Bus Sound Accentuation through Sensory Technology in Adaptive Transit Architecture

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Abstract. Architecture can respond to temporary phenomena, such as the Eid al-Fitr exodus, through an experience-based spatial approach. This study examines how bus sounds, as a key marker of mass movement during the exodus, can be architecturally processed using a vibration-based sensory system. Drawing on Plowright's conceptual method, the design explores a dynamic soundscape that integrates the moment and the atmosphere of space. The system comprises a special bumper that generates vibrations as the bus passes, a piezoelectric microphone that captures these vibrations, and a sound-reflective fabric that directs the resonance toward the microphone. The resulting sound is then channeled to loudspeakers at strategic transit points. This concept is applied to the context of a shadow terminal, an informal transit space active only during the exodus season. The results demonstrate that integrating sound into site elements can enhance spatial perception and create a more adaptive spatial experience that is responsive to time and context. Thus, bus sounds are not only recorded but also re-curated as atmospheric triggers in a temporary architectural landscape.

1 Introduction

The phenomenon of the Eid al-Fitr homecoming (mudik) in Indonesia creates a major temporary shift in urban activity. Every year, millions of people return to their hometowns, triggering a surge in transportation and a rapid conversion of space. Typically quiet transit areas transform into strategic hotspots with high mobility. In 2024, the Ministry of Transportation recorded a 56% increase in homecoming travelers from the previous year, reaching 193.6 million people (Figure 1). Intercity buses remain the dominant mode of transportation, used by 20.3% of total travelers [1]. This makes buses not merely a means of transportation but a symbol of the annual rhythm of urban society.

Indonesia's Idulfitri *mudik* homecoming is among the world's largest annual migrations, with over half the country's population (roughly 146–193 million people in recent years) traveling at the end of Ramadan. This surge overwhelms transit infrastructure, causing massive traffic jams and associated environmental burdens [2,3]; for instance, authorities estimated that the 2024 Eid travel period would generate about 58,000 tons of additional solid

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waste [4]. Facing similar challenges of scale, other global events have demonstrated temporary urban solutions: during the Hajj pilgrimage, the tent city of Mina spans 20 km^2 with over 100,000 fire-resistant tents to accommodate some 2 million pilgrims, while India's Kumbh Mela establishes an "ephemeral megacity" on a floodplain, deploying extensive modular infrastructure that is later dismantled post-festival. These examples highlight both the possibilities and complexities of large-scale, short-term transit architecture in addressing seasonal overcrowding and environmental strain.

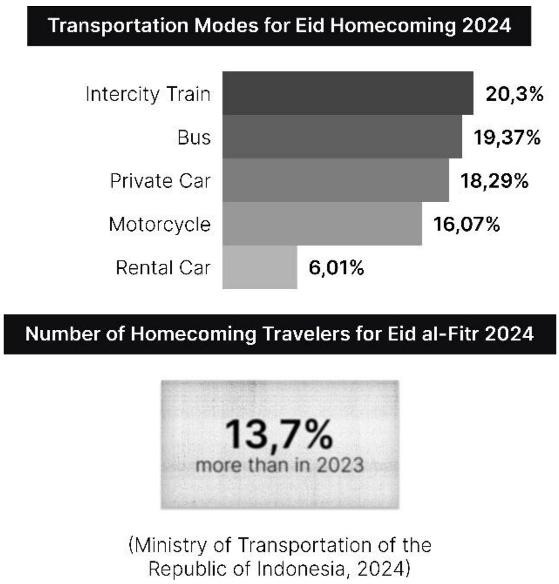

Fig. 1. Statistics on homecoming travelers in 2024 from the Ministry of Transportation show a surge in the number of travelers and the dominance of bus transportation [1].

Homecoming is a temporary and cyclical social phenomenon (Figure 2). In this context, sound—particularly from vehicles—plays a role as a marker of moments and a shaper of atmosphere. The soundscape can be said to reflect environmental conditions [2] and can emphasize its role in shaping spatial perception. During the homecoming flow, vehicle sounds serve as an indicator that a space is active, providing an opportunity to integrate sound elements into moment-based architectural designs [5]. The cyclical increase of homecoming generates a unique, temporally defined acoustic environment where vehicle-generated sounds—particularly the low-frequency engine noise of buses, braking sounds, horn bursts, and tire-pavement interactions—serve as temporal indicators and structural frameworks for collective movement. By utilizing these auditory markers as design elements, "moment-based" architecture can effectively organize thresholds, queues, and navigation (e.g., responsive canopies, adaptive acoustic barriers, and light signals) that align perception with real-time crowd behavior. Since the soundscape reflects environmental conditions and influences spatial clarity, designers can integrate psychoacoustic metrics (e.g., loudness, sharpness, fluctuation intensity) with event patterns to enhance the overall experience.

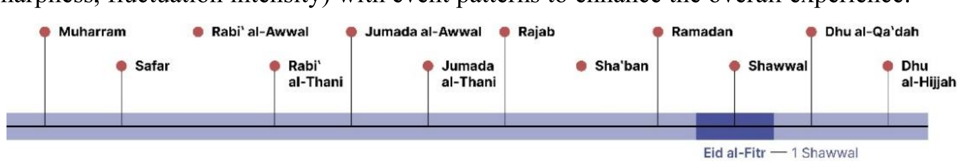

Fig. 2. The visual representation of the annual cycle of Eid al-Fitr emphasizes the pattern of repetition as a temporary social phenomenon.

Additionally, a complementary vibration pathway—utilizing accelerometers on pavements, platforms, or facades—captures axle-pass frequencies and RPM harmonics from buses to deduce mass movement when microphones are overwhelmed, or privacy is a concern. Closing the loop from urban dynamics to perception and deployable spatial interventions on predictive soundscape models, standardizing soundscape preference assessment, and applying a soundscape approach to traffic noise [6,7], while others show examining audio-visual interactions that shape residential soundscapes, correlating public transport presence with noise annoyance, profiling interior bus noise, evaluating tube-shaped bus shelters for noise mitigation, measuring traffic-induced ground vibration using smartphones, assessing physiological responses of city bus drivers to noise and vibration, and modeling noise reductions from electric buses. This study examines how bus sounds, a crucial indicator of mass movement during the exodus, can be structurally examined using a vibration-based sensory system, thereby corroborating prior findings.

2 Methods

A framework is a crucial foundation for design, enabling designers to explore ideas through a pattern-based, context-driven, or conceptual approach. This framework involves a belief system (a belief filter) that shapes how design issues are viewed. This filter also determines the approach used, reflects established values, and guides decision-making. This flow continues through the selected design methods and tools, resulting in a final design proposal that reflects the entire thought and problem-solving processes.

Figure 3 summarizes the stages of thinking applied to the design process. The approach begins by exploring the social, cultural, and technical contexts, which then generates a hypothesis in the form of an architectural representation that captures a temporary moment. The stages involved include formulating criteria, selecting elements, and developing concepts into a design proposal. The final output is a temporary transit architectural design that is only active during the homecoming season, in response to the seasonal increase in spatial intensity [8].

In the idea-generation process, the approach is to highlight how architecture can accentuate the moment's temporary nature. Moment-based architecture emphasizes time as a design boundary and as a parameter in determining design priorities. In the context of this study, the event in question is Eid al-Fitr, which serves as the primary trigger for the need for temporary transit spaces. During the homecoming season, city infrastructure must adapt to accommodate the mass movement of residents. Temporary spaces, such as shadow terminals, become essential to accommodate the surge in passenger volume. Furthermore, strategic points are also used as service posts that provide directions, information, and emergency facilities. The existence of these spaces demonstrates the urgency of spatial design that is responsive to time and temporary situations.

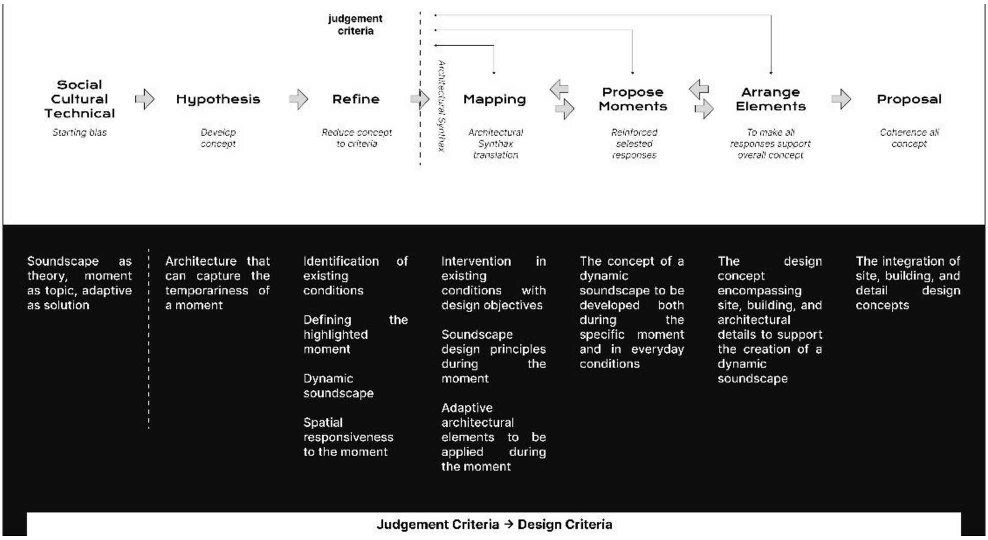

Fig. 3. The flowchart of the design framework illustrates the stages, from identifying the socio-cultural context to developing a temporary architectural concept for homecoming.

The design methodology (Figure 4) begins with data collection on the homecoming season, potential soundscapes, and adaptive architectural principles. Next, the data is analyzed to identify needs and principles that support the creation of a consciously engineered acoustic environment. This analysis is then synthesized into design concepts and criteria that are applied in the design. The design process is iterative, allowing for repeated refinements to ensure the resulting design truly addresses the needs of temporary transit spaces. This approach ensures that the designed architecture can respond to moments effectively and efficiently.

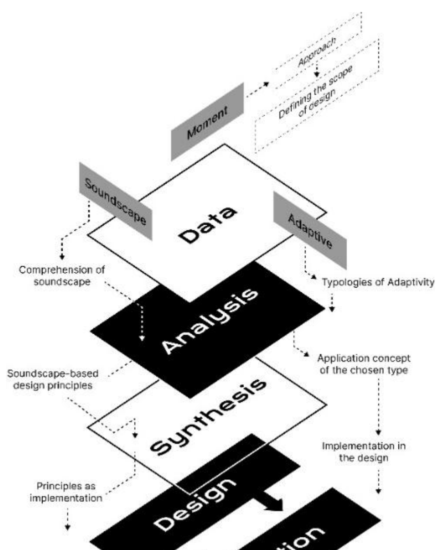

Fig. 4. The flowchart of the design framework shows the stages, from identifying the socio-cultural context to the formation of a temporary architectural concept for homecoming.

The location of the interconnected site in Figure 5 illustrates the model used to evaluate bus acceleration characteristics. It is in the vicinity of the Purabaya Bus Terminal, replacing the existing shadow terminal. This option was created to enhance the Mudik atmosphere while managing traffic and noise simultaneously.

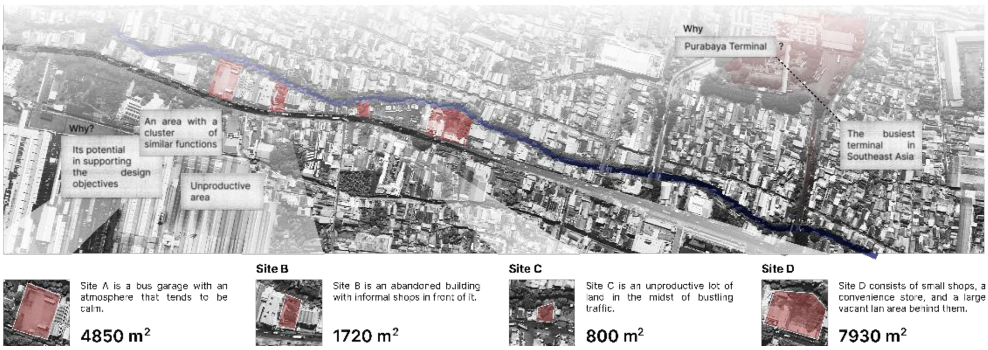

Fig. 5. The location of the interconnected site (A-B-C-D).

3 Results and Discussion

3.1 Precedents

To design a system capable of accentuating bus sounds as part of a temporary transit spatial experience, this study reviews several precedents for soundscape installations that utilize vibration as the primary driver of sound formation. One of the most relevant is Bill Fontana's Harmonic Bridge (2006), an installation that transforms the structure of London's South Bank Bridge into a vibration-based soundscape (Figure 6). Using piezoelectric microphones, the system captures physical vibrations transmitted from the metal structure by pedestrian and vehicular traffic, rather than recording airborne sounds like conventional microphones. These vibrations are then processed into a real-time sound composition, which is played through speakers in another location, allowing listeners to re-experience the spatial activity through a dynamic, repetitive acoustic dimension. This installation demonstrates how physical structures can be engineered to produce vibrant soundscapes without the direct intervention of musical elements [9].

Another precedent is Soundscape by Mandai Architects (2020), an immersive installation that integrates AGC glass technology—a transparent, vibration-sensitive glass—as an active acoustic medium. When users walk on the floor or touch the glass panels, a system of sensors and sound amplifiers captures these vibrations. It transforms them into resonances that respond to their intensity and body position. The result is a contextually changing soundscape that adapts to the user's presence and movement within the space. This installation highlights the significance of the interaction between the body and material as a driver of personalized acoustic experiences. Like Harmonic Bridge, this project utilizes vibrations as a primary data source. Still, its focus is on the relationship between user participation and real-time sound output, demonstrating the potential to integrate sound systems into passive architectural elements, such as glass or flooring.

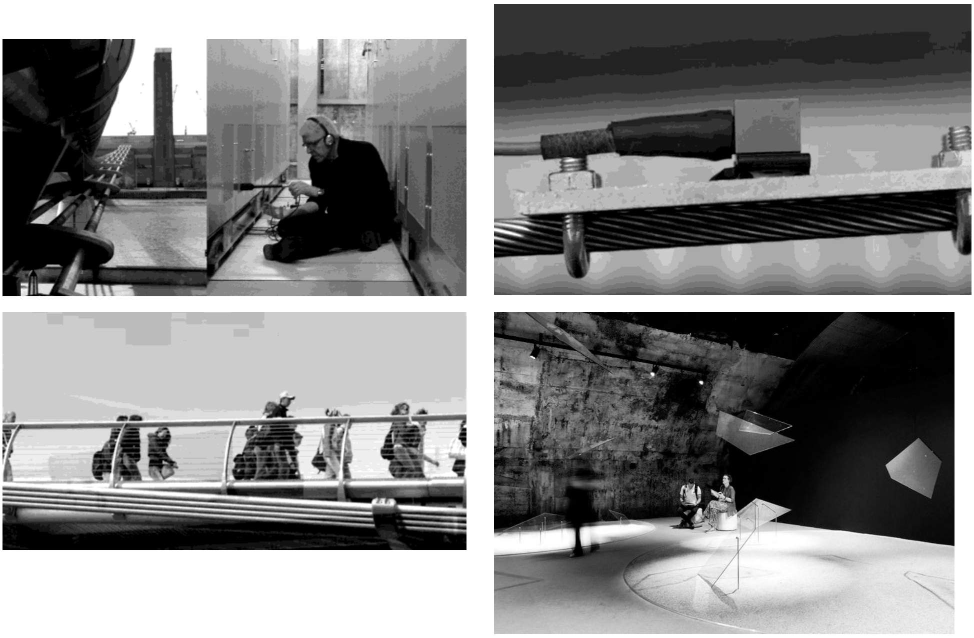

Fig. 6. Precedent review: Bill Fontana's Harmonic Bridge installation, which visualizes the transformation of a bridge structure into a vibration-based soundscape. The Harmonic Bridge project utilizes piezoelectric microphones, located on the South Bank in London, where pedestrians pass by. Mandai Architects' Soundscape installation utilizes AGC glass panels as an interactive medium that responds to body movement with sound resonance.

Source: https://www.archdaily.com/897183/soundscape-mandai-architects

These two precedents provide a strong foundation for developing architectural systems that can emphasize specific sounds as part of a space's identity. In the context of this project, the approaches used in Harmonic Bridge and Soundscape can be adapted to construct a system that explicitly captures and amplifies the sounds of buses. For example, vibrations generated by bus wheels as they pass over a bumper in a transit area can be captured using piezoelectric sensors and then transmitted to speakers at specific points through a simple processing system. To enhance the sound resonance, acoustically reflective elements, such as stretched fabric, can be used to reflect sound vibrations toward a microphone. With this approach, the architecture becomes not only a passive transit space but also a medium for recording and transmitting the acoustic atmosphere characteristic of the mudik (homecoming) moment itself. This approach opens up the possibility of designing moment-based soundscapes as a more powerful and contextual form of spatial experience.

3.2 Simulation and Study Models

To understand how sound can be passively directed and amplified, a series of simple simulation experiments was conducted to investigate the behavior of sound when it interacts with surfaces. The results showed that when a hard, open surface reflects sound waves, the sound is enhanced by specular reflection and no energy is absorbed. Conversely, in the intense situation of Mudik noise, when the sound source is partially covered, the sound still experiences a resonance enhancement, but with a more limited reflection direction and slightly lower intensity (Figure 7). This phenomenon is supported by the basic principle of

acoustic reflection, which states that sound incident on a surface is reflected in proportion to the angle of incidence and the material's properties
. This simulation represents the first step toward understanding how architectural elements can be optimized as natural sound amplifiers, without the aid of electronic systems, through spatial layout and form.

The experiments continued with form studies using models based on concave, convex, and a combination of flat and curved geometries. Concave surfaces can focus sound waves to a single point, while convex surfaces spread sound over a wider area, in accordance with the principle of diffuse reflection in room acoustics. Furthermore, the use of fabric as a flexible reflective surface exhibits a distinctive acoustic response: depending on its tension and curvature, it can amplify reflections in specific directions or dampen others, much like a dynamic membrane in the design of a performance space. This study's mockup (Figure 8) was used to explore potential shapes that allow for sound amplification from a specific source, taking into account the desired direction, distribution, and resonance characteristics [10,11].

The basic properties of sound waves, such as propagation direction, reflection, diffraction, and interference, are essential for spatially accentuating bus sound. Sound waves tend to travel in a straight line from their source, but can be bent (diffracted) when passing through gaps or objects and reflected by hard surfaces. When appropriately directed, these reflections can enhance the perception of sound at a specific point without increasing its original volume. Furthermore, the phenomenon of interference, when two sound waves meet and reinforce each other (constructively), can also be used to emphasize specific sound moments. In this design context, vibrations caused by bus wheels passing over tread elements such as bumpers can be maximized by directing reflections to a microphone receiver equipped with a simple resonator. Thus, the manipulation of shapes and materials that support reflection and the direction of sound propagation can be used as an accentuation strategy without the need for additional electronic amplification systems. This approach allows spatial design that not only considers visual form but also acoustic performance in response to time and moments [12,13].

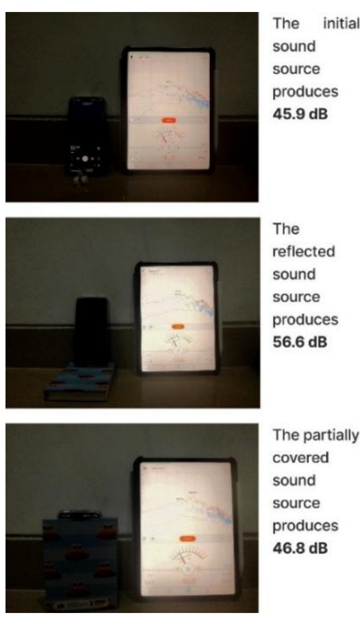

Fig. 7. Experimental simulation of the behavior of sound waves against surfaces, showing the difference in response between reflections from open and partially closed surfaces in amplifying sound resonance.

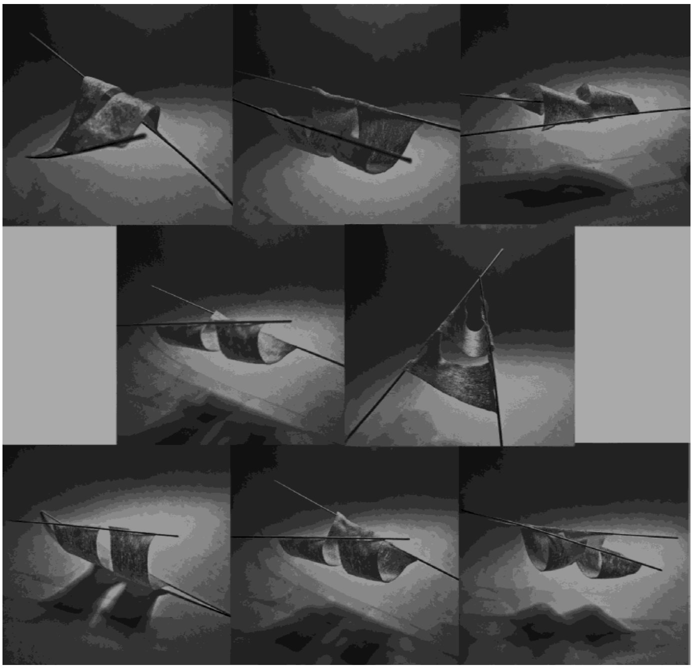

Fig. 8. Concave, convex geometry of reflective fabric used to test the potential of the shape to passively direct, diffuse, and amplify sound from a particular source.

3.3 Discussion

This design was developed using Plowright's (2014) concept-based framework approach, which bases spatial exploration on moments rather than merely functions [8]. The homecoming moment, with its massive, temporary movement patterns, is seen as a crucial moment in shaping the atmosphere of the transit space. This approach positions bus sounds as soundmarks, acoustic markers representing specific places and times [2,14]. The designed system consists of three main elements: special bumpers placed in the bus's wheel tracks to generate vibrations, piezoelectric microphones that record vibrations from the metal structure beneath the overpass railing, and sound-reflective fabric oriented over the bumpers to focus reflections on the microphones. This system does not rely on natural noise or vehicle sound volume; instead, it uses vibrations as a source of acoustic data. This aligns with the working principles of the Harmonic Bridge by Fontana (2006), in which structural vibrations generate a constantly changing soundscape that follows spatial activity.

The system's implementation spans four interconnected site zones (Figure 9). Land A, the primary arrival point, presents an initial impact sound as a marker of activity. Lands B and C are more transitional. Meanwhile, in Land D, sound creates the rhythm of the open space. Each land was designed according to soundscaping principles, which use sound as a shaping element of the spatial experience. The placement of loudspeakers, sensors, and reflectors was determined through mockup simulations, which demonstrated that the direction of reflection can be focused to enhance sound perception. This is achieved by utilizing hard materials and reflective surfaces, which can increase sound intensity through directional amplification and reduce diffusion.

Site A-B

Site C-D

Fig. 9. Proposal for design.

The sound quality captured by piezoelectric microphones is pure and minimizes environmental interference, as piezoelectricity responds directly to vibrations from solid media, not air. This type of microphone is well-suited for architectural contexts that seek to capture physical frequencies rather than open acoustics. Reflective fabric, with its specific tension and geometry, acts as a passive resonator, directing reflections and enhancing sound focus at the sensor point (Figure 10). The effects of shape (concave and convex) demonstrate that geometry plays a crucial role in determining the direction and quality of sound reflection, in line with the principles of acoustic diffraction and reflection. The transport hub consists of a series of atmospheres. Tensile canopies cover the concourses to create a light, weather-modulating "roofscape." This is like Frei Otto's lightweight membrane structures, which use minimal material to cover large areas while altering how people experience space. On purpose, sound is treated: the sound of the bus moving and the sound of the reflective corridor panels become part of the site's soundscape, which is the acoustic environment as it is perceived in context, rather than just noise. The temporary bridge serves as both a viewpoint and a social "destination." People are guided through enclosed corridors to a view of the river. This compression-and-release sequencing is typical of the architectural promenade, in which routes are planned to showcase views and contrasts along the way. Lastly, it suggests an intuitive wayfinding method—people are "indirectly guided" by spatial cues, sightlines, and landmarks, which should help passengers find their way through complicated hubs just as well as signs do.

This system not only serves as an architectural complement but also actively contributes to creating a temporary spatial experience. When the bus arrives, and its wheels touch the bumper, a sound impulse is produced. The sound is transmitted as a spatial signal, forming a kind of "atmospheric alarm" that is only active during the homecoming period. This indicates that space can "pulse" seasonally [5], allowing the soundscape to be programmed to respond to the intensity and rhythm of urban life. This passive approach also enables the system to be used sustainably with minimal energy consumption, making it particularly relevant for temporary adaptive architecture. If developed as a module, this system can be replicated at other seasonal transit points in large cities, positioning sound not only as a representation of activity but also as a spatial strategy consciously designed and directed.

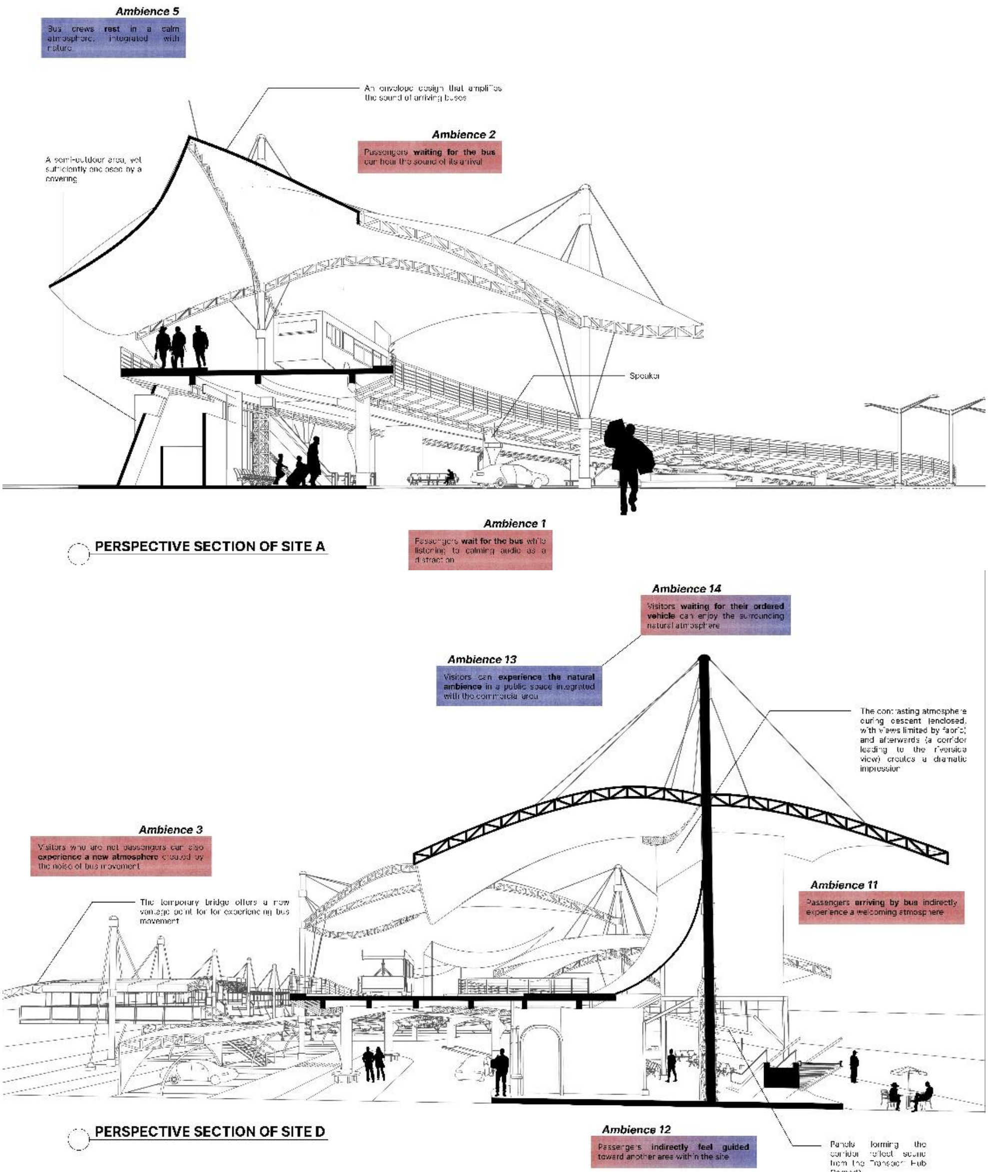

Fig. 10. Reflective fabric.

4 Conclusion

This research demonstrates that temporary architecture can enhance seasonal moments such as the Eid al-Fitr homecoming (mudik) by accentuating the sound of vehicles, particularly buses, as a key element in shaping spatial experience. Adopting a concept-based framework, the design aims to create a system that uses the physical vibrations of bus activity as a consciously curated sound source. This system consists of vibration-inducing bumpers, piezoelectric microphones to capture structural vibrations, and reflective fabric as a resonance-directing medium, all of which operate passively yet effectively.

The application of this system at several points within the site demonstrates that sound can function not only as background but also as atmospheric, navigational, and rhythmic markers. This confirms that soundscapes can be an effective design strategy in guiding users' spatial experiences over time. In addition to addressing the need for temporary transit architecture, this design also opens new possibilities for exploring sound-based architecture, which has been strategically underutilized in the Indonesian urban context.

Overall, this approach not only represents the presence of vehicles but also reproduces their presence in the form of a distinctive and contextual acoustic landscape. With the ability to operate passively and adaptively to the moment, this system has the potential to be replicated and further developed as a prototype for temporary public space designs that respond to the dynamics of human movement and time in a multisensory manner.

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