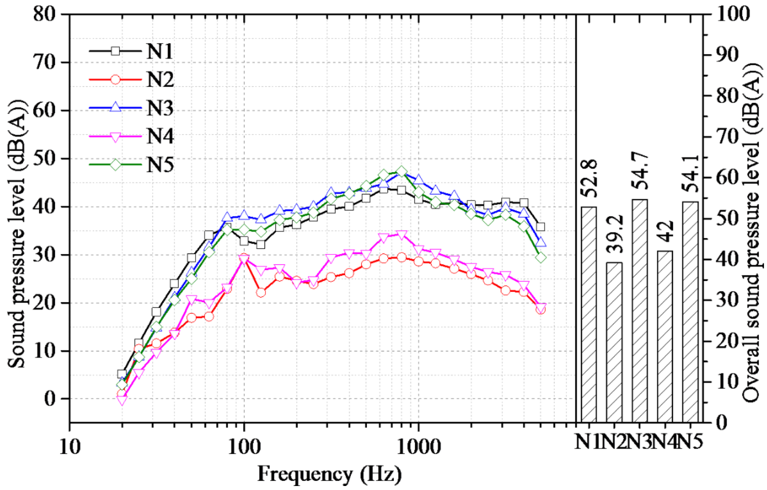

Fig. 14. Indoor and outdoor noise from the urban rail transit induced by a train running through the nearer track.

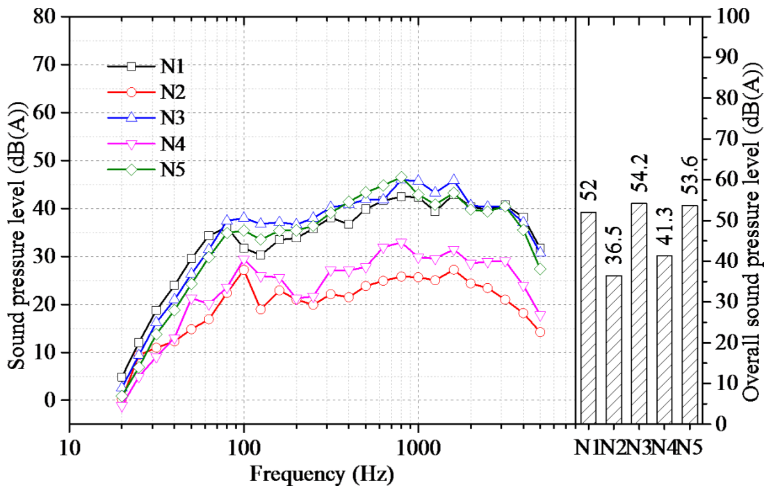

Fig. 15. Indoor and outdoor noise from the urban rail transit induced by a train running through the farther track.

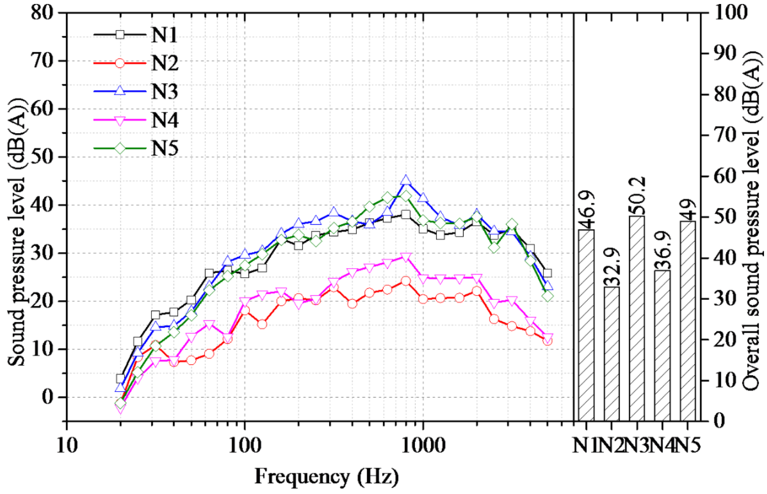

Fig. 16. Indoor and outdoor background noise at Location 2.

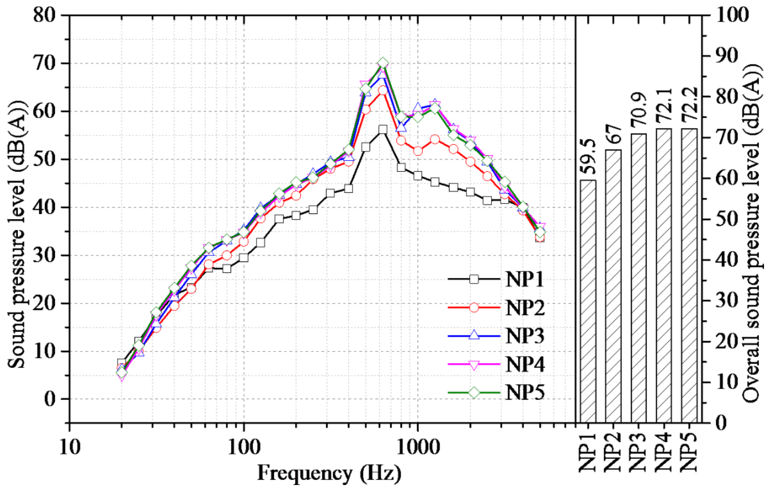

Fig. 17. Outdoor noise from the high-speed railway.

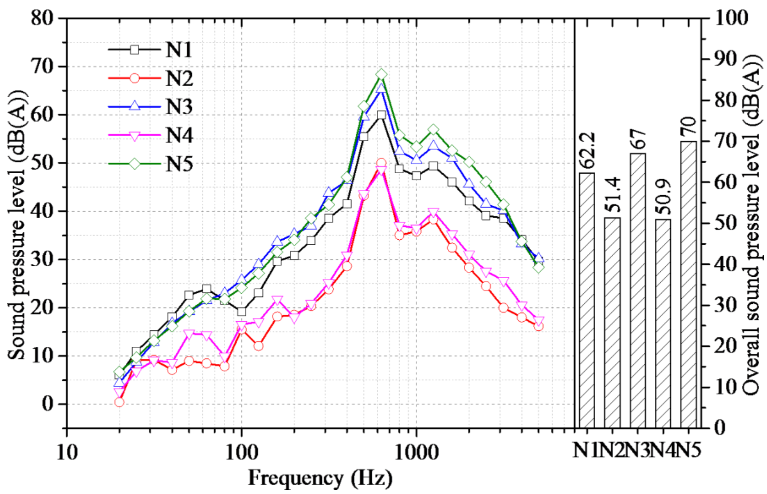

Fig. 18. Indoor and outdoor noise from the high-speed railway.

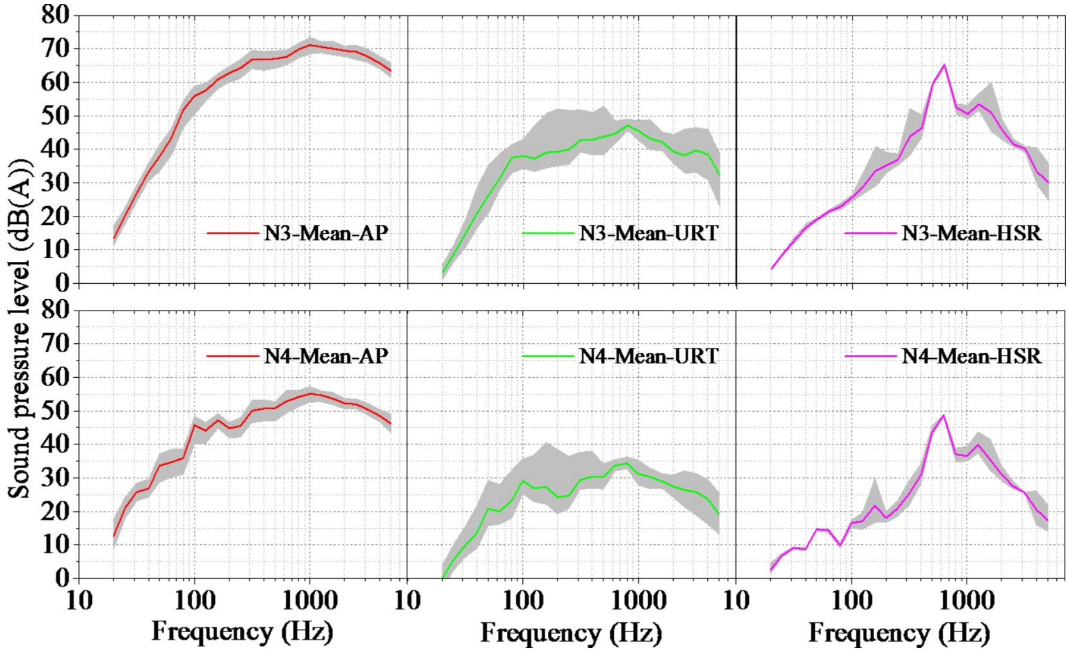

Fig. 19. Measured sound pressure levels inside and outside the residence.

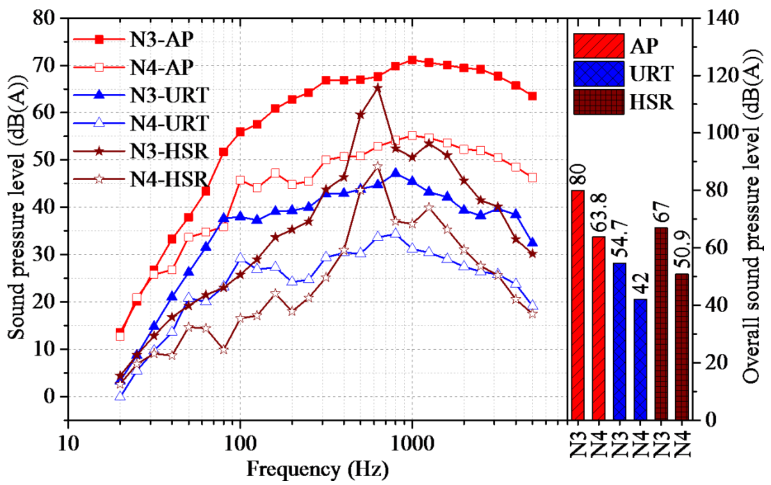

Fig. 20. Indoor and outdoor noise from various sound sources.

The dominant frequency ranges of airplane and urban rail transit noise were quite broad, making it challenging to control these two types of noise. The variability of airplane and high-speed railway noise was relatively small, but the uncertainty of urban rail transit noise was significant.

Figure 20 shows the indoor and outdoor sound pressure levels of the airplane, urban rail transit near the track, and high-speed railway noise, respectively. Based on this figure, the sound pressure level of airplane noise was the highest, followed by high-speed railway noise and urban rail transit viaduct noise.

As shown in Fig. 21, the transmission loss (*TL*) from the outdoor to the indoor point of multiple transportation noise mainly occurs in the frequency bands above 50 Hz, and the outdoor noise is reduced by 10.8 to 16.3 dB(A) due to the shielding of walls or windows, which indicates that these barriers have a good noise reduction effect on the noise sources. Notably, the *TL* of the high-speed railway noise on the first floor was much lower than that on the second floor. This may be the reason why no obstacle is in the higher position between the measurement point on the second floor and the high-speed railway, except for the propagation medium air; this measurement point was mainly affected by high-frequency wheel-rail noise. However, buildings and vegetation around the ground have sound attenuation. Compared with the *TL* of urban rail transit and high-speed railway noise, the *TL* of airplane noise was the largest. Furthermore, airplane noise was the largest source of sound pollution in residential rooms.

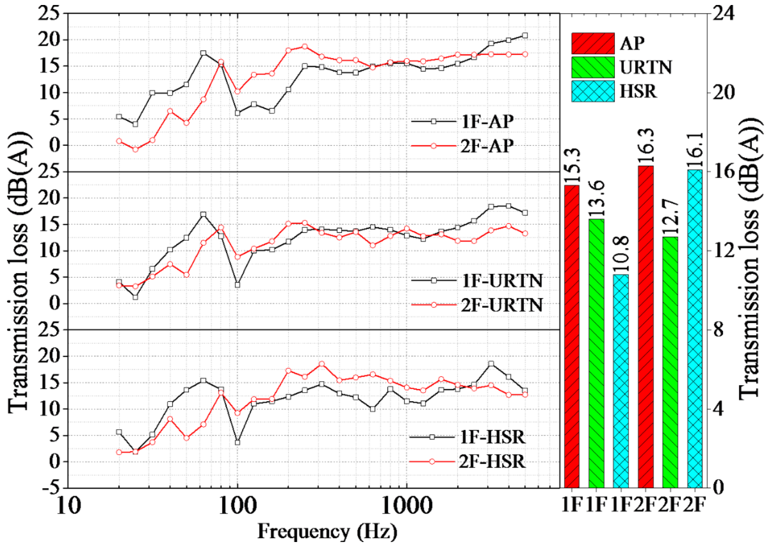

Fig. 21. Transmission loss between indoor and outdoor noise (1 F: the first floor, 2 F: the second floor).

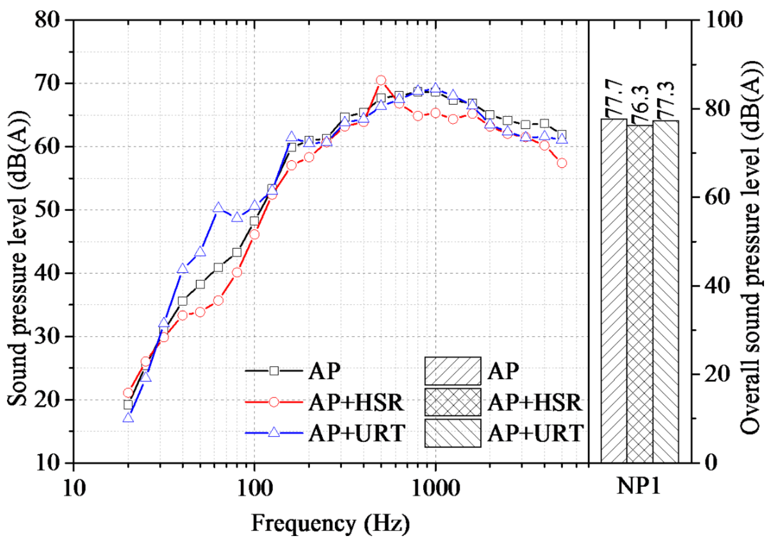

Fig. 22. Comprehensive noise of measuring point NP1.

Mixed sound source
There is interaction between sound sources, and there may be overlap in certain frequency bands. Therefore, based on the results of on-site testing, the noise exposure was analyzed when multiple sound sources coexist. The airplane noise and its mixed noise with urban rail transit (AP + URT) noise or high-speed railway (AP + HSR) noise at NP1 and NP5 measurement points are shown in Figs. 22 and 23. In Fig. 22, the peak value of high-speed railway noise occupies a dominant position when airplane noise and high-speed railway noise coexist. When airplane noise and urban rail transit noise coexist, the low-frequency band is dominated by urban rail transit noise, and the high-frequency band is dominated by airplane noise. In Fig. 23, due to the fact that the influence of bridge structure-borne noise on NP5 is smaller than that of NP1, the dominant low-frequency noise of the mixed noise of airplane and elevated rail transit is relatively reduced compared to airplane noise. The difference of overall sound pressure levels between airplane noise, airplane noise combined with high-speed railway noise, and airplane noise combined with urban rail transit noise is not significant, but the overall sound pressure level of mixed noise is slightly lower, which may be due to the counteraction effect between the noises.

Figures 24 and 25 show the mixed noises at measurement points N12 and N16 in Test 3. Compared with Figs. 22 and 23, there are no regularity in the differences between urban rail transit noise and various mixed noises in Figs. 24 and 25. This indicates that the sound source (airplane noise or high-speed railway noise) has little influence on mixed noise because it is far away from the measurement points in urban rail transit section.

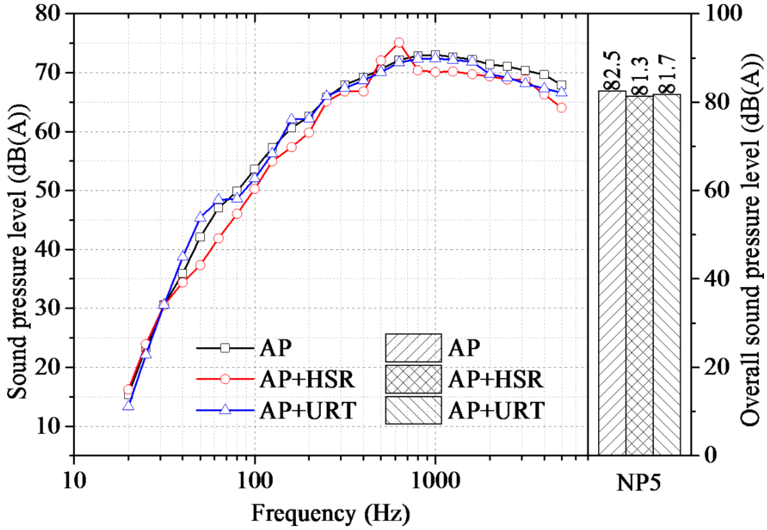

Fig. 23. Comprehensive noise of measuring point NP1.

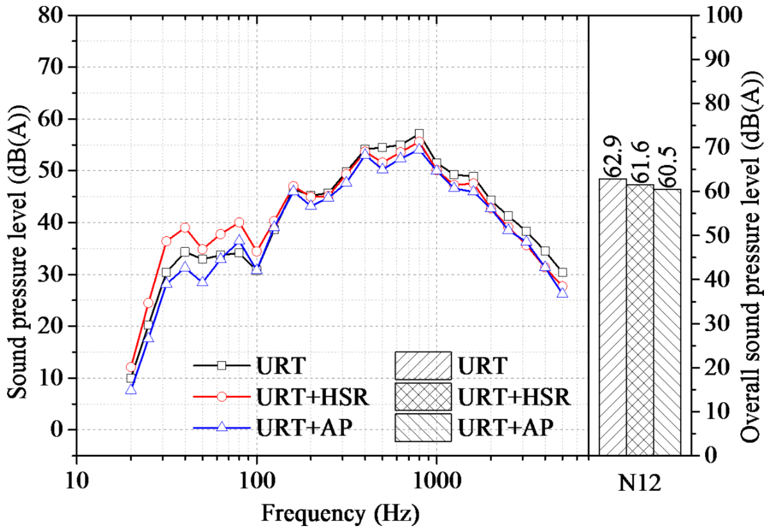

Fig. 24. Comprehensive noise of measuring point N12.

Noise reduction evaluation of sound barrier

For elevated urban rail transits, sound barriers[72] are widely used to relieve the impact of transportation noise on residents. The structural forms of sound barriers are diverse, including vertical, semi-enclosed, and fully-enclosed. Among them, the fully-enclosed sound barrier has the best noise reduction effect, but it has the problems of high cost and relatively large secondary structural noise[73,74], so its application is relatively limited. Vertical sound barrier is the most common structural forms, and a deep understanding of their noise-reduction characteristics is important in the design of elevated urban rail transit. Herein, the noise reduction effect of vertical sound barriers is characterized by insertion loss (IL)[75], as shown in Eq. (2).

$$IL = 20\lg\frac{p_{\mathrm{before}}}{p_{\mathrm{after}}} \tag{2}$$

where, p_{before} and p_{after} are the sound pressure of the same receiver point before and after installation of sound barriers in Pa, respectively. The IL is the difference of sound pressure level before and after installation of sound barriers in dB, which directly reflects the noise reduction effect of the sound barrier. Due to the inconsistent sound pressure levels of sound sources with and without sound barrier cross-sections, it is impossible to directly calculate IL using Eq. (2), so an analysis of the TL is introduced to indirectly obtain the value of IL. The TL is the difference between the sound pressure level of the trackside measurement point at the noise source position and the wayside measurement point at the noise receiver position, as shown in Eq. (3).

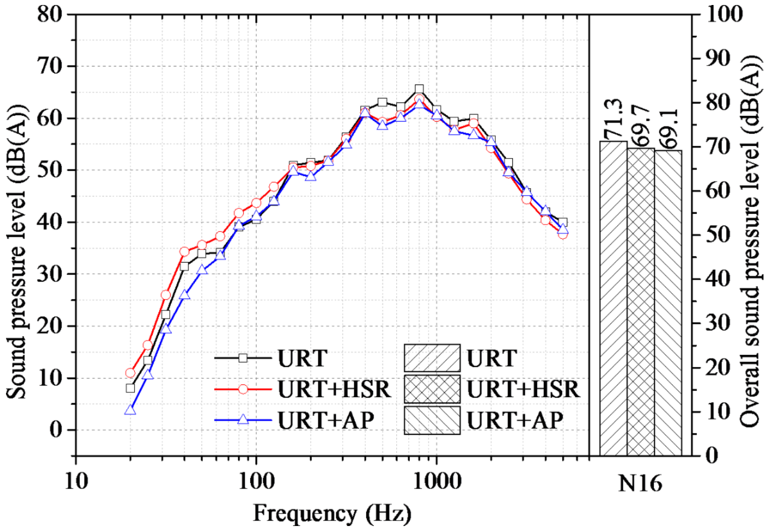

Fig. 25. Comprehensive noise of measuring point N16.

$$TL = L_{\mathrm{a}} - L_{\mathrm{b}} \tag{3}$$

where, L_a and L_b represent the sound pressure levels measured at noise source and noise receiver position in dB(A), respectively.

$$\begin{aligned} IL &= TL_1 - TL_2 \\ &= (L_1 - L_2) - (L_3 - L_4) \end{aligned} \tag{4}$$

In the formula, TL_1 and TL_2 are the transmission losses of the section with and without sound barriers, respectively; L_1 and L_3 represent the sound pressure levels measured at the trackside measurement points of the section with and without sound barriers, respectively; L_2 and L_4 are the sound pressure levels measured at the wayside measuring points of the section with and without sound barriers, respectively.

Figure 26 shows the test results for the trackside noise in the two sections. M1 and M2 are the average values of the overall sound pressure levels at three trackside noise measurement points in the two sections and are used as the source intensity of the elevated urban rail transit noise. Evidently, the sound source intensity of the urban rail transit viaduct in the section with a sound barrier was 4.7 dB(A) larger than that in the section without a sound barrier, owing to the reverberation of the wheel-rail noise. In addition, the spectral characteristics of the source intensity of the two sections differed; therefore, the *IL* of the sound barrier cannot be calculated directly using the sound pressure levels of the corresponding bridge-side points of the two sections. Hence, the *TL* between the trackside noise measurement points and the measurement points 7.5 or 25 m away from the track centerline was first calculated and then used to obtain the *IL* of the vertical sound barrier.

Figures 27 and 28 show the *TL* from the trackside points to N7–N16 on the side of the box girder with and without the sound barrier. The *TL* at the measurement points 7.5 m from the track centerline was 18.2–29.7 dB(A) for the sound barrier section and 10.2–22.7 dB(A) for the section without the sound barrier. Furthermore, the *TL* from the trackside points to the points 25 m away from the track centerline were 28.1–34.0 dB(A) with the barrier and 19.6–27.1 dB(A) without the barrier.

Figure 29 shows the *IL* at N7 to N11 on the box-girder side, 7.5 m away from the track centerline. The *IL* trend at each measurement point was not consistent in the frequency domain. In particular, the *IL* at N7–N11 varied significantly in the frequency band above 400 Hz. The *IL* in the frequency band above 40 Hz was positive, indicating that the vertical sound barriers had a good noise reduction effect in the middle- and high-frequency bands. However, a negative *IL* means that the sound barrier does not reduce the noise from the urban rail transit below 40 Hz, but instead amplifies the noise. This may be caused by structure-borne noise radiating from the sound barrier. The overall *IL* at N7–N11 on the box-girder side were between 7.0 and 15.9 dB. The *IL* at N9 was the largest, with a value of 15.9 dB, among the points from N7 to N11. The sound pressure level of N7, located 1.2 m above the ground, was dominated by bridge structure-borne noise, so its *IL* was the least among the points 7.5 m away from the track centerline. The *IL* at N11 was also relatively small because the position of N11 was higher than the top of the sound barrier.

The *IL* of measurement points N12–N16, 25 m from the track centerline, is shown in Fig. 30. The overall *IL* at N12–N16, 25 m away from the track centerline on the box-girder side, was between 6.9 and 8.6 dB. The *IL* at N12 was close to that at N7 because the sound barriers mainly reduced the wheel-rail noise, and the bridge structure-borne noise was dominant at these two measurement points. The *IL* spectral curves of the measurement points 25 m away from the track centerline on the box-girder side were similar, except for N12.

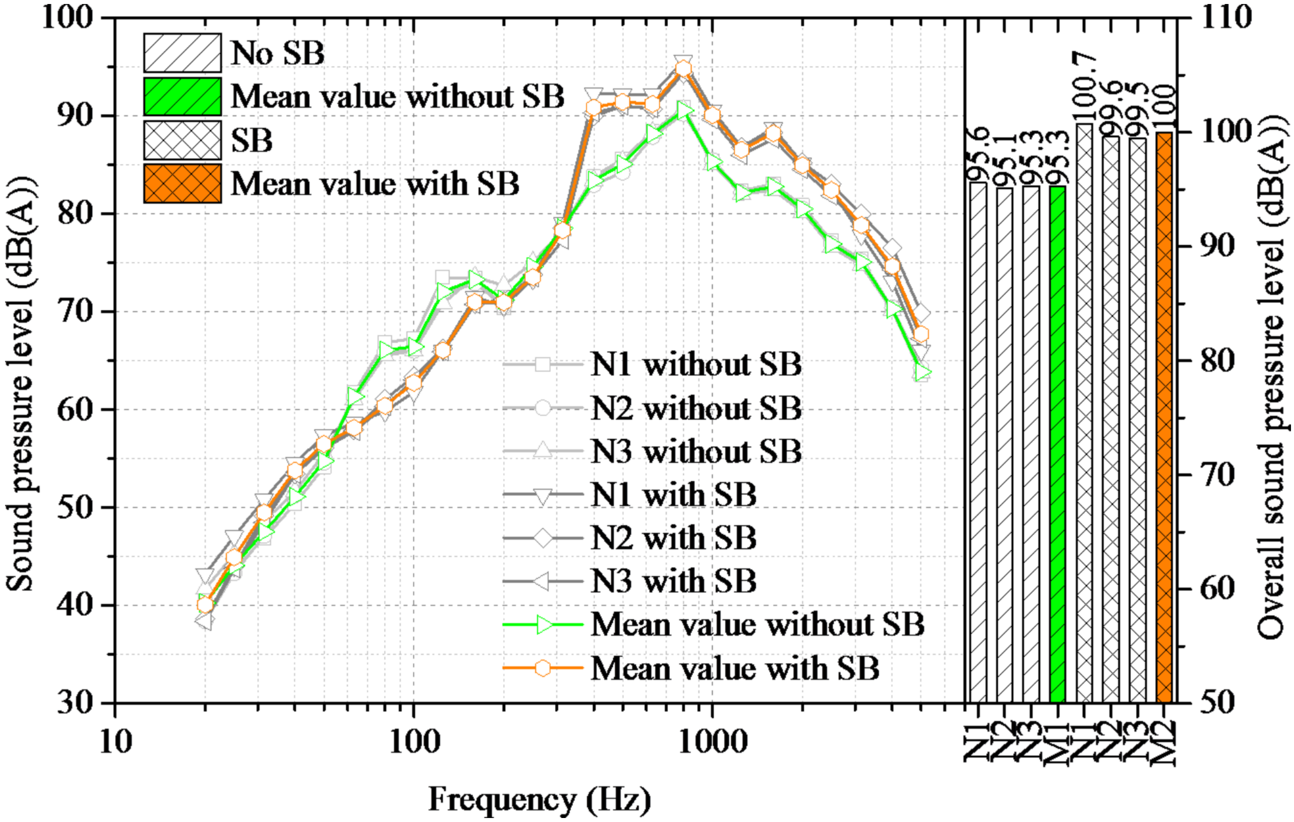

Fig. 26. Test results of trackside noise at the sections with and without a vertical sound barrier (SB).

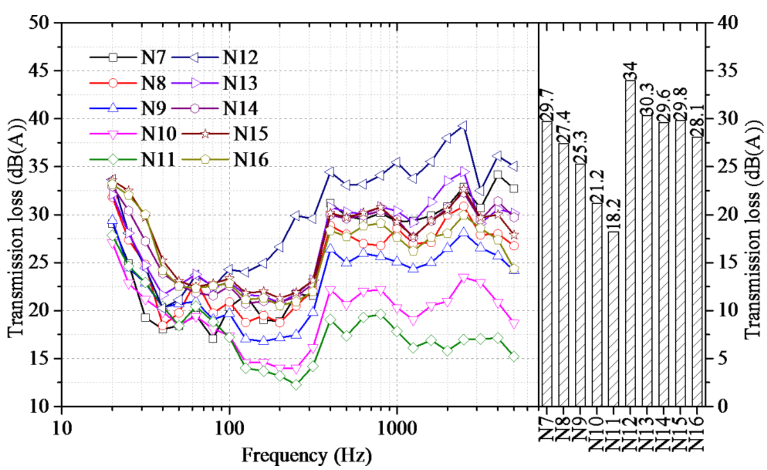

Fig. 27. Transmission loss of the noise in the box-girder side of the vertical sound barriers section.

Dose-response relationship

Based on the above analysis, it can be seen that residents react differently to different traffic noise sources. It is not enough to analyze the characteristics of the noise source, but it is also necessary to introduce other acoustic metrics for evaluating annoyance. The A-weighted day-evening-night noise level L_{den} and night noise level L_{n} are used in the assessment of long-term noise levels[76,77]. L_{den} is expressed in decibels and calculated according to Eq. (5)[43].

$$L_{\mathrm{den}}=10\lg\left(\frac{12}{24}10^{0.1L_{\mathrm{d}}}+\frac{4}{24}10^{0.1(L_{\mathrm{e}}+5)}+\frac{8}{24}10^{0.1(L_{\mathrm{n}}+10)}\right) \tag{5}$$

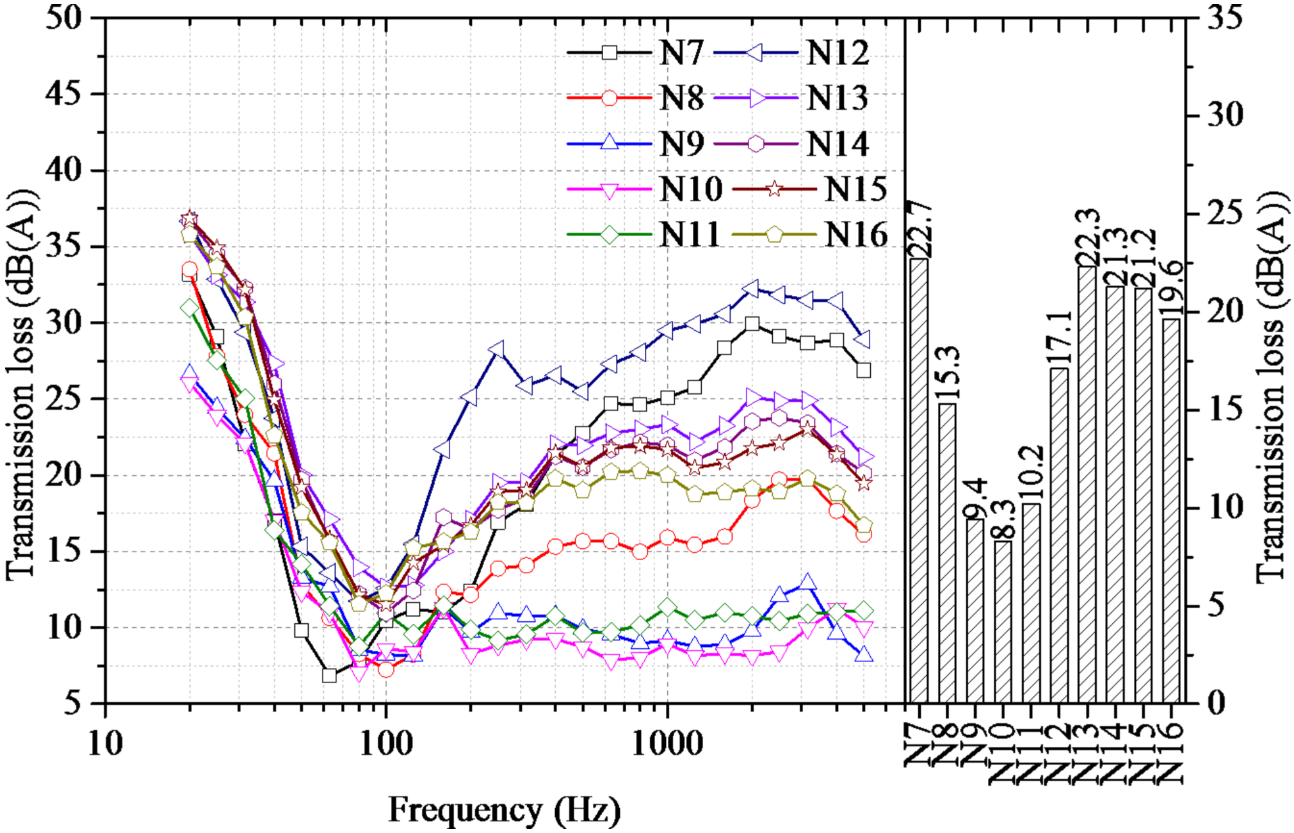

Fig. 28. Transmission loss of the noise in the box-girder side of the section without the vertical sound barriers.

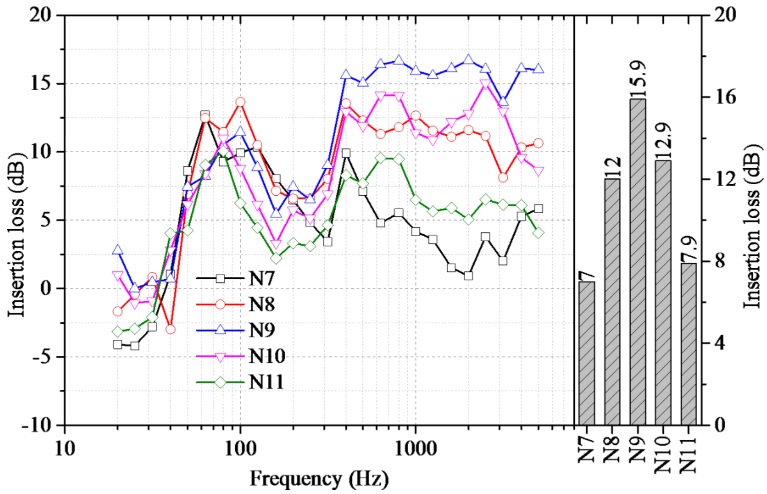

Fig. 29. Insertion losses of measurement points 7.5 m away from the track centerline on the box-girder side.

where L_d, L_e, and L_n are the A-weighted average sound levels for the day from 6:00 a.m. to 6:00 p.m., the evening from 6:00 p.m. to 10:00 p.m.), the night periods from 10:00 p.m. to 6:00 a.m., respectively. These time intervals are not fixed and may vary from country to country[78].

The short-term noise levels obtained from this test are used to estimate the indicators of long-term noise levels (L_d, L_e, L_n) calculated by Eq. (6) and then the A-weighted day-evening-night noise level (L_{den}) is estimated according to Eq. (5). The noise levels of hours were obtained from the measurement over 5 days. The sound pressure data during the transportation vehicles or airplanes passing through time period t and background noise sound pressure for these four types of traffic noise were extracted from the test noise data. The day, evening and night noise levels (L_d, L_e, and L_n) for these four noise sources were calculated based on the operation

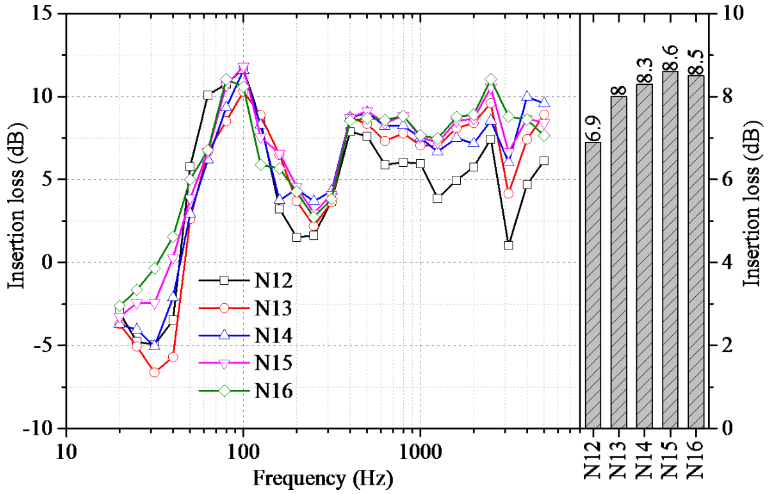

Fig. 30. Insertion losses of measurement points 25 m away from the track centerline.

Area	L_{den} (dB(A))	Urban road	High-speed railway	Urban rail transit	Airplane
AP	L_{den} (indoor)	36.9	43.9	56.6	56.6
	L_{den} (outdoor)	53	61.4	68.8	76
	%HA	0	17	44	100
URT	L_{den}	65.4	65.1	68.4	64.7
	%HA	9.9	1	9.9	1.7

Table 3. L_{den} and the highly annoyed (%HA) under various sound sources.

Area	L_{den} (dB(A))	N12	N16	%HA
URT	L_{den} (no SB)	67.2	68.4	24
	L_{den} (SB)	65.4	67.8	8.2

Table 4. L_{den} and the highly annoyed (%HA) of the cross-section without and with sound barriers.

frequency and the overall sound pressure level of transportation vehicles or airplanes and background noise levels during three time periods.

$$L_i = 10\lg\left(\frac{1}{N}\sum{}_{j=1}^{n}10^{0.1L_j}\right) \quad (6)$$

where, L_i is L_d, L_e, L_n, representing day, evening, and night noise level, respectively. L_j is the equivalent continuous A-weighted sound pressure level of time period j. N is the number of time periods.

The calculated the A-weighted day-evening-night noise levels under different sound sources are shown in Table 3. L_{den} (indoor) and L_{den} (outdoor) are the day-evening-night noise level of indoor and outdoor noise radiated from various noise sources, respectively. In the vicinity of the airport, despite the influence of urban roads, high-speed railways, and elevated urban rail transit noise, airplane noise remains the largest source of noise. L_{den} in outdoor caused by airplane noise reaches 76 dB(A), causing 100% highly annoyed among surrounding residents. A significant difference, 19.4 dB(A), was found between indoor noise and outdoor noise radiated from airplane. In the area near the elevated urban rail transit, the L_{den} of urban road noise is 3 dB(A) less than that of elevated urban rail transit, but the percentage of high annoyance level is the same. The L_{den} of urban rail transit in the vicinity of the airport and away from the airport is equivalent in magnitude, but the percentage of high annoyance of the former is 34% high than that of the latter, which may be due to the accumulation of airplane noise.

Table 1 indicates that the presence of sound barriers can reduce the high annoyance level, which needs a quantitative analysis. In order to further determine the necessity of setting up sound barriers, Table 4 provides the L_{den} and high annoyance levels for measuring points N12 and N16. L_{den} (no SB) and L_{den} (SB) are the day-evening-night noise level at the section without and with sound barriers, respectively. The L_{den} of N16 measurement point compared to N12 indicates that the noise exposure above the top surface of the sound barrier is higher than that below the top surface. This may result in sound barriers having no noise reduction effect on residents living in high-rise buildings. The presence of sound barriers can indeed reduce the L_{den} in residential areas by 0.6 and 1.8 dB(A), resulting in a decrease in high annoyance levels from 24 to 8.2%. This result indicates that the sound barrier has good application value.

Conclusions

The transportation noise in a region near an international airport connected to an urban rail transit viaduct was investigated in this study. A questionnaire survey was conducted on the annoyance level of residents suffering from transportation noise in this region, and the sound pressure levels of airplanes, urban rail transit viaducts, and high-speed railway noises were measured. The influence of noise radiating from airplanes, elevated urban rail transit, high-speed railways, and urban roads on surrounding residents was investigated, and the noise reduction effect of the vertical sound barrier was analyzed. All interviewed residents near the airport were highly annoyed with airplane noise, and some were also annoyed with the noise from the urban rail transit and high-speed railway connecting to the airport. Sleep was the most frequently interrupted activity due to transportation noise. Transportation noise during 19:00–24:00 most affected the residents near the airport and urban rail transit. The distance from residences to the viaduct, sensitivity of residents to noise, and sound barriers were strongly correlated with a high annoyance level for urban rail transit noise under a confidence interval of 95%. Meanwhile, the annoyance level of urban road noise is dependent on the distance between the residence and the road, noise sensitivity, and life pressures. Airplane noise remains the largest source of sound pollution in residences near the elevated urban rail transit and airport. The broad dominant frequency ranges of airplane and urban rail transit noise make it challenging to control these two types of noise. The source intensity of the elevated urban rail transit in the barrier section is 4.6 dB(A) higher than that in the section without a sound barrier owing to the reverberation of wheel-rail noise. The insertion loss of the urban rail transit noise at 7.5 m and 25 m away from the track centerline was 7–15.9 dB and 6.9–8.6 dB, respectively, indicating that above 40 Hz, the vertical sound barrier has a good noise reduction effect on the urban rail transit viaduct. The dose-response relationship indicates that the L_{den} of outdoor noise is 19.4 dB(A) higher than indoor noise radiated from airplane. The presence of sound barriers can reduce the L_{den} in residential areas, resulting in a decrease in high annoyance level from 24 to 8.2%. This study shows that the operation of transportation lines brings many negative impacts to the surrounding residents. The location, later operation and maintenance of transportation lines should be considered comprehensively to reduce traffic noise.

Data availability

The data within the paper are available from the authors upon request. Requests for data should be addressed to Song, L. Z. (E-mail addresses: songlizhong@ecjtu.edu.cn).

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Quanmin Liu: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, and Writing - review & editing. Kui Gao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, and Writing - original draft. Lizhong Song: Funding acquisition, Investigation, Project administration, Resources, and Writing - review & editing. Linya Liu: Project administration, Supervision, and Writing - review & editing. Yunke Luo: Conceptualization and Writing - review & editing.

Declarations

Ethics approval and consent to participate
The experimental plan of this study (questionnaire survey in this article) was developed based on the best practice guidelines for noise annoyance developed by the International Commission on the Biological Effects of Noise, guidelines from ISO/TS 15666: 2021, and the Chinese Standard GB/T 42473 – 2023. All methods were carried out in accordance with relevant guidelines and regulations. All experimental protocols in this manuscript are reviewed and approved by the Science and Technology Ethics Committee of East China Jiaotong University before implementation. This work is carried out under local and ethical requirements.

Competing interests
The authors declare no competing interests.

Informed consent
was obtained from all subjects and/or their legal guardian(s).
Only Figs. 1 and 4 in this manuscript involve personally identifiable information, and the aforementioned subjects or participants gave informed consent to publish the above identifying information/images in an online open-access publication.

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