Determination and verification of speech intelligibility from sound systems in tunnels

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Abstract

Achieving reasonable speech intelligibility in a highly reverberant space is one of the more difficult problems encountered by a sound system designer. With the addition of high ambient noise and a demand for life-safety voice messages, vehicle road tunnels present a clear challenge. Improving speech intelligibility requires optimum type and placement of loudspeakers and acoustic modelling software is a required tool. Where knowledge of the acoustic properties of the materials used in the tunnel is known or can be determined, acoustic modelling provides an assurance of what will be heard. A road tunnel in Auckland New Zealand, AMETI Panmure Covered Box (PCB), is used as a test case where acoustic modelling has provided confidence in achieving high speech intelligibility and this has been confirmed through commissioning measurements..

An original Article

Introduction

Standards in New Zealand for emergency warning systems generally require pre-recorded voice messages [1]; there may be different messages for various stages of an emergency or for different locations within a site. Messages are generally preceded by warning tones and sometimes live voice messages may be used, for example a fireman's microphone. When the area where the message is played is highly reverberant like a maintenance depot, railway station or road tunnel, the intelligibility of the message becomes a prime consideration. The criteria for minimum intelligibility is defined in the standards that are commonly used [1] and the measurement of intelligibility can now be qualified. This is easily performed in real-time.

That leaves the sound system designer with the problem of designing a sound system that can reproduce pre-recorded and live speech messages with a received intelligibility in these reverberant spaces that satisfy the standard used. To get some idea of the intelligibility of a sound system before it is installed, acoustic modelling is a mandatory tool. This article describes some modelling tools and techniques that have been used to achieve a successful result for a combined road and pedestrian tunnel in Auckland New Zealand; the Auckland Manukau Eastern Transport Initiative Panmure Covered Box or AMETI PCB. Detailed test measurements during & after installation of the sound system have been used to validate the modelling process.

AMETI Tunnel

Part of the AMETI group of projects, the PCB tunnel is a combined vehicle and bicycle tunnel that reduces congestion and facilitates patronage of the new rail and bus station around Panmure area of Auckland. This tunnel is 220 metres long, 21 metres wide, averages 6.2 metres high and is of cut-and-cover construction. The tunnel walls and roof are precast concrete, the base is mastic asphalt and as the tunnel has no fire deluge system, the concrete roof needs to be protected from fire damage with a mineral cladding system. Promatect H, a proprietary 20 mm thick mineral board suspended below the roof is used to achieve this. Bicycle lanes sit astride two opposing vehicle lanes and for this reason it was decided to equip the tunnel with an emergency sound system. The sound system, required to satisfy Fire evacuation standards, uses tone and pre-recorded speech but there is also provision for general purpose speech from a remote microphone mainly to aid public safety but also for prevention of crime and vandalism.

Initial design

The one small advantage that tunnels have over other large acoustic spaces is their high plan aspect ratio (length to width). The high aspect ratio would suit a single high power loudspeaker with a very narrow beam pattern that would provide sound for the entire tunnel. Unfortunately, air and boundary absorption preclude this approach in all but the shortest and narrowest tunnels but a variation of it is usable. A longitudinal array is an array where each loudspeaker is incrementally delayed along the length of the tunnel, the delay time relating to the loudspeaker spacing and velocity of sound in air.

In the initial design for the PCB tunnel, two rows of six loudspeakers were modelled with the two rows offset from the centreline of the tunnel by 7 metres. The loudspeakers mount to the underside of the ceiling at approximately 35 metre spacing along the tunnel with the starting pair directly under the north portal. The choice of loudspeakers is also quite straight-forward as there are only two types commonly available that satisfy tunnel use; DNH DUP40 and Duran AXYS AFB-260. Both feature high degrees of electrical and mechanical durability, 20 by 20 degree radiation patterns, suitable speech bandwidth and high output power. High electrical efficiency is achieved due to their use of compression drivers and long flare length horns. The AFB-260 was chosen for AMETI PCB mainly due its low profile and wider bandwidth.

Acoustic Modelling

As the PA system is required to be used as a life-safety system it has been designed from the ground up to comply with recognized standards [1] [2]. As well as electromechanical attributes such as fire survival cabling, back-up power supplies and fault logging, acoustic attributes also apply. These consist of the PA system having sufficient loudness to overcome maximum expected ambient noise or Signal to Noise ratio (S/N), as well as meeting a defined intelligibility criteria.

Maximum ambient noise levels in tunnels can be very high. Measurements of dynamic traffic sound levels inside other New Zealand road tunnels show sound levels within the range of 70 to 80dBA. The sound level of traffic noise during an emergency is unknown and we have allowed a 10dB margin above dynamic traffic measurements for this. AS 60849 requires that signal-to-noise ratio (S/N) be no less than 6dB with a maximum sound pressure level of 105dBA [1]. Using the speakers mentioned above it is relatively easy to produce A-weighted sound pressure levels in the range 95 to 100 dB inside the tunnel and S/N values of 6-10dB can easily be achieved.

Speech Transmission Index Public Address (STIPA) [2] is a recognized standard for intelligibility that can be predicted using modelling tools and measured in real time. For example; the AS 60849 Standard [1] requires that a PA system provide sound with a STIPA of at least 0.5 for speech where the content is unknown by the listeners. As the speech content is unknown to the listeners and we are required contractually to provide a compliant system, then STIPA of 0.5 becomes the design standard. AFMG's EASE AURA [3] software was used to predict STIPA over the listening plane (1.5 m above the road surface) of the tunnel. The hybrid deterministic and stochastic ray tracing methods employed by AURA [4] vastly reduce computational time compared to a soley deterministic approach. AURA additionally supports multi-processor PCs, further reducing computation time. As an example, the entire listening plane of PCB tunnel modelled using a 4x4 metre patch with all 12 loudspeakers active takes around 10 minutes on a 16 processor PC. But like all modelling techniques, any reliable output requires accurate inputs and the most difficult of these to obtain is the octave band absorption coefficients, α, for the surface materials. Absorption coefficients of common materials like concrete are easily obtained but sourcing these for the fire rated ceiling material proved more difficult.

Tunnel Ceiling

Reinforced concrete needs to be protected from heat damage from single and multiple fire events, and ablative coatings or panels are generally used to do this. To simplify cladding around the castellated roof beams a suspended ceiling clad with Promatect H mineral fibre board [5] was used. Promatect H is primarily a fire protection system and the manufacturers do not provide any acoustic specifications for their product. To progress the acoustic modelling we need to determine the absorption coefficient, ▯, for this material which comprises 37% of the entire tunnel volumetric area.

To determine the absorption coefficient of Promatect H, a reverse engineering technique was used. RT60 measurements were made in the centre of the tunnels after a considerable amount of ceiling had been installed. The unfinished ceiling was only at the portals so the RT60 measurements made in the centre was still considered representative. Multiple balloon pops were analysed on a NTI XL2 portable audio analyser and averaged to produce an RT60 plot (Figure 1).

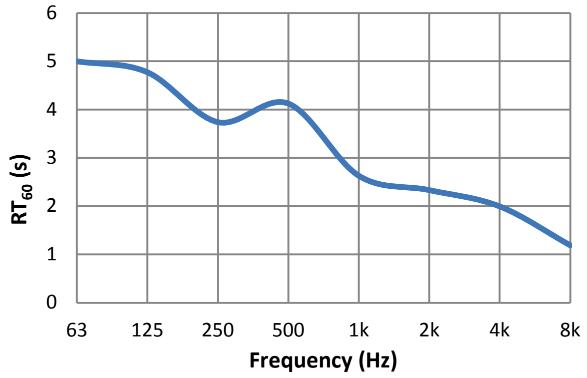


Figure 1. Average measured RT_{60} in centre of tunnel

Using the EASE "Optimize Reverberation Time" routine, it is then possible to adjust α for a dummy ceiling material to achieve the measured RT60 values. The dummy ceiling material with the calculated α can then be renamed and used in the model. It is also possible to generate α from samples using laboratory measurements although this is a relatively difficult process made more difficult if multiple layers or air gaps are used. Mathematical modelling techniques that can analyse multiple stacked acoustic materials such as AFMG SoundFlow [6] have proved to be a low cost and useful tool to do this. Figure 2 shows a SoundFlow prediction of the ceiling with Promatect H suspended 340 mm (on average) below the castellated concrete roof beams. From Figure 1, the reader may notice a reduction in measured RT60 at 250Hz, this dip directly relates to the air gap between the roof and the Promatect H mineral board. This is easily identified using SoundFlow software where a corresponding peak in α is shown in Figure 2. The air gap improves the overall α of the ceiling material reducing reverberation in a critical part of the

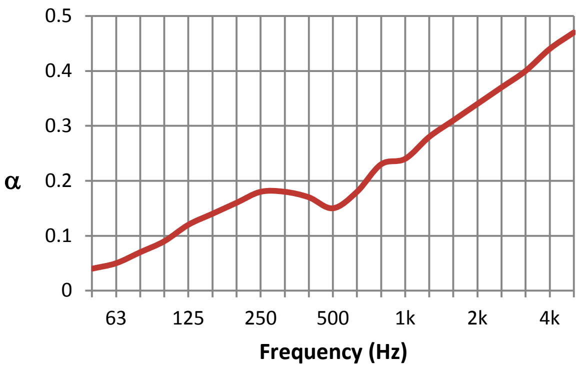


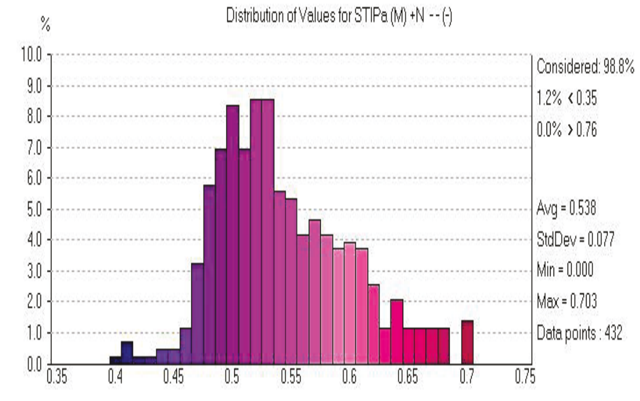
Figure 2. Estimated absorption Coefficient (α) of Promatect H (20 mm) suspended 340 mm below roof

voice spectrum thus improving the intelligibility of speech at any point inside the tunnel. The value of the Promatect H on the suspended ceiling derived from both EASE RT60 optimization and SoundFlow are nearly equal, <1% Standard deviation, across the 8 octave bands.

STIPA prediction and verification

The absorption coefficients for concrete walls and asphalt are from data tables and previous measurements; these are ($\alpha_{average}$) 0.04, 0.12 respectively. The portals are treated as pure absorbers i.e. α =1. These and the loudspeaker positions and corresponding delays were entered into the model and STIPA prediction using EASE AURA was performed. As STIPA predictions are highly sensitive to ambient noise, a noise file is required for use in any simulation. A pre-recorded file using measurements of traffic noise in a similar tunnel (Terrace Tunnel Wellington) was used as a noise file for the STIPA simulation. The average noise from each 1/3 octave band equals 70dB broadband for this file. The simulation showed that STIPA for the entire listening plane averaged 0.54 STIPA. This exceeded the design criteria and was useful when the initial loudspeaker locations were revised to accommodate vehicle height restrictions.

The relocation required that the two rows of speakers were moved above the pedestrian lanes and angled 10° towards the tunnel centreline. Remodelling showed that the STIPA criterion was still achieved thus avoiding the need for complex construction to recess the speakers above the ceiling. Figure 3 shows STIPA distribution from the revised loudspeaker mounting positions and Figure 8 shows predicted STIPA over the entire listening plane.



(c) EASE 4.4 / EASE Hall / 6/08/2014 11:09:39 a.m. / Bartons Sound Systems Ltd Robert Waddell

Figure 3. Predicted STIPA distribution across entire listening plane using revised loudspeaker positions. The colour scale also relates to Figures 5 and 7

One significant advantage of STIPA over any other method of determining intelligibility is that real-time measurements can be easily made. During commissioning, spot measurements made along the centreline of the tunnel using an NTI XL2 with STIPA option showed very close agreement with predicted STIPA. The agreement with modelled prediction was so close that it warranted a more detailed examination, as doing so would enhance the predictive ability of the modelling process. To do this, STIPA measurements were made on a 3m by 3m grid between speaker Right3 and Right4 and between the right tunnel wall and the centreline (Figure 4). The detailed test area is shown in Figure 4 and Figure 7.

Measured and predicted results are compared in Figures 5 and 6. Note that the bottom right corner, C4-R13 of each chart corresponds to a position directly under loudspeaker Right3 and C1-R1 corresponds to a position 4m in front of Right4 near the centreline of the tunnel. Although only a small area of the tunnel was examined, all 12 speakers are activated in both measured and modelled charts, this

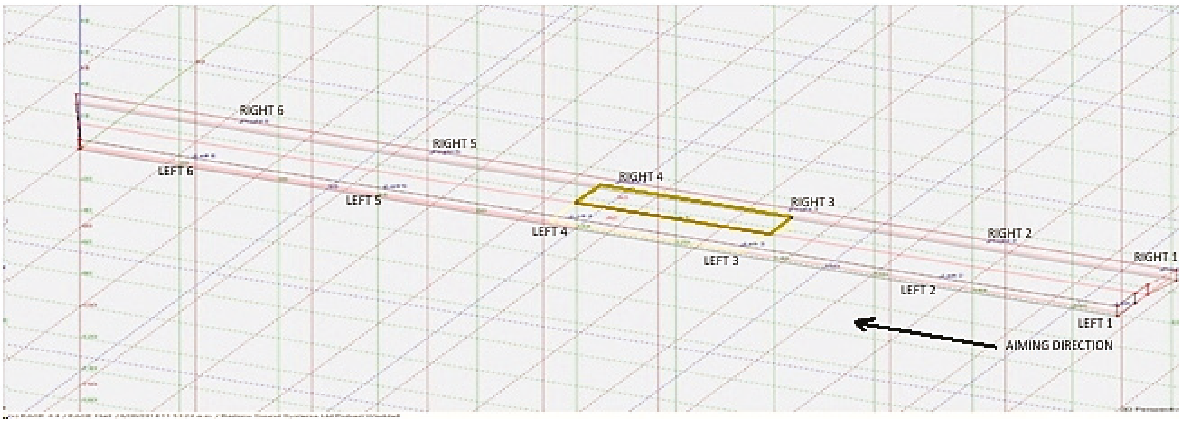


Figure 4. Iso view of the tunnel shows loudspeaker layout and the detailed test area (rectangular box)

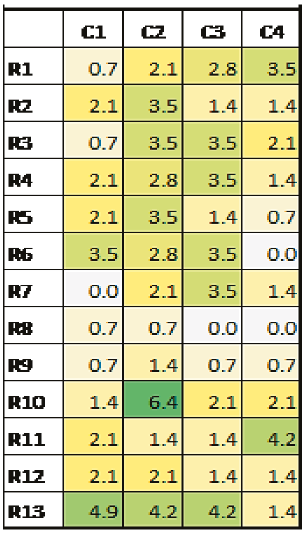
being a necessary requirement for any STI prediction or measurement.

MEASURED	C1	C2	C3	C4
R1	0.56	0.57	0.58	0.55
R2	0.56	0.58	0.58	0.58
R3	0.57	0.59	0.59	0.59
R4	0.58	0.59	0.61	0.57
R5	0.59	0.61	0.58	0.58
R6	0.58	0.58	0.61	0.61
R7	0.56	0.59	0.65	0.62
R8	0.55	0.55	0.6	0.63
R9	0.52	0.55	0.62	0.65
R10	0.54	0.6	0.58	0.61
R11	0.52	0.56	0.57	0.62
R12	0.55	0.55	0.56	0.57
R13	0.57	0.56	0.57	0.57

MODELLED	C1	C2	C3	C4
R1	0.55	0.54	0.54	0.6
R2	0.53	0.53	0.56	0.56
R3	0.56	0.54	0.54	0.56
R4	0.55	0.55	0.56	0.55
R5	0.56	0.56	0.56	0.57
R6	0.53	0.54	0.56	0.61
R7	0.56	0.56	0.6	0.6
R8	0.54	0.56	0.6	0.63
R9	0.53	0.53	0.61	0.66
R10	0.52	0.51	0.55	0.64
R11	0.55	0.54	0.55	0.56
R12	0.52	0.52	0.54	0.59
R13	0.5	0.5	0.51	0.55

Figure 5. (a) Measured STIPA (b) Modelled STIPA

Although the comparison shows that the measured STIPA is actually slightly higher than the modelled STIPA, this is a result of low ambient noise when the measurements were made. The most important aspect of the detailed analysis is that STIPA follows the radiation pattern of loudspeaker Right3. This pattern equivalence indicates that there is excellent agreement between measured and modelled results. Figure 6 shows standard deviation in percentage for measured and modelled for each 3m patch; overall the STIPA standard deviation for the detailed test area is less than 1.5%.



	C1	C2	C3	C4
R1	0.7	2.1	2.8	3.5
R2	2.1	3.5	1.4	1.4
R3	0.7	3.5	3.5	2.1
R4	2.1	2.8	3.5	1.4
R5	2.1	3.5	1.4	0.7
R6	3.5	2.8	3.5	0.0
R7	0.0	2.1	3.5	1.4
R8	0.7	0.7	0.0	0.0
R9	0.7	1.4	0.7	0.7
R10	1.4	6.4	2.1	2.1
R11	2.1	1.4	1.4	4.2
R12	2.1	2.1	1.4	1.4
R13	4.9	4.2	4.2	1.4

Figure 6. Difference (Standard Deviation as %) between measured & predicted results

Conclusion

To comply with internationally recognized standards relating to life-safety systems, speech intelligibility needs to exceed a defined threshold for a large percentage of the listening area. For AS 60849 this is 0.5 STIPA or its equivalent on a Common Intelligibility Scale graph [1].

Longitudinal arrays of loudspeakers with incremental signal delays between sections are now the standard for sound systems in tunnels as they can increase intelligibility markedly over other speaker systems.

Sound absorbers are used to improve STIPA values. Almost every material used in a tunnel needs to be utilised as a sound absorber; this includes the concrete and asphalt even though their sound absorption coefficients may be very low. It is expected that the addition of fire protection coatings or cladding will improve STIPA and these materials will need to be tested to determine α. Quite often the sound absorbing properties of these materials can be enhanced by small modifications in their design or by the way they are installed.

Intelligibility can be easily predicted and measured using low cost software and measurement instrumentation. If a single material with unknown ▯ is used, this can be determined by RT60 measurements and may be confirmed with absorber modelling software. Verification of the model is a straight-forward task and allows confidence for modelling future projects.

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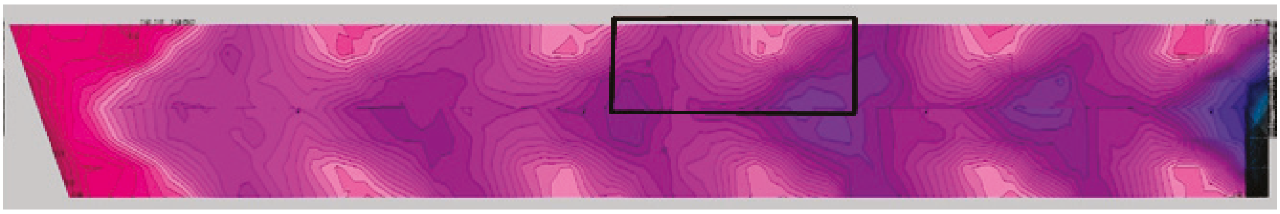

Figure 7. Shows PCB tunnel STIPA prediction on listening plane 1.5m above road and pedestrian level. The loudspeakers are pointing from right to left and are located approximately 4.7 m above the listening plane. In this figure, the 4m by 4m patches have been converted to contours. The rectangle shows the detailed test area.