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Mixed-Effects Modeling of Urban Alley Characteristics for Road Noise Mitigation in High-Traffic Areas in Isfahan, Iran

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ABSTRACT

Background: Among urban features, alleys have a unique potential to influence noise patterns through their structural attributes. This study aims to evaluate how specific alley characteristics, such as width, building height, and curvature, can mitigate traffic noise in urban environments, particularly in arid regions with limited greenery.
Methods: This field-based observational study, conducted in Isfahan, Iran, during spring 2024, investigates the noise-attenuating effects of alley characteristics, where noise levels and structural variables were analyzed using a non-linear mixed-effects model across six measurement points from 0 to 50 m within selected alleys. Initial noise levels at alley entrances averaged ≈70 dB (mean), decreasing to ≈44 dB at 50 m, demonstrating a significant reduction.
Results: The mixed-effects model revealed that fixed effects of structural characteristics explained 73% of the variance in noise attenuation (Marginal $R^2 = 0.726$), while the full model with random effects for alley variations accounted for 89% (Conditional $R^2 = 0.888$). Entrance width showed a positive association with noise, whereas building height and curvature significantly reduced noise propagation. Vegetation indices showed no significant impact on noise levels, likely reflecting the very low vegetation density (NDVI ≈0.14). This suggests that structural alley features, rather than greenery, dominate noise mitigation in arid regions.
Conclusion: These findings underscore the importance of urban alley design in noise management, highlighting the role of narrower entrances, taller buildings, and curved pathways to enhance livability in noise-prone urban areas. Optimizing these structural features in urban planning can significantly reduce noise exposure, and future research should explore their applicability across diverse urban contexts.

1. Introduction

Urban areas are becoming increasingly noisy, primarily due to heavy traffic (González et al., 2023). In developing nations, the rise in urban populations and car ownership is anticipated to further increase noise levels, exacerbating adverse effects on city residents. Extensive research has documented the health risks associated with such noise exposure, linking it to auditory issues, like hearing impairment (Amoatey et al., 2020), as well as non-auditory impacts, including cardiovascular problems, sleep disruption, cognitive decline, and mental health concerns (Krittanawong et al., 2023). To address these risks, various strategies have been proposed to reduce exposure to traffic noise, focusing on controlling noise at its source, limiting its transmission along the pathway (Tsoi et al., 2023), or enhancing protections for affected individuals (Balasbaneh et al., 2020).

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Reducing traffic noise at the source often involves addressing vehicle noise generation, with the adoption of electric vehicles representing a proactive and impactful approach to urban noise management; however, this solution is often not feasible in developing countries such as Iran. Additionally, urban residents commonly employ self-protective measures, primarily through building designs that incorporate soundproofing materials to reduce sound transmission, especially for buildings near high-traffic areas. (Eren et al., 2024). Such measures include the use of thicker walls, double-glazed windows, and other noise-dampening features to shield occupants from external noise (Amran et al., 2021). In addition to controlling noise at the source and receiver, focusing on the pathway between them offers another strategy for managing noise transmission (Arsalan et al., 2024; Sakieh et al., 2017). Physical noise barriers are commonly installed as obstacles between the noise source and the receiver to block or reduce sound transmission effectively (Kotzen & English, 2014). While effective, these barriers can detract from the visual appeal of urban landscapes. Additionally, urban land-use planning can serve a similar purpose by creating buffer zones between high-traffic areas and residential neighborhoods. For example, urban parks are often strategically integrated into city planning as natural noise barriers, utilizing their ecosystem function of sound reduction to enhance urban livability (Arsalan et al., 2024). While green spaces are effective noise buffers, research on intricate urban forms, such as alleys, remains limited, particularly in arid regions with sparse vegetation. Alleys, as narrow, often overlooked elements of city layouts, offer unique potential for noise management due to their structural characteristics, making them a critical yet underexplored feature for mitigating traffic noise in urban environments like central Iran.

In various regions worldwide, including central Iran, alleys serve an important role in linking urban spaces. These narrow corridors, usually located between busy roads and residential areas, are mostly residential with minimal commercial or institutional activity (Collecchia et al., 2014). Their confined width, enclosed structure, and unique design make alleys intriguing for noise control. Priyatna (2024) explicitly uses the term “acoustic tunnel” to describe how narrow alleyways “channel street noise inward while also transmitting the ambient sounds of domestic life outward,” rendering them distinctive noise environments. Additionally, recent studies indicate that structural factors such as alley width, building height, and spacing, and sound-absorbing or deflecting materials can affect how noise from busy roads permeates these spaces. For instance, Gimper et al. (2010) describe alleyways as corridors that muffle loud noises due to their narrow design. Moreover, Collecchia et al. (2014) highlight that these physical characteristics impart specific acoustic behaviors, potentially making alleys effective for in-path noise mitigation.

In some regions, such as Isfahan City, central Iran, alleys have become semi-private spaces accessible only to residents. These alleyways, shielded from through-traffic, provide a quieter environment for those who live adjacent to noisy roads. Their increasing exclusivity and the absence of external traffic make alleys promising subjects for studying how their structural characteristics may influence noise propagation. By assessing the unique configurations and attributes of alleys, this study seeks to understand their potential role in urban noise propagation and evaluate ways in which they might be harnessed in urban noise management strategies. Given the limited research on alleys as noise mitigation features, particularly in arid climates like central Iran, where greenery is scarce, this study addresses a critical gap. Unlike previous studies focusing on green spaces or noise barriers (Arsalan et al., 2024), this is among the first to systematically examine alley curvature using a non-linear mixed-effects model, a novel approach for modeling complex noise attenuation patterns in urban settings. While non-linear models have been applied to urban noise (Pocock & Lawrence, 2005), their use in analyzing alley-specific structural factors, such as curvature and entrance width, in arid environments remains unexplored. Recognizing that noise diminishes with distance along the alley regardless of absorbing or propagating materials, a mixed-effects model was used to investigate the factors influencing noise reduction within alleyways. The findings of this study will contribute to evidence-based urban design guidelines that promote the creation of quieter and more livable urban spaces, especially in areas with high levels of traffic noise. The main objectives of this study are to (1) analyze how specific structural features of alleys-such as width, building height, and green biomass-affect the propagation and attenuation of noise from nearby roads, and (2) quantify the relative contributions of alley entrance width, building height, and curvature to noise attenuation using a non-linear mixed-effects model to inform urban design.

2. Materials and Methods

2.1 Study Areas and Noise Measurement Location

For this study, we selected a recently developed part of Isfahan City, central Iran (32 °40 28" N and 32° 39' 59" N latitude, and 52° 39' 02" E and 51° 40' 15" E longitude), which meets our criteria for analyzing noise attenuation patterns. The main roads in this area connect significant parts of the city, yet there are no secondary roads to funnel traffic from residential neighborhoods to these main roads. As a result, there is an immediate transition between major roads and the smallest category of urban roads that form alleyways. In contrast to main and secondary roads, these alleyways are predominantly pedestrian areas, often with very short lengths, typically less than 100 m. The selected region is located approximately 7 kilometers from the city center and is zoned for vertical development to accommodate future population growth. Unlike the southern part of the city, this area represents the arid nature of the region, with minimal space allocated to alley design. As shown in Figure 1, we systematically surveyed the area to identify alleys that best matched our criteria, including: (1) no elevation changes along the alley, (2) exclusive residential land use with no other functions, (3) no physical barriers inside the alley other than the outer building walls, and (4) alley-lined vegetation limited to small shrubs and trees.

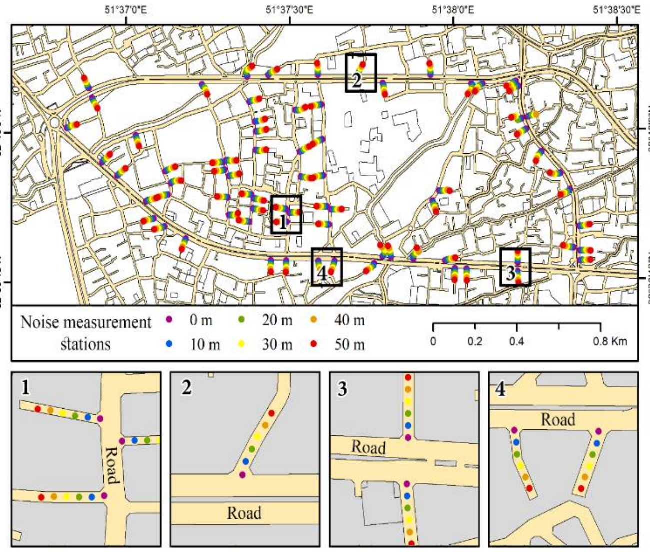

Figure 1. Noise measurement stations located in alleys at varying distances from the road, ranging from the entrance (0 m) to 50 m inside the alley

2.2 Noise Measurement Protocol and Setup

To measure noise levels under controlled conditions, we recorded noise in 5-minute intervals. This interval was chosen due to occasional disturbances, such as noise generated within the alley itself or vehicles passing through, which could interfere with our target noise attenuation model. Measurement points were established at specific distances (0, 10, 20, 30, 40, and 50 m) from the alley entrance (Figure 1) to capture the noise attenuation profile along the entire length of the alley. Each of these points was equipped with a sound level meter (CASELLA CEL-440), allowing for concurrent noise recordings across all distances, ensuring that each measurement was made under identical external conditions to reduce variability. The device at each measurement point was positioned centrally along the width of the alley, 1.5 m above the surface, avoiding placement near corners to ensure representative data. During each measurement, the operator left the device unattended to minimize interference. Measurements were conducted in late spring 2024, specifically between 10:30 and 12:30. Each 5-minute measurement was repeated 10 times, with concurrent recordings at all measurement points (0-50 m) to minimize temporal variability in traffic noise. Traffic conditions were monitored to ensure relative stability in sound power levels during the measurement period, reducing potential differences in sound pressure levels across points. The CASELLA CEL-440 sound level meter was set to compute the equivalent continuous sound level for each 5-minute measurement, which inherently applies logarithmic averaging by converting sound pressure levels to the linear domain, averaging them, and converting back to decibels (dB).

2.3 Variables Affecting Noise Decay in Alleys

To analyze the factors influencing noise decay within alleyways, we categorized variables into three main groups: alley entrance characteristics, internal characteristics, and vegetation. The entrance characteristics include the Entrance Width Measure (EWM) and Entrance Building Height (EBH). EWM represents the width of the alley at its entrance, assuming that wider entrances can allow more noise from the main road to penetrate the alley. EBH refers to the height of buildings directly at the entrance, which may act as vertical noise barriers. Taller buildings at the entrance were assumed to shield the alley′s interior from road noise, thus reducing initial noise levels (Torija & Flindell, 2014).

The internal characteristics of the alley consisted of Alley Width Mean (AWM), Path Curvature Index (PCI), and Building Height Mean (BHM). AWM influences sound reflection and dispersion within the alley space (Collecchia et al., 2014), as wider alleys provide more open space, facilitating sound dissipation. PCI was calculated based on the overall shape of the alley path (Eq. 1) to capture the impact of alley curvature on noise propagation, as more curved alleys may obstruct direct sound waves and enhance noise reduction. In the PCI equation, values closer to 1 indicate straighter alleys, while values above 1 reflect increased curvature, which is expected to influence noise attenuation by dispersing sound waves as they encounter bends in the path. BHM was also considered as a measure of vertical enclosure, which could either amplify noise through reflections or reduce it by creating a more confined environment, depending on the height and layout of buildings (Lee & Kang, 2015).

The vegetation indices were derived using 10 m-resolution Sentinel-2 Normalized Difference Vegetation Index (NDVI) data captured in 2023 (Figure 2) and include the Vegetation Index Mean (VIM) and Vegetation Index Standard Deviation (VIS). VIM represents the average vegetation density within the alley, which is critical for noise attenuation, as denser vegetation absorbs sound and reduces overall noise levels (Sakieh et al., 2017). VIS captures the spatial variability of vegetation along the alley; higher variability suggests uneven vegetation density and potentially uneven noise attenuation (Arsalan et al., 2024). NDVI values for vegetation were calculated using Eq. 2, where NIR is the surface reflectance of the near-infrared band 8, and Red is band 3. NDVI values range from -1 to 1, with higher values indicating denser vegetation. The mean NDVI within each alley was considered as VIM, while the standard deviation, reflecting vegetation diversity and distribution, was used as VIS.

$$PCI = \frac{\text{Alley Path Length}}{\text{Straight} - \text{Line from Entrance to EndAlley Path Length}} \quad \text{Eq. 1}$$

$$NDVI = \frac{NIR - Red}{NIR + Red} \quad \text{Eq. 2}$$

The urban layout, including building footprints and alley dimensions, was obtained from the Isfahan Municipality. Distance measurements were extracted using GIS-based tools, while building height measurements were derived from a high-resolution digital elevation model (DEM) with sub-meter accuracy (Figure 2). To calculate EBH and BHM, we subtracted the ground elevation (DEM values at the road and alley surfaces) from the building height values, providing precise height measurements for each alley structure.

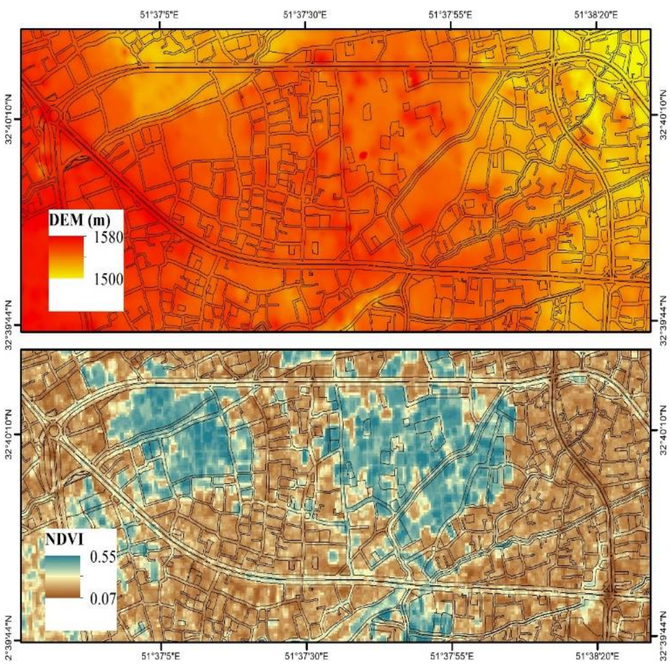

Figure 2. High-resolution Digital Elevation Model and Sentinel-2-derived NDVI layer of the study region

2.4 Noise mitigation modeling using a fixed-effect model

The best modeling approach for this study is a mixed-effects model, which effectively captures both the decreasing effect of noise as it propagates inside alleys and the contributions of specific alley characteristics described above. This model is well-suited to accommodate both fixed effects (such as alley width, building height, and vegetation) and random effects (variations among individual alleys), providing a comprehensive framework for analyzing noise decay in complex urban environments. Preliminary analyses and findings from similar studies (Pocock & Lawrence, 2005) suggest that noise decay follows a decreasing power pattern. This relationship reflects the rapid initial decrease in noise near the source, followed by a more gradual reduction further into the alley. Given this pattern, we used a non-linear version of the mixed-effects model, allowing for an accurate representation of the noise attenuation curve and improved fit to the data. We run this model using the nlme function from the nlme package in R, which is designed for fitting nonlinear and linear mixed-effects models to fit a nonlinear mixed-effects model where NoiseLevel was modeled as a nonlinear function of distance (Eq. 3) where α, β, and γ are the parameters that control the shape and starting level of noise decay with distance, V_i represents fixed effects for various alley characteristics (I = 1, 2, ... , n) and u_{AlleyID} is a random effect for each alley, allowing for variability in the noise levels across different alleys.

$$NoiseLevel = \alpha . Distance^{-\beta} + \gamma + \sum_{i=1}^{n} V_i + u_{\text{AlleyID}} \quad \text{Eq. 3}$$

To evaluate the effects of alley characteristics on noise attenuation, we used a nonlinear mixed-effects model. Model performance was assessed using two R² measures: Conditional R² (R_c^2), representing the variance explained by both fixed and random effects, and Marginal R² (R_m^2), indicating variance explained solely by fixed effects. A high R_c^2 suggests the model captures both alley characteristics and individual variations effectively, while R_m^2 isolates the predictive power of fixed characteristics, such as alley width, building height, and curvature, on noise levels. Fixed-effect estimates were calculated to provide insights into the directional impact of each characteristic, with negative estimates indicating noise reduction with distance, while positive estimates implied reflective contributions to noise. The correlation matrix among fixed effects was finally calculated to highlight interactions, revealing potential combined influences on noise attenuation. Residual analysis was also calculated to confirm the model's fit, showing minimal unexplained variance and validating its accuracy in capturing noise decay patterns.

3. Results and Discussion

3.1 Noise Attenuation Patterns

Noise levels were measured at varying distances from the road and exhibited a clear attenuation trend consistent with expected sound decay principles (Figure 3). At the alley entrance (0 m), the mean noise level was 69.70 ± 5.24 dB, ranging from a minimum of 57.59 dB to a maximum of 82.75 dB. This range reflected the highest intensity of noise emissions and was accompanied by substantial variability, as indicated by the relatively large standard deviation (± 5.24 dB). This variability suggests fluctuating noise levels near the source, possibly due to inconsistencies in traffic noise emission. As the distance from the source increased, the mean noise level decreased, with reduced variability (Table 1).

Table 1. Mean noise levels (± standard deviation) and ranges at varying distances from the alley entrance.

Distance (m)	Mean Noise Level (dB)	Range (dB)
0	69.70 ± 5.24	57.59–82.75
10	60.95 ± 3.99	51.32–70.99
20	54.21 ± 3.05	47.41–61.92
30	48.60 ± 2.79	40.53–56.12
40	45.93 ± 2.33	40.12–53.48
50	44.12 ± 2.68	38.38–49.81

These values indicate a progressive stabilization of the noise pattern with increasing distance, reflected in the decreasing standard deviation values. A Tukey test revealed that the noise level at 50 m was the first distance showing no statistically significant difference from the previous measurement at 40 m, suggesting a plateau in noise attenuation beyond this distance. Moreover, the decreasing power regression model provided the best-fit curve to the data, with an R^2 of 0.96 and an equation of $y = 63.533e^{-0.008x}$, indicating that the slope becomes relatively constant after 50 m.

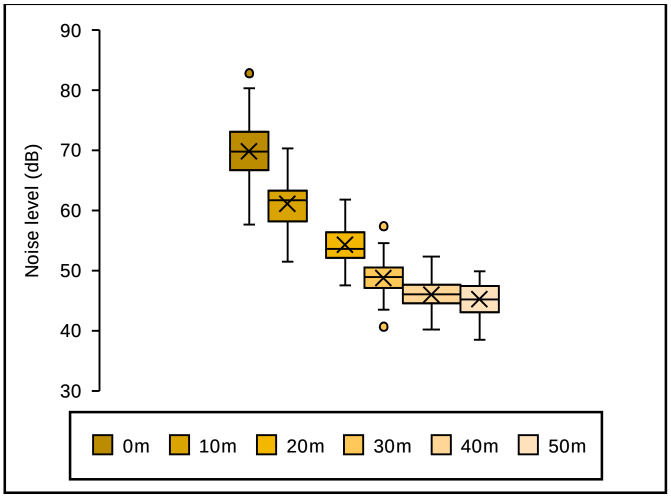

Figure 3. Box plot of noise levels at various distances within alleys, measured up to 50 meters from the road. Outliers are indicated by individual points positioned beyond the whiskers

Road traffic is the primary source of noise in urban environments, affecting residents whose homes are situated close to major roads. Although the internal design of apartments can help reduce noise exposure, particularly at night, the strong desire to enjoy the outdoor atmosphere in Isfahan during spring increases residents' exposure to traffic noise. As expected, our findings indicate that alley areas within residential blocks near roads are subject to the highest noise levels, with a mean of 69.70 ± 5.24 dB. Additionally, noise levels showed the greatest variability at closer distances to the road, as reflected by larger standard deviations. This suggests that sound intensity fluctuates more near the source, likely due to variations in vehicle noise emissions and gaps in traffic flow.

Beyond 20 m from the road into the alley, noise levels decreased to an acceptable mean of 54.21 ± 3.05 dB, within the European Union (EU) Noise Directive's recommended range of 50-55 dB (Kalawapudi et al., 2020). This reduction confirms the expected attenuation of sound over distance, with noise levels steadily diminishing as the measurement point moves further from the source. Our results showed that the urban morphology near roads appears to be highly effective in mitigating road noise, contrasting with findings in open spaces (such as limited tree woodlands), where it can take over 100 m for noise to drop from approximately 80 dB to around 50 dB in a power-decay pattern (Pocock & Lawrence, 2005). The impact of alley morphology, which contributes to this observed difference, also aligns with the study by Collecchia et al. (2014), who found that alleyway walls influence noise levels across the alley width. Therefore, understanding these differences in attenuation patterns between various landscapes and alley configurations has practical implications for urban noise management, making effective urban planning and residential design adjacent to noisy areas crucial for protecting residents from traffic noise.

3.2 Alley Characteristics and Their Impact

Descriptive statistics and Kolmogorov-Smirnov (KS) normality test results for eight urban alley variables are given in Table 2. The mean AWM was 13.13 ± 3.38 m, with a range of 6.00 to 23.08 m, indicating moderate variation in alley widths while, EWM showed a wider width with a mean of 20.89 ± 6.19 m, which indicates a more considerable variability in entrance widths. The AOI index averaged 90.80 ± 9.62, with values from 67.15 to 120.07, suggesting that alleys are mostly located perpendicular to the main road. The PCI index showed a mean of 1.28 ± 0.17, ranging from 1.00 to 1.80, showing limited variability in alley tortuosity, denoting that most alleys are straight lines vertically located to the main road. BHM and EBH indices have means of 6.17 ± 1.11 and 14.32 ± 4.00 m, respectively, indicating that entrance buildings are generally taller than the average building height along alleys. EBH, with a maximum height of 25.00 meters, exhibits greater variation compared to BHM, which has a maximum of 9.89 m. The RS-based VIM and VIS were 0.14 ± 0.08 and 0.13 ± 0.05, respectively, indicating limited and relatively stable vegetation density. The KS normality test shows that most variables follow a normal distribution (p > 0.05), except for VIS (*p-value* = 0.02), which slightly deviates from normality.

The mixed-effects model assessing the decay of road traffic noise within alleys performed well in explaining the variance in noise levels (Table 3). The model's marginal R_m^2 was 0.726, indicating that 72.6% of the variance in noise decay was explained by the fixed effects alone. When accounting for both fixed and random effects, the conditional R_c^2 reached 0.888, suggesting that the model accurately captured the influence of both fixed predictors and random variations between alleys. The VIF values for all predictors were below 5, with the highest VIFs observed for VIM (3.525) and VIS (3.215), indicating low to moderate multicollinearity.

The model showed variability in noise attenuation among different alleys due to the inclusion of AlleyID as a random effect, with an estimated variance of 0.668. The residual variance was found to be 3.642, suggesting that there remained substantial unexplained variation in noise decay, likely due to additional environmental or structural factors that could be captured by the fixed effects. Among the fixed-effect variables (Table 4), the effect of distance from the road was found to be highly significant (Estimate = -0.596, p < 0.001; β ≈ -0.85), with noise levels decreasing as the distance into the alley increased. This aligns with the general expectation that sound diminishes with increased distance from its source. This variable displayed the strongest association with noise decay, as reflected in both the magnitude of the estimate and its statistical significance. This indicates that distance is by far the dominant factor in explaining noise attenuation, overshadowing the contribution of other predictors.

Table 2. Descriptive statistics and Kolmogorov-Smirnov (KS) normality test results for eight urban alley variables

Variable	Descriptive statistics							KS normality	
	Mean	StdDev	Min	25%	Median	75%	Max	Statistic	*p-value*
Alley Width Mean (AWM)	13.13	3.38	6.00	10.80	12.85	15.25	23.08	0.08	0.69
Entrance Width Measure (EWM)	20.89	6.19	6.00	17.37	21.52	24.99	33.74	0.06	0.91
Alley Orientation Index (AOI)	90.80	9.62	67.15	84.14	90.50	97.49	120.07	0.04	1.00
Path Curvature Index (PCI)	1.28	0.17	1.00	1.16	1.30	1.38	1.80	0.07	0.85
Building Height Mean (BHM)	6.17	1.11	4.07	5.34	5.98	6.80	9.89	0.09	0.53
Entrance Building Height (EBH)	14.32	4.00	3.55	11.84	13.88	16.92	25.00	0.10	0.40
Vegetation Index Mean (VIM)	0.14	0.08	0.05	0.07	0.12	0.20	0.38	0.13	0.13
Vegetation Index Standard Deviation (VIS)	0.13	0.05	0.09	0.09	0.13	0.21	0.21	0.18	0.02

The AWM did not significantly influence noise levels (Estimate = 0.259, *p-value* = 0.393; β ≈ 0.05), denoting that wider alleys did not facilitate greater noise penetration. In contrast, the EWM index was positively associated with noise levels (Estimate = 0.080, *p-value* = 0.009; β ≈ 0.12). Accordingly, alleys with wider entrances may allow greater noise entry from the main road. Although significant, the effect size of EWM was modest compared to distance, suggesting its influence is secondary but still relevant for design considerations.

The AOI exhibited no significant effect on noise attenuation (Estimate = 0.004, *p* = 0.662; β ≈ 0.01). It seems that the direction in which alleys are oriented relative to the main road does not substantially impact the decay of road noise. However, variations in building height were found to be significant enough to impact noise decay, in which tall buildings (both BHM and EBH indices) were found to be significant predictors (Estimate for BHM = -0.400, *p* = 0.045; β ≈ -0.11; Estimate for EBH = -0.220, *p* = 0.007; β ≈ -0.15). The stronger effect of EBH compared to BHM suggests that entrance buildings play a particularly important shielding role**.** Consistent with the hypothesis that curvature obstructs the direct path of sound waves, a significant negative association was observed for the PCI index with noise levels (Estimate = -2.650, *p* = 0.008; β ≈ -0.18), suggesting that curved alleys significantly reduce noise propagation, thus attenuating noise more effectively than straight alleys. In fact, curvature emerged as the most influential structural factor after distance, highlighting its potential as a design strategy for noise mitigation**.**

Neither greenery-related variable showed a statistically significant association with noise decay (Estimate for VIM = 0.082, *p* = 0.593; β ≈ 0.02; Estimate for VIS = -8.845, *p* = 0.371; β ≈ -0.04), which was unexpected, as vegetation is generally considered to absorb or obstruct sound. However, the very small β values confirm that vegetation played almost no role in this arid context, where low NDVI levels limited its contribution relative to structural features.

Table 3. Summary of model diagnostics and random effects for the mixed-effects model assessing noise decay in alley

Scaled residuals					REML at conv.	Var. of Random effects		Model performance	
Min	1Q	Median	3Q	Max		AlleyID	Residual	R_m^2	R_c^2
-2.962	-0.643	-0.060	0.605	3.454	2427.100	0.668	3.642	0.726	0.888

Table 4. Fixed effects estimates, standard errors, variance inflation factors (VIF), and approximate p-values for predictors in the mixed-effects model assessing road traffic noise decay within alleys

Fixed Effects	VIF	Estimate	Std. Error	Std. β	Adjusted *t value*	Approx. *p-value*
(Intercept)	-	64.454	3.992	–	16.147	<0.001
Distance	1.000	-0.596	0.011	-0.843	-58.925	<0.001
AWM	1.867	0.259	0.067	0.054	0.855	0.393
EWM	1.453	0.080	0.031	0.128	2.620	<0.009
AOI	1.085	0.004	0.010	0.010	0.437	0.662
PCI	2.716	-2.650	1.008	-0.173	-2.630	<0.009
BHM	1.730	-0.400	0.199	-0.102	-2.010	<0.045
EBH	2.659	-0.220	0.081	-0.145	-2.700	<0.007
VIM	3.525	0.082	0.154	0.027	0.535	0.593
VIS	3.215	-8.845	10.271	-0.032	-0.895	0.371

This study identified specific alley characteristics as key factors influencing noise attenuation, particularly entrance width, building heights, and alley curvature. In terms of entrances, both horizontal and vertical urban morphology parameters were found to play a significant role in noise reduction. Specifically, tall buildings at the entrance served as effective vertical barriers, shielding the inner alley from direct road noise. Although the importance of vertical barriers is well-documented, it is often discussed in the context of structures located near busy roads or railway lines (Peplow et al., 2021); however, this study introduces tall buildings functioning as vertical obstructions, similarly reducing noise in a larger-scale urban context. Moreover, wider alley entrances were shown to allow greater sound penetration from the main road, indicating that wider openings offer less resistance to sound waves, permitting deeper noise penetration into alleys. The importance of these parameters introduces the concept of a "noise bottleneck" in urban design, which could be applied to safeguard residential areas close to noisy roads. Despite their importance, the role of alley entrance characteristics in noise reduction has not yet been extensively studied and is often discussed in the context of greenery rather than structural features (Rodríguez Martínez, 2022), which could be more practical for arid regions with limited greenery options to counter road traffic noise propagation.

The results also showed that the mean building height along the alley and the alley curvature are as important as entrance characteristics. Similarly, it can be concluded that tall buildings have a noise-blocking effect inside the alley, gradually dissipating sound as it moves inward. This finding aligns with those of Collecchia et al. (2014), which showed that alley physical structures influence noise propagation and mitigation within alleys. Although most alleys in the study region were found to be straight-lined urban elements, our results showed that curved alleys demonstrated a stronger noise attenuation effect, as evidenced by the significant negative association between PCI and noise levels. This negative relationship is supported by sound wave behavior in built environments, where bends and obstacles in the path of sound waves cause diffraction and scattering, thereby reducing the distance that noise can effectively travel. Some studies also view this as a factor in lowering vehicle speeds, thereby making the pathway quieter (Tang & Wang, 2007). It appears that curved pathways in urban areas offer distinct advantages by impacting both the source noise emission and the propagation of noise within urban elements, benefiting residents.

3.3 Correlations and Urban Design Implications

The correlation matrix of fixed effects (Table 5) revealed notable relationships among alley characteristics. Particularly, a strong negative correlation was observed between Intercept and EWM (-0.520), as well as AWM (-0.461), suggesting that wider alleys and entrances may inherently reduce baseline noise levels, likely due to increased open space that facilitates sound dispersion. In contrast, curved alleys exhibited lower noise due to the negative correlation of PCI with the Intercept (-0.301), potentially by disrupting direct sound pathways. Accordingly, both wider entrances and increased path curvature contribute to noise reduction but through distinct mechanisms: one by maximizing open space and the other by altering the path of sound transmission. An interesting trade-off emerges between PCI and BHM, which are moderately negatively correlated (-0.305), suggesting that more curved alleys often have shorter average building heights, a pattern that may influence sound reflection within alleys. This contrasts with EBH, which is negatively correlated with BHM (-0.278), indicating that taller entrance buildings are associated with shorter buildings within the alley itself. This configuration could reinforce the noise-blocking role of taller entrance structures, creating a layered effect of sound shielding and gradual dissipation as noise enters the alley. While vegetation metrics show weaker correlations with most variables, the VIM index had a moderate negative correlation with EWM (-0.370), indicating that wider alley entrances tend to have lower vegetation density, possibly due to spatial limitations. Unexpectedly, vegetation density-measured via VIM and VIS indices—showed no significant link to noise reduction. This may stem from the low vegetation levels in the alleys studied, typical of arid cities, where structural features like tall buildings likely dominate noise dynamics. While greenery did not emerge as a primary factor, its spatial relation to built elements may still influence acoustics through airflow or occasional sound absorption. Future research should include areas with varying vegetation and urban forms to better understand these interactions. This study focused on a specific area of Isfahan, so the findings may not fully apply to other contexts. Measuring noise at multiple heights could clarify the vertical effects of buildings. Though the research took place in spring, when foliage peaks-seasonal variations in noise levels should be explored, as they may affect propagation. A broader investigation of building heights and alley dimensions could yield further insight into effective noise mitigation strategies. Moreover, future studies should explore a hybrid approach to modeling traffic noise, where noise is treated as coming from a single point close to the road (for faster noise reduction) and as a spread-out source farther away (for slower reduction). This could better capture how noise travels through alleys, providing clearer guidance for designing quieter urban spaces.

These findings highlight the interplay of alley morphology in noise mitigation. Wider entrances and curvature reduce noise through distinct mechanisms-open space versus sound path disruption-while tall buildings create layered shielding. Urban planners can leverage these insights to design residential areas near noisy roads, prioritizing narrow entrances, taller buildings, and curved pathways to minimize noise exposure, particularly in regions like Isfahan, where outdoor activities amplify noise concerns.

Table 5. Correlation matrix of fixed effects showing relationships among alley characteristics influencing road traffic noise attenuation

	Intrcept	Distance	AWM	EWM	AOI	PCI	BHM	EBH	VIM
(Intercept)	1.00	-0.06	-0.46	-0.52	0.07	-0.30	0.02	-0.33	-0.14
Distance	-0.06	1.00	-0.10	-0.15	0.05	-0.20	-0.17	-0.12	-0.20
AWM	-0.46	-0.10	1.00	-0.18	0.05	0.25	0.05	0.26	0.03
EWM	-0.52	-0.15	-0.18	1.00	0.16	-0.27	-0.20	0.22	-0.37
AOI	0.07	0.05	0.05	0.16	1.00	-0.25	-0.01	-0.21	-0.31
PCI	-0.30	-0.20	0.25	-0.27	-0.25	1.00	-0.31	-0.28	-0.33
BHM	0.02	-0.17	0.05	-0.20	-0.01	-0.31	1.00	-0.28	0.03
EBH	-0.33	-0.12	0.26	0.22	-0.21	-0.28	-0.28	1.00	-0.14
VIM	-0.14	-0.20	0.03	-0.37	-0.31	-0.33	0.03	-0.14	1.00

4. Conclusion

This study demonstrates the critical role of structural alley characteristics-such as building height, entrance width, and alley curvature in mitigating road traffic noise within urban environments in Isfahan. Our results indicate that tall buildings at alley entrances serve as effective vertical barriers, significantly reducing direct noise from nearby roads. The concept of a noise bottleneck emerged as an important design consideration, as narrower entrances restrict sound penetration, offering a potential strategy for shielding residential areas close to busy roads. Moreover, curved alleys proved beneficial for noise attenuation, as sound waves experience diffraction and scattering when encountering bends, thus reducing noise levels further into the alley. Conversely, wider alley entrances allow greater noise penetration, highlighting the need for thoughtful design to balance accessibility and noise management. These findings underscore the effectiveness of urban morphology in reducing traffic noise, with practical implications for urban planners aiming to enhance livability in densely populated areas. These results provide practical insights into optimizing alley configurations, suggesting that urban planners should prioritize alleys with entrances narrower than 10 m, buildings taller than 15 m at entrances, and curved pathways to optimize noise mitigation, thereby enhancing urban livability in high-traffic areas.

Authors' Contributions

Zohreh Alizadeh: Conceptualization; Methodology; Supervision; Writing-review & editing. **Atefeh Chamani:** Formal analysis; Investigation; Software; Validation; Visualization. **Bahareh Lorestani:** Data curation; Resources; Project administration; Writing-review & editing. **Ali Asgarian:** Visualization; Writing-original draft; Writing-review & editing.

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Conflicts of Interest

The authors have declared no competing interests.

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Ethical considerations

The proposal for the present study was reviewed and approved by the Research Committee of Isfahan (Khorasgan) Branch, Islamic Azad University. (Research code: 162912663).

Using Artificial Intelligence

The authors utilized the DeepSeek Chat (free online platform) to refine grammar and enhance language clarity using the prompt: "Check grammar and improve language.

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