Commissioning the Public Address System for a New Road Tunnel

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ABSTRACT

New Zealand's longest road tunnel was opened to traffic in July 2017. At a length of 2.4km, Waterview Tunnel completes the Western Ring Route, an alternative north-south motorway link across Auckland. The tunnel includes multiple technical systems to manage public safety, including a deluge fire protection system, tunnel ventilation and jet fans, emergency lighting, emergency telephones, variable message signage, CCTV cameras, radio rebroadcast system, and a public address (PA) system. Initial tuning and commissioning measurements of the PA system raised concerns that the system may not meet design requirements for speech intelligibility in the main tunnel bores. A review of the installed PA was conducted, and options considered for improvement. This paper covers the review process, options considered, testing, and resultant performance of the PA system after implementation of upgrades and retuning. Some general recommendations for PA system design and commissioning are presented, to inform future implementation of systems in similarly challenging environments.

1 INTRODUCTION

Waterview tunnel is a twin-bore road tunnel with three vehicle lanes per bore. Each bore is designed for uni-directional traffic flow, is approximately 2.4 km long, and at the deepest point approxiately 45 m below the surface. The bores are connected at regular intervals by emergency cross passages (eighteen in total).

Public safety in the tunnel is managed through a combination of inherent design attributes, technical systems, live monitoring and emergency management protocols. Technical systems within the tunnel include a deluge fire protection system, tunnel ventilation and jet fans, emergency lighting, emergency telephones, variable message signage, CCTV cameras, radio rebroadcast system, and a public address (PA) system. These systems are connected to dedicated control rooms, enabling live-monitoring and operation.

The PA system supports emergency management protocols by providing automated notification alarms and voice-messaging. Live announcements can also be broadcast throughout tunnel from the control centres. In total, over 100 high-powered loudspeakers are used in the main bores, with over 50 additional loudspeakers providing coverage within cross-passages and auditory beacons outside each passage. WSP were asked to review the tunnel PA system after initial system tuning and commissioning measurements raised concerns that the system may not meet design requirements for speech intelligibility within the main tunnel bores.

The entity responsible for overall project delivery was the Well Connected Alliance, a partnership between the New Zealand Transport Authority (NZTA) and a group of infrastructure design and construction companies. WSP was a member of this project Alliance, with a role that included design of ventilation, operation and safety systems, as well as a design management role. The installation of public address systems was delivered by an international distributor as part of a design and construct package under the Alliance.

2 PERFORMANCE SPECIFICATION

Performance requirements for the PA system had been set out in a project specification, issued some years prior to actual installation and commissioning of the system. The specification referenced relevant New Zealand and Australian Standards for emergency sound systems (NZS4512, AS1670.4), and defined objective expectations for sound levels and intelligibility for the contractor to reference in their design and check during commissioning.

Amongst various requirements for installation and system interfacing, the performance specification included electroacoustic requirements for sound levels to be within a specified range, relative to ambient noise (Well-Connected Alliance, 2015):

> *The tunnel zones shall be designed to exceed the maximum expected background sound level of 90 dB(A) by at least 10 dB(A), but not exceed 105 dB(A) at any normally accessible point (which in this case is defined as 1.5 m above the carriageway).*

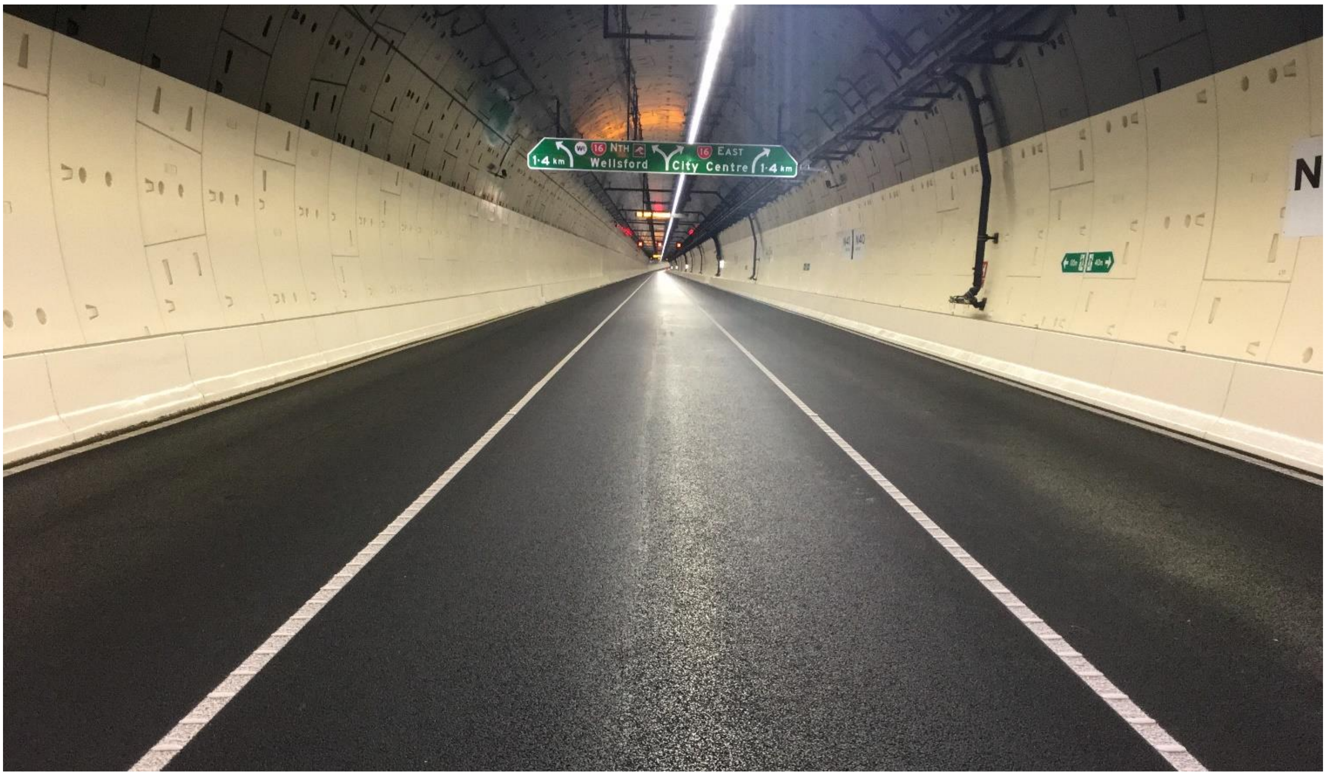
Further, minimum requirements for speech intelligibility under different ambient noise conditions were specified:

> *The speech transmission index (STI-PA) shall at all locations within the tunnel and the cross passages be ≥0.5 at ear height when the ambient noise is less than 85 dB(A) and ≥0.45 for ambient noise above 85 dB(A).*

As the PA system was included in fire and life safety systems, the project specification set the expectations for building consent within a regulatory context. Demonstrable conformity to the specification was expected, before a code compliance certificate could be requested or approved by the local authority.

3 DESIGN CONSTRAINTS

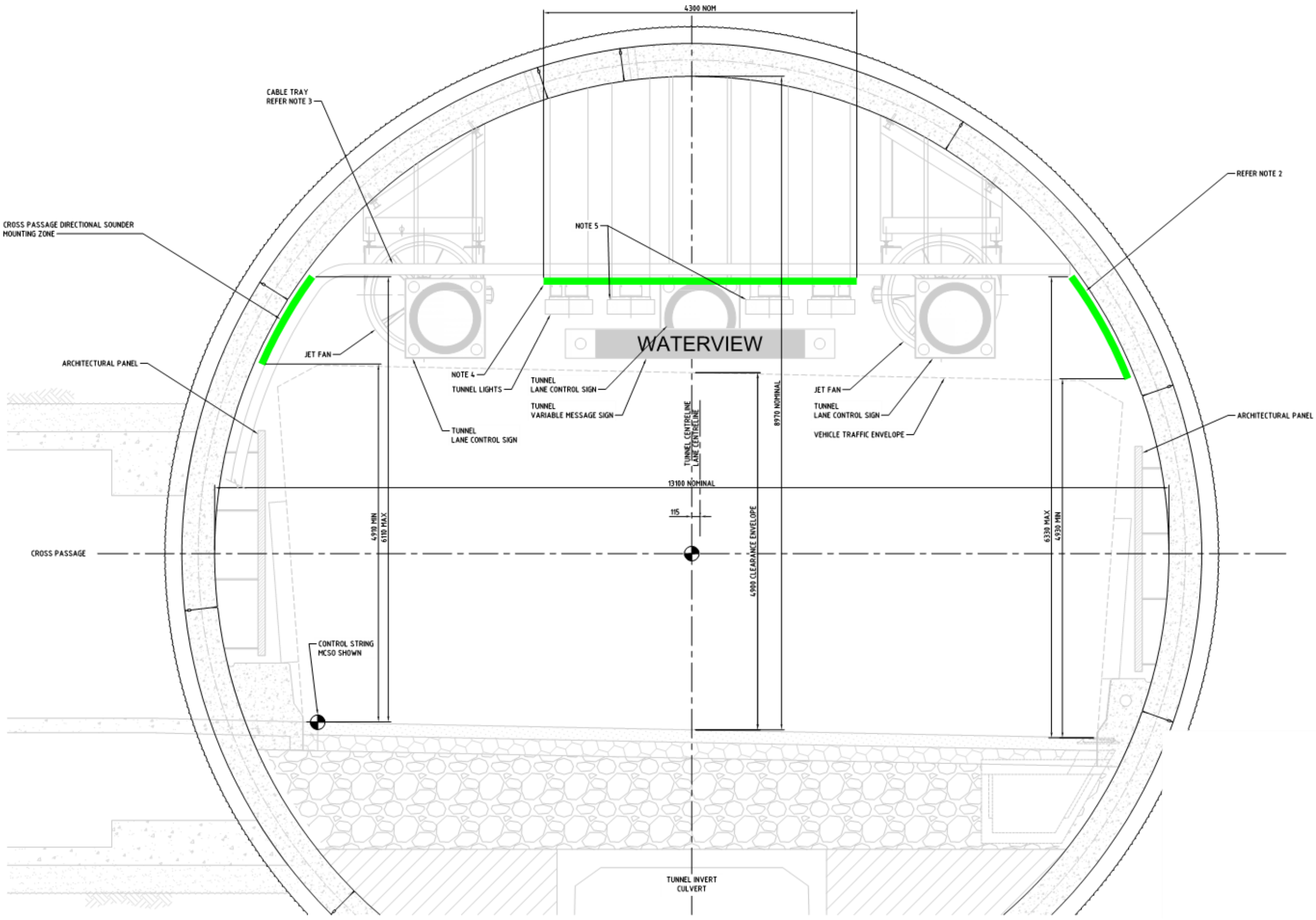
When WSP commenced review of the PA system, construction of the tunnel was largely complete (Figure 1). The ability to making substantial changes to existing tunnel design or infrastructure was limited. Key constraints on the PA system that were fixed included tunnel geometry, material finishes, and the ventilation system. Therefore conditions for reverberation and ambient noise levels within the tunnel were already well defined. The location and fixing of other services within the tunnel also limited potential scope for significant changes to loudspeaker layout or placement.



Source (Author, 2017)
Figure 1:Interior of Waterview Tunnel prior to opening

3.1 Tunnel Geometry

The main bores were each formed by a tunnel boring machine, creating a circular cross-section for the primary structure of interlocking concrete ring segments. A design drawing showing a typical section through one of the tunnel bores is shown in Figure 2, including primary tunnel bore structure, roadway, internal fixings, and general arrangement of technical systems. Technical services are generally located at high level, including suspended cable trays, light bars, loudspeaker mounts, and associated cabling.



Source (Well-Connected Alliance, 2013)

Figure 2: Typical tunnel bore section with mounting locations available for loudspeakers highlighted

3.2 Reverberation Time

The major surface finishes in the completed tunnel are tunnel linings (painted concrete) and road surface (asphalt). There are no materials provided specifically for acoustic absorption, and reverberation within the tunnel is significant. The reverberation time at mid-frequencies (RT_{MF}) is 6.4 s, increasing to over 8.4 s in the 400Hz one-third octave band as illustrated in Figure 3.

3.3 Ambient Noise

In the event of a fire in the tunnel, the ventilation system is used for smoke management. This system includes a bank of four tunnel ventilation fans within service buildings at each end of the tunnel and a network of 62 jet-fans located throughout the main tunnel bores. Jet fans within the tunnel are each capable of moving air at approximately 40 m^3/s, and are installed in pairs. All fans are reversible, allowing flexibility in airflow and smoke management. When run, the jet-fans are the dominant source of noise throughout the tunnel, even though all are fitted with 2D acoustic attenuators.

The average noise level throughout the tunnel with all jet fans operating was measured at 84 $dBL_{A,eq}$. However noise levels varied between a minimum of 71 $dBL_{A,eq}$ and maximum of 93 $dBL_{A,eq}$ due to variation in the longitudinal spacing between fans. Typical fan noise spectra in the tunnel is shown at Figure 4.

Further reduction in noise level from jet fans was investigated, and some discussions had with the fan supplier. However, the anticipated cost and timeframe to achieve only an incremental noise reduction to the installed fans was not viable while impovements to the PA system could still be be made.

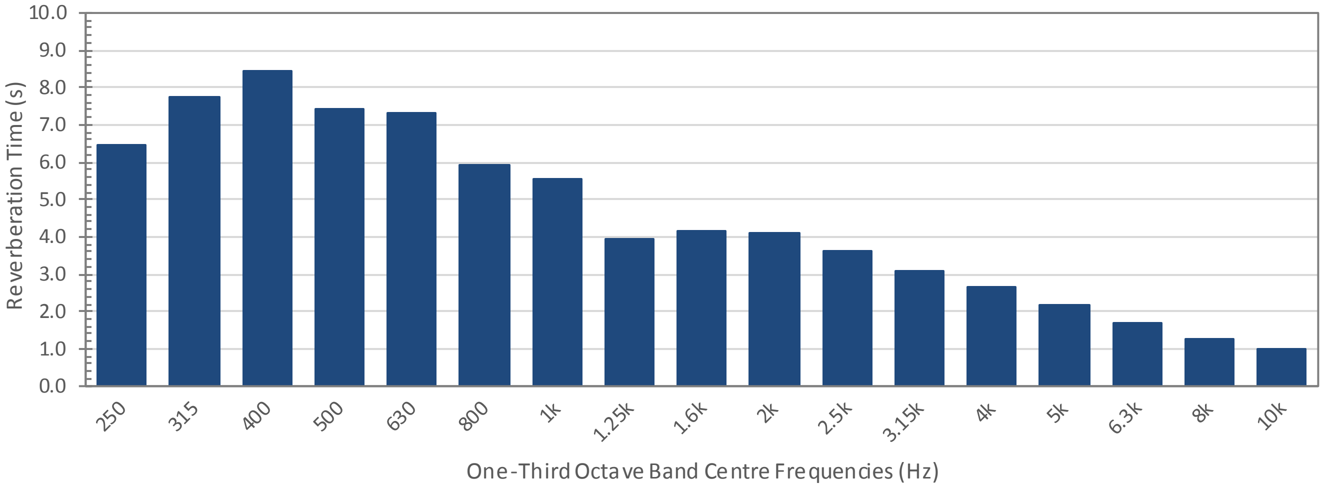


Figure 3: Averaged reverberation time spectra measured in the tunnel (250 Hz to 10 kHz)

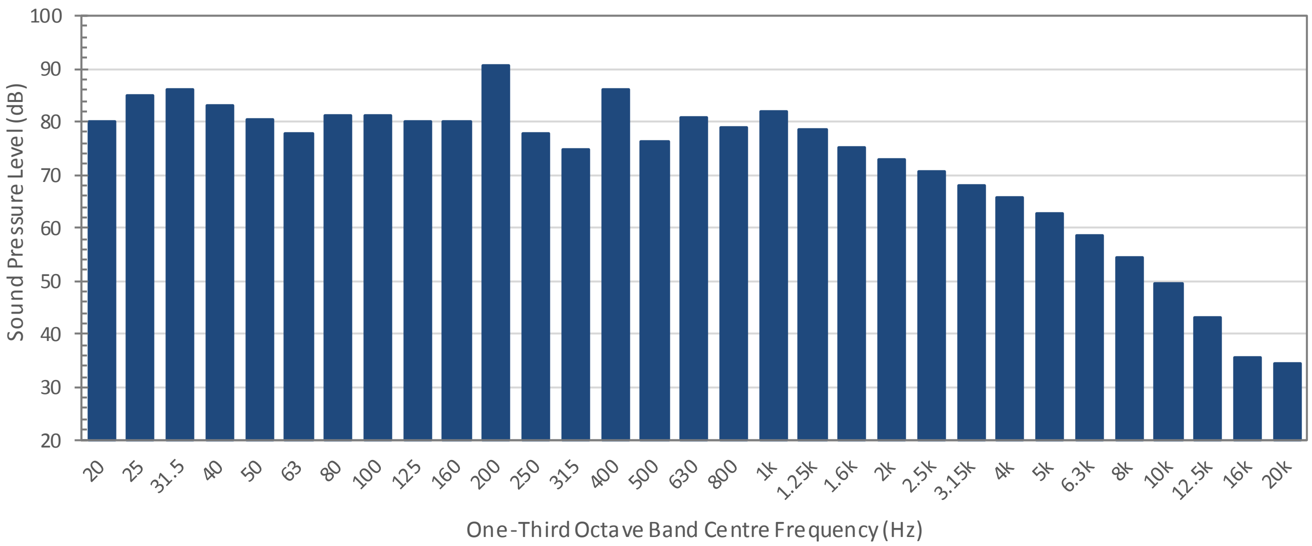


Figure 4: Typical ambient noise spectra measured in the tunnel (jet fans operating)

4 REVIEW OF THE INSTALLED SYSTEM

4.1 General Description of the System

The installed PA system consisted of high-powered, horn-loaded compression driver loudspeakers mounted to an overhead cable tray running the length of the tunnel. Loudspeakers were spaced regularly at 50 m intervals, and each connected to a dedicated amplifier channel, with time delays set for time-alignment of the system. Amplifiers and control units were rack-mounted installed in communications rooms located in the ventilation buildings and off a central cross passage.

Active noise compensation is not provided, so there are no microphones included in the system. However, control logic does allow for preset gains to be triggered with tunnel control systems, so a reduced gain setting is available for announcements when jet fans are not triggered.

4.2 Inspection Checks

During the initial review, a wide range of checks and inspections were completed. Due to limited periods available for access in the tunnel, many of these were completed with extensive assistance from site crews and local sub-consultants.

Preliminary system checks included:

- Inspection of site installation records.
- Review of submitted design reports and system modelling.
- Visual inspection of loudspeaker mountings, connections and transformer tappings.
- Measurement of loudspeaker line impedances.
- Measurement of voltages at amplifier outputs, and at loudspeaker connections.
- Measurement of individual and group loudspeaker responses.
- Measurement of time-alignment between loudspeakers.
- Inspection of audio message files stored on the system.
- Inspection of configuration files used to store system parameters and operational logic.

4.3 The Major Symptom

Although there were many aspects of the design and installation that required inspection or testing to determine potential improvements, the major concern from the outset was an apparent lack of signal gain required to overcome ambient noise levels. This is clearly illustrated in Figure 5 with a comparison of fan noise and loudspeaker output for a STI-PA test signal produced at maximum system gain.

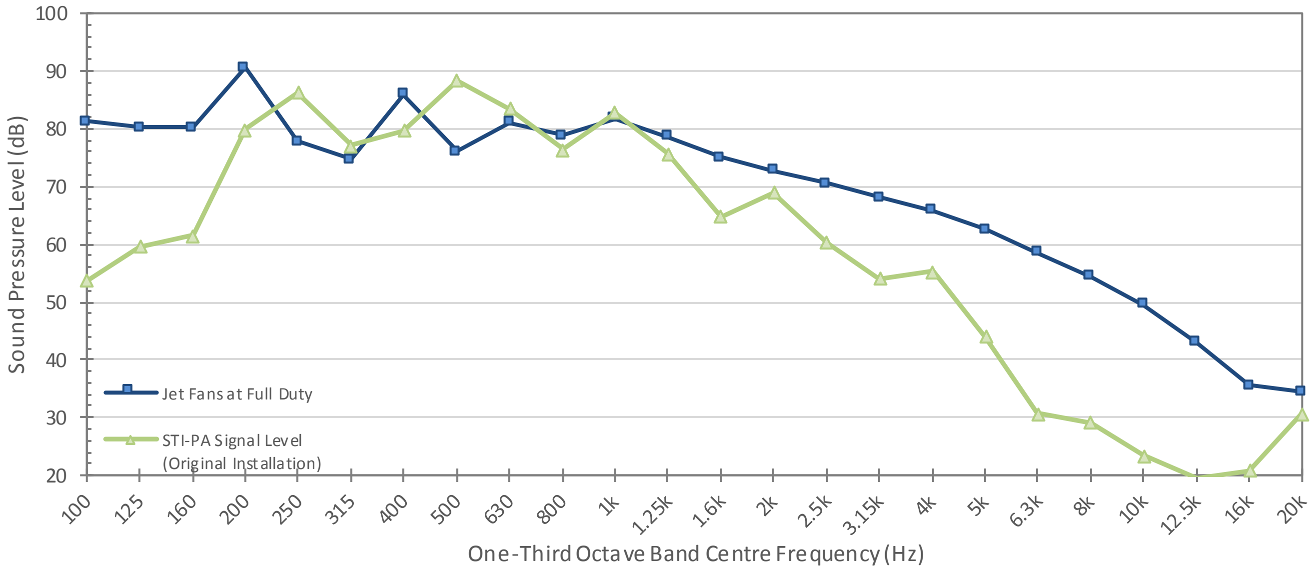


Figure 5: Comparison of ambient noise and loudspeaker output with standard STI-PA signal

4.4 Loudspeaker Performance

Following initial in-situ measurements, a sample of loudspeakers were removed from the tunnel and tested under controlled conditions in an anechoic chamber at The University of Auckland (Figure 6). This testing was conducted to investigate the possibility of faulty units, and to confirm actual loudspeaker performance in relation to published product data sheets.The testing also allowed investigation of loudspeaker performance to quantify distortion levels at higher gain settings, providing additional that the manufacturer did not have data on. These tests were witnessed by a technical representative from the loudspeaker manufacturer, as they shared an active interest in any potential faults or manufacturing defects affecting their product.

Source (Author, 2017)
Figure 6: Loudspeaker testing in the anechoic chamber at The University of Auckland

4.4.1 Sensitivity and Frequency Response

Measurements were made using voice recordings, pink noise, and swept-sine signals to assess loudspeaker performance for loads, and to relate performance to use in practice, as well as to technical datasheets. The on-axis reponse for a typical unit tested is shown in Figure 7, as measured with swept-sine signal inputs.

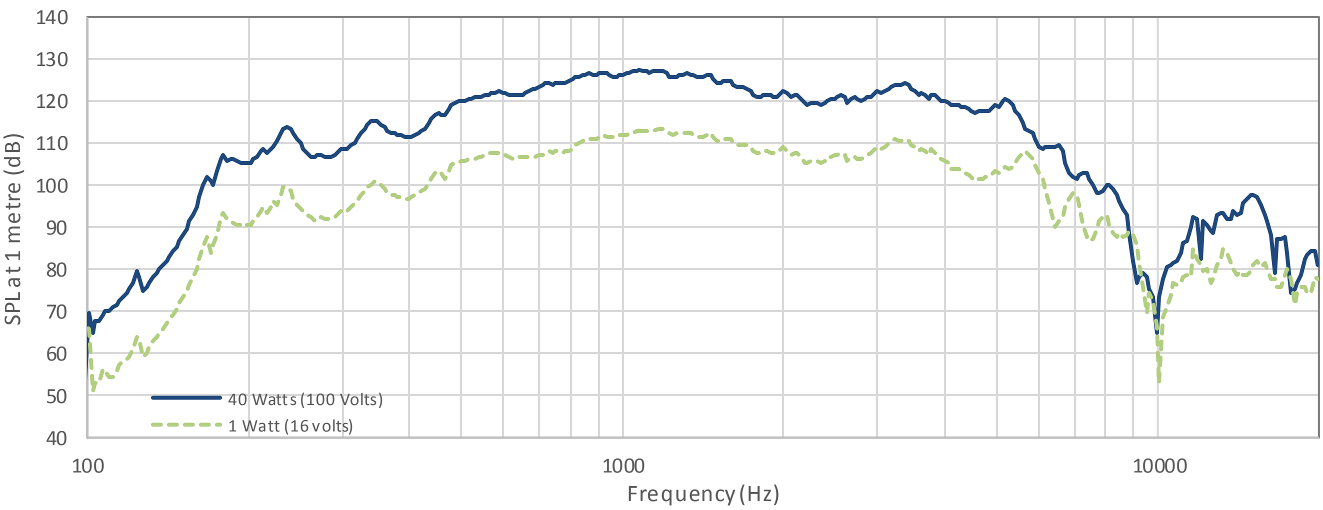


Figure 7: Loudspeaker on-axis response at 1 W / 1 m reference and at rated power

The useful frequency reponse is approximately 430 Hz to 6 kHz (+3/-10 dB). Whilst a broader frequency response would allow improved speech reproduction, the measured responses were consistent between units, and also consistent with the manufacturer’s published data. Therefore, the question of systemic driver failure or production faults could be discounted.

4.4.2 Distortion

One aspect that the manufacturer could not provide technical data on was the level of distortion expected in operation. In-situ tests and listening had indicated audible distortion, whilst the system was still below the sound pressure levels required to achieve intelligility targets. During the anechoic testing, distortion levels were measured for varying input level, with acceptable levels of distortion observed at lower gain (around 3% THD for 1 W). At rated power, distortion levels were more significant at approximately 15% THD, and up to 25% in the region of 3 – 4 kHz. These response and distortion values are plotted in Figure 8.

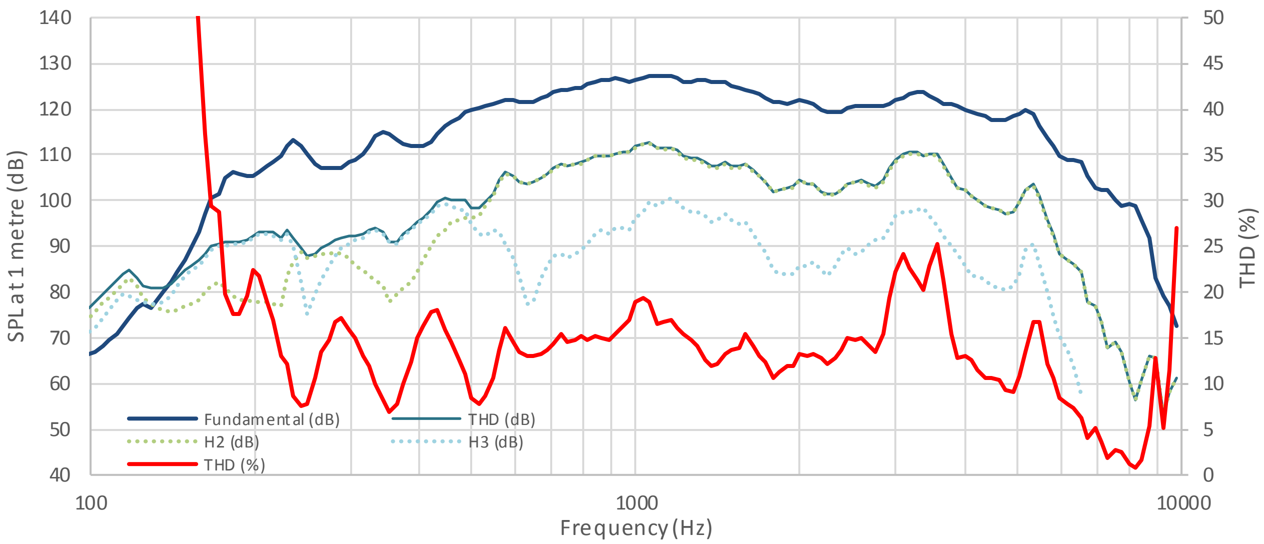


Figure 8: Loudspeaker response and harmonic distortion at rated power

4.4.3 Directivity

Whilst directivity is an important consideration for selection of tunnel loudspeakers, the extensive data capture required for directivity measurements precluded this within the limited time frame available for testing. Directivity was however investigated via acoustic modelling for loudspeaker placement/aiming with a number of potential loudspeaker models and using manufacturers' published directivity data.

5 DESIGN MODELLING

In addition to inspection and testing of the installed system, a series of computer-based electroacoustic models were reviewed. These had been submitted by a sub-contractor to the system supplier during the design and tender process, to confirm the proposed design would meet all design criteria. However closer review revealed a series of misunderstandings and some assumptions used for modelling had resulted in reporting of modelling results that failed to identify design aspects that were in fact unlikely to achieve the required performance.

Some of the shortcomings in electroacoustic modelling were relatively simple oversights, which in many applicatiions may not have had any significant impact on actual performance. However, as the loudspeakers in this system were required to operate close to (or beyond) their practical distortion limits to compete with high ambient noise levels, any assumptions around input signal or available gain did have significant impacts on the performance assessment.

Key details that were either omitted or misinterpreted in early modelling work, resulting in an highly constrained system design included:

- Spectrum corrections: differentiating between broadband signals and speech spectra.
- Crest factor: compare a standard STI-PA signal (14.5 dB) with a sine-tone (3 dB).
- Power handling: Matching modelled gain to the practical (broadband) limits of a selected loudspeaker.
- Headroom: Including a suitable level of headroom to allow system adjustment and tuning.
- Model extents: Including sufficient geometry to adequately represent loudspeaker spacing.

Subsequent modelling provided good agreement with in-situ measurements, once appropriate inputs for tunnel geometry and surface properties had been made, and essential gain corrections for loudspeaker power handling, input spectra and crest factor had been applied.

6 OPTIONS FOR SYSTEM UPGRADE

A broad range of options were considered during the review process including:

- Replacement of all loudspeakers (with an alternative loudspeaker model), whilst maintaining amplifiers, cabling and spacing as far as practicable.
- Duplication of loudspeakers with a second unit adjacent to each existing loudspeaker (e.g. daisy-chained off existing loudspeaker cabling).
- Supplementation of existing system with intermediate loudspeakers placed between existing units along the length of the tunnel (also requiring additional amplifier channels).
- Alteration of loudspeaker tilt angles, alone or in combination with options for additional loudspeakers.
- Step-up transformers to boost output voltage for maximum amplifier gain.
- Replacement of loudspeaker drivers with an alternative model to fit existing horns.

6.1 Preferred Upgrade Option

Ultimately, the preferred option was to replace drivers with an alternative model that could be simply screwed onto the existing horns. This option provided a new driver with improved frequency response, sensitivity and power handling, without needing to alter loudspeaker mountings, cabling, amplifers or control systems. The physical installation could be completed within a limited timeframe, for relatively modest capital cost, and with minimal alterations to installed infrastructure.

After extrapolation of in-situ prototype testing and computer based modelling, this option was predicted to be capable of achieving averaged STI values of 0.43 to 0.45 throughout the tunnel. It was recognised that some risk remained of resulting performance below the original specification, and presented substantially lower risk in terms of cost, delays and additional tunnel closures that would have been necessary to pursue the other upgrade options considered.

7 UPGRADED SYSTEM PERFORMANCE

Installation of the new drivers to existing loudspeakers was completed during scheduled tunnel closures beginning in late 2017, and completed in early 2018. Extensive re-tuning of the system followed, with final tuning and validation measurements completed by May 2018. The resulting PA system performance throughout each tunnel bore is summarised in Table 1:

Table 1: Resultant PA performance under high ambient noise conditions

Measured Parameter	North-bound	South-bound
Average ambient sound pressure level, *SPL* with all jet fans operating	84.5 dBA	84.0 dBA
Average system sound pressure level, *SPL* for STI-PA test signal at maximum system gain	96.2 dBA (σ = 0.9 dB)	98.6 dBA (σ = 0.8 dB)
Average speech transmission index, *STI* with all jet fans operating	STI 0.44 (σ = 0.05)	STI 0.45 (σ = 0.06)
Change in average *SPL* from original benchmarking	+5.2 dB	+7.6 dB
Change in average *STI* from original benchmarking	+0.07	+0.06

These results exceeded expectations for upgrad of the existing system without substantial changes to the basic system infrastructure. The results met the original performance specification in one bore, deviated marginally in the other bore, and overall exceeded a minimum acceptance criteria that had been agreed with NZTA prior to proceeding with the upgrade. The improved performance was sufficient for acceptance as part of the integrated fire and life-safety strategy for the tunnel, and allowed final code compliance certificates to be applied for, and issued by the local authority.

8 GENERAL RECOMMENDATIONS FOR SIMILAR PROJECTS

Based on the experiences described, there are many details during design, modelling and installation that can prevent a PA system from achieving the required level of performance. This is especially so for systems located in challenging acoustic environments such as road tunnels. The following sections present some broad recommendations for approaching the design and implementation of similar PA systems, to avoid the challenges encountered during commissioning of the Waterview Tunnel PA system.

8.1 Establishing Electroacoustic Criteria

During the very early stages of a project, establishing appropriate criteria and unambiguous specifications is essential to defining the performance that a system should achieve. Where local standards may only provide general guidelines, referencing international guidelines can be helpful. For instance, specific consideration of electroacoustics, tunnel environments and setting STI criteria with statistical ranges are well established in the Netherlands (TNO, 2010). Other useful design references include model specifications, such those published by the German Federal Highway Research Institue (BASt, 2012).

8.2 Design Reviews

During design phases, a few simple checks are likely to identify and help avoid common pitfalls. Design, modelling, and tender reviews should include explicit confirmation of acoustic constraints, critique of the design response, and consideration of relevant electroacoustic parameters, including at minimum:

- Reverberant conditions.
- Anticipated ambient noise levels (including distribution of noise sources such as jet fans).
- Allowance for a speech spectrum (versus full-bandwidth test signals).
- Crest factor of speech (versus crest factors for sine tones or pink noise signals).
- Power handling (and distortion limits) of selected loudspeakers, for broadband input signals.
- Ratio of direct to reverberant level for the system design.
- System gain structure and overall headroom.

8.3 Tuning and Commissioning

Finally, allowing adequate time and resources to thoroughly tune a system onsite is essential to achieving optimal performance of any PA system, especially for systems expected to perform a critical life-safety role in highly constrained acoustic environments. Substantial performance improvements can be achieved through careful setting of gain structure, equalisation, dynamics, time-delay and system control.

ACKNOWLEDGEMENTS

The process described in this paper was only possible with a collaborative effort involving many individuals over a number of months. A number of special mentions are deserved:

- The Well-Connected Alliance board and project managers who all approached the challenges described with patience and led an open, collaborative culture that enabled development of practical and timely solutions.
- Glenn Leembruggen (Acoustic Directions) who conducted extensive on-site tuning to extract the maximum possible performance out of the installed system.
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