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# ENHANCING URBAN ACOUSTIC COMFORT: THE ROLE OF FREE SURFACES, GREEN SPACES AND WATER BODIES IN MITIGATING ROAD TRAFFIC NOISE

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## ABSTRACT

This study examines the role of urban free surfaces—parks, trees, water bodies and open squares—in mitigating road traffic noise in adjacent buildings. Case studies focused on built-up areas near roads with defined traffic levels, including aligned frontages, widened streets and urban courtyards with corner buildings.

Free surfaces were analyzed using parameters such as the green-to-paved surface ratio, grass-to-tree vegetation ratio, tree height, and percentages of green areas, paved areas and water bodies. Noise level measurements (LAeq), were taken at different times of the day and under various weather conditions, to understand the acoustic contributions of these surfaces. Qualitative data and measurements enabled the verification of parameter distributions (e.g., green-to-paved surface ratio, grass-to-tree ratio, vegetation height) in relation to LAeq, considering seasonal features and surrounding building heights. Multivariate regression identified linear relationships between factors. Finally, an average dynamic absorption coefficient was estimated for open spaces, treating them as equivalent absorbing areas. This coefficient, influenced by seasonal and meteorological variations, allows modeling of open spaces as acoustically active surfaces. It also provides a basis for designing optimal configurations, offering practical recommendations for urban planners and policymakers to improve acoustic comfort in urban environments.

**Keywords:** *road traffic noise, urban design, acoustic measurement, acoustic absorption, multivariate regression model, optimization algorithm*

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## 1. INTRODUCTION

Acoustic absorption in urban spaces is a crucial topic for improving the quality of life in densely populated cities. With the increase in urban noise, mainly due to traffic and other human activities, it is essential to develop effective strategies to reduce noise pollution and enhance the acoustic environment. The importance of developing quiet areas within urban environments is addressed at the European directive level by the European Directive 2002/49/EC "European Directive relating to the assessment and management of environmental noise".

In this context, urban design should not be limited to considering noise indicators, but must also integrate human perception into the definition of the acoustic landscape. Aspects such as acoustic quality, the type of predominant sounds, and acoustic contrast with the surrounding environment are indeed decisive, as well as thermal and visual comfort [1].Greenery, in city landscape or building envelopes, helps mitigate the urban heat island [2], with trees and hedges reducing peak temperatures by up to 7 K and green roofs by up to 3 K. Alongside thermal control, greenery components and water bodies contribute to citizens' mental balance and noise mitigation. Water bodies like lakes and rivers can cool urban areas by evaporation: 1 kg of water can lower the temperature of 2000 m³ of air by 1 K. Water surfaces are generally cooler than built environments, reducing air temperature through convection. Passive systems such as pools and fountains are commonly used in public spaces for both decoration and climate regulation [3, 4]. There is growing interest in the relationships between acoustics and urban planning, particularly in how factors such as urban density, morphology, land use, street distribution, the surrounding street environment and green spaces influence sound dynamics [5, 6]. [7,8] developed models to characterize urban sound environments, focusing on selecting key variables that aid in decision-making for the effective characterization of environmental urban noise. Some studies have shown that sound fields in urban squares surrounded by reflective façades present a uniform reverberation time (RT), while the initial decay time (EDT) is low in the near field and increases rapidly with distance, approaching the RT. Sound pressure level (SPL) attenuation is generally smaller with geometric boundaries compared to diffuse ones, unless the height/width ratio is high [9, 10]. Adding absorptive materials to façades or the ground can increase sound attenuation by 2-4 dB. Reducing building height or creating spaces between buildings can further provide sound attenuation [10]. Directives promoting urban acoustic design face the challenge of integrating acoustic planning with urban design. This process requires the support of specialized technicians and adequate time for accurate calculations, which are often difficult to manage during the preliminary design phases. For detailed analyses, the UNI 9613-2 standard is used to calculate the ground effect attenuation (Agr) for a specific octave band. Agr is determined by summing the attenuations of the three regions involved in the sound path—source (As), receiver (Ar), and intermediate (Am)—based on the ground factors of the corresponding terrain (Gs, Gr, Gm) and the source (hs) and receiver (hr) heights. Ground factors range from G = 0 for reflective surfaces (pavement, concrete, water) to G = 1 for highly absorptive surfaces (agricultural soil, sand, earth), while for mixed terrain, $0 < G < 1$, depending on the fraction of porous ground.

This work purposes a data-driven optimization framework, implemented in Python, developed to determine the optimal distribution of urban surfaces (green areas, paved areas and water bodies) to achieve a target equivalent sound absorption coefficient (α_eff) for a given available area. The workflow is based on Leq measurements conducted in urban spaces with different geometric configurations and various horizontal surface treatments, and consists of three key steps: data preprocessing, regression modeling, and constrained optimization.

## 2. METHODOLOGY

### 2.1 Selection of Study Sites

Three urban configurations were chosen for consideration: Aligned Frontages, Widened Streets, and Courtyards (Fig. 1). For each of these, 15 study sites were identified across the neighborhoods of Rome's EUR and Parioli districts (Fig.2). This selection ensured that the buildings were from the same construction period, and therefore had similar construction techniques and materials. The buildings facing the chosen open spaces are also of comparable height, ranging from 5 to 6 stories. the focus of this phase is to account for and compare the effects of the planimetric configuration of the buildings on the open spaces between them, rather than different aspect ratios. The selected sites are also similar in terms of building density, typology and traffic volumes.

### 2.2 Measurement Campaign

The case study employed Brüel & Kjær 2250 sound level meter to measure and collect data on the environmental SPL of selec ted urban areas. SPL was measured on working days in February 2025. To ensure consistent traffic conditions, measurements were carried out during three time intervals: 8:00–10:00, 12:00–14:00, and 16:00–18:00. Sound pressure levels were recorded at a height of 1.5 meters, corresponding to the average ear level of a standing person. At each measurement point, 15-minute recordings were performed. The weather during the measurement was stable, sunny, with a temperature of 15-20°C and a wind speed of 3 m/s.

### 2.3 Data Collection and Processing

The sound pressure levels measured at each receiver point were normalized with respect to the same traffic volumes to obtain comparable results. The actual Lw was adjusted to 74 dB, which corresponds, according to the ROUTES NMPB 96 model, to 86 light vehicles and 8 heavy vehicles passing at a speed of 50 km/h. This reference Lw′ was chosen since it reflects average traffic volumes across the dataset, and ensures a balanced comparison without biasing results toward high or low traffic intensity scenarios. To adjust Lp accordingly, the general relationship between sound power level and free-field sound pressure level was used.

$$Lp=Lw-10\log(S) + DI - A \quad (1)$$

where S is the area over which the sound energy is distributed, DI is the directivity, and A is the attenuation in the propagation path from source to receiver, which accounts for atmospheric absorption, ground effect, presence of barriers, and additional types of attenuation such as vegetation, industrial sites and densely built-up areas.

**Figure 1.** (a) Widened Street-Tipo1, (b) Aligned Frontages-Tipo2, (c) Courtyards-Tipo 3.


**Figure 2**. Measurement points in EUR

If the propagation type, the distance of the measurement point from the source, the directivity, and the environment remain constant, we can assume:

$$Lp'=Lp+(Lw'-Lw) \quad (2)$$

Where Lw'=74 dB (3)

Having identified paved area, green area and water body area as predictive variables, it was necessary to recognize and assess the extent of these surfaces in each urban space examined. The spaces were analyzed by defining the study area as the space bounded by the streets (5.5 m width for each traffic flow direction) and the fronts of the buildings facing it (Fig 1). To determine the area occupied by trees, an average was considered for each tree between the area of the trunk and the area of the canopy.

## 3. RESULTS: ACOUSTIC ANALYSIS OF FREE SURFACES

### 3.1 Influence of Urban Configuration and Surface Composition on Noise Levels

Figures 3, 4, and 5 demonstrate the effect of green, paved, and water surface treatments on the frequency distribution of noise for the selected urban configurations. In Widened Streets, all surface types showed similar performance at frequencies up to 63 Hz, but differences emerged at higher frequencies. Green areas performed poorly at lower frequencies, while paved surfaces began to outperform green ones around 630 Hz.

**Table 1.** Measurements results.

| | | Point | Lw | Light vehicles | Heavy vehicles | Leq | L1 | L5 | L10 | L50 | L90 | L95 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TIPO2 | greenery | 1 | 74 | 86 | 8 | 60.08 | 71.7 | 66.9 | 64.5 | 54.3 | 48.7 | 47.1 |
| TIPO2 | pavement | 2 | 71.4 | 70 | 3 | 62.5 | 69.4 | 65 | 63.7 | 59.4 | 54.9 | 54 |
| TIPO1 | greenery | 3 | 70 | 69 | 1 | 61.9 | 71.2 | 67.9 | 65.3 | 57.2 | 52 | 50.5 |
| TIPO1 | pavement | 4 | 72 | 90 | 3 | 60.8 | 70.5 | 64.7 | 63.3 | 53.5 | 47.8 | 46.8 |
| TIPO3 | greenery | 6 | 73.6 | 99 | 6 | 58 | 66.9 | 62.7 | 61.1 | 55.4 | 49.7 | 48.8 |
| TIPO3 | greenery | 7 | 77 | 120 | 19 | 61.3 | 70 | 66.1 | 64.4 | 58.4 | 53.6 | 52.4 |
| TIPO3 | pavement | 8 | 78.3 | 316 | 16 | 64.7 | 75.2 | 67.5 | 65.4 | 60.8 | 57.5 | 56.8 |
| TIPO1 | water | 9 | 76 | 77 | 17 | 57 | 64.7 | 62 | 60.6 | 54.6 | 50.8 | 50.1 |
| TIPO2 | water | 10 | 77.3 | 153 | 19 | 65.1 | 72.2 | 69.5 | 68.2 | 63.7 | 59.2 | 58.1 |

**Table 2.** Analysis of free spaces treatments and Leq normalized results (Lp) with respect to Lw' = 74 dB.

| | | Green-Paved Ratio | Grass-Tree Ratio | Tree Height (m) | Green Area | Paved Area | Water Body | Green Area (%) | Paved Area (%) | Water Body (%) | Open Space (m²) | Lw (dB) | Lp (dB) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| TIPO1 | 3 | 2.00 | 0.3 | 3 | 5054.09 | 2523.91 | 0 | 67 | 33 | 0 | 7578 | 74 | 65.9 |
| TIPO1 | 4 | 0.16 | 0.5 | 3 | 2108.53 | 13010.67 | 0 | 14 | 86 | 0 | 15119.2 | 74 | 62.8 |
| TIPO1 | 9 | 0.37 | 0.4 | 3 | 2519.88 | 6813.34 | 1316.12 | 24 | 64 | 12 | 10649.34 | 74 | 55 |
| TIPO2 | 1 | 10 | 10 | 3 | 3952 | 0.00001 | 0 | 100 | 0 | 0 | 3952 | 74 | 60.08 |
| TIPO2 | 2 | 0 | 0 | 0 | 0 | 2084 | 0 | 0 | 100 | 0 | 2084 | 74 | 65.1 |
| TIPO2 | 10 | 0.82 | 10 | 3 | 4852 | 5923 | 28625 | 12 | 15 | 73 | 39400 | 74 | 61.8 |
| TIPO3 | 6 | 8.95 | 1 | 3 | 23594.37 | 2635.55 | 0 | 90 | 10 | 0 | 26229.92 | 74 | 58.4 |
| TIPO3 | 7 | 4.76 | 0.7 | 3 | 13711.22 | 2882.05 | 0 | 83 | 17 | 0 | 16593.27 | 74 | 58.3 |
| TIPO3 | 8 | 0 | 0 | 0 | 0 | 13390.73 | 0 | 0 | 100 | 0 | 13390.73 | 74 | 60.4 |

Water bodies provided the best acoustic benefits starting at 160 Hz. In Aligned Frontages, green spaces improved acoustic performance from 63 Hz to 1000 Hz due to the sound-absorbing properties of vegetation, but water bodies had mixed effects. They offered some benefits at lower frequencies but worsened at higher frequencies, likely due to reflection and scattering. In Courtyards, paved surfaces performed better than green areas, with a 6.45 dB higher Leq in paved areas, likely due to the reflective properties of paved surfaces that help distribute sound evenly. In general, a trend can be observed in the influence of surface treatments on acoustic performance of various urban settings: green areas offer sound absorption, water bodies excel at mid-to-high frequencies but can cause issues at lower and higher ones, and paved surfaces provide stable acoustic performance, particularly in courtyard environments. Urban designers should consider these factors when planning for desired acoustic outcomes.In the analysis of urban spaces, sound level fluctuations, evaluated between L90 and L5 (Table 1), varied depending on the surface type and traffic volumes. The smallest fluctuations were observed in Type 1 areas with water, while the highest occurred in Type 1 areas with green surfaces and pavement. These differences may be linked to the urban space configuration, as traffic volumes were similar, indicating the layout's influence on acoustics. For Type 2 areas, water features caused the least fluctuation, followed by pavement and green surfaces. However, the result is less reliable due to the traffic volume being double in the water scenario compared to the others. In Type 3 areas, fluctuations remained stable regardless of traffic volume. Notably, fluctuations in pavement areas with 300 vehicles were slightly lower than in green areas with 150 vehicles, suggesting that surface type is more influential than traffic volume on acoustic variation.

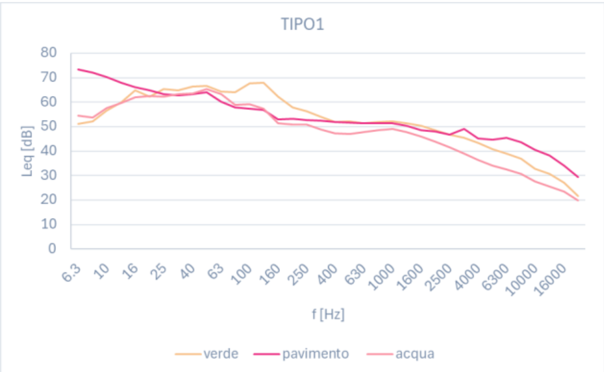


**Figure 3**. Widened Street.

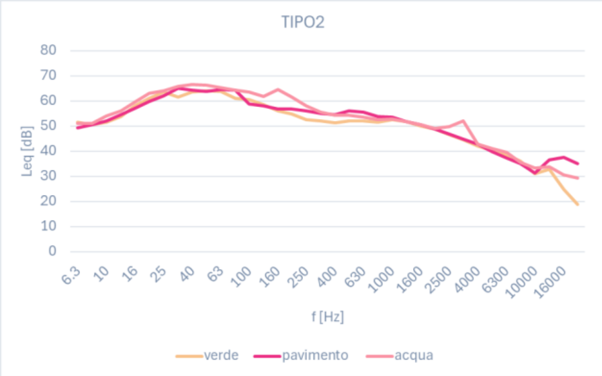


**Figure 4**. Aligned Frontages.

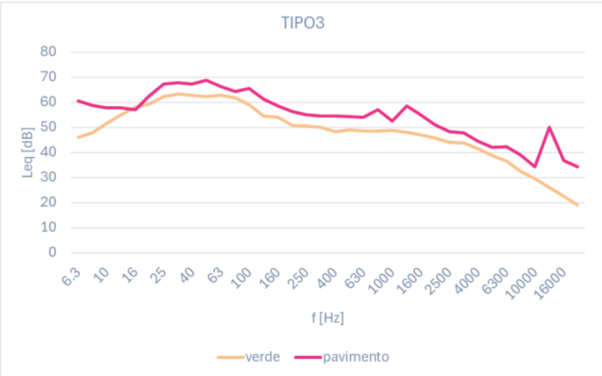


**Figure 5**. Courtyards.


**Figure 6**. Treatments and urban layouts influence on Leq.

The analysis of global noise levels (Leq) in identical urban configurations with varying surface treatments

(Fig. 6) revealed that in Widened Streets, water was the most effective treatment, followed by pavement and green surfaces. For Alignments, green surfaces performed best, with pavement and water following. In Courtyards, green surfaces also provided the best noise reduction, with pavement in second place. As a whole, water proved more effective in type 1 configurations than in type 2, suggesting that water sources contribute to better noise management. Pavement in type 1 yielded the best results, followed by type 2 and type 3, indicating that the materials used in type 1 are more efficient in reducing noise. Greenery performed best in type 3, with a decline in effectiveness in types 2 and 1. The ideal configuration was type 1 with water, while type 3 with pavement was the least favorable, possibly due to high traffic volume, which requires further normalization specified below.

### 3.2 Estimation of the Absorption Coefficient: Multivariate Regression and Linear Relationships

Having conducted several measurements in urban spaces containing open areas of various sizes, and having Leq data for comparable traffic volumes, it is possible to estimate an average absorption coefficient for an open space by treating it as an equivalent absorbing area. This approach is useful for modeling open spaces as acoustically active surfaces with a simplified overall behavior. Acoustic and surface data are loaded in Python from a CSV file, containing measured sound pressure levels (L_p_meas), source power levels (L_W), and surface percentages. The effective absorption coefficient (α_eff) is computed as:

$$\alpha eff = Seq/(\%Agreen+\%Apaved+\%Awater) \tag{4}$$

where Seq represents the equivalent absorbing surface area derived from acoustic measurements

$$Seq = 10\text{^}((LW-Lp,meas)/10) \tag{5}$$

A first-order polynomial regression (Ordinary Least Squares, OLS) is fitted to correlate α_eff with the three surface types. The model includes an intercept term to ensure physical interpretability, as there is always a contribution from the geometry of the surrounding environment and atmospheric conditions. The models obtained for the Widened Streets, Aligned Frontages and Courtyards configurations are reported in Eq. (6), Eq. (7), and Eq. (8), respectively, where GA = Green Area, PA = Paved Area, and WA = Water Body Area. Table 3 provides the distribution of surface treatments, the absorption coefficients calculated using Eq. (4) and Eq. (5), and those obtained by applying the models developed for Widened Streets.

$$\alpha eff = 0.000455 * 1 + 0.001461 * GA (\%) + -0.000654 * PA (\%) + 0.044671 * WA (\%) \tag{6}$$

$$\alpha eff = 0.000050 * 1 + 0.002657 * GA (\%) + 0.000626 * PA (\%) + 0.001747 * WA (\%) \tag{7}$$

$$\alpha eff = 0.000032 * 1 + 0.003972 * GA (\%) + 0.002599 * PA (\%) + -0.003357 * WA (\%) \tag{8}$$

**Table 3.** Comparison between α_eff calculated by acoustic equation and polynomial regression for Widened Streets (TIPO1).

| | Green Area (%) | Paved Area (%) | Water Body (%) | α_eff | α_eff_predicted |
|---|---|---|---|---|---|
| 0 | 67 | 33 | 0 | 0.06 | 0.08 |
| 1 | 14 | 86 | 0 | 0.13 | -0.04 |
| 2 | 24 | 64 | 12 | 0.79 | 0.53 |
| 3 | 20 | 69 | 11 | 0.40 | 0.48 |
| 4 | 26 | 69 | 5 | 0.25 | 0.22 |
| 5 | 45 | 50 | 5 | 0.28 | 0.26 |
| 6 | 30 | 60 | 10 | 0.48 | 0.45 |
| 7 | 20 | 69 | 11 | 0.40 | 0.48 |
| 8 | 26 | 69 | 5 | 0.25 | 0.22 |
| 9 | 50 | 45 | 5 | 0.20 | 0.27 |
| 10 | 15 | 80 | 5 | 0.11 | 0.19 |
| 11 | 35 | 55 | 10 | 0.52 | 0.46 |
| 12 | 10 | 85 | 5 | 0.10 | 0.18 |
| 13 | 40 | 50 | 10 | 0.35 | 0.47 |
| 14 | 5 | 90 | 5 | 0.08 | 0.17 |

Model significance is verified via summary statistics such as R-squared, p-value, correlation matrices and Variance Inflation Factor (VIF) (Tab.4, Tab.5).
The model for Typology 1 (Eq. 6) demonstrates a good explanatory capacity ($R^2 = 0.722$), with variable $x_3$ significantly contributing to sound absorption ($\beta = 0.0447$, $p < 0.001$). However, the presence of multicollinearity (Cond. No. = $6.94\times10^{18}$) suggests caution in interpreting the coefficients of $x_1$ and $x_2$, which are not statistically

significant. The multicollinearity analysis revealed a strong inverse correlation between green areas and paved surfaces ($r = -0.87$), further confirmed by VIF values > 10.
The model for Typology 2 (Eq. 7) shows an excellent fit to the data and is statistically significant overall. The p-values indicate that all variables are significant.
The model for Typology 3 (Eq. 8) explains 65.8% of the variability in α_eff and is globally significant ($R^2 = 0.658$, $p = 0.0005$), with $x_1$ and $x_2$ positively influencing α_eff ($p < 0.001$). However, the presence of multicollinearity (Cond. No. = $2.34 \times 10^{18}$) and non-normal residuals suggests caution in interpretation and highlights the need for improvements, such as handling multicollinearity through Ridge Regression techniques and increasing the sample size.

**Table 4**. α_eff prediction accuracy.

| | average Δ (eff-eff_predicted) | average α_eff_predicted |
|---|---|---|
| TIPO 1 | 0.082 | 0.294 |
| TIPO 2 | 0.012 | 0.164 |
| TIPO 3 | 0.026 | 0.293 |

**Table 5.** Statistical results.

| | **Variable** | **Std Err** | **t-value** | **p-value** |
|---|---|---|---|---|
| TIPO 1 | const | 6.62E-05 | 6.867 | <0.001 |
| | x1 | 0.001 | 1.049 | 0.315 |
| | x2 | 0.001 | -0.749 | 0.469 |
| | x3 | 0.008 | 5.946 | <0.001 |
| TIPO 2 | const | 1.70E-05 | 1.889 | 0.080 |
| | x1 | 0 | 17.708 | <0.001 |
| | x2 | 0 | 11.572 | <0.001 |
| | x3 | 0.002 | -1.752 | 0.102 |
| TIPO 3 | const | 1.71E-06 | 29.45 | 0.001 |
| | x1 | 8.77E-05 | 30.29 | 0.001 |
| | x2 | 8.34E-05 | 7.51 | 0.001 |
| | x3 | 0 | 8.85 | 0.001 |

### 3.3 Constrained optimization tool

A nonlinear optimization problem is solved to find the surface distribution that, given the total available area (A1) and a desired target value of *α_eff,* minimizes the squared error between predicted and target *α_eff*:

$$\text{minimize}(\alpha\text{pred}-\alpha\text{target})$$

subject to constraints:

$$A\text{green}+A\text{paved}+A\text{water}=A\text{total}$$

Bounds ensure each surface percentage lies within [0,Atotal]. The solver uses an initial guess of equal distribution (33% per surface).
The algorithm returns the optimal surface percentages (e.g., 45% green, 30% paved, 25% water) or reports convergence failure. The results of TYPE 2 appear to be evenly distributed among the treatment types (Tab. 6). Keeping the study area unchanged but imposing α_eff = 0.6, the optimization yields 64.4% Green Area and 35.6% Water Body.

## 4. CONCLUSIONS

The analysis was automated through a Python script that combines regression modeling and constrained optimization. Acoustic data were processed to compute an effective absorption coefficient (α_eff) for each studied area, which was then correlated with surface compositions using first-order polynomial regression (OLS), providing a characteristic polynomial for each urban configuration. An optimization routine was implemented to determine the optimal surface distribution to achieve a target α_eff under area constraints, offering a scalable tool for urban noise mitigation design to mitigate the impact of urban noise on receivers, in terms of sound pressure levels at building façades.

**Table 6.** Example of optimization algorithm application.

| | **Green Area (%)** | **Paved Area (%)** | **Water Body (%)** |
|---|---|---|---|
| | A1=100, α=0.3 | | |
| TIPO1 | 46 | 48 | 5.9 |
| TIPO2 | 33.3 | 33.3 | 33.3 |
| TIPO3 | 51.7 | 43 | 5.3 |

Summary of findings

- Configuration-specific α_eff integrates empirical acoustic measurements with surface composition.
- First-order polynomial terms prevent overfitting while effectively capturing linear relationships.
- The developed design tool provides practical, actionable recommendations and implications for urban planning.

Limitations and future research directions

- Besides area extension in widened streets and courtyards, aspect ratio and maximum source distance should also be considered.
- The linearity between α_eff and surface ratios is likely due to the limited number of samples; a greater number of experimental Lp will allow for extensions to higher-order terms, capturing nonlinear effects.
- The simplified method for α_eff proved valid for fixed-distance data; for greater flexibility with variable distances, the full physical approach including source geometry and directivity will be implemented.
- Increasing the sample size and refining the regression model will improve statistical robustness; future developments will include frequency-domain analysis and economic constraints in optimization.

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