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Structural Design and Optimization of Highway Noise Barrier Panels

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Abstract: To effectively mitigate the impact of highway traffic noise on the surrounding environment, this study conducts a systematic investigation into the acoustic characteristics, structural design, and material optimization of noise barriers. The noise reduction mechanism and key influencing factors of noise barriers are analyzed based on the principles of sound diffraction, transmission, and reflection. Particular attention is given to the effects of barrier height, length, installation position, and structural configuration on acoustic performance. According to engineering application requirements, design principles, and parameter optimization methods for noise barriers are proposed. Comparative analyses of the sound absorption properties of four panel materials—aluminum plate, steel plate, aluminum foam, and concrete—indicate that aluminum foam and concrete barriers exhibit superior broadband sound absorption performance in the low- and mid-frequency ranges, effectively improving the acoustic environment of highway traffic. The findings provide a theoretical basis and engineering reference for highway noise barrier design and material selection.

Keywords: Highway; Noise Barrier; Noise Reduction Design; Acoustic Performance; Material Optimization

1. Introduction

In recent years, with the rapid development of transportation networks and the continuous growth of vehicle ownership, traffic noise has become a significant factor affecting the quality of life and ecological environment of residents living along highways [1]. Long-term exposure to high-level noise environments can lead to psychological and physiological health problems, social complaints, and environmental conflicts [2]. Therefore, effectively controlling and reducing road traffic noise has become a key issue that needs to be addressed in transportation and environmental engineering.

As a passive noise control facility, noise barriers offer several advantages—such as ease of construction, remarkable noise reduction performance, and low maintenance costs—and have been widely implemented domestically and internationally for highway noise mitigation [3]. However, the acoustic effectiveness of noise barriers is influenced by multiple factors, including the propagation characteristics of sound waves, geometric parameters of the barrier, sound absorption properties of materials, structural configuration, and installation position. Furthermore, the design requirements vary significantly under different environmental conditions [4].

Current research indicates that the overall performance of noise barriers depends not only on their sound insulation capacity but also on the sound absorption structure, material type, and spatial arrangement. Traditional reflective barriers can effectively block direct sound transmission; however, they often generate secondary reflections between opposite sides of the roadway, reducing overall noise attenuation efficiency. In contrast, absorptive barriers utilize porous absorption and resonant energy dissipation to minimize broadband noise across a wider frequency range [5].

This study integrates acoustic theory, structural characteristics, and material properties to analyze the key factors affecting the noise reduction performance of barriers from the perspective of sound propagation mechanisms. It further proposes scientific principles for structural design and compares the acoustic performance of representative panel materials to identify optimal configurations. The research aims to provide theoretical support and practical guidance for designing and applying highway noise barriers, achieving a comprehensive optimization of acoustic performance, cost-effectiveness, and environmental compatibility.

2. Principles of Noise Reduction by Sound Barriers

2.1 Acoustic Principles of Sound-Insulating Barriers

The noise reduction effect of a sound barrier is primarily achieved by blocking the propagation path of sound waves. Its acoustic mechanism can be summarized into three fundamental processes: diffraction, transmission, and reflection. A schematic diagram of the sound propagation paths around a noise barrier is shown in Figure 1.

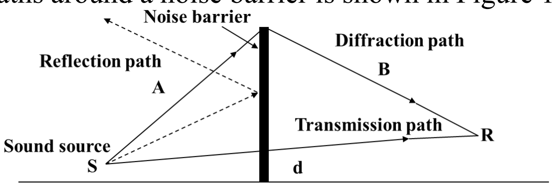

Figure 1. Schematic Diagram of Sound Propagation Paths around a Noise Barrier

When an incident sound wave encounters the barrier, a portion of the acoustic energy diffracts over the top edge of the barrier, another portion transmits through the barrier material and reaches the receiver point. In contrast, the surface of the barrier reflects the remaining portion. The overall insertion loss of the barrier depends on the distribution of sound energy among these three propagation paths [6].

(1) Diffraction

When a sound wave encounters an obstacle during propagation, diffraction occurs. A schematic diagram of the sound diffraction path is shown in Figure 2. The intensity of the diffracted sound energy depends on the sound's wavelength, the barrier's height, and the geometric relationship between the sound source and the receiver point.

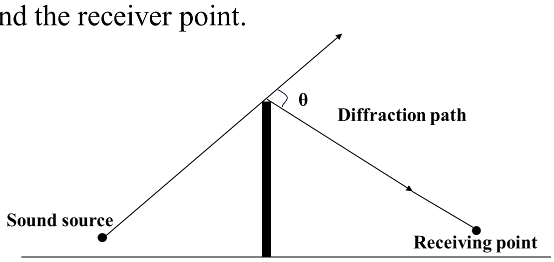

Figure 2. Schematic Diagram of Sound Diffraction Paths around a Noise Barrier

According to Fresnel's wave theory, the longer the wavelength, the more pronounced the diffraction effect becomes. Consequently, noise barriers are more effective in attenuating high-frequency noise, while their performance in isolating low-frequency noise is relatively limited [7]. In general, noise barriers exhibit significant noise reduction for frequencies above 2000 Hz, whereas their effectiveness decreases notably in the 800–1000 Hz and lower frequency ranges.

(2) Transmission

The phenomenon in which sound waves propagate through the barrier body is called transmission. The transmitted sound energy primarily depends on the barrier material's sound frequency, angle of incidence, and surface mass density. The Transmission Loss (TL) serves as a key indicator for evaluating the sound insulation performance of a noise barrier—the greater the TL value, the smaller the transmitted sound energy [8].

To ensure satisfactory acoustic insulation performance, the difference between the transmission loss and the transmission correction factor is generally required to be no less than 10 dB. Under this condition, the effect of transmitted sound on the overall noise reduction performance can be considered negligible.

(3) Reflection and Combined Effects

When noise barriers are installed on both sides of a highway, sound reflections between the two barriers can lead to multiple reflections and superposition, thereby reducing the actual noise attenuation effect. A schematic diagram of the sound reflection paths is shown in Figure 3 [9].

To minimize the reflected acoustic energy, an absorptive layer is often applied to the side of the barrier facing the noise source, or an absorptive-type structure is adopted. The sound absorption capability of such structures is typically characterized by the Noise Reduction Coefficient (NRC).

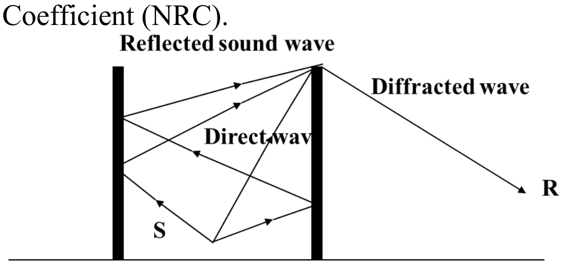

Figure 3. Schematic Diagram of Sound Reflection Paths between Noise Barriers

The net noise reduction achieved by a noise barrier results from combined diffraction attenuation, transmission correction, and reflection correction. A well-designed noise barrier typically provides an insertion loss of 5–15 dB, while it can reach approximately 25 dB under ideal conditions. By optimizing the structural configuration and material properties, the overall noise reduction performance of the barrier can be further enhanced.

2.2 Noise Reduction Mechanism of Absorptive Noise Barriers

Absorptive noise barriers achieve sound attenuation by installing sound-absorbing materials on the barrier surface or by designing the barrier as an absorptive structure. When an incident sound wave reaches the surface of the absorptive material or structure, a portion of the acoustic energy is reflected, another portion is absorbed, and the remaining portion is transmitted through the barrier and continues propagating.

The sound absorption coefficient (α) represents the proportion of incident sound energy absorbed by a material or structure; a higher value of α indicates better sound absorption performance. The sound absorption coefficient α can be expressed as:

$$\alpha = \frac{E_a + E_t}{E} = \frac{E - E_r}{E} = 1 - r \qquad (1)$$

Where:

E- total incident sound energy;

E_a- sound energy absorbed by the material;

E_t - sound energy transmitted through the material;

E_r- sound energy reflected by the material;

r- reflection coefficient.

The incident sound waves and the material's intrinsic properties primarily determine the sound absorption performance of porous materials or structures. Porous absorptive materials generally exhibit better absorption efficiency at high frequencies, while their performance in the mid- and low-frequency ranges is relatively limited. The underlying mechanism is that high-frequency sound waves induce rapid air motion within the pores, resulting in greater acoustic energy dissipation. In contrast, such an effect is less pronounced for mid- and low-frequency sounds.

2.3 Analysis of Factors Influencing the Noise Reduction Performance of Sound Barriers

The combined effects of sound insulation and sound absorption primarily govern the noise reduction performance of a sound barrier. Its effectiveness is influenced by various structural and acoustic factors, including the barrier's geometric parameters, installation position, material properties, and the noise spectrum characteristics of the sound source [10].

2.3.1 Influence of geometric parameters

The height and length of a sound barrier are the key geometric parameters affecting its noise reduction performance. Under a constant sound source intensity, an increase in barrier height effectively enlarges the path difference between the direct and diffracted sound waves, thereby increasing the insertion loss at the receiver point and enhancing the overall noise attenuation. However, the barrier height is constrained by wind load and structural stability, and excessive height is generally not recommended. Practical experience indicates that barrier heights within the 2–6 m range achieve a favorable balance between acoustic performance and economic efficiency. Meanwhile, extending the barrier length can reduce the influence of sound diffraction from both ends, although the improvement gradually diminishes with increasing extension. In engineering practice, the optimal barrier length is typically determined through acoustic calculations to balance cost and effectiveness.

2.3.2 Influence of installation position

The relative position of the sound barrier with respect to the noise source and receiver significantly impacts its performance. Both theoretical analysis and field measurements indicate that the closer the barrier is to the noise source, the larger the acoustic shadow zone it forms, resulting in better noise reduction. When the barrier is placed farther from the source or receiver, the path difference decreases and diffraction becomes more pronounced, reducing the attenuation effect. Consequently, highway sound barriers are generally installed along the shoulder or on the outer side of the crash barrier, as close as possible to the noise source, to maximize insertion loss.

2.3.3 Influence of sound-absorbing material properties

Sound-absorbing materials are typically applied to the side facing the noise source to minimize multiple reflections between barriers. A higher sound absorption coefficient leads to less reflected acoustic energy and thus greater overall noise reduction. Common absorptive materials include soft porous structures such as glass wool, mineral fiber, or aluminum foam, which dissipate part of the acoustic energy into heat through air friction and viscous resistance. Studies have shown that the noise reduction effect of sound-absorbing barriers is generally about 2 dB(A) higher than that of reflective ones.

Therefore, in high-noise environments, composite sound-absorbing structures should be prioritized.

2.3.4 Influence of structural configuration

The structural configuration of a sound barrier directly determines its acoustic performance. Field measurements indicate that various composite-type barriers outperform conventional vertical obstacles. Y-shaped barriers perform best, achieving insertion losses approximately 6 dB (A) higher than the vertical type. In addition, folded-top and curved-top barriers effectively suppress top-edge diffraction and are widely adopted as optimized configurations for highway noise control.

2.3.5 Influence of traffic noise spectrum

Traffic noise is determined by vehicle type and pavement characteristics, exhibiting a broad frequency distribution with energy concentrated in the mid- to low-frequency range. Spectrum analyses (Tables 1–2) show that small vehicles mainly produce mid- to high-frequency noise, while large cars generate predominantly mid- to low-frequency noise (80–1000 Hz). Sound barriers attenuate mid- and high-frequency components more effectively but are less efficient in absorbing and insulating low-frequency noise. Therefore, the traffic composition, vehicle speed, and pavement type should be carefully considered in sound barrier design. Increasing the barrier density or adopting composite absorptive structures for low-frequency noise control can effectively compensate for the limited low-frequency attenuation capability.

Table 1. Frequency Distribution of Vehicle Noise

Vehicle type	Vehicle speed (km/h)	Driving noise frequency (Hz)		Tire noise frequency (Hz)	
		Asphalt concrete pavement	Cement concrete pavement	Asphalt concrete pavement	Cement concrete pavement
Light vehicle	60~120	500~2000	630~2500	630~2000	800~2500
Medium vehicle	40~80	80~800	125~1600	160~1000	315~1600
Heavy vehicle	40~80	80~1000	250~2000	250~1000	315~2000

Table 2. Equivalent Frequency Values of Highway Traffic Noise under Different Vehicle Speeds

Vehicle type	Vehicle speed (km/h)	40	60	80	100	120
	Equivalent frequency (Hz)	63	63	63	63	125
Light vehicle Medium vehicle	Vehicle speed (km/h)	40	60	80	100	120
	Equivalent frequency (Hz)	63	250	500	500	500
Heavy vehicle	Vehicle speed (km/h)	40	60	80	100	120
	Equivalent frequency (Hz)	63	250	500	500	1000

3. Structural Design of Sound Barrier Panels

3.1 Design Procedure of Sound Barriers

The design of a sound barrier should comprehensively consider the characteristics of road traffic noise, environmental conditions, and protection objectives to systematically determine its acoustic and structural parameters. The general design process is illustrated in Figure 4.

First, based on the predicted traffic volume, vehicle types, and driving speeds, the target insertion loss is determined using a noise prediction model to ensure compliance with environmental noise standards at sensitive locations. Second, the topographical and geomorphological features should be carefully analyzed to fully use favorable terrain and provide the barrier design harmonizes with the surrounding environment.

Next, the optimal installation scheme should be selected according to the relative positions of the road and the noise-sensitive area. For highways, barriers are generally installed close to the noise source—typically along the shoulder or outside the crash barrier—to maximize the sound path difference and enhance attenuation.

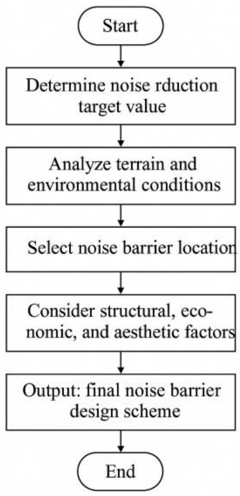

Figure 4. Noise Barrier Design Flowchart

Subsequently, the main dimensional parameters of the barrier, including height and length, should be determined. The height should be optimized under structural safety and visual integration constraints, generally not exceeding 6 m. At the same time, the length should cover the noise-sensitive area and extend appropriately at both ends to minimize edge leakage.

Finally, acoustic performance, structural stability, cost-effectiveness, and durability must be balanced during the integrated design stage. Particular attention should be paid to the aesthetic integration of the barrier with its surrounding landscape to achieve both functionality and visual harmony.

3.2 Design Principles of Sound Barriers

The design of sound barriers should satisfy noise control objectives while balancing structural safety, cost efficiency, and environmental compatibility, thereby achieving a unified optimization of acoustic performance and engineering feasibility. The key design principles involve location, height, and length, as illustrated in Figure 5.

The installation location has a significant impact on noise reduction performance. To maximize the acoustic shadow zone, barriers should be placed as close as possible to the noise source, ensuring that the protected area lies within the effective shielding range. Specifically, barriers on embankment sections should be positioned near the curb, while those in cut sections are best arranged outside the slope drainage channel. For bridge and underpass sections, barriers can be installed on or outside the crash barrier to ensure structural stability and acoustic efficiency.

The barrier height determines the noise reduction effect and should be selected according to the desired insertion loss and sound propagation characteristics. The height is typically controlled within 2–5 m for standard vertical barriers. When higher attenuation is required, folded-top or curved-top designs can be adopted. In addition, combining the barrier with topographic features such as embankments or slopes can effectively increase the relative height while reducing construction costs.

The barrier length should cover the noise-sensitive area and extend appropriately at both ends to minimize sound leakage. The recommended extension length is generally three to five times the barrier height. Adopting lateral enclosures or zigzag arrangements can further improve the overall attenuation effect when the overall length is limited.

Sound barrier design should achieve a comprehensive balance among acoustic performance, structural safety, and economic feasibility, providing reliable engineering support for highway traffic noise control.

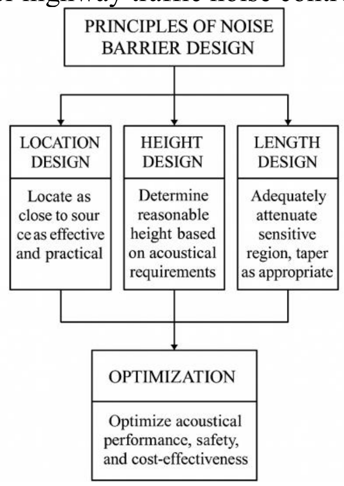

Figure 5. Principles of Noise Barrier Design

4. Optimization and Selection of Sound Barrier Panel Materials

Sound-absorbing materials can generally be classified into two categories based on their sound absorption mechanisms: resonant and porous absorptive materials [11]. The former category includes thin plates, perforated plates, and micro-perforated structures, typically fabricated from aluminum or steel. These materials possess high strength and good corrosion resistance; however, their effective absorption is limited to a narrow frequency range centered around the resonance frequency.

In contrast, porous absorptive materials dissipate acoustic energy through air friction and viscous resistance within their pores, exhibiting broadband and stable absorption performance. This category mainly includes fibrous, granular, and foam-type materials. Among them, metal foam has attracted considerable attention due to its structural strength and excellent acoustic properties, making it a primary focus in research and practical applications.

This study selected four representative materials—aluminum plate, steel plate, aluminum foam, and concrete—for sound absorption coefficient testing. The results are presented in Figures 6 and 7.

As shown in Figure 6, the sound absorption coefficients of the four barrier materials exhibit a generally consistent variation trend with frequency. All samples show a distinct absorption peak in the low-frequency range (500–1000 Hz), indicating a typical characteristic of resonant sound absorption structures. The aluminum and steel plate barriers display high absorption coefficients near the resonance peak (approaching 1.0). Still, the effective frequency band is narrow, and their absorption performance decreases rapidly beyond 1000 Hz. This observation verifies the earlier description that resonant absorptive materials exhibit narrow-band but high-peak absorption.

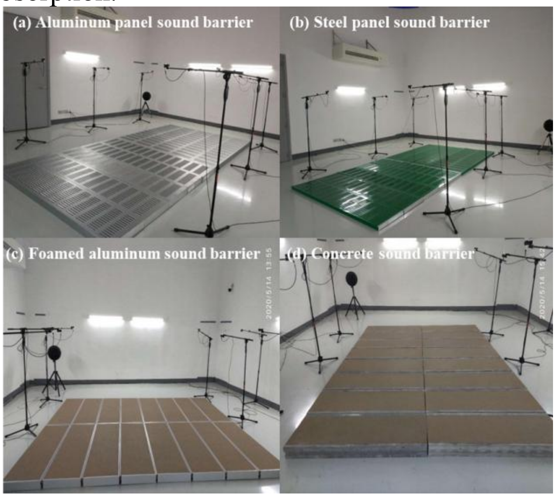

Figure 6. Appearance of Various Sound Barrier Panel Types

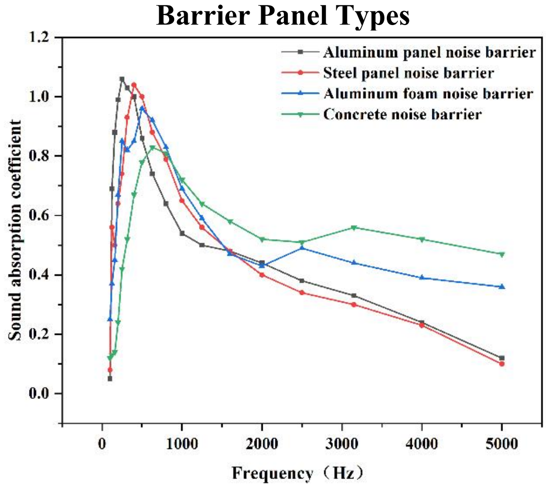

Figure 7. Analysis of Sound Absorption Coefficients of Various Sound Barrier Panel Materials

In contrast, the aluminum foam barrier performs better in the mid-to-high frequency range (1000–4000 Hz), with a smoother curve and overall absorption coefficients above 0.4. This behavior reflects the combined effect of structural resonance and porous absorption inherent to metallic foams. The concrete barrier shows the highest and most stable absorption coefficients in the same frequency range (approximately 0.5–0.7), suggesting that its internal pore structure effectively facilitates acoustic energy dissipation. Overall, for traffic noise sources dominated by mid- to low-frequency components, aluminum foam and concrete barriers exhibit better broadband absorption characteristics, making them more suitable as sound barrier panel materials. Although aluminum and steel panels possess weather resistance and impact strength advantages, their acoustic performance can be enhanced by integrating porous layers or perforated resonant structures to broaden the absorption bandwidth and improve overall noise reduction efficiency.

5. Conclusions

This study systematically investigated the noise reduction characteristics and optimization strategies of highway sound barriers from acoustic mechanisms, structural design, and material selection perspectives. The main conclusions are as follows:

(1) Acoustic mechanism: The noise reduction performance of sound barriers is governed by the combined effects of diffraction, transmission, and reflection, among which diffraction control is the key to improving insertion loss. Increasing barrier height, optimizing the top-edge structure, and reducing reflective surfaces can effectively enhance noise attenuation within the acoustic shadow zone.

(2) Structural factors: The barrier's height, length, placement, and configuration significantly impact acoustic performance. Barriers should be installed as close to the noise source as possible, with optimal heights typically ranging from 2 to 5 m and appropriate end extensions to minimize sound leakage. Y-shaped and folded-top configurations exhibit superior overall performance.

(3) Material properties: Aluminum foam and concrete panels show strong sound absorption and structural stability in the mid-to-low frequency range, making them well-suited for traffic noise control. Although aluminum and steel panels possess high strength and weather resistance, they should be combined with porous or perforated structures to broaden the absorption bandwidth.

(4) Design optimization: By comprehensively considering acoustic propagation, terrain conditions, and economic constraints, a reasonable determination of geometric

dimensions and material combinations can balance acoustic efficiency with engineering feasibility, enhancing noise reduction effectiveness and long-term performance.

In summary, the design of sound barriers should prioritize acoustic performance, constrained by structural safety and economic feasibility, while aiming for environmental harmony. Establishing an integrated "acoustics–structure–materials" optimization framework provides a solid theoretical and practical basis for future highway noise control engineering.

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