



Designing and Complying with the Acoustic Objectives for Underground Railway Stations

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Abstract - The four largest capital cities in Australia are currently constructing and commissioning what tend to be their biggest CBD public rail transportation infrastructure projects in a generation. These projects all come with significant acoustic challenges, some of which are well planned for, and some which emerge during later stages of construction and commissioning. With a focus on the diverse and acoustically complex architecture associated with rail stations, the aim of this paper is to examine how some of the challenges posed by fixed station facilities have been identified and practical solutions were developed by the various acoustic teams charged with testing and commissioning of these operational stations. The aim of this paper is to discuss lessons learnt from the commissioning across multiple station sites and working with multiple contractors. These lessons will potentially inform the design and setting of acoustic objectives for future underground railway (station) projects in Australia.

1 INTRODUCTION

Recently, Australian capital cities have been investing significantly in the expansion and upgrading of their public transport networks. This investment is predominantly focused in and around their Central Business Districts (CBDs). In particular, there has been a focus on the provision of underground railway systems. The Perth Metronet, Brisbane Cross River Rail, Melbourne Metro Tunnel and Sydney Metro being examples. This paper draws on knowledge of all these projects.

Management of noise and vibration tends to be treated differently according to its provenance, which can be split into two categories: railway operations and fixed facilities. Depending on the nature of the noise or vibration source, and the type of sensitive receiver potentially affected, cumulative impacts may also need to be considered. Potential operational scenarios of noise and vibration are summarised in Figure 1.

The paper is primarily related to the acoustic performance of stations and the plant and equipment housed or associated with these stations, and how it compares to the objectives set by legislation, conditions of project approval or by contract specifications. It does not consider the in-car noise levels, or noise and vibration resulting from rail / wheel interactions.

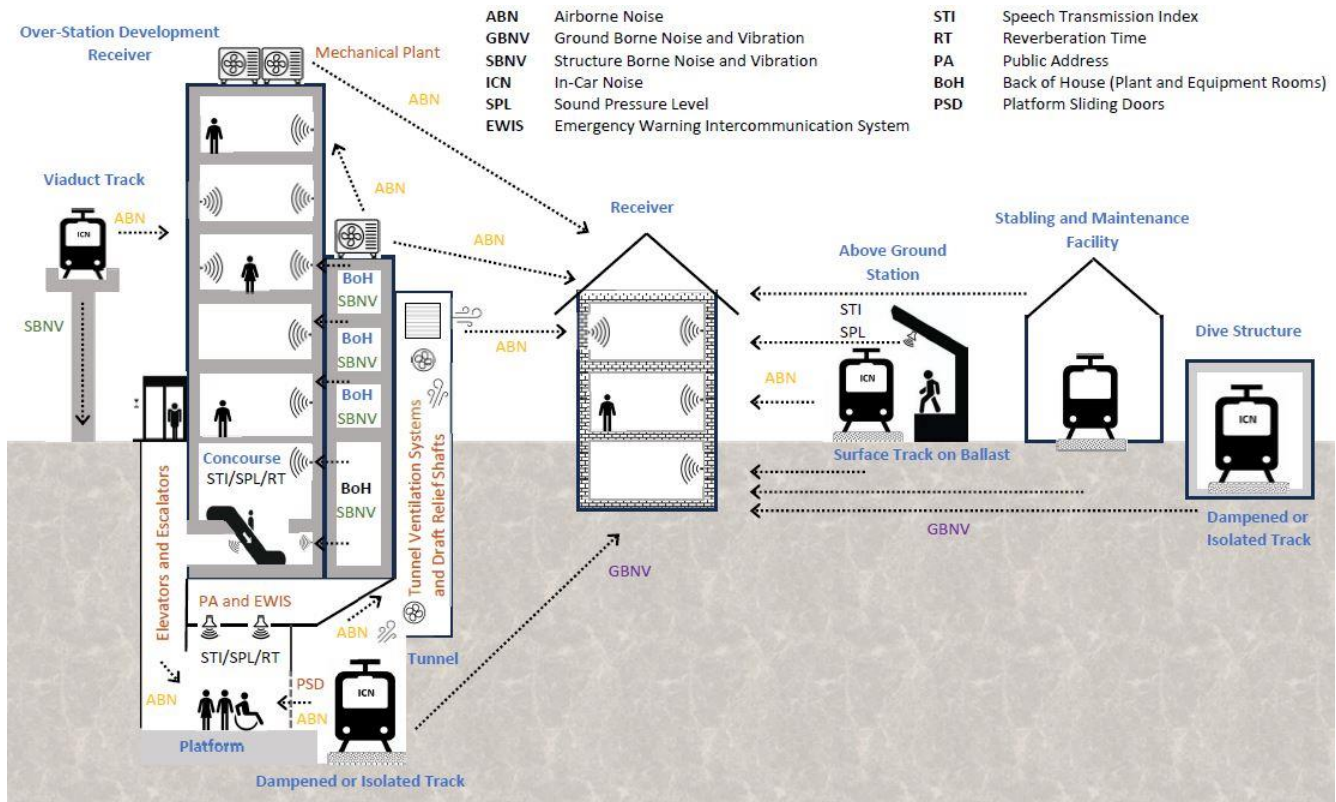


Figure 1 – Overview of Noise Sources associated with Rail Infrastructure

2 NOISE AND VIBRATION REQUIREMENTS

There are several reasons for why consideration of noise and vibration associated with underground station infrastructure may be required. In some cases, the requirements may be legislated, in others they may be objective levels recommended in the project approval conditions or non-mandatory guidance, or they could be project specific objectives set in contract documentation to satisfy customer experience.

2.1 Legislation

In Australia, most environmental requirements are administered at the state level. In NSW, the impacts of noise on sensitive receivers (e.g., residences, commercial businesses, schools) must be considered under two State Legislative Acts. These are the *Protection of the Environment Operations Act (1997)* which is administered by the NSW Environment Protection Authority (EPA), and the *Environmental Planning and Assessment Act (1979)* which is administered by the NSW Department of Planning Housing and Infrastructure (DPHI). Whilst not legislative instruments themselves, there are also a range of standards and codes such as Australian Standards AS 2220.2 (1989) and AS 1670.4 (2018) which relate to Emergency Warning and Intercommunication Systems (EWIS) which must be addressed in order for an Occupation Certificate to be issued.

2.2 Project Approval Conditions

Following assessment of environmental requirements, the relevant approval authority (DPHI in NSW) may approve the construction of an infrastructure project subject to a set of Conditions of Approval (CoAs). These conditions may reference State or Federal guidance documentation such as the National Construction Code or in the case of operations, the NSW EPA *Noise Policy for Industry (NPfI)*, NSW *Rail Infrastructure Noise Guideline (RING)* and the NSW *Assessing Vibration: A Technical Guideline*.

Whilst environmental requirements are not intended to protect the amenity of station workers or passengers, they do apply to non-associated sensitive receivers, and the operation of items of station equipment such as Tunnel Ventilation Systems (TVS) or Draught Relief Shafts (DRS) which vent air and noise externally are assessed against recommended impact levels derived in the NPfI.

2.3 Contract Specifications

Prior to tender for construction of large infrastructure such as new stations, Particular Specifications are developed to ensure a minimum standard of design deliverables is set. These specifications ultimately become contract requirements and will often reference Australian and International Standards or include project specific goals for noise and vibration objectives such as Speech Transmission Index (STI) for non-emergency announcements.

3 NOISE AND VIBRATION CHALLENGES

Acoustically, stations (particularly those with underground components) present complex spaces that are very difficult to work with and model.

3.1 Environmental Conditions of Approval

Environmental CoAs associated with operation of a station generally only relate to noise and vibration impacts to non-associated receivers rather than to those areas associated with the station which will have acoustic objectives set by building requirements. Outside of these conditions, detailed attention to structure borne noise and vibration impacts is required where there are over station developments and retail tenancies within the station to ensure they are 'fit-for-purpose'.

3.2 Back of House Areas

Fire Life Safety (FLS) and Occupational Health and Safety (OH&S) requirements are typically the driving factor for the design of Back-of-House (BoH) areas. These areas are the rooms and spaces behind sealed doors (not open to the public) that house plant including ventilation fans and electrical equipment. These are basically concrete box spaces that are highly reverberant, and in many cases, very noisy. In practice it is generally impractical or unnecessary to have specific noise and vibration amenity targets for these irregularly occupied areas. However, as the BoH area houses the dominant noise and vibrating plant that propagates throughout the whole station, it is important that they are space proofed to allow for further mitigation if required.

3.3 Front of House Areas

Front-of-House (FoH) areas are the rooms and spaces open to the public that primarily consist of the concourse and platforms, but also includes, station entrances, adits and pedestrian tunnels as well as retail and commercial facilities that may be part of the station. Architectural requirements often mandate high impact resistance finishes for walls within passenger reach. These walls typically consist of rigid glass-fibre reinforced concrete panels or sandstone, whilst floors are typically polished concrete or tile surfaces to assist with durability and cleaning. All these building elements have very low sound absorption coefficients. Additionally, there are usually large atriums between the concourse and platform levels which contain escalators and lifts, whilst adits will often be present to provide a thoroughfare between the Up and Down platforms. Modern underground platforms also have floor-to-ceiling screens and sliding platform doors for passenger safety and to manage smoke ingress in the event of a tunnel fire.

The areas to incorporate sound absorptive material within the spaces are therefore very limited, especially in long tunnels and adits with relatively low ceiling heights. Cumulatively, all of these structural features lend themselves to being highly reverberant spaces. This can be further compounded by noisy plant and equipment including tunnel ventilation systems and train operations that result in air pressure gradients between tunnels and platform areas which often results in aeolian noise between gaps and sliding platform doors.

4 DESIGN CONSIDERATIONS

4.1 Tunnel Ventilation Systems

Tunnel Ventilation Systems (TVS), typically contain various large fans comprising Tunnel Extraction Fans (TEF) and Tunnel Ventilation Fans (TVF). The TVS system operates in multiple modes and configurations, but from an acoustic perspective, Normal, Congested, and Emergency operations are typically considered.

The main considerations for down duct noise usually include acoustic attenuators. Due to space constraints, attenuators are not always directly connected to the fans and the plantroom will be used as the intake plenum. As a guide for future design considerations, noise levels of up to 107 dB(A) have been measured in a TVS plantroom with 50 mm sound absorptive treatment to all walls and with three fans running (115 dB(A) SWL each). Whilst a TVS with attached attenuators achieved noise levels of approximately 93 dB(A) (128 dB(A) SWL) without any absorptive treatments within the space. This equates to a SPL range from 80 to 85 dB(A) when measured trackside directly underneath the outlets with a further reduction of 5 to 10 dB when measured at 10 metres from the outlet.

During the design phase, platform noise levels are typically assumed to closely match an NR spectrum relating to the noise objectives. It was however found that the measured Z-weighted TVS emergency mode spectrum on platforms tends to be surprisingly flat with an approximate range of 10 dB. An assumed NR spectrum would therefore typically assume noise levels too high in low frequencies and too low in higher frequencies. This aligns with the findings in reverberation time (RT) as noted in Section 4.3. Typical (average) octave band correction relative to the overall noise levels is provided in Table 1. Noise levels at the centre of the platform, furthest away from the TVS, were generally up to 7 dB lower compared to noise levels at the end of the platform.

Table 1 - Average octave band correction relative to overall dB(A) for platform TVS 'emergency mode' levels

	Octave band correction relative to overall dB(A) for Octave Band Centre Frequency, Hz							
	31.5	63	125	250	500	1k	2k	4k
Station 1	-8	-13	-10	-8	-3	-6	-4	N/A
Station 2	1	-3	-3	-5	-3	-7	-8	-9

Not all TVS 'Emergency modes' are the same. While the TVS SWL is unlikely to change, airflow volumes and damper configurations can vary widely. Airflow induced noise via dampers, external louvres and doors should be considered for the various emergency modes. Initial noise level concerns measured during commissioning were related to airflow induced regenerated noise. On the platform this tended to be mostly via a whistle of incorrectly sealed dampers or via small openings between the seals of the Platform Screen Doors (PSD). Externally, unexpected high noise levels were sometimes found via louvres and screens whose design areas were constrained by space requirements. This issue was often compounded by non-uniform distribution of airflow across the louvers and screens. Noise levels up to approximately 90 - 95 dB(A) SWL from (external) weather louvres were measured in 'emergency mode'.

TVS noise levels on the platform are usually considered with the assumption that the PSD is closed. Whilst it is noted that there are potential emergency scenarios (e.g. train or station fire), where the train is located within the station and all doors are to be opened while the TVS is running (i.e. the platform is therefore open to the tunnel), this scenario has not been modelled or measured during the commissioning phase, but should be considered further to assess the impact to the platform noise levels and EWIS .

In the design of TVS vibration isolation, contractors typically prefer using springs with a 25 mm static deflection for, whereas project specifications generally require 50 mm. Guidance from Table 49 in ASHRAE Chapter 49 (2023) indicates that 64 mm static deflection may be more appropriate, however it has been generally found that with correctly installed 25 mm static deflection springs – noise levels in spaces adjacent to TVS plant will be in the range of 50 - 60 dB(A) with barely perceptible vibration levels which is acceptable in most back-of-house areas. Where high structure borne noise and vibration is observed, it is often identified as resulting from incorrectly balanced/installed isolation systems that cause the springs associated with TVS plant to be bridged. In such situations, reductions of up to 14 dB have been achieved by simply readjusting springs, balancing fans and readjusting door seals. It is recommended that for TVS plant rooms near noise and vibration sensitive areas, further detailed analysis should be undertaken and a minimum 50 mm static deflection springs should be considered.

4.2 Building Services Noise

Noise and vibration control for Building Services, or Environmental Control Systems (ECS), is relatively straightforward. Due to the large back-of-house areas, most ECS have long ducts and pipes before they reach the occupied spaces. Additionally, ECS in large infrastructure facilities are designed with multiple levels of redundancy, with ECS only ever expected to run at a low capacity during normal conditions. Noise level criteria for internal spaces are also not onerous with typical public spaces allowing 50 dB(A) and above.

A key consideration for ECS is airflow-induced regenerated noise. ECS systems serving large FoH spaces (e.g., concourses) usually need to move large quantities of air. Mostly, the design of the diffusers and terminals are relatively small with tight bends, or hidden behind architectural features (e.g. louvres or perforated panels). It is therefore common to observe airflow induced regenerated noise in station concourse areas. Often this observation will be at a late stage of the project at which point, options to mitigate noise levels are limited to reducing air volumes as much as possible via either lower fan speeds further or rebalancing of the system.

4.3 Reverberation time

RT in FoH areas is generally specified to aid the Public Address (PA) system in achieving speech intelligibility objectives. However, an overly ambitious focus on achieving RT targets can lead to perverse outcomes, especially when there are differing expectations between architectural design and PA design teams. If not carefully managed, this will invariably result in two separate design approaches. The architectural design consultant's only objective will be to achieve the RT targets and will not accommodate feedback from the PA system designer on impractical audio acoustic constraints.

Figure 2 outlines the differences between the modelled (generally EASE) and measured RTs in various FoH areas across seven stations. The results indicate that the mean measured RT is within 10% of the predicted RTs. One standard deviation (SD) of the measured RT is within 30%. This equates to up to ~0.4 seconds in RT. It is noted that some outliers with measured RTs more than 1 second above the predicted RTs were found. Standard IEC 60268-16 (2020) concludes that RT uncertainties of >15% leads to significant STI uncertainty. If an SD uncertainty of 30% for RT is assumed, this implies an STI uncertainty/SD of > 0.06 (IEC 60268-16); which is significant and may need to be considered for design margins.

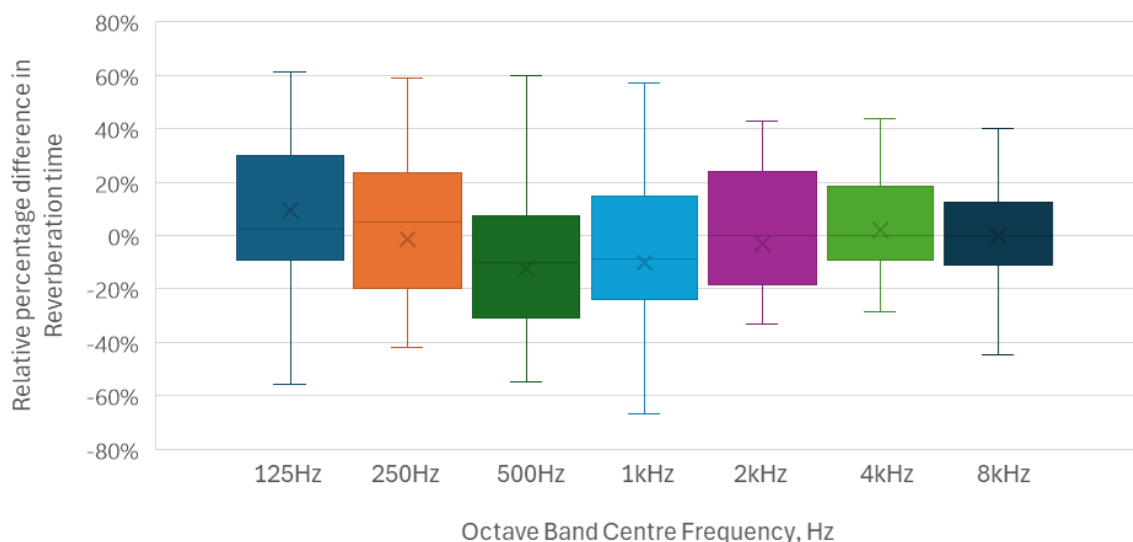


Figure 2 – Difference between modelled and measured reverberation time. Positive indicates higher measured RT compared to modelling results.

Site observations often do not reveal obvious causes for these differences in RT. Checks of architectural sound mitigation treatments usually show them to be installed as specified and correctly assumed in the room acoustic modelling. Station architecture does however lend itself to the presence of flutter echoes, particularly where there are (long) adits and high concourse areas which have relatively large sound reflective surfaces.

A more detailed analysis of modelled vs. measured data for a package of stations found that the actual RTs were lower in the lower frequencies (≤ 500 Hz) and higher in the higher frequencies (≥ 2000 Hz) compared to the modelling outcomes. This has not been further investigated at the time of writing. However, it is anticipated that this is mainly due to large panels acting as membrane absorbers and the use of perforated panels in combination with sound absorptive treatment affixed to the soffit, not directly behind the panels. Additionally, stations typically have large quantities of services in the ceiling voids which may have affected the RTs. Due to the large volumes and surface areas involved, even small absorptive properties could be responsible for the large discrepancies between modelled and measured RTs that were observed.

4.4 Public Address Systems (Front-of-House)

PA systems are a subset of the broader customer experience and wayfinding systems of a station. They must integrate with other systems such as message boards, on-train announcements, scheduling, and options for hearing-impaired passengers like push notifications. It may also include or be separate to a EWIS and needs to be future proofed for potential upgrades. This can result in conflicts between requirements for EWIS and contract specifications such as TfNSW Standard T MU TE 61005 ST (2020) for PA systems. Consequently, it is important for consideration be given to the system that will be chosen at the award date of contract, and how contemporary that system will be when a network opens after perhaps 10 years construction.

STI for PA system (STIPA) requirements are often ambiguous regarding whether an average STI or a percentage of floor space needs to meet a minimum STI, or the expectations related to masking noise and occupation levels. It has become more common for contract requirements to require an STI of 0.54 or higher. However, lower STI levels can be acceptable for 'emergency modes' type background noise. Regardless, the requirements and expectations need to be clearly articulated.

The competing objectives of RT and PA, combined with complex station architectural designs, make PA systems difficult to model. It is an observation that measured STIPA levels tend to be less than the modelled STI values. The reasons for these underpredictions vary per station, but can be generally attributed to the following:

- Reverberation times were not as uniformly distributed as modelled;
- Reverberation times in certain concourse and platform areas were higher than modelled;
- Flutter echoes were often present in large cavern stations and adits;
- Clipping of speakers due to long cable lengths and amplifier performance;
- Speaker frequency outputs were not even across all speakers; and
- Ambient masking noise tends to exhibit considerably different spectra compared that that modelled.

This often results in significant commissioning and fine-tuning of PA systems in FoH areas, usually very close to the station's public opening dates. Planning to use more versatile speakers that have more freedom to individually fine-tune speakers along with appropriate amplifiers and ability to modify frequency outputs are key lesson to be learnt. Consequently, it is highly recommended that there be a focus on the integration of architectural acoustics and PA to avoid a technical failure of STI targets.

Having noted all the issues identified above, it should also be noted that the STIPA results do not tell the whole story for the PA system's speech intelligibility. While the STIPA performance of some stations may not achieve the set targets, the STIPA for large areas of concourse and platform areas during congested and normal operating modes tends to be in the acceptable range between STI 0.55 and 0.65. Furthermore, alternative assessment methods more closely aligned with the intended use, such as Harvard Phonetically Balanced Word scores, resulted in relatively good Common Intelligibility Scale (CIS) results.

4.5 Fire Life Safety / Emergency Warning Systems (Back-of-House)

AS 1670.4 (2015) sets a Common Intelligibility Scale (CIS) objective of > 0.7 (equivalent to $STI > 0.50$) for BoH areas with background noise levels below 85 dB(A). This requirement applies for much of station BoH areas to keep levels below the Safework Australia requirements (i.e. 85 dB(A) $L_{eq;8 \text{ hour}}$). For areas below 85 dB(A) where

it is impractical to meet the CIS requirement, there are potential dispensations including for the installation of a Visual Alarm Device (VAD). It has been observed that whilst many contractors would conservatively install VADs. For others it has often been a last-minute retrofit for station BoH areas when it was realised how reverberant the spaces are and how difficult it can be to meet a $CIS > 0.7$, or the contractors assumed others would ensure compliance. It should be noted that the 2024 version of AS 1670.4 removes the dispensation to fit VADs when speech intelligibility cannot be met, except in spaces with high ambient noise.

4.6 Platform Screen Doors

TVS noise levels on the platform are typically modelled to achieve a noise level within the tunnel, assuming a Transmission Loss (TL) or Noise Reduction (NR). Specifications and industry best practice typically assume a NR of 15 dB. Based on the findings from TVS measurements, a range in NR of 10 - 15 dB was found to be practically achievable.

As previously noted, whistling was a particularly annoying characteristic caused by airflow between sliding door seals, fixed screens, and through header boxes above the screens and doors. The cause was identified as a mixture of misaligned seals and site tolerances. This was an issue that may not have been appropriately considered during the design phases. Further detailed assessments, modelling and wind-tunnel analysis should be considered for PSD systems prior to installation.

In cases where whistling was deemed excessive, acceptable levels were achieved by working with the contractor to readjust the mounting of the PSDs or install additional seals. These measures often resulted in improvements of 5 – 7 dB across the platforms. However, some outliers resulted in an improvement over 10 dB, providing satisfactory outcomes.

4.7 Escalators

Escalator noise needs to be considered seriously during the design stages, with procurement contracts should specifying them to be as quiet as practical, but not unrealistic. Early specifications adopted in Australia for station escalators include requirements of less than 55 dB(A) within concourse areas, including at escalator landings. With more experience it has become generally accepted that a more realistic target is in the range of 65 dB(A). However, even this more relaxed objective has proved challenging on many projects, with levels on newly installed escalators more in the range of 67 – 68 dB(A) on the landings with one location up to 73 dB(A) on the landing. Fortunately, it seems that most escalators are louder when newly installed, compared to when they have been running for a period of time as most components will be lubricated during operation. This tends to bring noise levels down. For example, the location where initially 73 dB(A) was measured, reduced to approx. 66 dB(A) after a few months in (low duty) operation.

One area that is regularly overlooked is the provision of sound absorptive treatment to the underside of escalators or long escalator adits. This space with exposed escalators tends to be a reverberant space devoid of speakers and often used for advertising space. It can therefore easily be non-compliant for PA system objectives.

5 ACOUSTIC DESIGN INTEGRATION STRATEGY

On large-scale projects like underground stations, multiple (sub) contractors and parties are involved, affecting the noise and vibration outcomes. A good Acoustic Design Integration Strategy (ADIS) is essential to ensure that the cumulative noise and vibration impacts of the station design are achieved upon completion. The breath of scope of this strategy needs to be wide. It should cover noise and vibration budgets, design margins, interface documentation and contractual requirements. Additionally, it should set out the systems engineering approach taken for a logical compliance testing regime.

5.1 Interface documentation

Station contractors typically have to produce their own Acoustic Design Integration Plan (ADIP) in response to the ADIS. Unsurprisingly, this generally results in different approaches to the ADIS between stations with a risk

of confusion for contractors across between multiple stations. The principle of having a ADIP and ADIS should result in better overall project outcomes. However, the integration and any subsequent design changes and agreed interfaces need be closely monitored by an Acoustic Design Integration Manager (ADIM). Moreover, the ADIM needs to ensure the ADIP is a 'live' plan and documents any agreed design principles and interfaces. It is essential that the ADIP remains a flexible document that allows for design changes throughout the project. The experience has been that most contractors provide their ADIP at the start of the project as a design deliverable and it never is updated or referenced to again during the project. Contractors should be flexible to ensure the best overall project outcomes. Contractual agreements sometimes preclude this in practice, resulting in some contractors going to extraordinary lengths to meet arbitrary objectives that do not result in improved project outcomes.

A common issue is contract timeline misalignments, which are a principal source of problems. Contractors may not want to commit at a very early stage, but this may be required by others to progress their design. The interface deliverables don't always align, and the design may be forced to progress on arbitrary numbers. Whilst agreements and negotiations around noise budgets occurred in practice, these changes are often not recorded or amended in the contract documentation. With ever changing design targets, any critical design aspects should be documented and form part of the contractual interface documentation. It is therefore important that 'shared responsibility' contract requirements and strategies are documented in a clear manner during the design phases in the ADIS or ADIP. It is also imperative that all contractors bear equal responsibility in finding solutions to mitigate any non-compliances.

5.2 Risk Management

While 'Risk Management' is a key component of all large infrastructure projects, it has been observed that the management of acoustic performance varies significantly across projects. Some contractors better appreciate risks and include pre-emptive measures for high-risk areas, while others take a more contractual approach and look toward possible variations. Whilst further discussion on this topic in this paper is not warranted, it can be summarised as noting that assessing risks due to acoustics is a very important part of overall risk management. Overall observations are, that contractors that underestimated the acoustic challenges generally experienced adverse time and cost implications.

5.3 Design Margins and Risks

Using reasonable assumptions and setting realistic design margins is crucial in the early design process to avoid significant cost implications. In some cases, design margins were minimized to the point where retrofitting additional measures to meet compliance was not possible, potentially resulting in suboptimal products delivered via concessions. Conversely, over-conservatism was also observed, particularly where multiple or less experienced contractors were involved. For these scenarios the cumulative effect of numerous layers of conservatism has been observed particularly where multiple or less experienced contractors have been involved.

However, while the authors are not able to provide a definitive example of over-conservatism, they have observed compliance or regulatory anxiety on the part of contractors, leading them to recommend that margins should be revisited as a design matures so that they can be reduced in line with any corresponding reduction in project risk.

5.4 Systems Engineering Approach

Acoustic consultants typically work comfortably in niche environments with a well-defined scope of work that can be packaged and signed off. Large infrastructure projects lack the project familiarity found in smaller developments, necessitating a classical Systems Engineering approach. This approach, shown in Figure 3, focuses on the design and whole system by systematically decomposing and defining tasks, then integrating and recombining them.

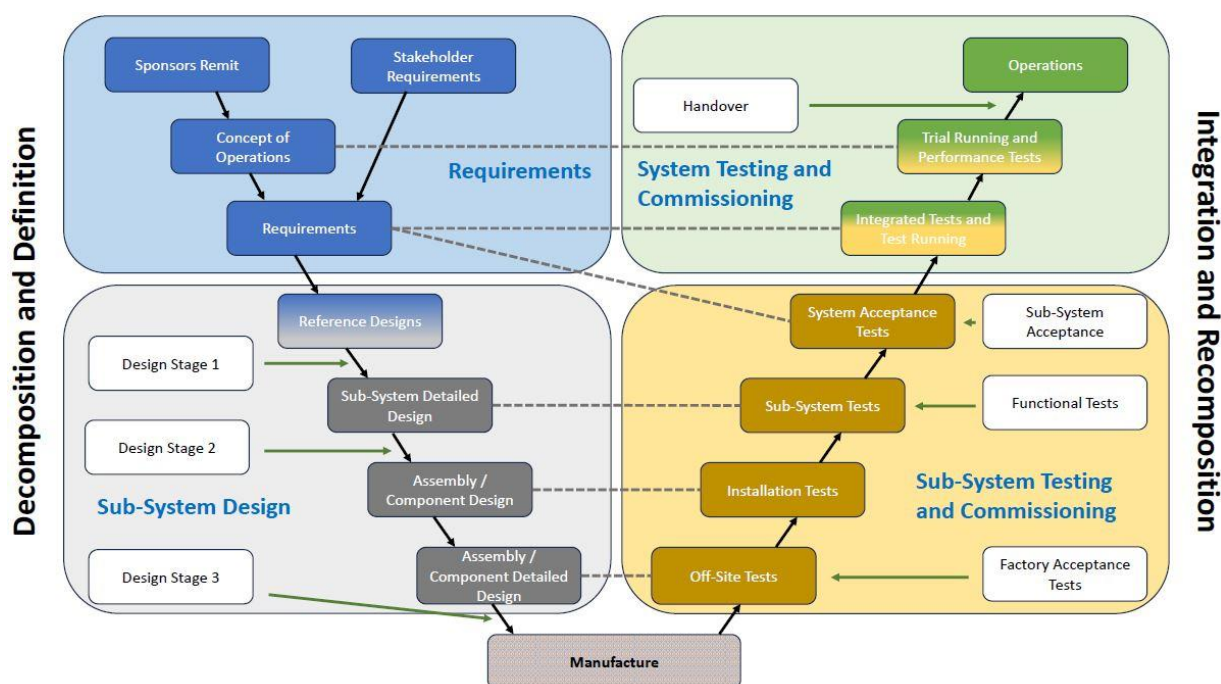


Figure 3 – Systems Engineering Approach

When the time of final commissioning comes, there is often little to no time to rectify any non-compliances. Therefore, acoustic risks should be minimized as much as possible before the commissioning process begins. While it is appreciated that this will create additional work for the parties involved, it does reduce the non-compliances. The authors estimate that at least 2/3 of the issues discovered during commissioning could have been identified and rectified earlier during the construction phase.

To apply an effective Systems Engineering approach, the overall station system is decomposed into a series of sub-systems, ensuring that requirements are cascaded and remain compliant with the top-level requirements at each stage. Each step needs to satisfy the preceding step. Whilst not just limited to acoustics, the overall objective of Systems Engineering is to have confidence that all the systems work before the final commissioning.

5.5 Commissioning

An observation on many, if not all (infrastructure) projects, is that contract requirements only include design targets and seldom clearly seem to outline the expectation for commissioning. It would therefore greatly assist if the key deliverable of, "How is the contractor expected to demonstrate compliance?" was better articulated. When the time comes for commissioning, meeting programmed timelines is the key driver. The contractual requirements are often re-defined and stripped back to basics. Any ambiguous wording in the contract will likely be revisited even though this may already have been clarified during the design phases. This often takes up valuable time, that may not be available. For example, simple requirements such as criteria are often not clearly defined as to whether they are intended as absolute minimum or average, nor are the expected number of test locations in large spaces. Commissioning, therefore, often comes down to subjective interpretations of the acoustic consultants. Early agreement to a detailed commissioning plan is essential to close out and define expectations.

Based on the authors' experience, commissioning of the sub-systems and whole system should focus on agreed design assumptions, rather than contract requirements that are often superseded by design modelling and installation modifications. Any expectations agreed during the design phases should be clear and unambiguously included as a requirement in the commissioning plan. As project teams move on and different people get involved, commissioning teams often refer back to the contract requirements. It is therefore imperative that both the contract requirements and change register are clear how compliance is to be assessed during commissioning.

A critical example is the interface between the architectural acoustic design and the PA system. If the interface documentation are not enforced, the way contracts are often established means that both the station contractor

and the PA contractor may technically claim they have met their contractual requirements without delivering what is ultimately required for the final system to comply. While this paper does not intend to examine specific non-compliances, it should be a lesson learnt that unambiguous and split responsibility contract clauses cause confusion and contractual discussions during commissioning.

Unfortunately, due to dependency on completion of multiple other systems, noise and vibration are often last in the contractor's program of commissioning. This can result in delays or redundant testing by other contractors or have implications for other contractors that are reliant on certain outcomes. Witnessing of the independent ADIM is therefore essential to the commissioning process to identify any potential issues early. To ensure an effective commissioning process in line with the Systems Engineering approach, the following order should be considered:

- Sound Insulation Ratings (e.g. doors, partitions, Platform Screen Doors, etc);
- Station Reverberation Times;
- Tunnel Ventilation Systems;
- Station Mechanical Services;
- Cumulative environmental noise and vibration emissions; and
- Public Address System Speech Intelligibility.

5.6 Lessons Learnt on the Acoustic Design Strategies

A summary of the projects reviewed in this paper concludes that despite best efforts, the intent of the ADIS was not well transferred into contractual commitments or practice. For example, in one case, a contractor was responsible for vibration isolation but not for meeting the overall structure-borne vibration criteria. In another case, an exhaust fan, which was well designed, became 10 dB louder at a receiver when a downstream contractor made design changes. The challenge therefore becomes how to design a contract mechanism that can adapt to these types of changes by moving the scope and costs between contractors. In this respect, the ADIS needs to have considerably more contractual weight than it is typically afforded so that integration moves from an optional invitational discussion between contractors to one that is mandatory and enforceable by the ADIM. The experience has been that where there are many parties, (particularly if there are separate station contracts on a new network) then consistency becomes increasingly fragmented with no system-wide approach to address what are essentially recurrent issues across multiple sites.

6 DISCUSSION

Underground rail projects are extremely large and complex, with issues, misalignments, and ambiguous interpretations bound to occur. The best way to manage these projects is to anticipate issues and introduce transparent management practices during the early design stages. The vast majority of acoustic challenges on the projects that have informed this paper were managed very well. This paper seeks only to identify some of the difficulties and pitfalls that can be expected with the construction of underground stations, and where possible to propose ways to improve the outcomes. This can only occur if considered and discussed early enough in the process, avoiding lengthy discussions and time wasted later in the project.

Most issues discussed in this paper arose during the commissioning phase. The key reason being that the issues were often not dealt with at the appropriate time. Non-compliances showed up as a surprise at the end of the project when time becomes the governing factor, and it is difficult to hold back the progress of the overall process of the project. This will generally result in sub-optimal solutions and outcomes. The key role of the ADIM should be to adopt a pro-active strategy, seek to minimise unexpected non-compliance outcomes, deal with potential conflicts and align expectations between contractors. They should operate in an impartial role to create a true 'best for project' approach. This will however require clear lines of authority and referenced in the contractual requirements.

7 CONCLUSIONS

Noise and vibration considerations are crucial at many levels in the delivery of major infrastructure such as underground railway stations. PA systems, architectural acoustics, environmental acoustics, ventilation, air conditioning and mechanical services, structure-borne noise and vibration, and psychoacoustics all require consideration and management. This paper broadly touches on the experience that the authors have had on various projects in Australia, mainly during the commissioning phase.

While the authors and the focus of this paper has been on identifying challenges and pitfalls, it needs to be recognised that overall, the acoustic outcomes on all projects considered have been overwhelmingly positive. Given the complexity of the projects, this is a credit to the design teams involved. There have been very limited adverse comments regarding noise and vibration aspects associated with the final projects at the time of writing, and many initial concerns have been proven to be unfounded. These types of projects demonstrate that Australia can deliver world class underground railway systems, but it needs significant effort and management to guide it.

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