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Railway Noise Propagation and Exposure Assessment Along the Urban Tehran- Tabriz Line

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Railway noise is an increasing concern in densely populated urban corridors, where reliable attenuation models are essential for land-use planning. However, field-based comparisons of different train categories under consistent conditions remain limited, particularly in Iran. This study investigated noise propagation from passenger trains, freight trains, and railbuses along a 4.2-km urban section of the Tehran–Tabriz railway near Kavousieh Station, Qods City. Measurements were conducted at seven distances (7.5–200 m) during three pass-bys for each train type. Smartphone measurements were cross-calibrated with a reference sound-level meter, and, after background-noise correction, spatial noise distributions were mapped using Ordinary Kriging. Train-specific logarithmic attenuation models were then developed and validated using grouped leave-one-distance-out cross-validation. Passenger trains produced the highest noise levels, reaching about 99 dB(A). The models achieved R^2 values of 0.9700–0.9845, demonstrating excellent agreement between predicted and measured noise levels. Using a 60 dB(A) criterion, estimated setback distances were approximately 191, 160, and 103 m for passenger trains, freight trains, and railbuses, respectively. Compared with the normalized FRA benchmark, the proposed models showed substantially smaller prediction errors at 200 m. These findings provide practical attenuation relationships for urban railway planning and establish a baseline for future railway acoustics and noise prediction studies in Iran.

1. Introduction

Railway transportation plays an important role in sustainable mobility because of its high transport capacity, energy efficiency, and comparatively low environmental impact. Nevertheless, the expansion of railway infrastructure through densely developed urban areas has increased the exposure of nearby communities to railway noise [1,2]. This issue is particularly important where residential and commercial developments are located close to existing railway corridors. Prolonged exposure to transportation noise has been associated with annoyance, sleep disturbance, cardiovascular effects, and reduced quality of life, making railway noise an important consideration in environmental assessment and urban planning [3-5].

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Railway noise is produced by several interacting mechanisms, including wheel–rail contact, surface roughness, braking, traction equipment, aerodynamic effects, and vibration of track and structural components [6–10]. The relative contribution of these mechanisms depends on train speed, vehicle length, axle loading, rolling-stock characteristics, track condition, and track structure [1,9,10]. For conventional railway operations, wheel–rail interaction generally represents a major source of airborne noise, whereas structural characteristics can modify both sound generation and propagation [9]. Differences between ballasted and slab tracks, for example, can influence the vibration and radiation behavior of the track system [6]. Sound reflections from bridges, buildings, and other urban structures may also modify local sound-pressure levels and produce spatially complex exposure patterns [8]. Consequently, attenuation observed in an urban railway corridor may differ from the idealized reduction expected under unobstructed free-field conditions.

Reliable assessment of railway noise therefore requires field measurements that account for both source variability and site-specific propagation conditions. ISO 1996-1 provides a general framework for describing, measuring, and assessing environmental noise, while railway-specific measurement procedures are addressed in ISO 3095 [13,26]. Nevertheless, field measurements remain subject to uncertainties arising from instrumentation, calibration, environmental conditions, train operation, background noise, and receiver location [14]. Conventional sound-level meters provide reliable measurements but may restrict the number of locations that can be monitored simultaneously. Smartphone-based acoustic acquisition has consequently been explored as a complementary approach for increasing spatial coverage, provided that the devices are appropriately cross-calibrated and their limitations are clearly acknowledged [16].

A range of empirical, analytical, and numerical approaches has been developed for railway-noise prediction [17–19]. More recent studies have examined the influence of rail roughness, track structural properties, and wheel–rail interaction using numerical and hybrid techniques such as finite-element and statistical-energy-analysis methods [20–22]. Although these approaches provide valuable information about noise-generation mechanisms, their application may require detailed input data that are not always available in urban field investigations. Empirical distance-decay relationships provide a more direct means of characterizing attenuation under observed operating conditions, but their reliability depends on the range and quality of the measurement data. Spatial interpolation techniques, including Ordinary Kriging, can additionally illustrate variations between monitoring locations, although their results should be interpreted in relation to the density and spatial arrangement of the measurement network [27,28]. External comparison with established propagation formulations can further assess whether field-derived trends are physically plausible, while recognizing differences in source assumptions and site conditions [30].

Despite the growing international literature on railway-noise assessment, published field evidence remains limited for the specific rolling-stock, track, operating, and urban conditions of the Iranian railway network. In particular, few studies have comparatively evaluated the distance-dependent attenuation of passenger trains, freight trains, and railbuses under consistent track and environmental conditions. This limits the availability of locally derived relationships for preliminary noise-influence and setback assessments. The present study addresses this gap through a comparative field investigation at a representative monitoring section within a 4.2-km urban segment of the Tehran–Tabriz railway corridor in Qods City, Iran. The objectives are to: (1) characterize the noise levels produced by passenger trains, freight trains, and railbuses at multiple receiver distances; (2) illustrate their spatial noise patterns using Ordinary Kriging; (3) develop and cross-validate train-specific logarithmic distance-decay models; (4) compare the field-derived relationships with a normalized Federal Railroad Administration propagation benchmark; and (5) estimate train-specific distances corresponding to an adopted environmental-noise screening criterion. The principal contribution is the development of internally validated, site-specific attenuation relationships for three railway vehicle categories operating within the same urban corridor.

2. Research Methodology

The methodological workflow of the study is presented in Figure 1. The investigation comprised five main stages: (1) study-area selection and monitoring-network design; (2) field measurement of train pass-by and background noise; (3) data screening and quality control; (4) spatial interpolation, regression-model development, and cross-validation; and (5) comparison with a reference propagation formulation and estimation of train-specific screening distances. This workflow was designed to characterize the distance-dependent attenuation of railway noise under the observed operating and urban conditions.

Figure 1. Schematic workflow of the study methodology

2.1. Study Area

The study area is located south of Kavousieh Railway Station in Qods City, west of Tehran, Iran, along the Tehran–Tabriz railway corridor. A 4.2-km railway segment passing through a densely developed residential–commercial area was considered to describe the surrounding urban context. Buildings are located on both sides of the railway, with the closest building façades situated approximately 18 m from the nearest track. The location and spatial extent of the investigated corridor are shown in Figure 2.

Figure 2. Aerial view illustrating the location of Kavousieh Station and the adjacent residential district in Ghods City, Tehran.

Seven receiver locations, designated M1–M7, were positioned approximately perpendicular to the railway at distances of 7.5, 15, 25, 35, 50, 80, and 200 m from the nearest track centerline. This configuration characterized the reduction in railway noise from the immediate trackside area to the far-field receiver, where pass-by levels approached the ambient acoustic conditions. The monitoring

section and receiver arrangement are presented in Figure 3a and 3b.

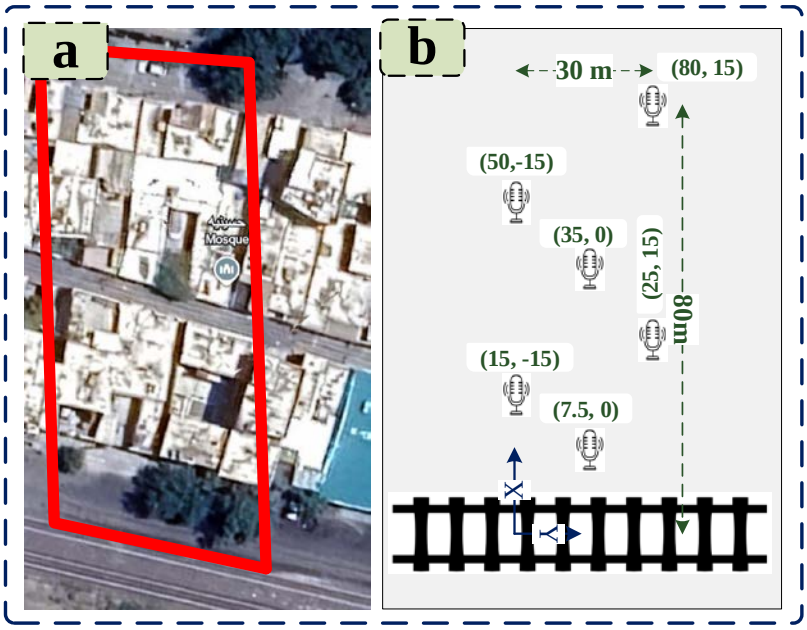

Figure 3. Characteristics of filed investigation: a) field study domain, b) measurement setup and microphone placement

The investigated section consisted of a conventional ballasted track fitted with 60E1 (UIC60) rails and concrete sleepers. A straight track section was selected to minimize the contribution of curve squeal and other curve-related noise mechanisms. No visible rail defects or severe surface irregularities were identified during the field inspection; however, rail roughness was not instrumentally measured. The measurements therefore represent the combined airborne noise generated under the observed track and operating conditions rather than the isolated contribution of an individual wheel–rail or vehicle-related source.

Three railway vehicle categories were investigated: passenger trains, freight trains, and railbuses. During the monitored operations, passenger trains travelled at an approximate speed of 100 km/h, with an axle load of approximately 18 t and formations of 6–12 coaches. Freight-train speeds ranged from approximately 60 to 80 km/h, with axle loads of approximately 30 t and formations of 10–25 wagons. Railbuses operated at approximately 80 km/h, had an axle load of approximately 14 t, and consisted of six cars. These categories represented the principal railway operations observed during the field-measurement campaign.

2.2. Field Noise Measurements

Acoustic measurements were performed at all seven receiver locations using six synchronized iPhone 16 smartphones (Apple Inc., USA) and one reference sound-level meter. The smartphones used their built-in microphone systems and identical default settings in the MOTIV Audio application, consistent with smartphone-based acoustic acquisition reported in previous railway studies [16,21]. Before and immediately after each measurement session, the six smartphones were placed alongside the reference meter in the same acoustic field. Device-specific correction offsets were derived from the simultaneous readings and applied to improve inter-device consistency and identify potential drift. After cross-calibration, the six smartphones were deployed at M1–M6 (7.5–80 m), and the reference sound-level meter was installed at M7 (200 m). This arrangement provided simultaneous observations at all seven receivers. The devices were mounted on tripods with microphones 1.5 m above ground level and maintained in a consistent orientation relative to the track, following the receiver-positioning recommendations of ISO 1996-2 and ISO 3095

[25,26]. Three independent pass-bys were retained for each passenger-train, freight-train, and railbus category. For each event, only the interval during which the train was present was used to calculate the equivalent continuous A-weighted sound pressure level, L_{Aeq}. The event window began when train sound became distinguishable from the ambient condition and ended after the train had passed and the level returned toward the pre-event baseline. The same window-selection rule was applied to every train category and receiver. For every measurement session, background noise was recorded at all seven receiver locations during a 30-min period without train activity. The resulting $L_{Aeq,30\,min}$ values represented the location-specific ambient baseline and were compared with the corresponding pass-by levels. Thus, both pass-by and train-free observations were available at each of the seven receiver positions. Measurements were conducted during daytime under clear and dry conditions, without precipitation and with negligible wind. These conditions minimized, but did not eliminate, meteorological variability in the observed propagation. Figure 4 illustrates the field arrangement and recording procedure.

Figure 4. Field noise measurement setup: (a) microphone at 7.5 m from the railway track; (b) nighttime measurement; (c) measurement near residential buildings; (d) real-time sound level meter display.

2.3 Data Processing and Spatial Analysis

Following data collection, all measured values were categorized by train type and measurement location. For each category, noise levels were analyzed as a function of receiver distance, and regression-based curve fitting was applied to quantify attenuation trends. For clarity and reproducibility, the regression model corresponds to a logarithmic relationship between L_{Aeq} and distance, consistent with standard environmental noise propagation behavior. The goodness-of-fit of each regression model was evaluated using the coefficient of determination R^2 , the root mean square error (RMSE), and the mean absolute error (MAE). To assess the predictive capability of the developed attenuation models, a grouped leave-one-distance-out cross-validation (LOOCV) procedure was additionally performed. In each validation iteration, all three pass-by measurements corresponding to one receiver distance were excluded from model calibration, and the excluded observations were subsequently predicted using the model developed from the remaining receiver distances.

Georeferenced acoustic data were imported into Surfer software for spatial analysis. The interpolation was performed using Ordinary Kriging, which assumes spatial autocorrelation between neighboring observations and provides an optimal unbiased estimator for generating continuous surfaces from discrete field measurements. Ordinary Kriging was selected because it is one of the most widely adopted geostatistical interpolation techniques for environmental and transportation noise mapping, providing reliable spatial prediction of sound pressure levels from limited measurement locations through consideration of spatial dependence among neighboring observations [27, 28]. Noise distribution maps were generated using the Ordinary Kriging interpolation method to produce continuous spatial representations of railway noise across the study area. A linear isotropic semi-variogram model was adopted to characterize the spatial correlation structure of the measured sound levels. The interpolation was performed using a variogram slope of 1, an anisotropy angle of 0°, and an anisotropy ratio of 1. No polynomial drift or restricted search neighborhood was applied, and all available measurement points were included in the interpolation process. Because the adopted linear semi-variogram is an unbounded variogram model, finite nugget, sill, and range parameters are not defined in the same manner as for

bounded spherical or exponential models; therefore, these parameters are not reported. The interpolated noise maps were visually compared with the measured sound pressure levels to verify that the generated spatial patterns were consistent with the observed attenuation behaviour along the investigated railway corridor. The resulting spatial distributions clearly illustrated the decrease in railway noise with increasing distance from the track and enabled the identification of areas with elevated acoustic exposure. Finally, interpolated noise levels were compared with background noise to identify the distance at which railway noise approaches ambient conditions. This comparison was carried out using L_{Aeq} differences ΔL_{Aeq}, which is a standard approach in environmental noise impact assessment to quantify the contribution of railway operations above background levels. Based on these findings, implications for noise mitigation strategies in residential areas adjacent to railway tracks were derived. These implications are based on observed spatial decay patterns and are consistent with standard environmental noise zoning practices.

2.4 Data Processing and Quality Control

Background environmental noise was measured during periods without train activity immediately before and after each measurement session to establish the ambient acoustic baseline. During train pass-by events, only time intervals that clearly represented railway operations were retained for subsequent analysis. The measurement application applied A-frequency weighting and calculated L_{Aeq} over the selected train-pass-by interval [25, 26]. No additional digital frequency filter or automated statistical outlier filter was applied. The recorded sound-level data were carefully reviewed, and measurements clearly affected by unrelated transient noise sources, such as road traffic, pedestrians, aircraft, or other environmental disturbances, were excluded from the analysis. No observation was removed solely because of its magnitude or deviation from the fitted regression trend. The accepted measurements were subsequently classified according to train type, receiver distance, and repetition. Consequently, only quality-controlled railway pass-by measurements were used for statistical analysis, spatial interpolation, and attenuation-model development. The railway-induced noise increment ΔL_{Aeq} was subsequently calculated as the difference between the measured railway noise level and the corresponding background noise level.

3. Results

The analytical framework of this study is structured into four distinct, yet interconnected phases to comprehensively evaluate railway noise pollution. First, the field acoustic conditions are quantified through noise mapping of various train typologies. Second, based on field observations, an empirical logarithmic model is used to describe noise attenuation characteristics with distance. Finally, the physical and spatial datasets are used to derive implications for urban noise exposure and mitigation considerations.

3.1. Railway Noise Mapping and Spatial Distribution

Figure 5 illustrates the spatial distribution of the equivalent A-weighted sound pressure level L_{Aeq} generated using the Ordinary Kriging interpolation method. Panels (a–c) represent the background noise conditions measured before the passage of passenger trains, freight trains, and railbuses, respectively, whereas panels (d–f) show the corresponding railway noise distributions during train pass-by events. The background noise maps exhibit relatively uniform sound level distributions across the study area, indicating limited spatial variation under ambient conditions. In contrast, the railway noise maps reveal a distinct spatial gradient, with the highest sound pressure levels occurring adjacent to the railway track and gradually decreasing with increasing distance. Among the investigated train categories, passenger trains produce the highest overall noise levels, followed by freight trains and railbuses. The contour patterns also indicate that railway noise propagates predominantly in the direction perpendicular to the track, with a progressive reduction in the affected area as sound energy dissipates away from the railway track. Overall, the interpolated noise maps clearly demonstrate the dominant influence of train operations on the acoustic environment surrounding the railway and provide a visual representation of the spatial extent of railway noise exposure.

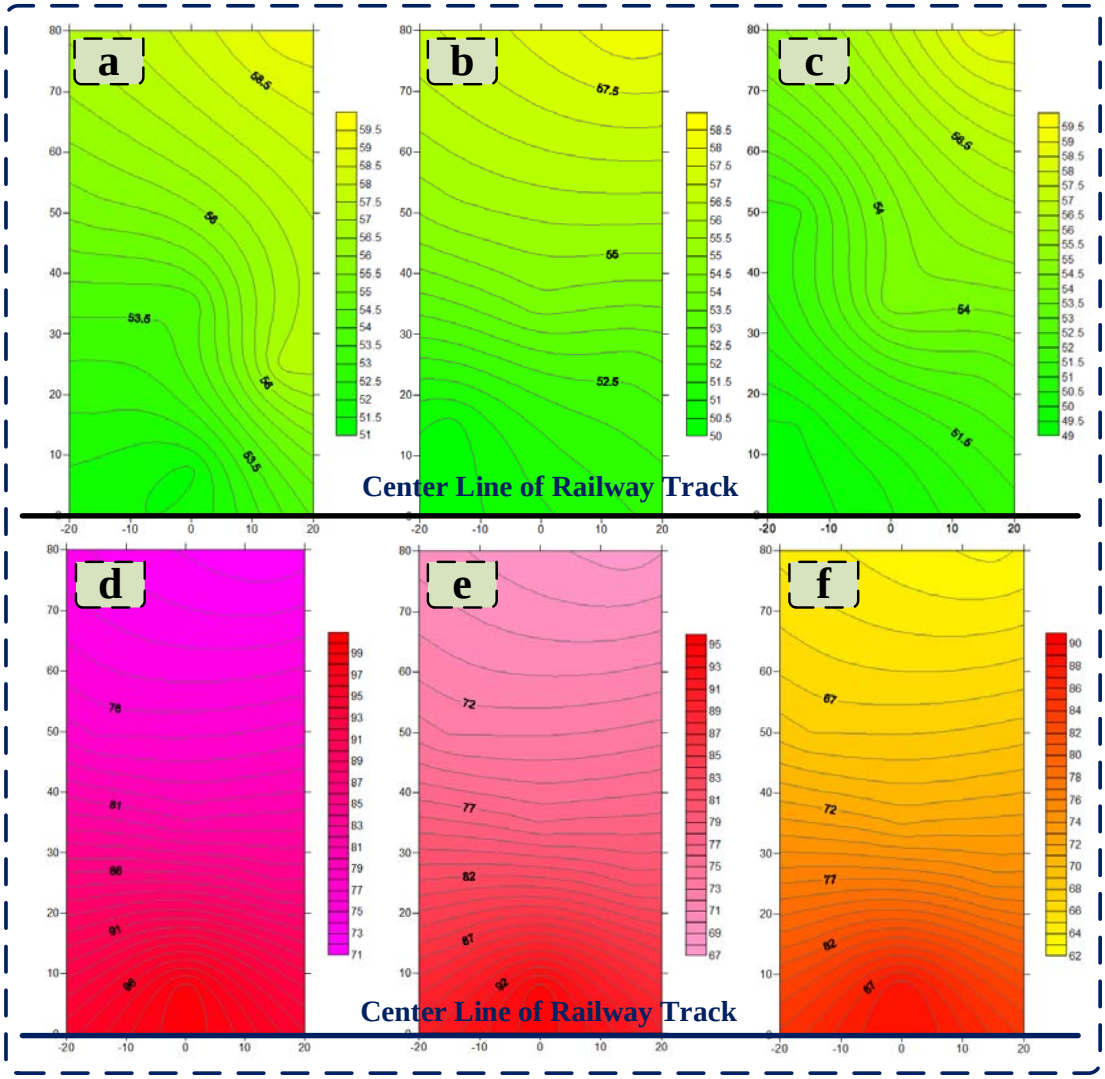

Figure 5. (a–c) Background noise maps; (d) passenger train; (e) freight train; (f) railbus showing spatial L_{Aeq} distribution along the railway track

3.2. Distance–Decay Behavior and Regulatory Compliance of Railway Noise

Figure 6 presents the measured attenuation of railway noise with increasing distance from the railway track for passenger trains Fig. 6a, freight trains Fig. 6b, and railbuses Fig. 6c. For each train category, three independent pass-by measurements were conducted at the selected monitoring locations, and logarithmic regression models were fitted to describe the attenuation of the equivalent A-weighted sound pressure level L_{Aeq}. The average background noise level measured during the monitoring campaign is also shown in each subplot to illustrate the convergence of railway noise toward the ambient acoustic environment. In addition, the horizontal dashed line represents the maximum permissible environmental noise level of 60 dB for commercial–residential areas according to Environmental Noise Standard [3, 22].

As shown in Fig. 6a, passenger trains generated the highest sound pressure levels among the investigated railway vehicle categories. Although the measured noise levels decreased continuously with increasing distance, the fitted attenuation curve indicates that compliance with the regulatory limit of 60 dB(A) is achieved only at a distance of approximately 195 m from the railway track. This result demonstrates that passenger train operations produce the largest acoustic influence zone within the investigated track. Fig. 6b illustrates the attenuation characteristics of freight trains. Compared with passenger trains, freight operations exhibited slightly lower sound pressure levels but maintained elevated noise over a considerable distance. According to the

empirical model, the predicted sound level reaches the regulatory threshold at approximately 155 m, indicating that freight train operations also require a substantial setback distance to satisfy the environmental noise standard. The attenuation behavior of railbus operations is presented in Fig. 6c Among the investigated train categories, railbuses produced the lowest sound pressure levels throughout the monitoring distances. The fitted logarithmic model shows that the equivalent sound pressure level decreases to the allowable limit at approximately 105 m, representing the smallest acoustic influence zone observed in this study.

A direct comparison of the three attenuation models is provided in Fig. 6d Although all railway vehicle categories exhibit a logarithmic reduction in sound pressure level with increasing distance, noticeable differences are observed in both the initial noise levels and the rate of attenuation. Passenger trains consistently maintained the highest predicted sound pressure levels, whereas railbuses showed the fastest approach toward the background acoustic condition. Freight trains exhibited an intermediate attenuation pattern throughout the investigated distance range.

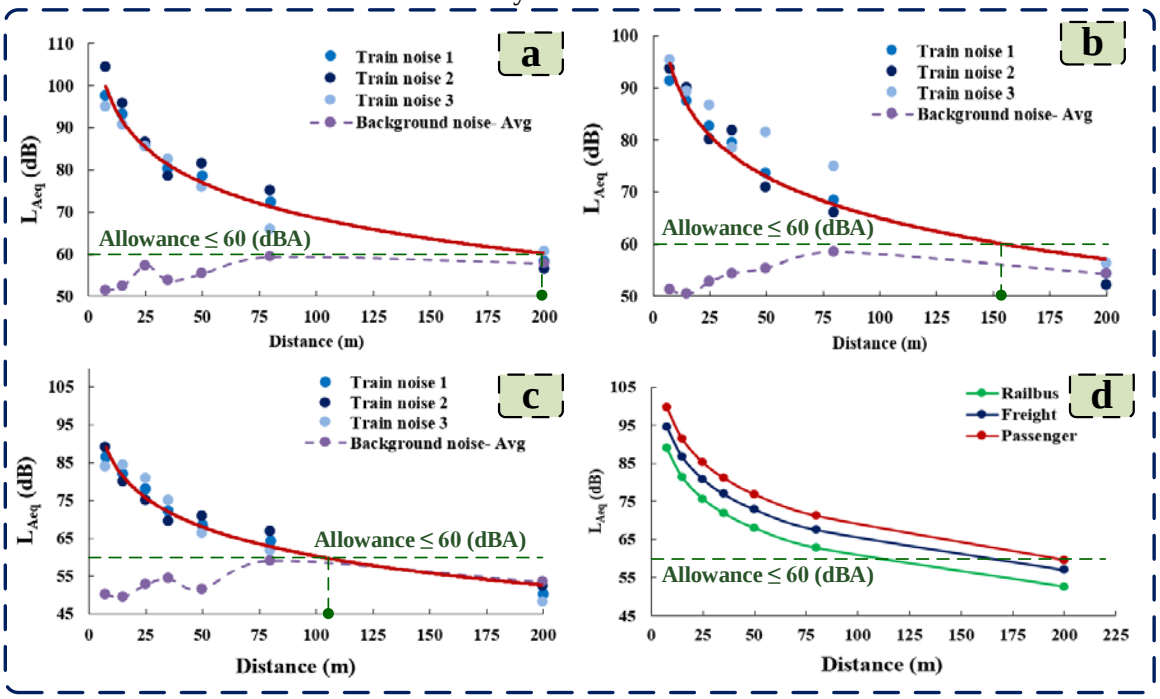

Figure 6. Noise attenuation with distance for (a) passenger, (b) freight, and (c) railbus trains, and (d) comparison of all train types showing logarithmic decay and convergence to background noise.

The statistical performance of the developed logarithmic attenuation models was evaluated using both fitting statistics and grouped leave-one-distance-out cross-validation (LOOCV). The fitting performance was assessed using the coefficient of determination (R^2), fitting RMSE (F-RMSE), and fitting MAE (F-MAE), whereas the predictive capability of each model was evaluated using LOOCV RMSE (L-RMSE) and LOOCV MAE (L-MAE). The estimated acoustic setback distance corresponding to the environmental criterion of 60 dB(A) was subsequently calculated from each validated regression model. Approximate 95% confidence intervals were further estimated for the predicted setback distances to quantify the uncertainty associated with the regression-based predictions. The results are summarized in Table 1.

As shown in Table 1, all three logarithmic attenuation models exhibited excellent fitting performance, with coefficients of determination ranging from 0.9700 to 0.9845 and fitting RMSE values below 2.2 dB. Although the LOOCV errors were higher than the fitting errors, as expected for independent prediction, the cross-validation results indicate satisfactory predictive capability, with L-RMSE values ranging from 3.17 to 4.61 dB. Together, the fitting and cross-validation statistics demonstrate that the proposed logarithmic models are both well fitted to the observed data and capable of providing reliable predictions for unseen receiver distances. These results demonstrate that the

developed attenuation models provide reliable predictions of railway-noise decay under the investigated field conditions and are suitable for estimating train-specific acoustic setback distances. he calculated approximate 95% confidence intervals indicate that the predicted setback distances are associated with a reasonable level of statistical uncertainty. Therefore, the proposed distances should be interpreted as site-specific planning guidance rather than universally applicable threshold values.

Table 1. Summary of the logarithmic regression models developed for railway noise attenuation.

Train type	Regression equation	R^2	F-RMSE (dB)	F-MAE (dB)	L-RMSE (dB)	L-MAE (dB)	60 dB(A) distance (m)	Approx. 95% CI (m)
Passenger	$-12.08\ln(d)+124.13$	0.9845	1.19	0.98	3.17	2.50	191.2	161.0–221.4
Freight	$-11.44\ln(d)+117.68$	0.97	2.17	1.68	4.61	3.63	159.9	118.2–201.5
Railbus	$-11.11\ln(d)+111.48$	0.9765	1.69	1.38	3.78	3.06	103.0	82.7–123.4

Figure 7 presents the variation of the equivalent railway noise increment ΔL_{Aeq}, defined as the difference between the measured railway noise level and the background noise level, for the three investigated train categories as a function of receiver distance from the railway track. As illustrated in Figure 7a, the highest additional noise level was observed for passenger trains at the nearest monitoring location (7.5 m), reaching 40.53 dB, followed by freight trains 39.2 dB and railbuses 36.2 dB. The relatively higher ΔL_{Aeq} recorded for passenger trains is consistent with their higher operating speeds, which generally increase railway noise emissions [9]. The attenuation characteristics of railway noise are presented in Figure 7b. For all train categories, ΔL_{Aeq} decreases continuously with increasing distance from the track owing to propagation losses, including geometric spreading, atmospheric absorption, ground interaction, and scattering by surrounding urban features [25, 29]. Nevertheless, the attenuation rates differ among the train categories. Railbuses exhibit the most rapid reduction, with approximately 15 dB attenuation within the first 25 m, whereas passenger and freight trains maintain considerably higher ΔL_{Aeq} values over intermediate distances. At approximately 50 m, both passenger and freight trains still produce additional noise levels of about (20-23) dB above the background level. The relatively slower attenuation of freight train noise is likely related to its greater train length, higher axle loads, and stronger wheel–rail interaction, which generate a larger proportion of low-frequency sound. These low-frequency components are less susceptible to atmospheric and ground attenuation, allowing freight train noise to persist over longer propagation distances [9 ,25]. Beyond approximately 80 m, the attenuation curves gradually flatten, indicating a reduced attenuation rate as propagation losses become dominant. At a receiver distance of approximately 200 m, ΔL_{Aeq} approaches 0 dB for all train categories, indicating that railway noise becomes comparable to the measured background noise under the conditions of the present study. These results suggest that most of the railway noise reduction occurs within the first (50-80) dB from the track, highlighting the importance of adequate setback distances and appropriately designed noise barriers for mitigating residential exposure to railway noise.

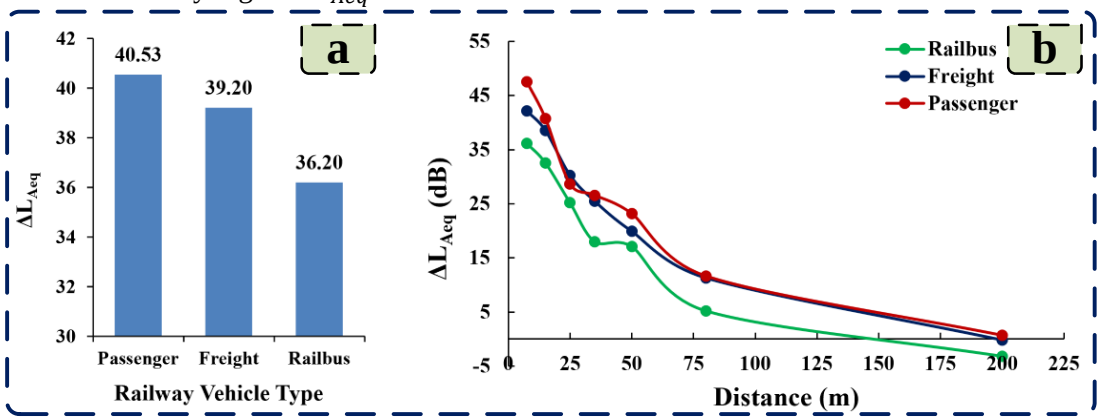

Figure 7. (a) Maximum railway noise increase above background levels; (b) distance-dependent noise attenuation for passenger, freight, and railbus trains.

existing urban areas such setback distances are difficult to achieve because of land-use constraints. Under these conditions, engineering mitigation measures should be implemented along the railway track to reduce environmental noise exposure. Among the available source-control techniques, rail grinding has been widely recognized as an effective approach for reducing rolling noise by improving wheel–rail contact conditions and eliminating rail surface irregularities. In addition to reducing environmental noise, this technique contributes to improved track condition and lower maintenance requirements [25]. Therefore, periodic rail grinding is recommended as a practical maintenance strategy for the investigated railway track. Where additional mitigation is required, low-height acoustic barriers installed along the railway track represent an efficient engineering solution. Experimental studies have shown that these barriers can provide significant noise reduction while requiring considerably less installation space than conventional noise barriers, making them particularly suitable for densely developed urban environments [26].

Recent investigations further indicate that combining source-control measures with propagation-control techniques provides greater overall noise reduction than implementing a single mitigation strategy. Specifically, integrating regular rail grinding with appropriately designed low-height acoustic barriers has been shown to achieve superior acoustic performance under operational railway conditions [27]. Overall, the empirical attenuation models developed in this study provide practical tools for estimating railway noise influence zones and can support railway authorities and urban planners in determining appropriate setback distances and selecting effective mitigation strategies for existing and future railway tracks.

3.3. Comparison with a Reference Distance-Decay Formulation

To examine the external consistency of the field-derived relationships, the proposed logarithmic models were compared with the distance-decay formulation presented by the Federal Railroad Administration (FRA) [30]. Although the FRA formulation was originally developed for high-speed ground transportation assessment, it was not applied here as a complete source-prediction model. Only its distance-decay and building-row shielding terms were used as a normalized propagation benchmark. The source-level and speed-dependent terms were excluded by normalizing the predictions to the corresponding field level at 15 m. The FRA formulation applies a distance correction of $15\log_{10}(d/d_0)$,together with 3 dB shielding attenuation for the first intervening building row and an additional 1.5 dB for each subsequent row, up to a maximum attenuation of 10 dB [30]. The observed numbers of intervening building rows at 15, 25, 35, 50, 80, and 200 m were 1, 2, 3, 4, 6, and 16, respectively.

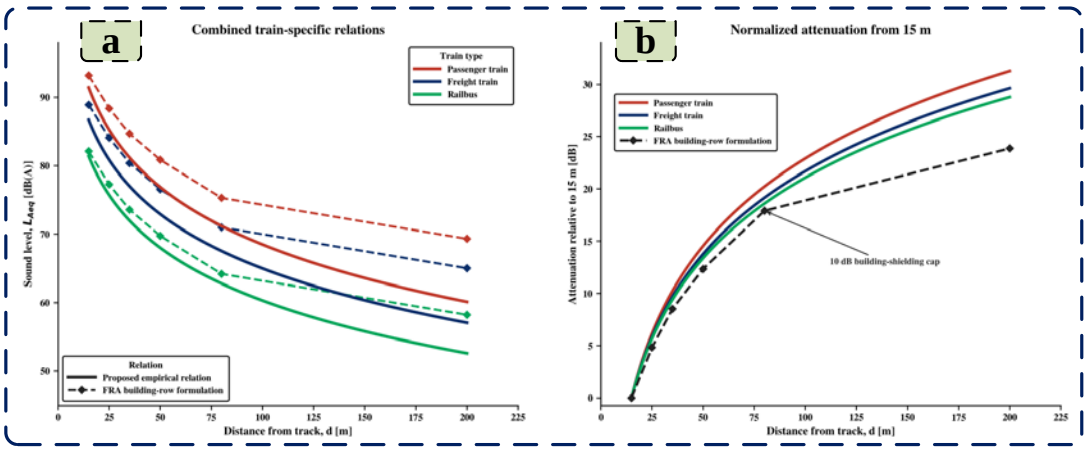

Figure 8. Comparison of the proposed empirical relationships with the normalized FRA distance-decay formulation [20]: (a) train-specific L_{Aeq}; (b) attenuation relative to 15 m.

As shown in Figure 8a, both approaches reproduce the expected reduction in railway noise with increasing distance. At 200 m, the proposed relationships differed from the measured mean levels by approximately 1.7, 2.9, and 2.4 dB for passenger trains, freight trains, and railbuses, respectively, whereas the corresponding deviations obtained from the FRA formulation were approximately 10.9, 10.8-, and 8.0-dB Figure 8b shows that the proposed relationships predict attenuation of approximately 28.8–31.3 dB between 15 and 200 m, compared with approximately 23.9 dB obtained from the normalized FRA formulation. The remaining differences can be attributed to site-specific propagation conditions, including ground interaction, atmospheric absorption, and shielding and scattering caused by the surrounding urban morphology [9,30]. Considering that the FRA formulation was used only as a generalized propagation benchmark, the overall agreement supports the physical consistency of the field measurements, while the smaller deviations and cross-validation results confirm the site-specific reliability of the proposed relationships.

4. Discussion and Practical Recommendations

The present study quantified the spatial propagation of railway noise under actual operating conditions and established empirical railway noise buffer zones for different train categories. Based on the developed logarithmic attenuation models, compliance with the Iranian environmental noise limit of 60 dB(A) was achieved at approximately 195 m for passenger trains, 155 m for freight trains, and 105 m for railbuses. These findings demonstrate that the required acoustic buffer distance strongly depends on train type and operational characteristics, providing practical guidance for environmental impact assessment and urban planning in railway tracks. Although different train categories exhibited different attenuation characteristics, the present field measurements were not designed to isolate the individual effects of operating speed, axle load, train formation, or wheel–rail interaction. Therefore, the observed differences should be interpreted as the combined response of these operational characteristics under the investigated field conditions.

The observed attenuation trends are consistent with previous studies reporting logarithmic railway noise decay with increasing distance and the dominant contribution of wheel–rail interaction to rolling noise generation [9, 25]. Compared with previous investigations in less densely developed railway environments, the relatively larger influence distances obtained in this study may partly reflect the characteristics of the surrounding urban morphology, where buildings and other structures may influence sound propagation through multiple reflections and reduced attenuation [3, 31]. From a practical perspective, the identified buffer distances indicate that maintaining an adequate setback from the railway track is the most effective strategy for protecting future residential and other noise-sensitive developments. However, in many existing urban areas such setback distances are difficult to achieve because of land-use constraints. Under these conditions, engineering mitigation measures should be implemented along the railway track to reduce environmental noise exposure. Among the available source-control techniques, rail grinding has been widely reported in the literature as an effective maintenance practice for reducing rolling noise by improving wheel–rail contact conditions and removing surface irregularities [32]. However, because rail roughness, maintenance condition, and before–after grinding measurements were not evaluated in the present field investigation, the effectiveness of rail grinding was not assessed directly in this study and no study-specific recommendation is made regarding its implementation. Where additional mitigation is required, low-height acoustic barriers installed along the railway track represent an efficient engineering solution. Experimental studies have shown that these barriers can provide significant noise reduction while requiring considerably less installation space than conventional noise barriers, making them particularly suitable for densely developed urban environments [33]. Recent investigations indicate that combining source-control and propagation-control strategies can provide greater overall noise reduction than implementing a single mitigation measure. Nevertheless, the present study directly supports only site-specific setback planning,

land-use management, and appropriately designed noise barriers, while other source-control techniques are discussed solely on the basis of published literature [34]. Overall, the empirical attenuation models developed in this study provide practical tools for estimating railway noise influence zones and can support railway authorities and urban planners in determining appropriate setback distances and selecting effective mitigation strategies for existing and future railway tracks.

5. Conclusion

This study characterized railway-noise attenuation at seven receiver distances between 7.5 and 200 m for passenger trains, freight trains, and railbuses operating within the same urban corridor. The three train categories exhibited a consistent logarithmic reduction in pass-by L_Aeq with distance. Passenger trains produced the highest near-track level, approaching 99 dB(A), followed by freight trains and railbuses. The fitted relationships achieved R^2 values of 0.9700–0.9845, F-RMSE values of 1.19–2.17 dB, and grouped cross-validated RMSE values of 3.17–4.61 dB.

Using the adopted 60 dB(A) screening criterion, the estimated distances were 191.2 m for passenger trains, 159.9 m for freight trains, and 103.0 m for railbuses. The normalized FRA formulation reproduced the general monotonic decay but showed larger deviations at 200 m than the field-derived relationships. The results provide site-specific evidence for preliminary acoustic screening and land-use assessment under comparable conditions. They do not establish universal regulatory setbacks or isolate the individual effects of speed, axle load, train length, rail condition, or urban morphology. Application to other corridors therefore requires additional pass-by measurements, documented reference instrumentation, frequency-resolved analysis, and independent external validation.

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