Acoustics 2019
Sound Decisions: Moving forward with Acoustics

Acoustic Design for the Melbourne Metro Tunnel Project

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ABSTRACT
The Melbourne Metro Tunnel Project is currently under construction, and is one of Australia's largest public infrastructure projects with a project value of over $11 billion. It includes 5 major new underground railway stations, and a pair of 9-kilometre single-track tunnels running underneath Melbourne's inner-north-west suburbs, CBD, and inner south-east suburbs. The tunnel alignment is near to a range of sensitive residential and commercial receivers and particularly sensitive medical and research precincts in Parkville and at RMIT. The acoustics, noise and vibration engineering is being undertaken by a team of 10 engineers (Arcadis Arup WSP JV) and includes 5 key areas of work: design of tunnel acoustic treatments for control of in-carriage noise, vibroacoustic design to control ground-borne noise and vibration affecting sensitive receivers, station acoustic design, noise control for fixed station infrastructure, and construction noise and vibration management. This paper provides an overview of these key aspects of the acoustic design for the project, and provides an insight into the key design challenges and design approaches adopted by the acoustic engineering team, as well as the practical aspects of working on a large infrastructure project with multiple stakeholders and approval pathways.

1 INTRODUCTION
The Melbourne Metro Tunnel Project is one of Australia's largest public infrastructure projects, with a project value of over $11billion. The project is currently under construction by the Cross Yarra Partnership (CYP) Design & Construction Joint Venture, a joint venture between contractors John Holland, Lend Lease and Bouygues. The engineering for the project is being undertaken by Arcadis Arup WSP Joint Venture (AAW), with the acoustic, noise and vibration engineering being undertaken by a team of approximately 10 full-time engineers from Arup and WSP.

The 9 km railway alignment is shown in Figure 1 below, and runs from Kensington in the West to Yarraville in the East. It passes beneath residential and commercial areas in Melbourne's inner-north-east suburbs, CBD and inner south-east suburbs, as well as the particularly sensitive medical and research precincts in Parkville and at RMIT University.

The engineering work includes five key areas of work;

- vibroacoustic design to control ground-borne noise and vibration affecting sensitive receivers,
- design of tunnel acoustic treatments for control of in-carriage noise,
- station acoustic design,
- noise control for fixed station infrastructure, and
- construction noise and vibration management

Undertaking the acoustic design for such a large infrastructure project presents a range of challenges to the engineer, including; a large project and specialist engineering team, complex and onerous contractual and statutory/planning requirements (technical and administrative/project management), numerous stakeholder and project interfaces, and, of course, complex technical engineering and analysis requirements.

Tender design work began in mid-2016, and included the development of preliminary design solutions for costing, design submissions and draft management plans, and importantly, clarification of potentially ambiguous or onerous design requirements. The project was awarded to CYP in mid-2017.

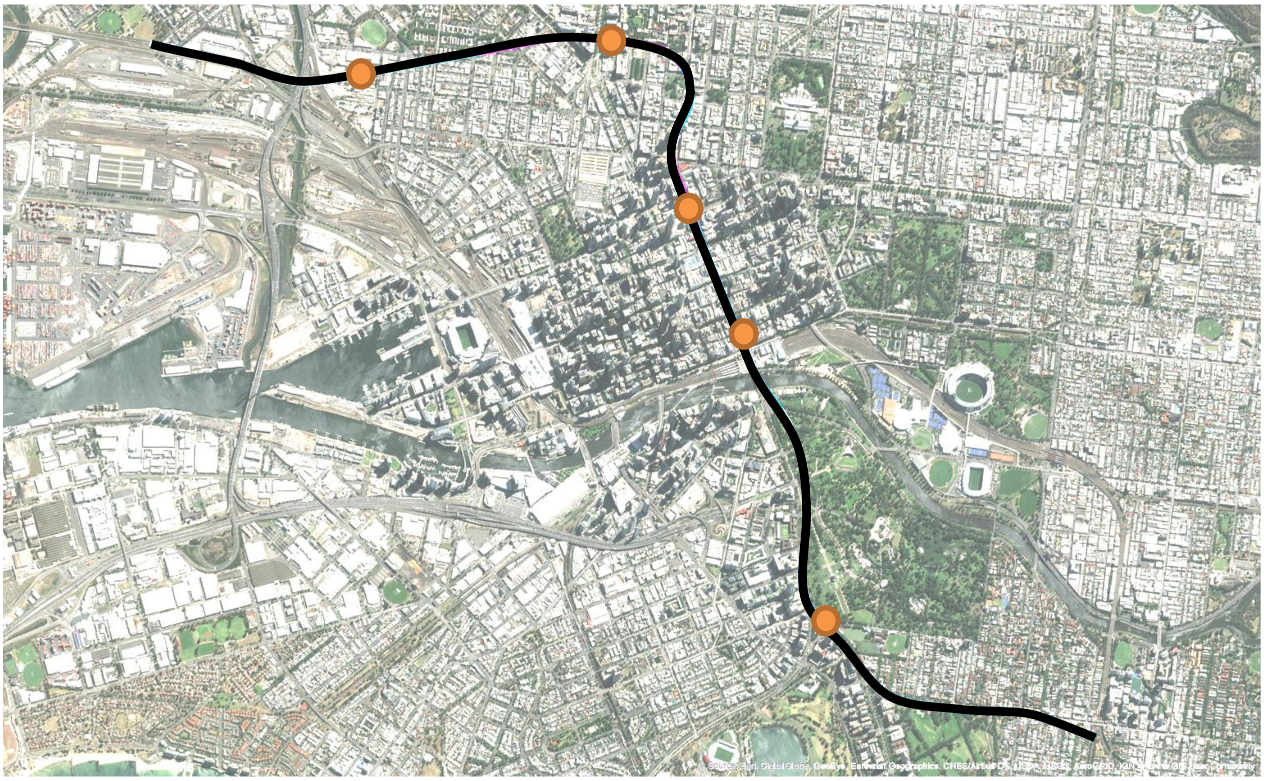


Figure 1: Melbourne Metro Tunnel Railway alignment.

2 ESTABLISHMENT OF PROJECT NOISE AND VIBRATION CRITERIA

The project was subject to a detailed environmental assessment and planning process (undertaken by Aurecon, Jacobs and Mott MacDonald JV (AJM) as the Technical Advisor (TA)), which helped to establish the noise and vibration criteria that would apply to the project, as well as develop the 'reference design' for the project which was provided to the tender teams.

The preliminary environmental assessment, which was undertaken as part of the reference design development, identified the key receivers which were likely to be impacted by the construction and operation of the railway tunnel, and developed preliminary design responses to mitigate noise and vibration impacts. The environmental design targets established for the project were subject to detailed scrutiny during a hearing by the Inquiry/Advisory Committee to the Victorian Minister for Planning undertaken in 2016. This process included a review of, and input to, the project requirements by a 'hot tub' of project and stakeholder consultants. The specific requirements are written as a series of 21 'Noise and Vibration' Environmental Performance Requirements (EPRs) in the Environmental Management Framework (EMF) endorsed by the Minister for Planning (Rail Projects Victoria, 2018).

The EPRs form the specific commitments to managing noise and vibration during the design, construction and operation for the project, and include, for example, guideline targets for construction noise and vibration, vibration impacts on structures, operational vibration affecting sensitive medical research and medical equipment (such as high performance microscopes) and groundborne noise and vibration from railway operations. The EPRs also include specific *management* requirements, where guideline noise and vibration targets are exceeded. These include adoption of the Residential Impact Management Guidelines (RIMG) to assist managing noise from *unavoidable* night-time works. The RIMG is aimed at providing 'direction on how to address residual impacts on residential amenity', particularly in regard to the need for architectural treatments and temporary relocation for residential receivers during unavoidable night-time works. The RIMG is based on previous guidance developed in the UK for CrossRail (Crossrail, 2007) and Transport for NSW's Construction Noise Strategy (TfNSW, 2012) and provides both sound level and time-based limits for night-time noise.

Due to the large number and complexity of the noise and vibration EPRs, and the somewhat inter-related nature of the various requirements, during the tender stage, each of the EPRs were converted into a flow-chart to enable the statutory obligations to be more easily understood. Figure 2 below provides an example of one of the management flowcharts for airborne noise during weekends, evenings and public holidays.

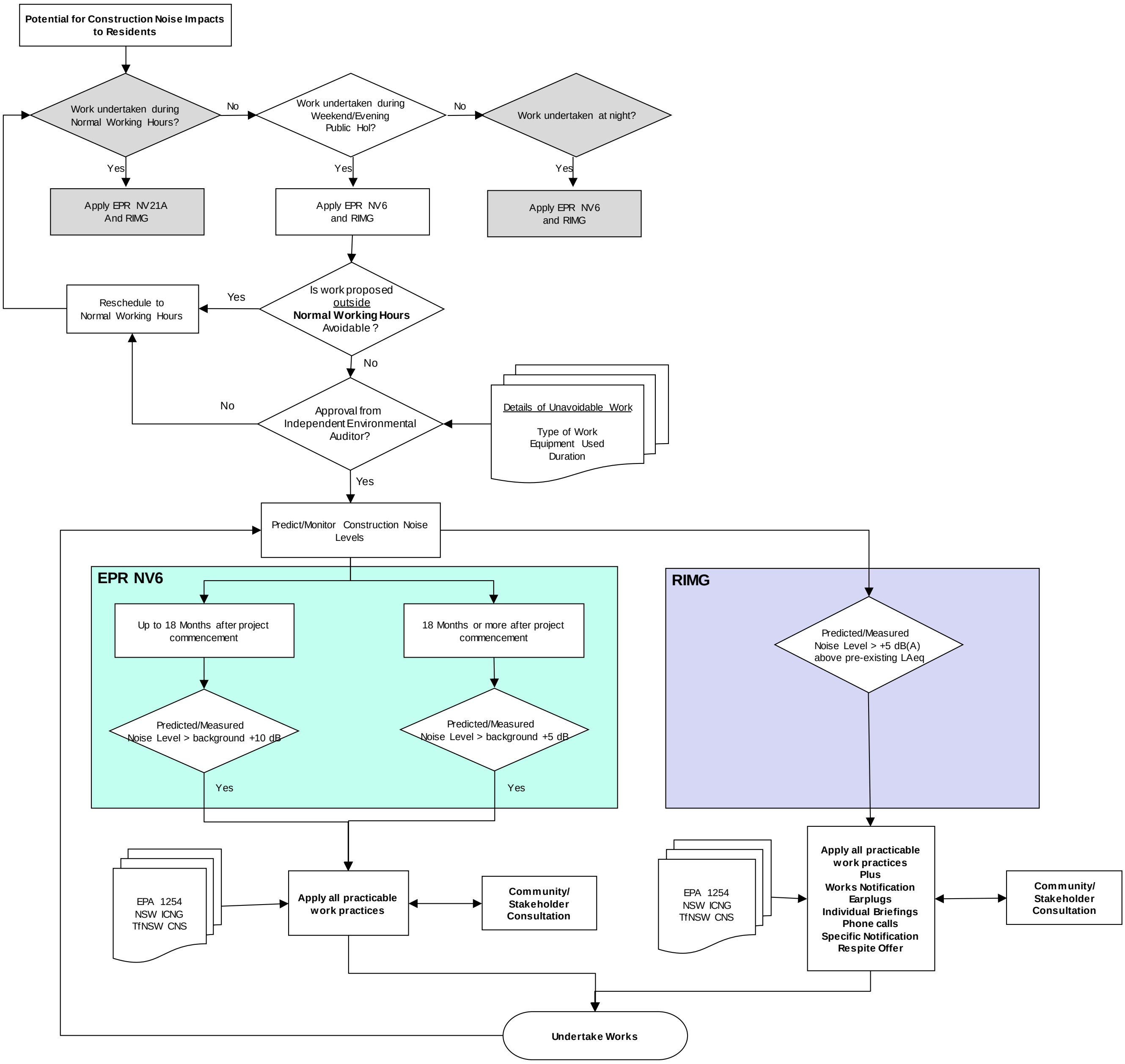


Figure 2: Example EPR flowchart, airborne noise during weekends, evenings and public holidays.

In addition to the statutory requirements for noise and vibration, which consider emissions from the project to external receivers, the contractual documents (the Project Scope and Technical Requirements, PS&TR) provide further requirements related to noise and vibration impacts for the project itself, including in-car noise within the tunnels, and station and facilities acoustic performance.

Compliance with the statutory requirements of the EPRs and contractual requirements of the PS&TR is governed by complex layers of review and acceptance by RPV's TA (AJM), the project Independent Verifier (IV) (AECOM), an Independent Environmental Auditor (IEA) (Broner Consulting) and the stakeholders' technical advisers (Resonate, Marshall Day Acoustics, Cogent etc.).

3 OPERATIONAL GROUNDBORNE NOISE AND VIBRATION

The mitigation design to control potential impacts from groundborne noise and vibration (GBN&V) from the railway affecting residential areas, and highly sensitive health and research precincts in Parkville and RMIT's city campus on Elizabeth Street is one of the key design aspects of the new railway. GBN&V is due to vibration generated from the rolling of the wheels over the track at the wheel-rail interface being transmitted via the track system into the surrounding tunnel and ground. This vibration propagates via the ground into nearby building structures, where the vibration can potentially be felt by occupants, and is also re-radiated by the structure as airborne noise. GBN&V impacts are primarily controlled by the selection of vibration isolating resilient track fixings, including resilient baseplates, booted sleepers or floated slab tracks (FST) which tune the train-track system resonance to lower frequencies, thereby reducing A-weighted sound levels.

Note that the highly-resilient track fixings which are necessary to control groundborne noise and vibration, also result in a lower track decay rate (that is, they allow additional rail vibration because the rail is not strongly coupled to the mass of the track support structure) which acts to increase airborne noise radiation by the rail within the tunnel, thus increasing the in-car noise levels.

The GBN&V design has been developed adopting the following methodology;

- Identification of sensitive receivers and update of sensitive receiver register
- Review of groundborne noise and vibration criteria at sensitive receivers; in particular for very sensitive laboratory uses at Parkville and RMIT
- Site vibration measurements at critical equipment, often including measurement of the performance of the equipment's own vibration isolation systems.
- Development of groundborne noise and vibration model for route alignment (CTRL/HS1 model, see below)
- Review of vibration mitigating trackform options, (including interface with track design)
- Estimation of trackform system insertion gain performance, (Interface with rolling stock/HCMT)
- Site vibration measurements to determine reference source vibration level, including track roughness measurements
- Estimation of ground propagation and coupling loss factors
- Model validation vibration measurements (MURL and at-grade railways)
- Prediction of groundborne noise and vibration levels
- Selection of appropriate trackform design options for groundborne noise and vibration control to surrounding receivers.

3.1 Review of Sensitive Receivers

The location and land use of potentially sensitive receivers has been compiled from project aerial photography, building outline and basement survey information from the project GIS, the register of sensitive equipment developed during the Environmental Impact Statement (EIS) and additional site observations and stakeholder consultation undertaken by the project team.

The location of the critical equipment identified in the register has been reviewed with the relevant stakeholders, the manufacturer's specifications confirmed, and where practicable, ambient vibration levels and the extent of integral vibration isolation of the equipment confirmed by site vibration surveys. This has been particularly challenging due not just to the large number of sensitive items, but also because of the disparate assessment criteria that are adopted by various equipment manufacturers.

3.2 GBN&V Prediction Methodology

Modelling of the transmission of GBN&V has been undertaken using the Channel Tunnel Rail Link/High Speed 1 (CTRL/HS1) prediction methodology developed in the UK in the 1990's. The CTRL/HS1 method is an empirical model based on over 3,000 individual railway vibration and noise measurements (Ashdown, 1995a, 1995b, 1996, Greer, 1993) and has been well validated for railway systems in the UK, Singapore and Australia. The calculation procedure is consistent with ISO 14837 (International Organisation for Standardisation, 2005) and takes account of all key parameters, including rolling stock design, train speed, track design, tunnel design, tunnel depth, ground conditions, receiving building foundations and receiving building type.

The calculation procedure generally consists of three stages; source terms, propagation and building response.

Speed correction has been undertaken using the CTRL/HS1 calculation procedure which accounts for differences in the rail fastening spacing, the spacing between axles on the train, vehicle mass and changes in dynamic forces generated by the combined wheel/rail surface roughness between the reference source term train/track system and the proposed system.

Groundborne noise levels (L_{pASmax}) near the centre of ground floor and basement rooms and equivalent Vibration Dose Values (eVDV) are calculated from RMS one-third octave band vertical velocities (evaluated for the period whilst a train is passing) outside the building of interest.

3.3 Source Levels

The reference source vibration level has been derived from measurements of at-grade vibration undertaken in metropolitan Melbourne for existing metropolitan rolling stock. The CTRL/HS1 method adopts an at-grade measurement at 10 m from the track, since this enables easier and more comprehensive measurements than using an in-tunnel vibration or force density measurements. The reference source terms are adjusted in the model to take account of the loading, unsprung mass and geometric differences between the reference source rolling stock (ie X'Trapolis) and the proposed High Capacity Metro Trains (HCMT) rolling stock. Figure 3 below shows the normalised source level measurements and reference source level adopted for the modelling.

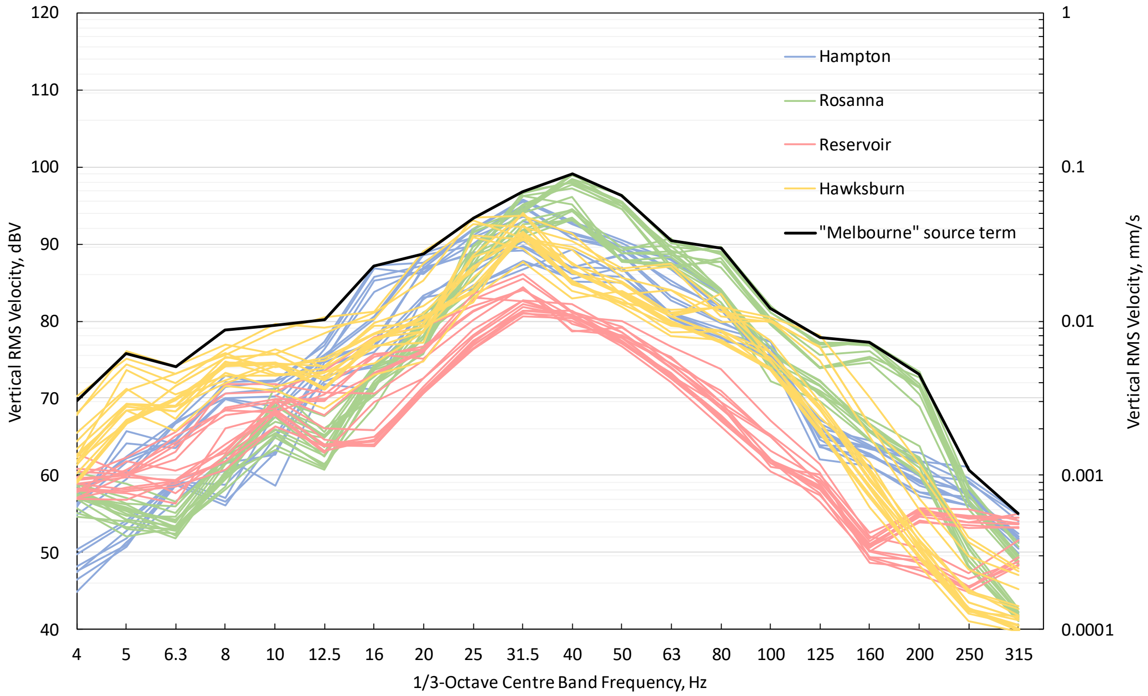


Figure 3: Normalised source level measurements ($dBL_{v,passby}$ re 10^{-9}m/s) at four at-grade locations and adopted reference source level.

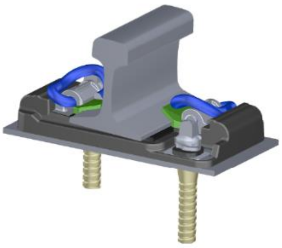
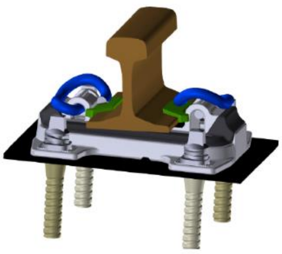
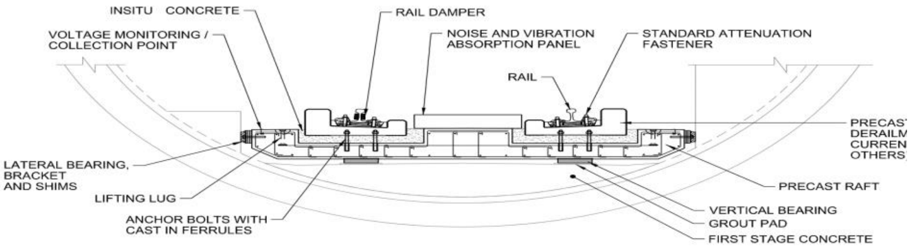
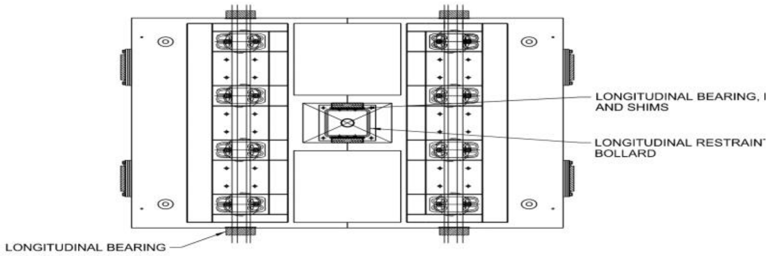
3.4 Trackform Options and Insertion Gain

Several trackform options were evaluated by the trackform and acoustic designers. The trackform selection cannot be undertaken in isolation because it needs to be closely coordinated with track and permanent way engineers to suit the preferred construction arrangements (eg pre-cast or cast-in-situ trackforms) which strongly influence construction cost. Furthermore, highly resilient rail fixing assemblies can result in other adverse consequences including potentially greater rail roll and the subsequent wheel/rail interface effects (excessive gauge widening, potential for corrugation seeding), increased wheel/rail radiated noise levels, as well as compatibility of, responsibility for and stakeholder acceptance of components from potentially mixed product suppliers.

Note that booted sleeper or bi-block trackforms (eg. Sateba High Attenuation Sleeper (HAS), Sonneville LVT) were considered, but were unable to be used due to the requirement to provide a derailment containment curb on the trackform.

The trackform selection therefore concentrated on three primary track types, standard and high performance resilient track fastening assemblies with deflections between 1.5–4.5 mm, and a very high performance floating track slab on elastomeric bearings or steel springs (see Table 1 below).

Table 1: Trackform options

Standard Performance eg. Delkor Alt-1 Pandrol Vipa Vossloh 300	 
High Performance eg. Delkor Egg Vossloh 336	 
Very High Performance Floating Slab Track (FST)	 

Trackform stiffness transitions have been designed to achieve delta deflection of 0.5 mm/second train travel, which generally results in transitions approximately 22 m long.

Trackform corrections have been undertaken by adjusting for the Insertion Gain (IG) of the various alternative trackforms which have been calculated using the IGITUR (Insertion gains in tracks of underground railways) model developed by the Institute of Sound and Vibration Research (Jones, 1996; Sheng et al 1999, Sheng et al 2004). The insertion gains are expressed in decibels with reference to a hypothetical 'highly stiff' reference trackform.

Initially the FST design was based on elastomeric bearings and a natural frequency around 10–11 Hz. While this preliminary trackform performed very well in regard to groundborne noise emissions, the amplification of very low-frequency vibration at the natural frequency was found to be problematic in achieving the necessary groundborne vibration levels at very sensitive equipment at research facilities in Parkville, which have particular sensitivity at frequencies around and just below 10 Hz. The analysis suggests that adopting a slightly higher FST natural frequency of around 14.5 Hz can actually result in better compliance with the low-frequency groundborne vibration targets, while increased groundborne noise levels remain within the design targets. The adopted track IGs are shown in Figure 4 below.

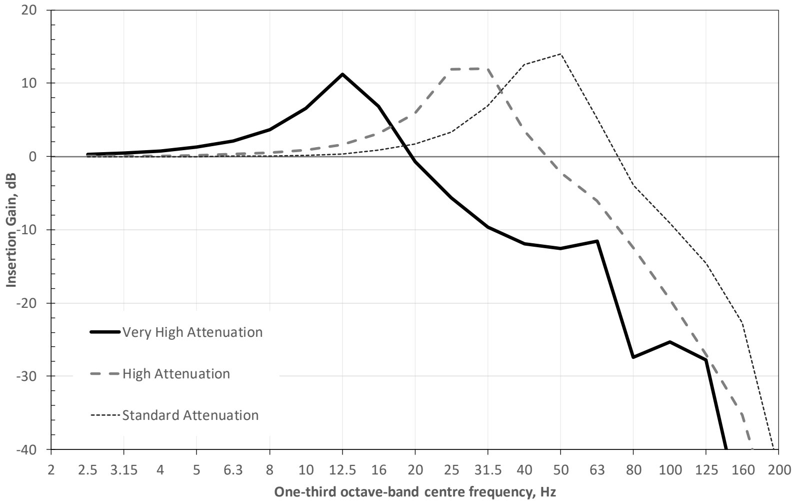


Figure 4: Calculated trackform Insertion Gains, dB re PACT.

3.5 CTRL/HS1 Model Validation

The CTRL/HS1 model has been reasonably well validated on a range of international projects. Nevertheless, for this project, additional validation has been undertaken at three sites above the recently completed ECRL in Sydney (documented by others) and two sites above the MURL in Melbourne where vibration measurements of rail pass-bys above tunnels and reference source vibration data are broadly available. Since it is usually impractical to directly measure the groundborne noise level, the measured groundborne vibration levels have been converted into pseudo-measured groundborne noise levels for comparison with the output from the groundborne noise and vibration model.

The results of this validation study, in terms of the pseudo-measured groundborne noise level, are shown in Figure 5, and are overlaid on top of validations undertaken previously on international rail systems. It should be noted that since the ECRL results have been based on measurements published for other projects, there is considerable uncertainty regarding the precise input parameters.

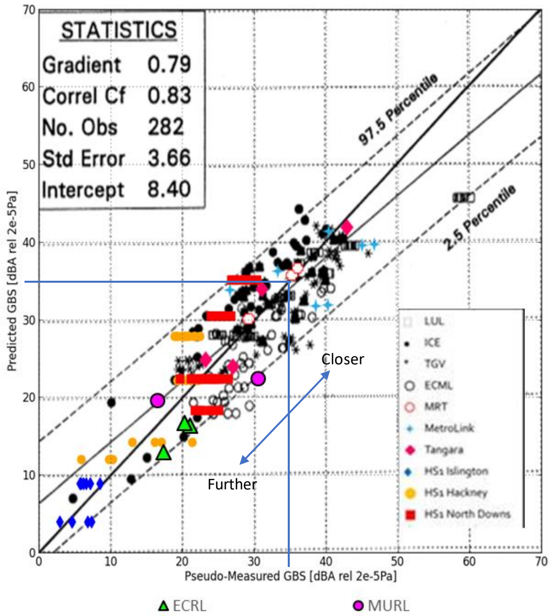


Figure 5: CTRL GBN&V model validation.

The validation results indicate reasonable agreement between the predicted and measured noise levels. Accordingly, a contingency of + 3 dB has been adopted in all of the groundborne noise and vibration predictions.

3.6 Track Roughness

The primary driver of the GBN&V level is the vibration emission from the wheel/rail interface, which is strongly influenced by the wheel and rail roughness. However, the level of wheel and rail roughness is beyond the ongoing control of CYP. The system rail roughness has been estimated based on in-situ rail roughness measurements taken at at-grade locations on the Melbourne metropolitan railway system and within the MURL. The roughness measurements were undertaken using a Rail Measurement Systems Corrugation Analysis Trolley (CAT) during an after-last-before-first (ALBF) night-time rail possession, generally during the night before undertaking the reference vibration measurements (see Figure 6).

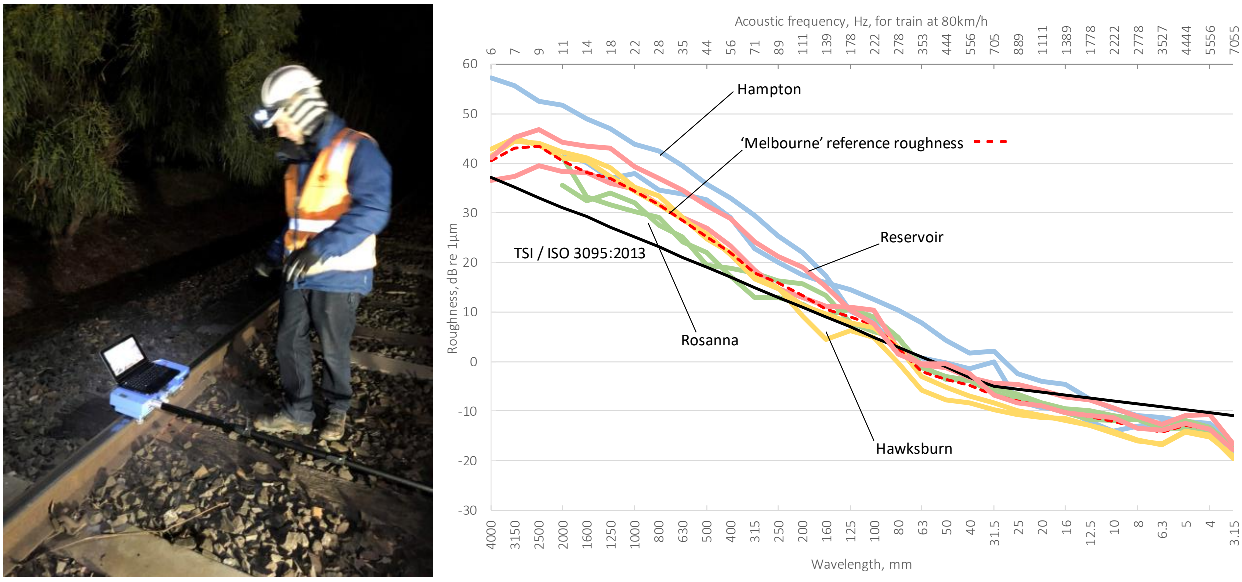


Figure 6: Melbourne network system rail roughnesses, re ISO 3095 (2013).

4 Track Design

The modelling results show that an unmitigated alignment adopting Standard Attenuation trackform would result in widespread exceedance of the groundborne noise and vibration targets for the project. Therefore, a mitigated trackform arrangement including high-performance vibration isolating track fixings and sections of FST has been adopted as a 'base design' to control groundborne noise and vibration emissions from the railway to achieve the noise and vibration performance requirements (see Figure 7).

The mitigated trackform design results in compliance with the PS&TR groundborne noise and vibration requirements and consists of approximately 4 km of very high attenuation FST, 10.5 km of high attenuation track fixings and 5 km of standard attenuation fixings.

The natural frequency of the FST trackform has been carefully tuned to ensure that residual structureborne vibration achieves the specific targets at sensitive equipment identified in the Parkville and RMIT University precincts. It is proposed to verify the actual sensitivity of the most critical equipment closest to the tunnel alignment because the manufacturer's specified vibration targets are extremely low (ie significantly below vibration criterion VC-E (ASHRAE, 2015)). This will be undertaken by using an electro-dynamic shaker to structurally excite the building near to the equipment, while directly measuring the impact on machine operation using a standard calibration test target. This will enable the actual vibration sensitivity of the equipment to be better understood.

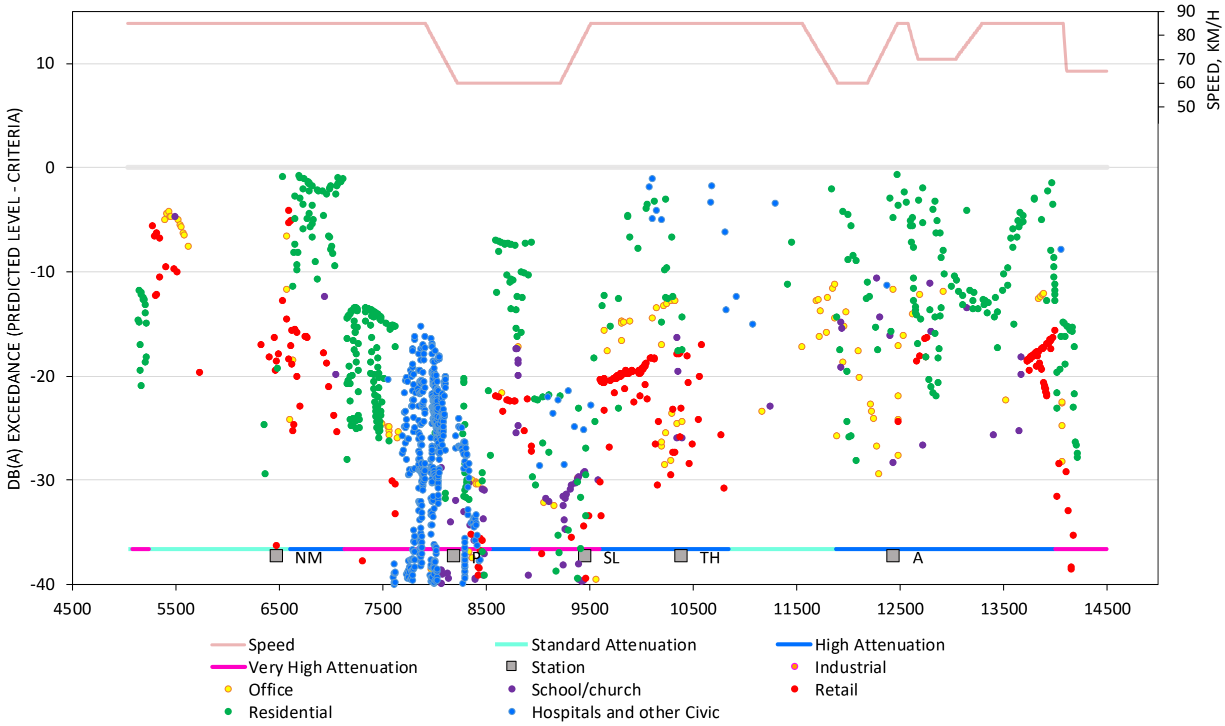


Figure 7: Alignment wide GBN predictions with optimised track design.

5 DESIGN OF TUNNEL ACOUSTIC TREATMENTS FOR CONTROL OF IN-CARRIAGE NOISE

The project includes a requirement to achieve an in-carriage noise level of 75 dBA within the carriage and 72 dBA in the drivers compartment when the train is travelling in the tunnel ($L_{Aeq,5sec}$, not to be exceeded for more than 20% of travel time). Since the train supplier (Evolution Rail) is required to provide a vehicle that has a maximum in-carriage noise level of 72 dBL_{AFmax} (60 km/hr, at-grade track), this implies an allowable increase in noise within the tunnel of around 4–6 dB.

This increase in noise within the tunnel comes from a combination of the increase in reverberant noise within the tunnel itself (called the 'tunnel gain'), as well as the increase in noise emission at the wheel rail interface due to a reduction in the track decay rate (TDR) which occurs as a consequence of the soft track fixings required to control GBN&V emissions from the railway.

Several early railway tunnels in Australia, the Melbourne Underground Rail Loop (MURL) and the Sydney Eastern Suburbs Line (ESL) have incorporated in-tunnel sound-absorbing elements, usually affixed to the side-walls of the rail tunnel, to reduce the reverberant build-up of sound within the tunnel, but there is little design information publicly available for those systems. More recently, the Epping Chatswood Rail Link (ECRL) opened with relatively high in-carriage noise levels despite the inclusion of sound-absorbing panels in the tunnel. Additional sound-absorbing panels and rail dampers were required to reduce overall in-car noise levels to acceptable levels (Coker & Anderson, 2010; Weber & Sburlati, 2010). It is noted that these types of treatments (especially track dampers) can introduce additional maintenance requirements in the tunnel environment.

Tunnel absorption within the four-foot (ie between the tracks) and on the tunnel side walls, as well as rail dampers have therefore been considered as options to mitigate in-carriage noise levels within the tunnel.

5.1 In-carriage noise modelling methodology

At the time of the design work, the new HCMT rail vehicles were not constructed, and could not be used to inform the design process. Therefore, the in-carriage noise modelling has been undertaken in two ways. The first is by undertaking reference measurements within existing X'Trapolis vehicles travelling within the existing MURL tunnel, and then adjusting the measurements to account for the differences between the X'Trapolis and HCMT's vehicle speed, likely track roughness, track emissions (TDR), rolling stock sound insulation properties and tunnel gain (between the MURL and Melbourne Metro Tunnel).

The second approach was to adopt the 'theoretical' at-grade in-carriage noise levels within the HCMT vehicle (supplied to the design team by Evolution Rail) and apply adjustments to account for differences between at-grade ballasted track and Melbourne Metro Tunnel's rail roughness, track emissions (TDR) and tunnel gain.

In each case, further penalties were applied to account for the potential for curving noise in accordance with the CNOSSUS-EU guidance (2012), ie +0 dB for radius (R) > 500 m, +5 dB for 300 m < R < 500 m and +8 dB for R < 300 m, depending on the design curve radius.

5.2 In-Carriage Source Level Measurements

In-carriage noise levels were measured in an existing X'Trapolis train travelling within the MURL in accordance with ISO 3381 (2005), as shown in Figure 8 below. The measurements were undertaken at eight locations across two carriages (motor/trailer), and in sitting (1,200 mm) and standing (1,600 mm) positions during multiple trips through the MURL. The measurements were conducted adjacent to carriage doors, mid-carriage, carriage windows, as well as in the rear driver's cab.

Figure 8: In carriage noise level measurement locations within X'Trapolis rolling stock.

Noise levels within the X'Trapolis in the MURL tunnel between Southern Cross and Flinders Street Stations, normalised to a vehicle speed of 60 km/hr and ISO 3095 (2013) reference roughness, are shown in Figure 9 below.

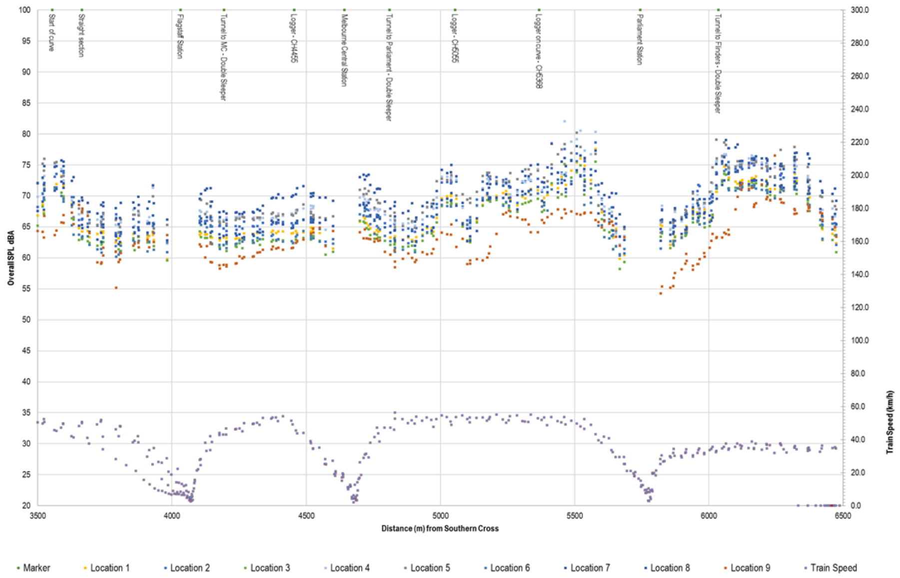


Figure 9: X'Trapolis in-carriage noise levels within MURL, $dBL_{Aeq,5sec}$ re 20 µPa, normalised to 60 km/hr and ISO 3095 reference roughness.

5.3 Tunnel Gain

The tunnel gain was estimated by constructing Odeon models of the MURL and Melbourne Metro Tunnels (including a rail vehicle, where necessary), and predicting the in-tunnel noise level approximately 1,200 mm above the carriage floor external to the rail vehicle based on a noise emission source at the wheel/rail contact area. The MURL model incorporated the three sound-absorbing pods installed on the tunnel wall (used to control reverberant noise), with the absorption characteristics validated against reverberation time (RT) measurements undertaken within the MURL. The Melbourne Metro Tunnel model included a range of scenarios ranging from no absorption, to absorption on both side walls and within the four-foot (ie between the tracks).

Figure 10 below shows the predicted tunnel gain, relative to the gain in the existing MURL tunnels, which include the absorptive pods.

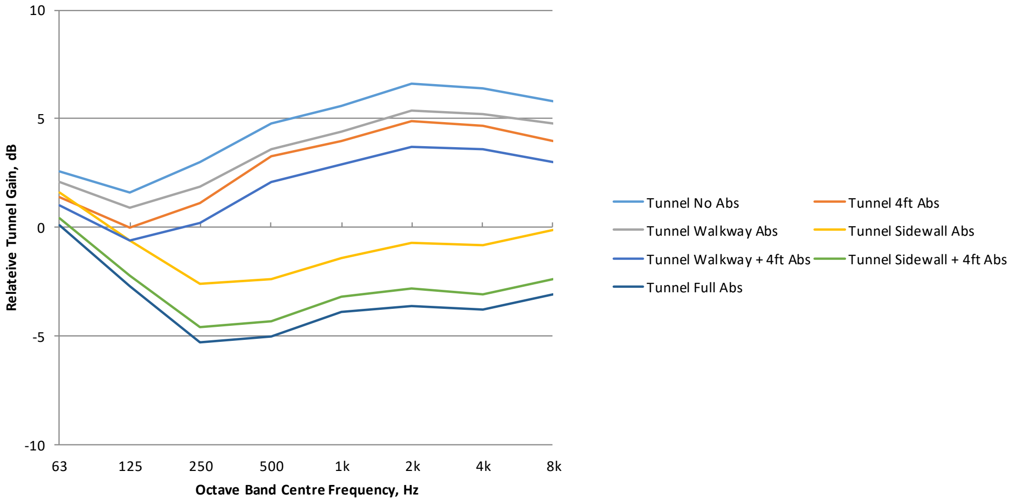


Figure 10: Tunnel gain, relative to MURL Tunnel performance.

5.4 Track Decay Rate (TDR)

The influence of the TDR of the selected track fixing assemblies on noise radiated at the wheel/rail interface is examined in more detail by Setton et. al (2019).

5.5 In-tunnel treatment requirements

The in-carriage noise level modelling indicates that both four-foot and sidewall absorptive panels are required to achieve the design target of 75 $dBL_{Aeq,5sec}$, for 80% of the trip time. However, noise levels could exceed 75 dBA occasionally if curving noise (eg. flanging) occurs at several of the tight-radius curves in the alignment.

The analysis shows that the level of compliance with the project requirements is extremely sensitive to small changes in the predicted in-carriage noise level. An uncertainty budget was prepared and showed that additional noise control would be required to meet the requirements at U90–U95 uncertainty levels. Therefore, an allowance for track dampers has also been recommended, pending confirmation of in-car noise levels during commissioning.

6 STATION ACOUSTIC DESIGN

The project has a range of specific acoustic requirements for the stations and tunnels, including background noise levels, partition sound insulation, reverberation times for occupied areas, and speech intelligibility requirements for the Public Address/Emergency Warning and Intercom System (PA/EWIS). Key requirements include an RT <2.0 sec on concourses, and <1.8 sec on station platforms to assist in providing appropriate PA/EWIS performance.

The acoustic design for each of the five stations has included;

- Review of the internal acoustic design and speech intelligibility targets
- Development of acoustic models of stations, including platforms, concourses, adits, links (Odeon)
- Design of architectural acoustic finishes in stations for reverberation control (Interface with Station Architecture and PA design (by Rail Systems Alliance (RSA))

- Calculation of external noise intrusion into stations, determination of sound insulation requirements as required.
- Speech privacy and noise intrusion between internal areas of stations (architectural interface for partition design).

Odeon models have been developed based on the architects' drawings for all of the key station areas to inform the design process and guide the type and location of acoustic finishes required in the entry, paid concourse, platform and adit areas. It is important to understand that it is not just the acoustic performance of materials that must be considered, but the finishes must be selected considering a complex range of engineering constraints including blast and fire performance, maintainability, durability and also the architectural intent for individual stations.

Furthermore, due to the large volume of some of the stations, achieving the RT requirements sometimes required significant amounts of absorptive material, which can be challenging to place in public environments, where the risk of vandalism or damage is relatively high. The acoustic design therefore required close and ongoing collaboration within the architectural team.

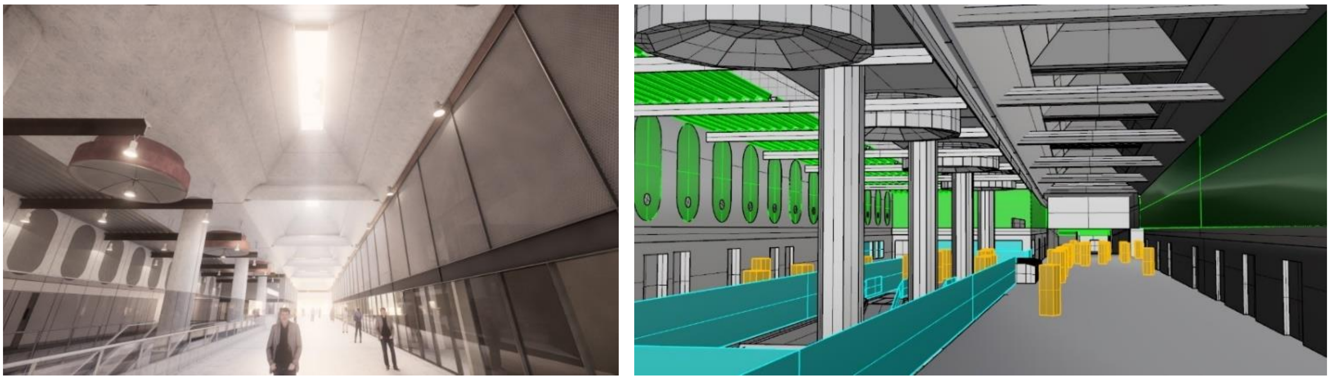


Figure 11: Architectural render and equivalent acoustic model constructed in Rhino for use in Odeon.

Figure 11 above provides an indication of the extent of detail applied to the acoustic model, compared with an architectural render of the same space.

6.1 PA/EWIS Systems

The PA and EWIS system design for the stations is subject to a challenging procurement interface, where CYP is responsible for designing and delivering the EWIS, including achieving a STIPA of 0.58, but the Rail Systems Alliance (RSA) are responsible for the design of the PA system within the station and tunnel environment. A combined PA/EWIS system has therefore been recommended to simplify both the system design and architectural integration.

7 NOISE CONTROL FOR FIXED STATION INFRASTRUCTURE

The Metro Tunnel project incorporates a wide range of fixed mechanical infrastructure, required to ventilate the tunnels and stations, to provide comfortable thermal conditions throughout stations, and to meet overall mechanical, electrical and hydraulic requirements. Equipment is distributed across all five stations, and two tunnel portal buildings.

The systems range from simple fan coil units (FCUs) serving individual back-of-house spaces to major heat-rejection plant and large tunnel ventilation fans (TVF) that are required to move substantial air volumes through the tunnels to manage congestion and emergency situations.

The acoustic design for fixed infrastructure has included:

- Establishment of background noise levels and confirmation of noise criteria established in previous phases
- Early involvement during concept design to provide input to mechanical design strategies, locations, space-proofing and system layouts

- Review of hundreds of individual mechanical systems, electrical substations, and hydraulic systems
- Detailed calculation of noise from each system, including duct-borne noise, duct-breakout, reverberant noise to station interiors, and environmental propagation
- Development of environmental noise propagation models using SoundPlan software for each site, including station environs, surrounding buildings, above-ground station structures, and all noise-emitting sources
- Recommending acoustic mitigation where required, including attenuators, isolation mounts, screening etc.
- Co-ordination with the architects, and with mechanical/structural/façade engineers for each station and portal site to integrate acoustic mitigation within the overall design.

The five new stations and two portal buildings are all located close to multiple existing noise-sensitive uses. The two CBD sites are also planned to incorporate over-station developments (OSD). The CBD locations are subject to particularly onerous design constraints, including unavoidable locations for major plant such as cooling towers and ventilation air inlets/outlets close to apartment buildings and hotels. The Parkville and RMIT sites are also close to a variety of hospital facilities, research laboratories, teaching spaces and residential areas, all requiring careful control of noise to maintain amenity. Major systems been designed in close coordination with the mechanical engineers (eg. to maintain sufficient access and airflow), the architects, structural engineers and façade engineers (eg. for detailing of acoustically attenuated façades) and other stakeholders to allow integration of adequate acoustic mitigation into the building design.

Indicative of the site constraints and strict limits on noise emission are ‘chiller pods’ being developed for the St. Kilda Rd site to enclose air-cooled chillers and meet noise emission targets to nearby residential buildings. Similarly, cooling towers and ancillary plant serving CBD stations are to be located in a low-rise structures, surrounded by high-rise commercial and residential buildings (Figure 12). In this location, in addition to preferencing water-cooled plant so that chillers can be located separately in a closed plantroom; a combination of attenuators, acoustic louvres and low-noise equipment options are being considered to manage noise from the cooling towers that are required at roof level.

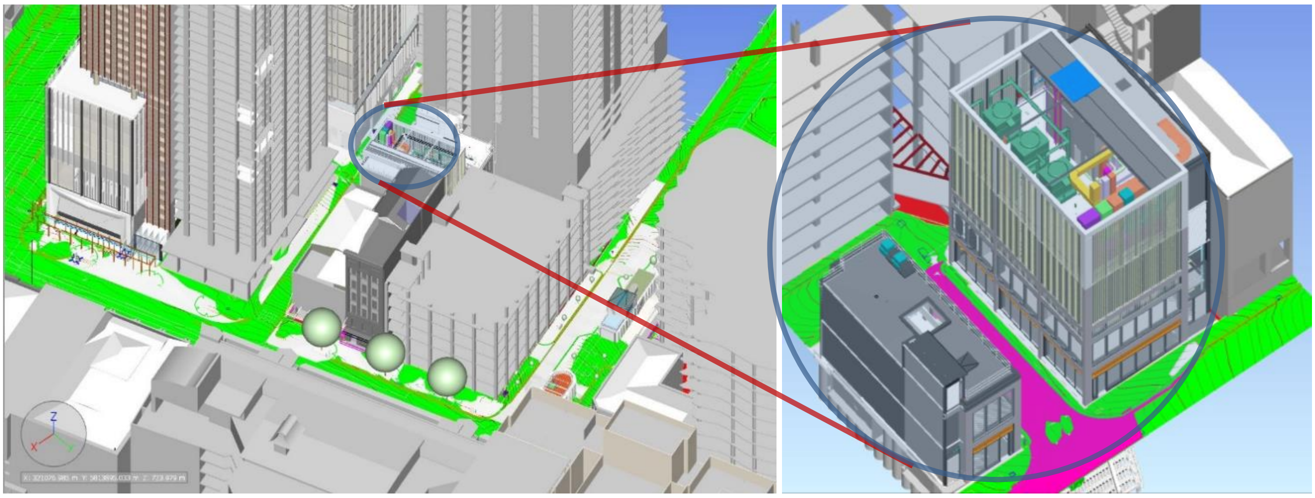


Figure 12: CBD site context with high-rise commercial and residential buildings (left) and detail of a low-rise structure containing essential heat-rejection plant (right).

8 CONSTRUCTION NOISE AND VIBRATION MANAGEMENT

AAW have also assisted CYP to manage noise and vibration during construction of the project in accordance with the project Environmental Management Framework (EMF), which requires comprehensive Construction Noise and Vibration Impact Assessments (CNVIA) to be undertaken for critical construction works and updated every 6 months to reflect the changing nature of the work-front and construction methodologies. John Heilig & Associates have undertaken the specialist construction groundborne vibration assessments for the excavation activities.

The key challenges have been the sheer size of the project, encompassing the five major station construction sites plus the two portal sites, all operating concurrently; the need for fast approval of construction works to enable commencement, and the changing and variable nature of construction works leading to last minute updates to noise modelling. Again, the Parkville and RMIT sites have proven critical due to the highly sensitive research equipment and bioresources which are sensitive to both construction noise and vibration. The specific nature of the EPRs in relation to impacts on bio-resources means that construction noise impacts have had to be predicted and measured in terms of species-specific frequency bandwidths, and adopting outdoor-to-indoor sound level differences to reflect potential internal noise levels. The team have also undertaken a range of site validation measurements for various construction activities, which have been used to validate the source levels and modelling assumptions for building sound insulation.

Due to the need to respond quickly to address project and construction site changes, the project has adopted Arup's SNAPshot online 'Site Noise Assessment Program' (https://snapshot.arup.digital) for modelling and assessment of construction noise. The software, shown in Figure 13 enables CYPs own environmental managers and site engineers to undertake basic site noise assessments, which enables quick turnaround and approval of simple construction scenarios, particularly for last-minute out-of-working-hours construction activities.

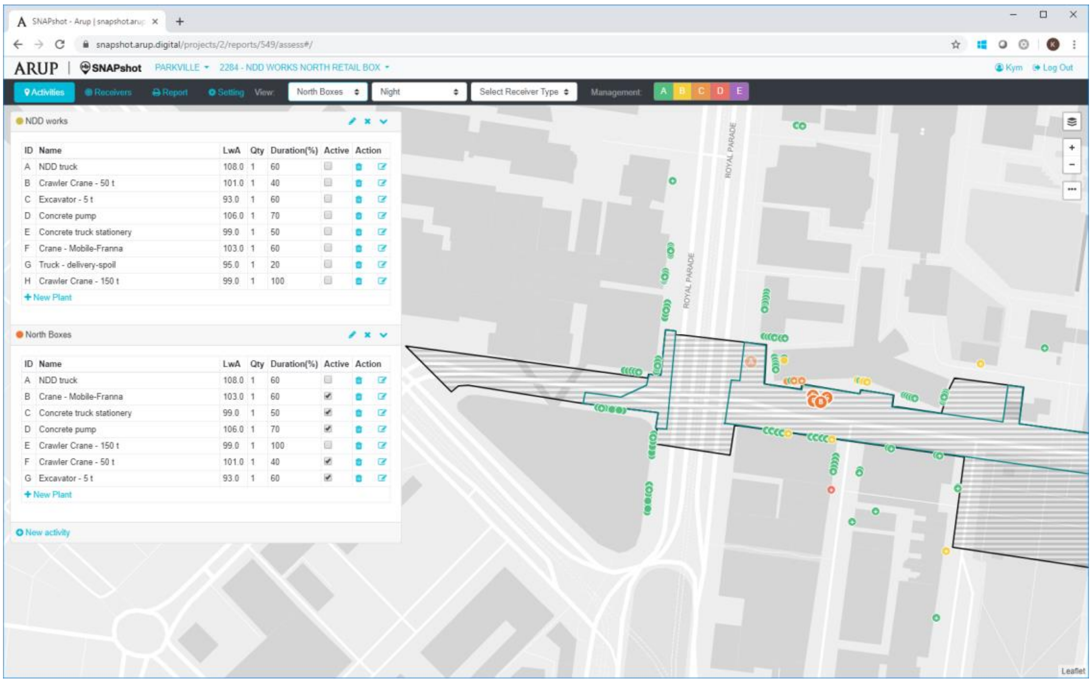


Figure 13: SNAPshot online construction noise management tool.

The project has also adopted the Metro Tunnel Environmental Monitor (MTEM), designed by WSP and Arup's digital teams, to assist with managing construction stage environmental impacts. The online system allows the active management of alerts and notifications from over 120 site monitors (noise, vibration, air quality etc.) across the 7 main construction sites. The system is used to record and manage not just noise and vibration, but a range of emissions from the construction sites in accordance with the project Environmental Management Plan (EMP).

The system allows the deployment of 'virtual sensors' to represent internal noise levels based on typical outside-to-inside noise reduction, and evaluation of impacts against a wide range of assessment criteria including dB(A), VDV, VC-x, and custom criteria such as weighted displacement levels and species specific hearing bandwidths for bioresources (see Figure 14)

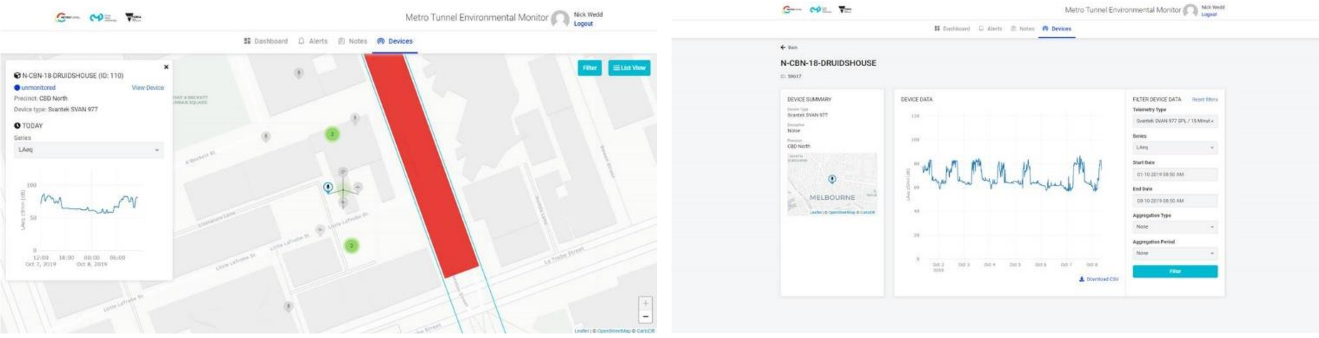


Figure 14: Melbourne Tunnel Environmental Monitor (MTEM) management system.

9 CONCLUSIONS

Very large infrastructure projects like the Melbourne Metro Tunnel project present a wide range of varied and interesting design challenges to the engineering team. Working closely with the construction contractors and their stakeholders has enabled the engineers to develop optimised acoustic design solutions for the stations and track alignment that will ensure that the construction and operation of the new underground railway will comply with the onerous environmental criteria established for noise and vibration during the project's approval process. The project has adopted several new digital tools to assist in managing construction noise and vibration.

ACKNOWLEDGEMENTS

The authors would like to thank the CYP Design & Construction Joint Venture and Rail Projects Victoria for permission to publish this work.

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