The Architectural and Cost Constraints of Increasing STI Criteria in Metro Stations: A Case-Based Analysis

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ABSTRACT

As successive Sydney Metro lines have been procured and delivered the Speech Transmission Index (STI) requirements for stations have shifted from a baseline of STI ≥ 0.50 applied in earlier projects like City & Southwest to a more stringent threshold of STI ≥ 0.54 with even higher targets in key locations. While the numerical increase appears modest, reduced tolerance for shortfalls, increased requirements for integration, and broader coverage expectations have significantly raised the design and construction burden. Speech intelligibility remains essential for safety and accessibility, but achieving these elevated targets poses increasing challenges within the architectural and operational constraints of underground stations. This paper presents a case-based analysis using an EASE model of a prototypical metro station, developed from current and proposed designs to evaluate the STI improvement achievable through incremental acoustic treatment. Real-world constraints on speaker placement and absorption, including platform screen doors, tunnel walls, plant, and wayfinding are explicitly modelled. Cost per STI increment is analysed using cost estimates from manufacturers, with margins for delivery, installation, and other associated costs based on quantity surveying data. The results reveal a point of diminishing returns, where marginal intelligibility gains demand disproportionately greater investment and coordination. The paper argues that while STI remains a valid performance metric, its implementation in guidelines must more realistically reflect the practical limitations of underground station design and construction. It offers data-driven recommendations to support the development of more achievable and context-sensitive performance targets.

1 INTRODUCTION

The Sydney Metro network has experienced significant expansion over the past decade, with each successive project presenting increasing challenges in meeting the STI requirements for station intelligibility. As the demand for improved speech clarity grows, these challenges are further compounded by the need to integrate effective acoustic treatments within the constraints of underground environments. Despite the more stringent criteria for speech intelligibility, the fundamental station design has remained largely unchanged, leaving available areas for the integration of absorption either constant or, in some cases, even more constrained. While the numerical increases in STI may appear modest, they introduce a host of technical and operational complexities. These challenges are exacerbated by the need to incorporate acoustic treatments within environments where factors such as architectural design, material selection, and operational systems limit the feasibility of implementing effective solutions.

This paper presents a case-based analysis of a prototypical metro station, modelled in EASE to evaluate potential STI improvements achieved through incremental acoustic treatments. The simulation approach, consistent with the ray-tracing methods used in previous station acoustics research and required by Sydney Metro, examines the interaction between acoustic performance and real-world design constraints.

The results highlight the diminishing returns associated with increasing absorption coverage and provide cost estimates based on manufacturer data. The findings suggest the need for a more nuanced approach to STI criteria and design strategies that take into account the practical limitations of station environments and the evolving demands for speech intelligibility in public transportation systems.

Although prior studies have explored acoustic treatments and electroacoustic strategies to improve speech intelligibility in underground stations, there is comparatively little published research quantifying the cost–performance relationship for STI improvements in these settings. This study addresses that gap by providing a detailed cost–benefit analysis of incremental acoustic treatment coverage.

2 BACKGROUND: EVOLUTION OF STI PERFORMANCE REQUIREMENTS FOR SYDNEY METRO

2.1 Sydney Metro Northwest

The Sydney Metro Northwest project, completed in 2019, established the initial STI performance criteria for the Sydney Metro network. The STI ≥ 0.50 target for Public Address (PA) intelligibility in all public areas was derived from industry requirements for both general and emergency communication intelligibility. This threshold aligns with the AS2220-1989, *Rules for emergency warning and intercommunication systems for buildings*, (now superseded AS1670 Parts 4 & 5 and AS4428 Parts 3 & 4), which outlined the minimum intelligibility levels required for effective communication in public spaces, particularly regarding emergency situations. The STI of 0.50 corresponds to 'Fair' intelligibility per IEC 60268-16:2020; sufficient for clear, comprehensible announcements under normal operational conditions. Compliance with this criterion was defined by ensuring that ≥ 95% of the station's Front of House (FOH) floor area met or exceeded this STI target.

2.2 Sydney Metro City & Southwest

The Sydney Metro City & Southwest line, completed in 2024, maintained the STI ≥ 0.50 requirement for public address intelligibility in all public areas, consistent with the criteria set for the Metro Northwest line and aligning with the minimum requirement for speech intelligibility in emergency scenarios. The compliance strategy also retained the requirement for ≥ 95% of the floor area to meet or exceed the STI threshold. A target STI ≥ 0.60 was included in the Station Design Standard Requirements Design Principles, however no data has been provided to confirm whether this higher target was achieved for any stations.

2.3 Sydney Metro Western Sydney Airport

The Sydney Metro Western Sydney Airport (SM WSA) project, currently under construction, introduced an enhanced STI performance criteria compared to previous Sydney Metro projects. This marks a departure from earlier projects, where STI targets were primarily aligned with emergency communication requirements, and instead introduce a Metro specific criterion for intelligibility beyond emergency applications.

The STI target for all public areas within the stations is set at STI ≥ 0.54, with ≥ 90% of the floor area required to meet or exceed this threshold. While this represents a modest increase in STI compared to earlier projects, it is noteworthy that compliance is required over a reduced total area.

Furthermore, the revision of the T MU TE 61005 ST Standard (2020) introduced an enhanced requirement for critical customer information zones, such as help points and customer service areas. This raises the STI target to a minimum STI ≥ 0.66 across a minimum area of 10 m^2 covering the customer information zone. This elevated threshold was designed to ensure that announcements in these zones are not only intelligible but also clear, even in acoustically challenging and high-traffic environments. The objective was to facilitate effective communication in demanding conditions, ensuring that all passengers, including those who are deaf, hard of hearing, or Language Background Other Than English (LBOTE), can understand critical journey information.

2.4 Sydney Metro West

It is the authors understanding that the design of the Sydney Metro West project, due to be delivered in 2032, incorporates the same or similar STI criteria as those established for the Sydney Metro Western Sydney Airport line.

3 ARCHITECTURAL AND ACOUSTIC CHALLENGES IN UNDERGROUND STATIONS

Achieving high speech intelligibility in large underground metro stations is challenging, particularly under increasingly stringent STI thresholds. From an architectural perspective, options for improving STI are also becoming progressively more constrained. Kim and Soeta (2013) have demonstrated that station dimensions, particularly station width and corridor height, have a significant impact on STI. Smaller cross-sectional areas in stations have been shown to improve STI by reducing reverberation and enhancing intelligibility. Raising the STI target from 0.50 to 0.54 across 90% of the station area, despite STI being a continuous scale, becomes progressively more difficult due to the complex acoustic environment typical of metro stations. Empirical measurements by Shimokura and Soeta (2011) in two island-platform underground stations found that intelligibility, assessed via STI and speech-weighted C50, was “good” or “fair” only within approximately 15 m of a loudspeaker, deteriorating to “poor” at greater distances due to delayed reflections from floors, ceilings, and lateral walls.

One of the fundamental challenges lies in controlling reverberation time (RT), which directly impacts speech clarity. In underground stations, where acoustics are often dominated by hard, reflective surfaces such as concrete, metal, and glass, sound reflections lead to long RTs that blur speech and degrade intelligibility. To improve intelligibility, a meaningful reduction in RTs is required, but this task is complicated by the fact that available surfaces for sound absorption are limited. Architectural constraints, including concerns related to vandalism, maintenance requirements, and the prioritization of functional surfaces for systems like ventilation, wayfinding, and advertising, limit the areas where acoustic treatments can be effectively integrated. The placement of absorptive materials is often constrained by competing demands for surfaces at the listening plane, such as platform screen doors, escalators, and signage. While the effectiveness of absorption depends on the transmission path between loudspeaker and listener, these constraints frequently relegate treatment to the soffit, where integration is easier but the acoustic benefit may be reduced. As a result, acoustic absorption is often relegated to the soffit where the benefit is reduced.

As a result, the amount of absorption that can be applied is often significantly limited, which directly impacts the achievable STI results. This issue becomes even more pronounced with increasing STI criteria, as architects are required to incorporate more absorption to meet higher intelligibility standards. However, the available surface area for such treatments remains restricted.

In addition to reverberation control, loudspeaker integration presents its own set of challenges. Achieving uniform sound distribution across large, irregularly shaped spaces in underground stations requires careful and precise speaker placement. However, the station’s architecture imposes a range of limitations. Factors such as sightlines (or “soundlines” to audience areas), maintenance access, and aesthetic design requirements significantly restrict feasible speaker locations. In many cases, to adhere to visual design standards, speakers must be concealed, which introduces additional challenges related to sound dispersion, as concealed speakers often cannot direct sound as efficiently as those in more visible locations.

Furthermore, concealing speakers within the station fabric, such as in walls or ceilings, is often impractical due to limited available space and difficulties associated with coordination between various station systems. The station’s infrastructure layout further complicates speaker reticulation, as available pathways for wiring are often limited by the need to accommodate other critical systems. These factors result in the use of suboptimal PA design strategies, often resulting in less-than-ideal speaker placements. In the instances where speakers may be concealed behind architectural elements, such as perforated panels, wayfinding portals, or signage, this can potentially impair sound propagation and may reduce coverage in the target audience area. This compromises the effectiveness of the PA system, as sound dispersion is restricted, making it more challenging to achieve consistent intelligibility throughout the space, and in the context of an STI requirement needing to cover a minimum area, in this case ≥ 90 %, can pose significant coordination challenges.

Additionally, the placement of column-mounted speakers is often restricted by tilt angle limitations, while height requirements are strictly enforced to prevent vandalism, further constraining speaker positioning. Saher, Hill, and Clouston (2008) found that in a metro platform environment, achieving an ‘Average STI–standard deviation’ of 0.43 required approximately 135 m² of ceiling absorption with recessed loudspeakers, but around 280 m² with column loudspeakers. This illustrates that loudspeaker type selection can significantly influence the amount of absorptive treatment required to meet intelligibility targets. Further, Lau and Rowe (2015) observed in a Sydney concourse case study that poor-performing PA loudspeakers and suboptimal mounting positions contributed to significant deviations between predicted and measured STI, underscoring the importance of accommodating optimal loudspeaker placement in the design phase.

As a result, the design and integration of PA systems in underground stations require sophisticated solutions to balance these architectural limitations while ensuring uniform coverage and high intelligibility throughout the station environment.

4 METHODOLOGY: EASE MODELLING OF A PROTOTYPICAL METRO STATION

4.1 Modelling parameters

Acoustic modelling was undertaken in EASE 5.3 using the AURA room mapping module to evaluate STI. The concept of a “typical” metro station is not straightforward to define, given the considerable variation in architectural and acoustic characteristics between stations. To address this, the modelled station was developed as a prototypical case, informed by reference to existing metro stations on the City & Southwest, and Western Sydney Airport lines.

To ensure representativeness and consistency, only stations with comparable configurations were selected as reference cases. Specifically, both the modelled station and the reference stations share the same fundamental design, being an underground platform with at-grade concourse entry from street level. The platform layout adopts an island configuration, with the rail corridor located on either side, separated by platform screen doors. The model parameters, including platform and concourse dimensions, predominant surface finishes, loudspeaker distribution, and general spatial design, were derived directly from these existing stations.

As expected, previous studies have demonstrated that station dimensions, particularly width and height, significantly influence STI and overall speech intelligibility in underground stations. For instance, smaller cross-sectional areas have been shown to improve STI by reducing RT and enhancing sound clarity (Shimokura & Soeta, 2011). This finding underlines the importance of carefully constraining reference stations to those with comparable geometries, ensuring that the resulting prototypical model reflects a coherent and defensible representation of an underground metro station while avoiding the variability that would arise from including dissimilar designs.

The following surfaces were identified as available spaces for absorption: concourse ceiling, platform ceiling, platform end walls. Six models were assessed, with, 50%, 60%, 70%, 80%, 90%, and 100% of the total surface area available for absorption covered in absorptive panels.

Table 1 summarises the model inputs, basis of design, calculation settings and assumptions for the station models.

Table 1: Modelling inputs for EASE model

Parameter	Description
Ambient noise level	65dBA SPL
STI weighting	Male
EASE modelling corrections	‘With masking’ and ‘With noise’ corrections have been applied for all presented results to factor in background noise and psychoacoustic masking adjustments.
Map grid size	1 m
Audience plane height	1.5 m
Audience mapping areas	Covering all public areas, set to 0.5 m away from all vertical 'edge' surfaces
Number of particles – EASE	‘Intermediate Resolution' – 27000 particles
Calculation length – EASE	Minimum 'Extended Slow' – 7280 ms
STI assessment	IEC 60268-16 Ed. 5.0 b:2020 – Sound System Equipment - Part 16: Objective Rating Of Speech Intelligibility By Speech Transmission Index.

Note that the design was developed on the basis of the congested fan scenario, with an ambient noise level of 65dBA. These values have been derived by Resonate from both measured and empirical predictions of large axial fan noise under the different operational duties to simulate the anticipated dominant noise sources under congested fan scenarios. This is considered to be the highest background noise level in a non-emergency scenario and is a conservative assumption.

The EASE model results presented were obtained without additional optimisation through delay or equalisation adjustments.

The EASE model did not include human absorption to simulate an occupied station, as unoccupied modelling is understood to provide the most conservative assessment of STI performance. Modelling by Littleford and Gomez-Agustina (2019) found that the STI performance of a VA system on an underground platform increased by up to 0.2 points when a standing audience was introduced, confirming that unoccupied testing represents a worst-case condition and that in-service intelligibility may exceed design-stage predictions.

4.2 Loudspeakers

Loudspeakers were placed on the concourse walls, spaced evenly every 6 meters, on the platform ceilings, placed in two parallel rows every 3 meters. Speakers were also placed within the escalator portals. Loudspeakers were chosen based on characteristics such as directionality, intended location, and mounting requirements. The loudspeaker design is based on a typical loudspeaker strategy implemented in Sydney City & Southwest, and Western Sydney Airport metro lines. Table 2 presents the specifications of loudspeaker types used in the assessment:

Table 2: Loudspeaker types used in model

Type	Power	Location	Quantity
Column	20W	Concourse walls	14
Ceiling Speaker - Horizontal	6W	Platform ceiling	58
Ceiling Speaker - Vertical	6W	Escalator portals	4

Loudspeaker design was consistent between all assessments. Higher STIs may be achieved with fine tuning of loudspeaker location, types and angles.

4.3 Finishes and absorption

Absorption was applied to the ceilings such that the absorptive panel ran in five equally distributed strips running the length of the concourse, alternating with concrete along the length of the ceiling. For each model iteration, the width of each absorption band was increased such that it covered the appropriate surface area aligning with the % required.

Additionally, absorption was applied to the platform end walls such that absorption was placed as three horizontal strips, and expanded vertically for each iteration, such that the appropriate surface area was covered.

The identified areas available for absorption represent the likely allocation of absorptive surface area achievable within the architectural and operational constraints of an underground metro station. Platform soffits, concourse ceilings, and end walls are typically selected as treatment zones because they do not directly compete with critical systems such as signage, ventilation, wayfinding, or platform screen doors, which dominate other surfaces at the listening plane. The acoustic effectiveness of these higher-level treatments is likely to be constrained by the geometry of the space and the transmission paths between loudspeakers and listeners, though this is not guaranteed in all cases. Consequently, the ceiling strips and central wall bands modelled represent the practical upper bound of achievable absorption coverage and hence were selected as the basis of design for this study.

The NRC of the modelled absorptive material was 0.6, which represents a typical performance, while all other surfaces were treated as acoustically reflective finishes, including concrete, glazing, and steel, with a maximum NRC of 0.1. Figure 1 illustrates the metro station modelled in EASE, with the surfaces available for absorption highlighted in red (representing the 100% coverage scenario).

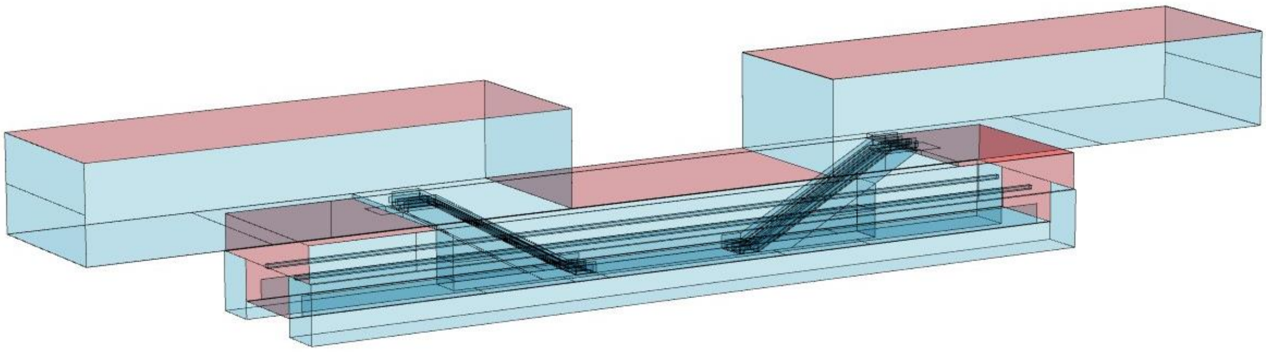

Figure 1: EASE model of typical metro station with surfaces available for absorption highlighted in red.

4.4 Scattering

The influence of sound scattering from structured surfaces and material textures was accounted for within the EASE AURA module. Scattering coefficients were assigned to each surface type using values derived from published literature, primarily following the Odeon-recommended coefficients for comparable construction materials.

5 RESULTS: ACOUSTIC PERFORMANCE IMPROVEMENTS AND DIMINISHING RETURNS

5.1 STI Performance Across Incremental Absorption Scenarios

The key performance metric adopted for this assessment is the STI, calculated as the mean STI value minus one standard deviation (Average - σ) across all receiver positions in the model. This approach reflects the requirement in public infrastructure for robust intelligibility under worst-case acoustic conditions, consistent with international standards (e.g. IEC 60268-16) and industry best practices. By integrating the spatial variability in intelligibility into the compliance assessment, the Average - σ measure offers a more conservative and operationally realistic indication of station-wide performance.

Table 3 and Figure 2 present the Average - σ values obtained for each scenario, along with the corresponding incremental improvement (ΔSTI) relative to the preceding configuration. Given the anticipated STI outcomes with coverage < 50%, the 50% coverage scenario serves as the baseline condition for all subsequent comparisons. The inflection region is annotated in Figure 2 and reflected by the post-60 % drop in Figure 3.

Table 3: Average STI, standard deviation, conservative intelligibility estimate (Average - σ) and incremental gains across treatment scenarios.

% Absorption	Average STI	σ	Average - σ	Δ
50	0.49	0.05	0.44	-
60	0.52	0.05	0.47	0.030
70	0.53	0.05	0.48	0.011
80	0.55	0.05	0.50	0.020
90	0.57	0.05	0.52	0.019
100	0.59	0.06	0.53	0.016

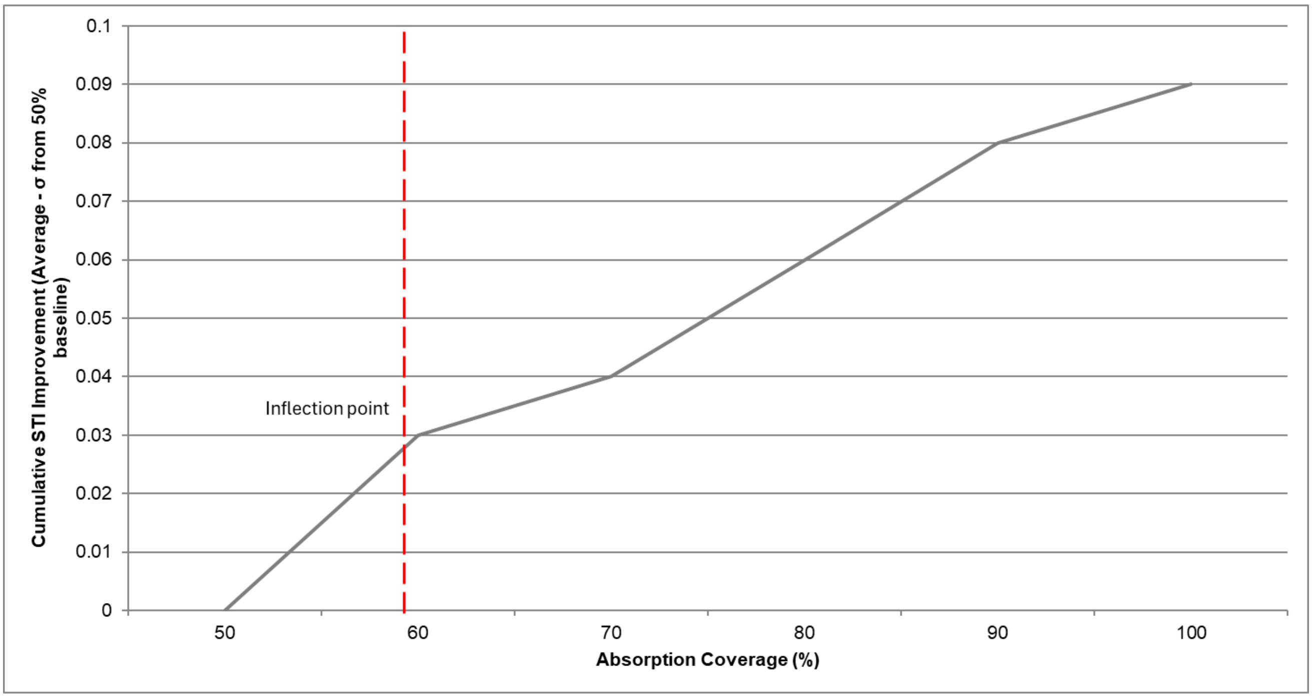

Figure 2: Cumulative improvement in Average – σ STI (from 50% coverage baseline) with increasing absorption coverage.

Table 4 presents a direct comparison of Average – σ values with the corresponding 90th-percentile STI results across absorption scenarios. This comparison shows how increasing absorption coverage progressively improves not only the overall mean but also the proportion of receiver points meeting or exceeding the STI threshold.

Table 4: Average STI – σ and 90^{th} percentile STI comparison

% Absorption	Average STI - σ	90^{th} percentile STI
50	0.44	0.43
60	0.47	0.45
70	0.48	0.47
80	0.50	0.48
90	0.52	0.50
100	0.53	0.52

The incremental gains in Average – σ for each 10% increase in absorption coverage are further summarised in Figure 3. The largest improvement (+0.03) occurred between 50% and 60% coverage, where early-stage treatment most effectively reduced dominant mid-frequency reflections from hard surfaces near the platform and concourse. Beyond this range, each additional 10% increase in coverage targeted areas with less acoustically significant reflection paths, producing progressively smaller gains, down to just +0.016 between 90% and 100% coverage.

This clear pattern of diminishing returns is consistent with field observations, where additional treatments or design refinements have yielded smaller-than-expected gains in intelligibility. For example, Lau and Rowe (2015) reported up to 0.3 STI variation between predicted and measured values at Wynyard Station in Sydney, noting that further absorption in already-treated areas delivered limited benefit due to non-uniform distribution. Similarly, Krikke et al. (2024) observed that during Sydney Metro City & Southwest commissioning, uneven reverberation time distribution, flutter echoes, and differences in ambient noise spectra constrained the effectiveness of late-stage treatments, leading to lower-than-predicted results in concourses and platforms.

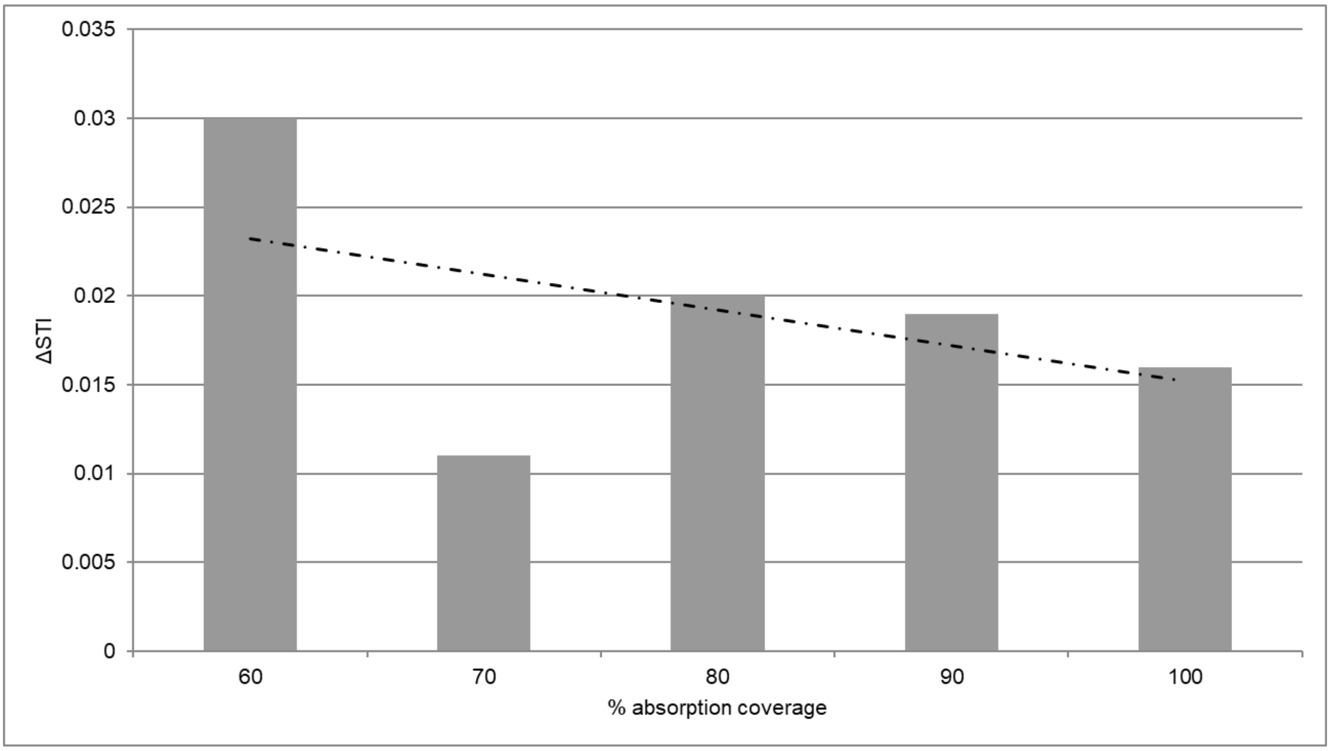

Figure 3: Incremental improvement in Average - σ per 10% absorption increase.

The rate of improvement declined from 60% to 70%, with a gain of only +0.011. This tapering trend is consistent with the theoretical behaviour of room acoustic response, where early treatment yields most benefit with a rapid decay of first-order reflections and reduces late-field reverberation, while additional treatment beyond a certain threshold primarily addresses diffuse or marginal energy contributions. Beyond a certain threshold, additional treatment predominantly affects diffuse or marginal energy components, yielding progressively smaller gains. Consistent with this principle, Gomez-Agustina (2012) reported that targeted application of ceiling and upper-wall absorptive panels in platform areas improved STI by up to 0.06, with the most pronounced benefits achieved when panels intercepted dominant reflection paths rather than being distributed uniformly.

Further increases to 90% and 100% coverage yielded smaller gains of +0.019 and +0.016, respectively. While these final steps continued the upward trend in Average – σ, the magnitude of improvement diminished, indicating a tapering response consistent with the behaviour of late reverberant energy in highly treated environments. The final increase from 90% to 100% provided the smallest relative gain, despite representing the largest incremental material addition in absolute terms.

These findings highlight a clear point of diminishing returns, beyond which additional treatment area yields acoustically minor improvements. Importantly, the conservative Average - σ values, rather than average STI alone, reveal that while earlier scenarios (e.g. 70% coverage) may reach average STI targets, only higher coverage scenarios can provide system-wide robustness under practical deployment conditions. This distinction has significant implications for design approval, performance validation, and long-term maintainability of acoustic systems in constrained underground environments.

5.2 Spatial Consistency and Treatment Sufficiency

Across all coverage scenarios, the speaker layout, source levels, background noise levels, and geometry remained constant. The standard deviation of STI values, taken across all receiver positions in the model, therefore provides an indirect indication of spatial variability independent of electroacoustic changes. In the results presented in Table 3, the standard deviation stayed constant at 0.05 for all absorption levels, increasing marginally to 0.06 only at 100 % coverage. This minimal variation suggests that, within the constraints of the assumed station geometry and loudspeaker design, increasing absorption coverage had little measurable effect on reducing spatial variability. The modelling methodology applied absorption evenly across all available surfaces in each scenario;

while this provides a consistent basis for comparison, it is unlikely to be achievable in practice due to architectural, services, and integration constraints. In real-world applications, the uneven distribution of absorptive treatments would be expected to result in greater spatial variability than indicated by these idealised results.

These findings indicate that increasing absorption coverage primarily improved mean STI, with negligible effect on spatial uniformity. This outcome aligns with the model's assumption of perfectly even absorption distribution, an idealisation unlikely to be realised in practice, which limits the direct applicability of the uniformity results and underscores the need for targeted treatments in low-STI regions.

The relative stability of the standard deviation values implies that the observed increases in the conservative Average – σ metric with higher absorption are primarily due to improvements in the mean STI, rather than a compression of the distribution. In practical terms, this means that absorption treatments improved the overall intelligibility baseline but did not significantly alter the spread between the best- and worst-performing areas in the model.

Localised performance deficits in acoustically disadvantaged areas, such as peripheral concourse regions or behind geometric obstructions, are therefore likely to persist even at high coverage levels, unless addressed through targeted electroacoustic or architectural design changes.

This has important implications for achieving elevated STI targets in designated information zones (i.e., ≥ 0.66 over a defined minimum area). While higher absorption coverage can raise the overall performance baseline, it does not inherently improve uniformity without targeted interventions. In practice, meeting both high absolute intelligibility and spatial consistency in these zones requires a coordinated approach, combining strategically placed acoustic treatments with optimised loudspeaker design and placement. In underground environments, where available surface area, integration with other systems, and durability requirements impose significant constraints, these measures must be included in the station design from the earliest stages. Retrofitting solutions such as absorptive canopies or close-proximity loudspeakers is rarely feasible once detailed design is complete, due to architectural integration, system coordination, and design hierarchy.

6 COST ANALYSIS: INVESTMENT VS. INTELLIGIBILITY GAIN

This section evaluates the financial implications of increased acoustic treatment coverage in relation to the resulting intelligibility gains. While STI performance was shown to improve incrementally with additional absorption, the rate of improvement diminishes with each successive coverage increment, a non-linear relationship. In contrast, the capital investment required for each step remains effectively linear, as each additional 10% coverage introduces a fixed quantity of material and installation effort.

As a result, the cost per unit of STI improvement increases with each step, particularly beyond the 60–70% coverage range. This divergence between linear cost increases and diminishing acoustic returns highlights the need to assess the cost-effectiveness of treatment not just in aggregate, but at each incremental stage of design.

6.1 Cost Basis for Acoustic Treatment Implementation

To support the cost assessment, a consistent cost basis was established for the supply and installation of absorptive treatments used in the station model. The system implemented in the modelling study and used as the basis of design comprises a 50 mm high-density mineral wool backing behind a custom-perforated 2 mm steel face panel, selected to meet architectural, durability, and acoustic performance requirements.

The raw material cost was established at AUD 300/m², based on the summation of supplier pricing for both the mineral wool, perforated panel, and framing. To this, an installation cost of AUD 200/m² was added, accounting for delivery, working-at-height, ceiling interface detailing, penetrations for services, and installation sequencing within a multi-trade environment. This figure is consistent with published cost ranges for specialist acoustic systems and includes typical contractor overheads and margins.

The cost model assumes negligible variation between concourse, platform soffit, and platform end wall zones, as the installation complexity, integration, and coordination with other trades are broadly comparable across these locations.

This results in a total approximate and rounded installed cost of AUD 500/m², applied uniformly across all treatment areas and coverage scenarios. No cost variation was applied between zones, as the installation complexity was assumed to be broadly equivalent across locations in the context of underground construction.

Using the surface areas defined in the EASE model geometry across the total station, the total installed cost per scenario was calculated to range from approximately AUD 808,000 at 50% coverage to AUD 1.62 million at full (100%) coverage, as summarised in Table 4. These figures form the basis for subsequent analysis of marginal and cumulative cost efficiency relative to STI performance gains.

Table 4: Cost basis for assessment.

Absorption coverage	Total Treated Area (m²), rounded	Estimated Installed Cost (AUD)
50%	1616	$807,835
60%	1939	$969,405
70%	2262	$1,130,970
80%	2585	$1,292,535
90%	2908	$1,454,100
100%	3231	$1,615,670

6.2 Cumulative Performance vs. Total Investment

To contextualise the efficiency of investment across the full range of coverage scenarios, cumulative STI improvement was plotted against total installed cost. As shown in Figure 4, the relationship is distinctly non-linear: early investments deliver comparatively large intelligibility gains, while the latter stages result in flattening performance returns. For example, the first AUD 808,000 of treatment (at 50 % coverage) establishes the baseline performance, with the most cost-effective gain occurring between 50 % and 60 % coverage, where a ΔSTI of +0.030 is achieved. In contrast, increasing coverage from 90% to 100%, at an additional cost of approximately AUD 162,000, yields only a +0.016 improvement in Average – σ STI. This asymptotic trend reflects the diminishing sensitivity of STI to added absorption once the dominant mid-frequency reflection paths have been treated and the acoustic field transitions from being predominantly specular to increasingly diffuse.

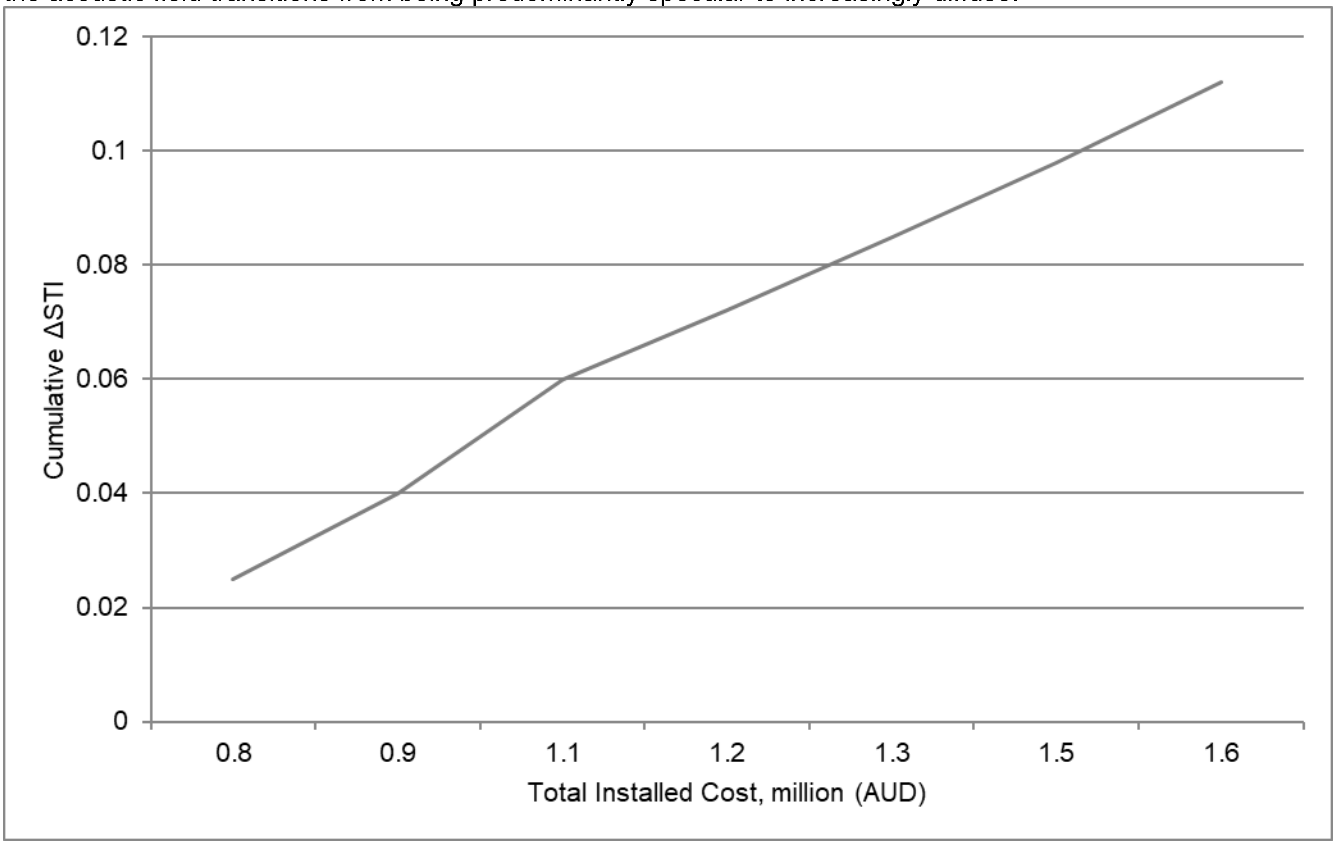

Figure 4: Cumulative STI improvement (Average – σ STI from 50% baseline) vs total installed cost.

The curve's inflection point, observed between 50% and 60% coverage, represents a practical threshold beyond which additional treatment becomes disproportionately expensive relative to its contribution to intelligibility performance. While further gains remain possible beyond this point, they may not represent the most efficient path to compliance when weighed against other station design constraints or alternative intelligibility improvement measures.

To further quantify the diminishing returns observed in STI performance, Figure 5 presents the calculated cost per 0.01 increment of ΔSTI for each 10% increase in absorption coverage. The marginal cost per 0.01 ΔSTI drops sharply between 50 % and 60 % coverage, then peaks immediately after at 60–70 % (≈ 147 k AUD). Beyond ~65 % coverage, the cost per unit of intelligibility improvement generally increases again, albeit with small fluctuations, highlighting that late-stage gains are disproportionately costly relative to earlier interventions. This metric provides a practical lens through which designers and project stakeholders can assess the marginal value of treatment beyond minimum compliance thresholds.

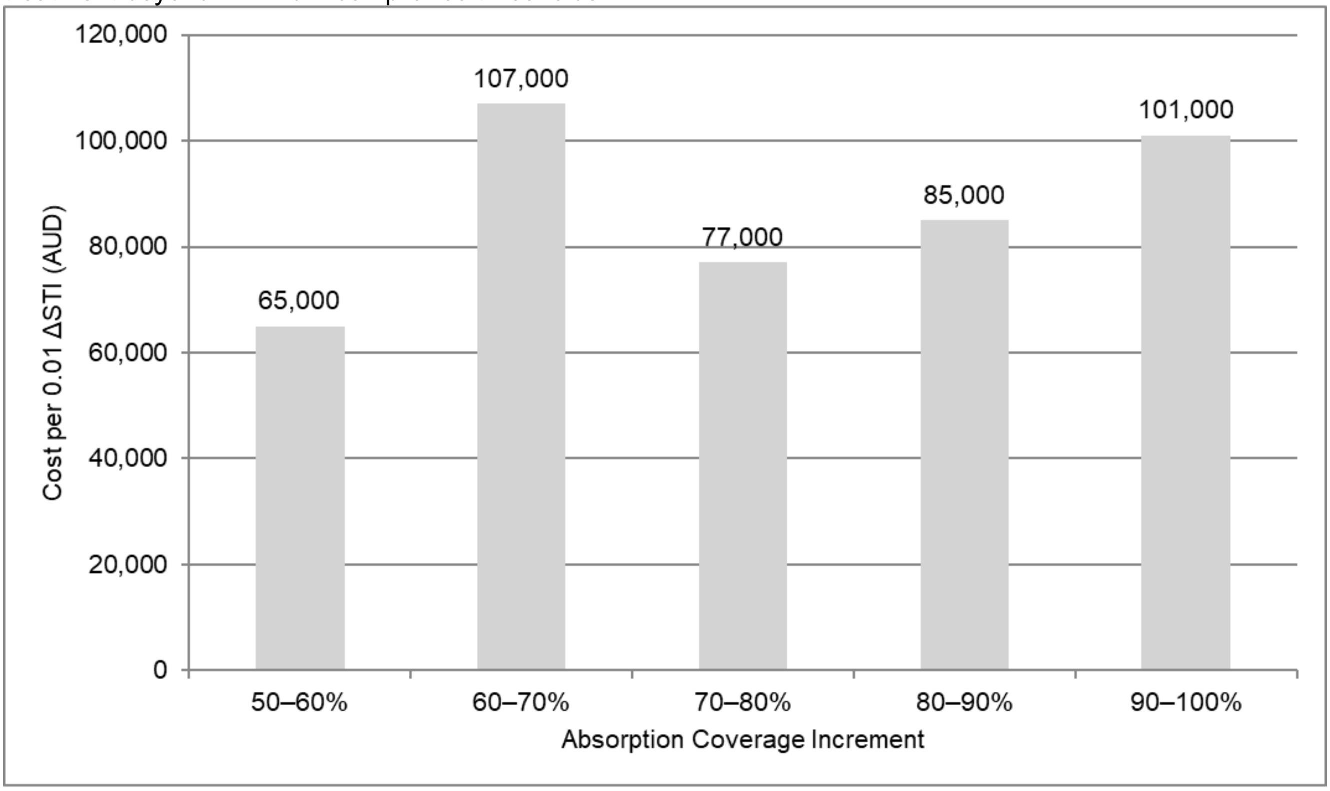

Figure 5: Cost per 0.01 ΔSTI Across Absorption Coverage Increments

Collectively, the cost-performance analysis demonstrates that while broad absorption coverage is essential to achieving speech intelligibility compliance, the marginal benefit of additional treatment decreases progressively as coverage increases. Attaining the final increments of STI performance, particularly to satisfy elevated zone-specific thresholds such as those required in information zones demands disproportionately greater investment relative to earlier treatment stages.

A frequently observed approach among non-specialist design teams is to respond to non-compliance by simply increasing the proposed absorptive surface area. However, the modelling data presented in this study clearly shows that such a strategy is both acoustically inefficient and cost prohibitive, particularly in underground environments where available surface area is constrained and system integration demands are high. These findings reinforce the need for a more integrated, performance-led design methodology that incorporates early acoustic input, strategically allocates treatment to acoustically sensitive areas, and accounts for the diminishing effectiveness of additive solutions in meeting elevated intelligibility criteria.

7 DISCUSSION: NAVIGATING THE TRADE-OFFS BETWEEN ACOUSTIC PERFORMANCE AND PRACTICAL DESIGN CONSTRAINTS

The findings of this study highlight the complex relationship between the increasing demands for STI and the practical constraints inherent in underground station design. As STI targets evolve from 0.50 to 0.54, and even higher in specific areas, achieving these goals presents both technical and multi-disciplinary challenges. The results clearly demonstrate the diminishing returns of incremental acoustic treatment, reinforcing the idea that the path to compliance may not be linear.

Our analysis reveals that early acoustic treatments yield the most significant improvements in STI. These treatments, which focus on addressing the dominant mid-frequency reflections from hard surfaces near the platform and concourse, contribute substantially to improving intelligibility. However, as coverage increases, the incremental improvements in STI become progressively smaller. Notably, the final increase from 90% to 100% coverage, despite requiring a substantial additional investment, only yields a marginal improvement of 0.016 in Average – σ STI. This diminishing return underscores the challenge of achieving higher STI targets, where further improvements necessitate disproportionately greater investment in treatment materials and installation efforts.

A key insight from this study is that, while STI remains a widely recognised performance metric, its application in underground environments must account for practical constraints that consider a holistic and integrated design approach, including architectural, material, and operational factors. Moreover, as absorption coverage increases, the benefits shift from addressing core intelligibility issues to mitigating late reverberation. Controlling this reverberation becomes increasingly difficult in constrained environments, where electroacoustic design, particularly the use of distributed loudspeaker systems, plays a more significant role. However, such considerations fall outside the scope of this study.

Additionally, the dataset shows negligible change in spatial dispersion (σ ≈ 0.05 across all scenarios, 0.06 only at 100%), so gains in the conservative Average – σ are driven primarily by increases in mean STI, not compression of the distribution.

As the EASE model applied absorption uniformly across available surfaces, an idealised distribution unlikely to be achievable in practice, spatial consistency did not materially change. However, in practice, uneven treatment would likely increase variability and leave acoustically disadvantaged outliers unless targeted electroacoustic or architectural interventions are used.

From a cost perspective, the analysis indicates that the financial burden of achieving higher STI targets escalates rapidly as absorption coverage increases. The total installed cost per square meter of absorptive treatment is relatively linear, but the return on investment in terms of STI improvement diminishes as the treatment area increases. The results suggest that focusing solely on increasing coverage to meet STI targets is not the most efficient strategy. Instead, a more integrated approach, which considers early-stage acoustic input, targeted treatment areas, and alternative electroacoustic measures (e.g., DSP tuning, steerable arrays, etc), is essential for cost-effective and practical design solutions.

Additionally, it is important to assess STI not only under unoccupied conditions (e.g., empty-room tests) but also in real-world operational environments. Where Littleford & Gomez-Agustina's (2019) research has concluded that there is a significant improvement on the STI performance of a VA system when a standing audience is introduced to an underground platform, the increase was more pronounced (by approximately 0.2 STI) when the occupancy density is increased. This finding is supported by Krikke et al. (2024), who observed that stations which fall short of the STI target in empty tests still exhibit acceptable intelligibility under normal, crowded conditions, with STIPA values typically ranging from 0.55 to 0.65 across most areas. This supports the notion that strict numeric targets should be contextualised within the real-world user experience. Furthermore, alternative intelligibility metrics, such as word recognition scores or phonetic tests, could offer a more comprehensive measure of performance, reflecting the operational realities of these environments.

8 CONCLUSION

This study examines the growing challenges of meeting increasingly stringent STI targets in Sydney Metro stations, where the STI requirements have shifted from a baseline of STI ≥ 0.50 to STI ≥ 0.54, with even higher targets in key areas. Through a case-based analysis using an EASE model of a prototypical metro station, the study demonstrates that early acoustic treatments provide the most significant improvements in STI, addressing mid-frequency reflections from hard surfaces near platforms and concourses. However, as coverage increases, the incremental improvements in STI become progressively smaller, revealing a point of diminishing returns. The final increase from 90% to 100% coverage, despite a substantial investment, yields only marginal improvements in intelligibility.

The paper highlights the role of spatial consistency and the impact of real-world constraints such as architectural limitations, speaker placement, and the integration of other essential systems. It also underscores the need for comprehensive treatment strategies that balance performance with practical considerations. From a cost perspective, the analysis reveals a non-linear relationship between cost and STI improvement. As absorption coverage increases, the total cost rises linearly, but the marginal return on investment diminishes significantly beyond 70% coverage. This finding points to the inefficiency of increasing coverage as a sole strategy to meet elevated STI targets and advocates for more cost-effective, integrated design approaches. Krikke et al. (2024) further emphasise the need for an Acoustic Design Integration Strategy (ADIS) that aligns architectural and PA system objectives from early design through commissioning, noting that lack of coordinated interface documentation can allow both building and PA contractors to meet their contractual requirements individually while failing to achieve overall intelligibility target.

Moreover, the study underscores the importance of considering real-world operational conditions in STI assessments, suggesting that strict numeric targets should be contextualised with actual user experience. Modelling by Littleford and Gomez-Agustina (2019) found that the STI performance of a VA system on an underground platform increased notably by up to 0.2 points when a standing audience was introduced, confirming that unoccupied testing represents a worst-case condition and that in-service intelligibility may exceed design-stage predictions. In stations that may fall short of STI targets in empty-room tests, intelligibility in crowded conditions may still meet operational needs, thanks to factors such as ambient noise levels and human presence. This highlights the potential value of alternative intelligibility metrics that incorporate contextual cues, offering a more comprehensive understanding of acoustic performance.

Ultimately, the study advocates for the development of more realistic, context-sensitive STI performance targets that account for both the practical challenges and acoustic complexities inherent in underground metro station design, ensuring a balanced approach to safety, accessibility, and cost-efficiency and guiding future updates to metro station acoustic performance standards.

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