Evaluation of speech transmission in a road tunnel

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ABSTRACT

Long reverberation times and high background noise levels associated with jet fans degrade speech transmission in road tunnels. Sound attenuation and reverberation time measurements in the Sydney Harbour Tunnel are used here to calibrate a mathematical model used to estimate speech transmission index STI. This study forms a basis for future work in the evaluation of acoustic design alternatives for public address systems required for communication to motorists who may become stranded within the tunnel during normal operations or tunnel emergencies.

INTRODUCTION

Road tunnels are now a common part of our urban transport infrastructure. Table 1 gives details of some of the major tunnels in Brisbane, Sydney and Melbourne. Twin tube, uni-directional tunnels are favoured for safety reasons.

Table 1. Australian road tunnels

Tunnel	Length (km)	Lanes/tube (3.5 m/lane)	City	Year
CLEM7	4.8	2	Brisbane	2010
Airport	5.7	2 and 3		2012
Link Northern	5.5	2		2014
Link Sydney	2.3	2	Sydney	1992
Harbour M5 East	3.9	2		1998
Lane Cove	3.6	2		2007
Eastern	1.1	3		1999
distributor Cross City	2.1	2		2005
Burnley	2.4	3	Melbourne	2000

This paper concentrates on acoustic issues associated with the fire and life-safety of a road tunnel; namely speech transmission of emergency announcements. Traffic noise is not considered. The experimental work reported was supported by the Sydney Harbour Tunnel Company through extending a late night fire test closure to make the tunnel available.

STRUCTURE

Figure 1 shows the curved internal cross section typical of a bored tunnel, showing centrally mounted jet fans used to longitudinally ventilate the tunnel. Banks of jet fans may be as close as 70 m to each other. Mined tunnels also have an arched cross section. Cut and cover construction generally gives a rectangular section.

The ceiling shown in Figure 1 is bare concrete. However this may be painted black in order to hide the discoloration caused by soot from diesel engines. If a smoke extraction duct is included in the design, the roof will be flatter. The ceiling of the tunnel may also become cluttered with deluge piping, cable trays and signage.

In Australian practice, panels, manufactured from coated compressed fibre cement sheets, are placed on the side walls to reflect light onto the roadway. These are cleaned regularly. The roadway has a surface of concrete or dense asphalt.

Figure 1. Bored tunnel cross section.

VENTILATION

Ventilation of road tunnels is concerned with i) pollution control during normal operation and ii) smoke control in the event of fire. Longitudinal ventilation (Figure 2) is commonly used for long tunnels. One of the major contributers to degradation in speech transmission is the prevailing background noise created by the jet fans. Jet fans are used to augment the longitudinal flow of tunnel air down the length of the tunnel for congested or stopped traffic. It is common in Australia for polluted air to be extracted and vented to atmosphere through a fan station located at the end of each tube. A portal inflow Q_p ensures that even the perception of air quality probems at ground level is avoided.

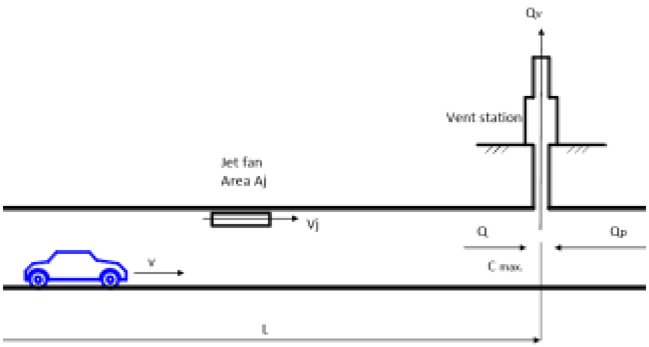

Figure 2. Longitudinal ventilation

Table 2 gives typical heat release rates for various vehicle fire scenarios. Fires of this size are associated with the liberation of large quantities of smoke.

Table 2. Typically adopted vehicle fire heat release rates.

Vehicle	Heat release rate MW
Passenger vehicle	5
Bus	30
Heavy goods vehicle, fully laden	50 - 100

In the event of fire in a uni-directional, longitudinally ventilated tunnel, the role of jet fans is to drive smoke in the direction of traffic flow. Traffic downstream of the fire will clear the tunnel, and stopped traffic will sit in a smoke free environment behind the fire. If smoke ducts are fitted to the tunnel, then jet fans will control air speed so that smoke flows toward the open extraction damper, thus giving clear air on both sides of the fire.

The need to drive the hot smoke, possibly against adverse portal pressures and (downhill) road gradients, determines the required jet fan capacity. A long road tunnel may require in excess of 20 jet fans. During a fire emergency, jet fans are the dominant noise source in the tunnel. This noise and the high reverberation times inherent to a tunnel may become a major impediment to communication during a fire emergency. Design of a public address system which meets adequate standards of speech transmission is a considerable challenge in this environment.

JET FANS

Figure 3 shows the internal details of a jet fan (with attenuators removed) with twelve blades in a 1.25 m diameter casing. Passing frequency of the blades is 288 Hz. The sound power histogram Figure 4, shows that the insertion loss associated with the addition of an attenuator on the inlet and outlet of the fan.

Figure 3. Jet fan internals

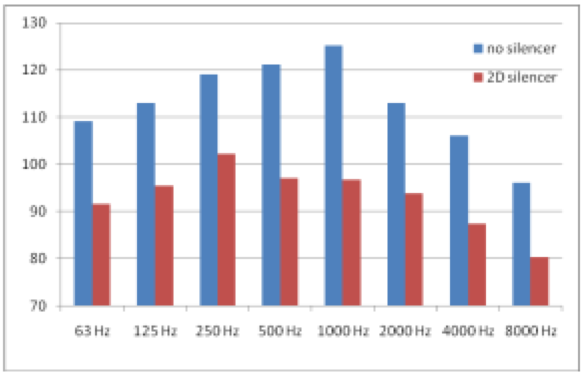

Figure 4. Jet fan sound power levels.

Typical road tunnel design specifications require that the noise level 2 m above the roadway and 5 m from the jet fans should not exceed 85dBA. Occasionally a noise rating (NR75) criterion is applied to the specification of jet fan noise attenuators.

PUBLIC ADDRESS SYSTEMS

During emergencies, pre-recorded messages along with spoken instructions from the operator are given to stranded motorists through the public address system. Figure 5 is a schematic resentation of a typical system.

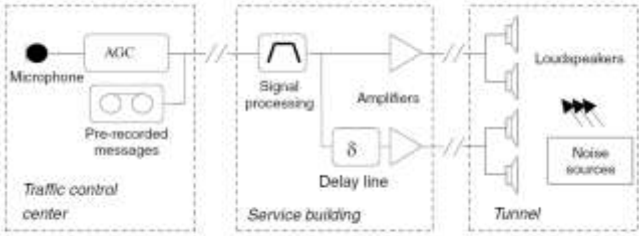

Figure 5. Traffic tunnel PA system

Australian road tunnels are usually divided into emergency zones 120 m in length. At each end of the zone is an egress passage crossing over to the adjacent tube. Each emergency zone is addressed individually. Address to the full tunnel occurs one section at a time.

Horn loud-speakers (Figure 6) are are used in the public address system. Ideally speakers should have a wide bandwidth 125 Hz and 8 kHz with speaker power chosen to provide sound pressure levels 15dBA above the background noise on the roadway. This margin is considered to be the minimum required for adequate speech transmission according to NFPA 72 (2002), Pincus (2006).

Figure 6. PA speakers

ACOUSTIC DESIGN

Nilsson (2009) describes human behaviour experiments conducted in a road tunnel evacuation experiment. One of the parameters examined was the effectiveness of the pre-recorded alarm and messaging system. Table 3 gives an indication of the effectiveness of the PA announcements. No mention was made of the prevailing background (fan) noise levels occurring during the experiment.

Table 3. Effectiveness of PA announcements;Nilsson (2009)

Audibility	Number of responses	
	In the vehicle	In the tunnel
Very clear	0	2
Moderately clear	2	6
Moderately unclear	4	5
Very unclear	3	1
Did not hear the pre-recorded alarm	1	0
Total	10	14

Poor audibility of the PA announcements to a motorist is addressed by use of a re-broadcasting system which allows messages to be received via the car radio. However, once the motorist has left the vehicle, or if they do not turn their radio on, the acoustic properties of the tunnel and PA system determine the quality of the communication.

SPEECH TRANSMISSION INDEX

In setting acoustic design specifications, the Australian tunnel industry only considers the need to reduce background (jet fan) noise. There is a general failure to consider the role of i) basic acoustical physics (reverberation) of the tunnel and ii) the quality of the PA system and speaker positioning in influencing speech transmission. In this respect the Australian industry lags behind European practice where a speech transmission index STI and STI-PA design criterion is being used (Mapp 2004), (van Wijngaarden (2006)).

STI includes all facets of the acoustic system and quantitatively determines speech transmission in terms of a single number lying between zero and one which, when compared with Table 4, gives a measure of the overall system performance.

Table 4. STI rating

STI range						
STI range	min	0.00	0.30	0.45	0.60	0.75
	max	0.30	0.45	0.60	0.75	1.00
Subjective rating		bad	poor	fair	good	excellent

Houtgast and Steeneken (1973) determined that speech transmission is related to the amplitude modulation of the mid to high frequency audio components of the voice signal. The modulation frequencies of interest were determined to lie in the range 0.1Hz to 24 Hz. Attenuation of the amplitude modulation, by reverberation and distortion, leads to significantly degraded speech transmission.

The Modulation Transfer Function (MTF) considers attenuation of the intensity of a carrier (see Figure 7);

$$i_i(t) = I_i(1 + \cos 2\pi F t) \qquad \textbf{Equation 1}$$

and the measured delayed (τ sec.) response;

$$i_o(t) = I_o(1 + \hat{m} \cos 2\pi F(t - \tau)) \qquad \textbf{Equation 2,}$$

at frequencies in the seven octave bands from 125 Hz to 8000 Hz for each of the 14 modulation frequencies given in Table 5.

Table 5. Modulation frequencies.

F (Hz)	0.63	0.80	1.00	1.25	1.60	2.00	2.50
	3.15	4.00	5.00	6.30	8.00	10.00	12.50

Equation 3 gives the modulation index *MTF* as a function of frequency *F* and the reverberation time *T* and signal to noise ratio (*S/N*) which is determined separately in each of the octave bands. Kang (2002) and van Wijngaarden (2006) describe how this [14×7] MTF matrix of is manipulated to determine the STI rating. The STI-PA criterion uses a subset of this matrix to more closely align with true speech.

$$MTF(F,k) = \left(1 + \left(\frac{2\pi FT}{13.8}\right)^2\right)^{-\frac{1}{2}} \left[1 + 10^{(-S/N)/10}\right]^{-1}$$

Equation 3.

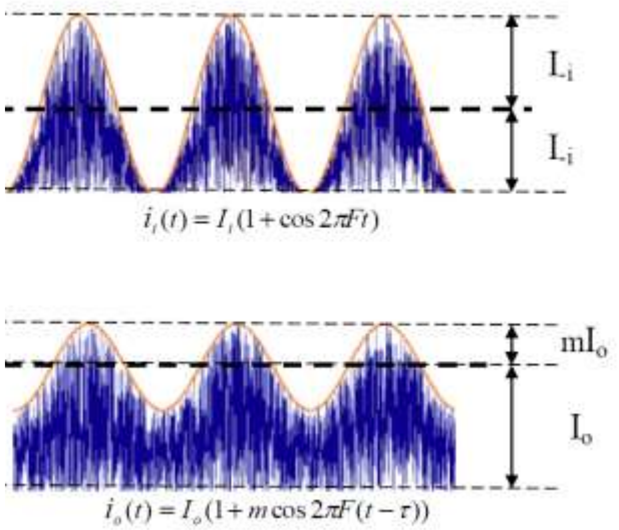

Figure 7. Amplitude modulation of speech signals; i) input and ii) measured response.

REVERBERATION

Kang (2002) uses an image-source method to predict the reverberation time of a "long space". This is a 2D model where it is assumed that reflections of sound from the tunnel walls are purely specular and the flow of acoustic energy proceeds continuously down the tunnel, without reversal. Energy is absorbed with i) each successive reflection and ii) with distance through absorption in the air. Sound pressure level decreases linearly with distance from the source. Reverberation time is dependent on the cross sectional geometry and absorption coefficients of the surfaces, but not on the length of the tunnel. This model is distinctly different from a "room" model where the reflections are 3D and a constant diffuse sound acoustic field is created throughout the space.

The analysis starts with the creation of a set of acoustic images which are the reflections of the source across the tunnel walls. The acoustic images theoretically spread infinitely in orthogonal directions to the tunnel axis. For calculational purposes this is limited to a [m×n] matrix of images.

Figure 8 shows a vertical cross section of the tunnel of height *a* with *n* images extending vertically on both sides of the omni-directional source *S*. Similarly there is an orthogonal set of *m* images extending horizontally on both sides of the tunnel.

The furthest images contribute sound energy to the receiver at a time later than the nearer images. At low acoustic frequencies where the reverberation time is long, it is necessary to include a larger number of images. Four hundred (m=n=400) were used in the theoretical analysis contained in this paper.

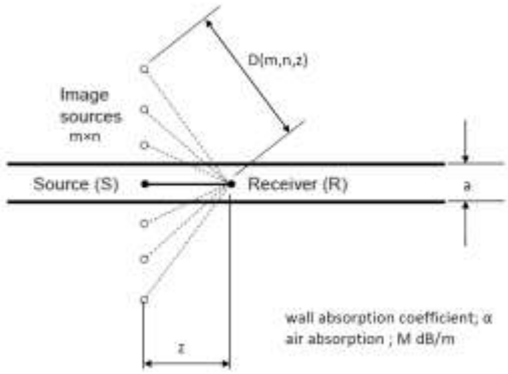

Figure 8 System of images and rays for a point source in a tunnel.

The distances *D(m,n,z)* are used to determine the arrival time of the acoustic energy *E(m,n,z)* at the receiver located a distance *z* from the source. In the analysis it is assumed that the direct sound arrives at time t=0 and that arrival of acoustic energy from the images arrives at time;

$$t(m,n,z) = \frac{D(m,n,z)}{c} - \frac{z}{c}$$ **Equation 4.**

Between time t and $t+\delta t$ the sound energy contributed by the image source (m,n) at the receiver is;

$$E(m,n,z) = \left(\frac{K_w}{D^2(m,n,z)}\right) e^{-MD(m,n,z)} (1-\alpha)^{|m|+|n|}$$

Equation 5.

K_w is a constant relating to the sound power of the source. Equation 5 accounts for; i) attenuations due to the absorption of the walls whose absortion coefficient α is assumed to be uniform and ii) attenuation through the air M dB/m.

A short time equivalent continuous sound level of the energy responses at the receiver is;

$$L(t,z) = 10\log_{10} \sum_{m=-\infty}^{\infty} \sum_{n=-\infty}^{\infty} E(m,n,z)$$

Equation 6.

EXPERIMENTAL ANALYSIS

Sydney Harbour Tunnel was used as a venue for acoustic testing. Each tube has a rectangular cross section 8.35m wide, 4.98 m high with a length 2.3km. No jet fans are located within this tunnel as it uses a semi-transverse ventilation strategy.

Back to back speakers were located at the mid-tunnel point as shown in Figure 9. This experimental sound source had some directional bias at high frequencies and was driven by pink noise. Ideally an omni-directional source should be used. It is important for the source to deliver sufficient power to replicate the sound pressure levels which would occur in a real emergency and to be sufficiently high above the experimental background noise level. In this instance the measured sound pressure level 5.4m from the speakers was 97dBA, with a background level of 33dBA.

A reference microphone (mic1) was placed 5.4 m in front of the speaker and a measurement microphone (mic2) was moved to several discrete locations down the tunnel to 118 m from the speakers.

Figure 9. Experimental setup, Sydney harbour tunnel (width 8.35 m,height 4.98 m, length 2.8 km)

Table 6 Test microphone locations.

	Ref. (mic.1)	Roving (mic. 2)			
X (m)	5.4	15.6	23.6	68	118

Figure 10 shows sample data recorded by the two microphones, including the signal decay when the excitation was cut. It can be noted from the figure that there is no obvious echo as a result of the signal returning after a reflection from the open portal. An echo would have appeared approximately 7 seconds after the signal was cut.

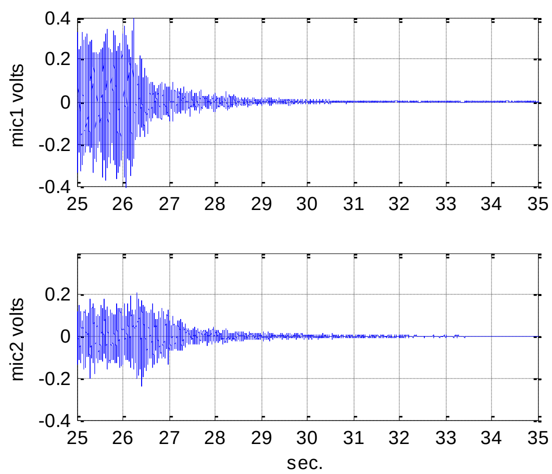

Figure 10. Reverberation test, source located mid-tunnel; pink noise excitation, mic1 5.4 m from source, mic2, 118 m from source.

Tunnel sound absorption along the tunnel was derived by comparing the third octave sound pressure level differences between the fixed reference microphone and the roving microphone. Table 7 contains the sound pressure level differences between the reference and roving microphones.

Table 7. SPL Level Difference (dB) between reference location and roving location.

Hz	63	125	250	500	1K	2K	4K	8K
15.6m	6.4	7.6	6.8	5.3	6.3	6.9	8.1	8.7
23.6m	5.7	7.7	7.5	6.8	7.5	7.4	9.1	11.2
68m	7.5	11.1	9.9	10.0	10.2	11.2	13.2	18.1
118m	8.6	12.3	11.1	11.6	11.8	13.5	17.6	26.8

Reverberation time (T60) was calculated by measuring the slope of the linear part of the measured decays at the five locations, following the acoustic excitation cutoff. Table 8 gives the measured T60 in octave bands.

Table 8. T60 (sec.) evaluated from decay slope of noise switch off.

Hz	63	125	250	500	1K	2K	4K	8K
15.6m	10.1	9.1	7.6	5.6	5.6	4.3	2.7	1.4
23.6m	12.4	10.2	6.8	5.7	5.5	4.1	2.6	1.2
68m	12.5	9.8	7.1	5.9	5.5	4.3	2.7	1.2
118m	13.6	8.9	6.5	5.8	5.7	4.3	2.7	1.1

Impulse response measurement in the tunnel was also attempted using a swept sine excitation. The signal to noise ratio obtained was poor at low frequencies but good agreement of T60 was obtained at frequencies greater than 500 Hz.

ACOUSTIC MODEL VS EXPERIMENT

Attenuation

Estimates of the acoustic absorption coefficients for the road, ceiling, side panels and barrier wall adopted for this study are included in Figure 9 and Figure 10. Absorption coefficients for air *M* are given in Table 11. Absorption of sound in air is dependent on the humidity as shown in Figure 11.

The lines plot the corresponding theoretical attenuations between 15.6 m and locations down the tunnel using the absorption coefficients contained in Figure 12 plots the measured and theoretically derived attenuation of sound down the Sydney Harbour Tunnel. Circles identify the measured attenuation in sound pressure level at the nominated frequencies at 15.6 m and 23.6 m, 68 m and 118 m distance from the source. The trend in both the experimental and model results is that, once away from the near field of the source, the attenuation of sound level is linear with distance. This continual decay in sound level is the major difference between a "long space" and a "room" where the sound level is constant throughout. Another distinction is that the effect of sound attenuation in air is significant in a long space and must be accurately accounted for.

Table 10 and Table 11. Theoretical values were taken at t = 2 seconds with a time window δt = 0.1 seconds using Equation 4 to Equation 6.

Table 9. References for tunnel surface acoustic absortpion.

	Description	Reference
Road	Dense asphalt	Ishida (1996)
Ceiling	Smooth concrete (painted)	Cox (2009)
Side panel	"Vitrathane" - glazed surface; on compressed fibre cement sheet 6mm on studs.	Estimated on the basis of glass. (Cox 2009)
Barrier wall	Smooth concrete (unpainted)	Cox (2009)

Figure 12 plots the measured and theoretically derived attenuation of sound down the Sydney Harbour Tunnel. Circles identify the measured attenuation in sound pressure level at the nominated frequencies at 15.6 m and 23.6 m, 68 m and 118 m distance from the source. The trend in both the experimental and model results is that, once away from the near field of the source, the attenuation of sound level is linear with distance. This continual decay in sound level is the major difference between a "long space" and a "room" where the sound level is constant throughout. Another distinction is that the effect of sound attenuation in air is significant in a long space and must be accurately accounted for.

Table 10. Adopted absorption coefficients

		125	250	500	1k	2k	4k	8k
Road	26%	0.02	0.02	0.05	0.70	0.25	0.57	0.57
Ceiling	32%	0.01	0.01	0.01	0.02	0.02	0.02	0.02
Side panel	30%	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Barrier	11%	0.01	0.01	0.02	0.02	0.02	0.05	0.05
Weighted average		0.013	0.013	0.024	0.198	0.082	0.174	0.174

Table 11. Absorption coefficient air dB/km at test conditions; 15°C and 73% relative humidity.

125Hz	250Hz	500Hz	1K	2K	4K	8K
0.36	1.1	2.4	4.1	8.6	25.4	90.2

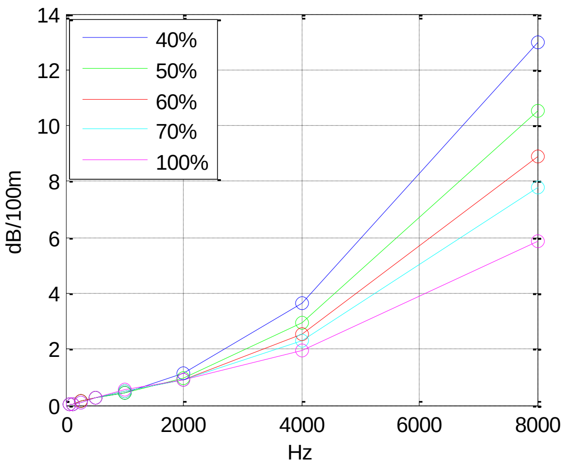

Figure 11. Variation of air absorption coefficient with relative humidity at 20°C.

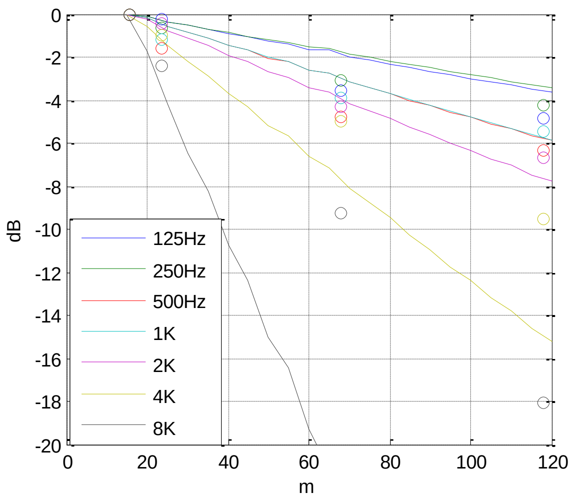

Figure 12. Measured and theoretical attenuation of sound in Sydney Harbour Tunnel.

The model under-predicts the absorption coefficient at low frequencies and over-predicts at higher frequencies. Lack of agreement may be due to the fact that ray tracing methods on which the model is based, assume that the wave length of sound is small compared with the cross sectional dimensions of the tunnel. The 5 m height of the Sydney Harbour Tunnel corresponds with an acoustic frequency of 70 Hz. Kutruff (2009) recommends that the wavelength be an order of magnitude smaller than the shortest room dimension. This possibly explains the underestimate of attenuation at low frequencies, where the sound acts as a plane wave. The deviation of the model prediction from measurement at high frequencies suggests that the estimate of the sound absorption in air is too high or the absorption coefficients used in the model are too high.

Reverberation

Figure 13 plots two simulated acoustic decay curves (red and blue), corresponding to different locations down the tunnel. Their asymptotes have equal gradients. T60 reverberation time is that taken by determining the gradient of the asymptote and calculating the time taken to decay by 60 dB at this rate. T60 reverberation time is invariant for all locations down the tunnel. In contrast the EDT (T10) reverberation times are position dependent. EDT reverberation time has a significantly smaller value than T60 reverberation time.

Measured T60 reverberation times from the Sydney Harbour Tunnel are plotted in Figure 14 at the octave frequencies. These are compared with values predicted from the model, showing that reverberation time decreases with increasing frequency. The model generally under-predicts the reverberation time, particularly at high frequencies. This is expected because the model also over estimates the attenuation at high frequencies as seen in Figure 12.

Figure 14 also plots the theoretical EDT at positions 15 m and 120 m from the source. As the receiver moves further from the source it is apparent that the EDT increases.

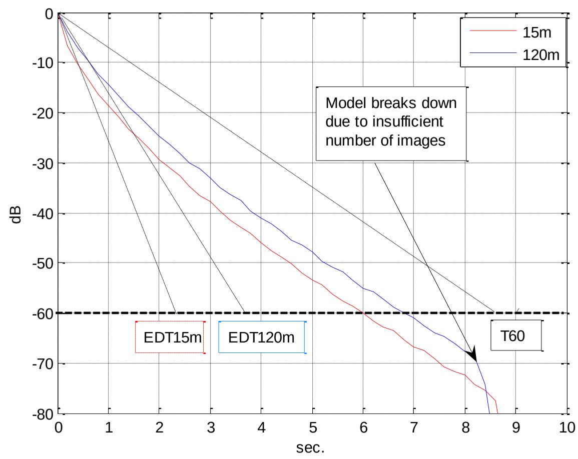

Figure 13 Theoretical decay of sound at 125Hz, *m* = *n* = 200; δt = 0.2 sec at 15 m (red) and 120 m (blue) from source.

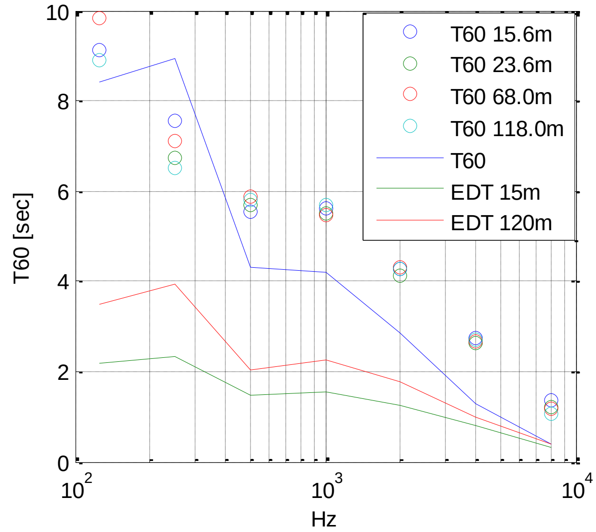

Figure 14. Sydney Harbour Tunnel RT60 reverberation time.

SPEECH TRANSMISSION

The modulation transfer function, plotted in Figure 15, was determined on the basis of the mean values of the experimentally determined EDT estimates given Figure 14. These values were substituted for *T* in Equation 3. Mapp (2004) is emphatic that EDT (not T60) is the appropriate measure of reverberation time which determines speech transmission because it represents the early decay of sound which is comprised of direct or early reflection energy.

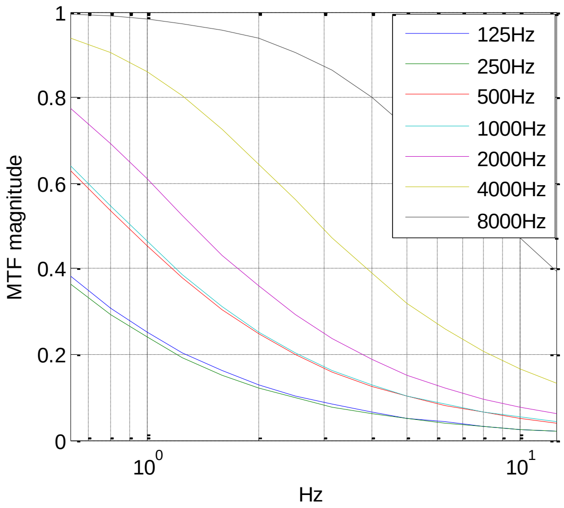

Figure 15. Modulation transfer function Sydney Harbour Tunnel using EDT 15 m.

The modulation transfer function is also further degraded by the presence of high levels of background noise relative to the sound pressure level measured in each of the octave bands.

Table 12 gives typical announcement and background sound pressure levels likely to be encountered in each of the octave bands for a pair of jet fans running. Two sets of speakers are considered; poor quality (low bandwidth) and high quality. Ideally the speakers should have a wide bandwidth with a flat frequency response from 125 Hz to 8 kHz.

Table 12 Signal and noise levels.

		Speaker bandwidth	
		Low	High
F(Hz)	Noise (dBA)	Signal to noise ratio (dB)	
125	65.0	-33.1	6.9
250	70.7	-14.4	5.6
500	76.9	-2.8	2.2
1000	82.3	-16.9	-16.9
2000	79.0	-12.8	-12.8
4000	73.0	-18.1	-13.1
8000	63.7	-23.9	-6.9
Total	85.3		

Table 13 compares STI values calculated for "low" and "high" bandwidth speakers with a flat frequency response. The amplifier is set with an increasing increasing gain. Sound pressure levels and STI are calculated 15m from the speakers.

Table 13. Change of STI with increasing speaker sound pressure level.

Increase in SPL (dB) @ 15 m.	Speaker bandwidth			
	Low		High	
	STI	Rating	STI	Rating
0	0.06	bad	0.14	bad
5	0.12	bad	0.22	bad
10	0.21	bad	0.32	poor
15	0.32	poor	0.42	poor
20	0.41	poor	0.49	fair

It is clear that low bandwidth speakers have a detrimental effect on STI. Also, there is a dimishing return in STI through increase in speaker power. Table 13 shows that it is not possible to achieve a speech transmission rating better than "fair" even with high quality speakers.

Table 13 also doesn't account for;

- the presence of multiple speakers.
- the fact that with increasing speaker power there will also be distortion, which decreases the speech transmission.
- psycho-acoustic effects of high sound pressure levels on a listener.

If these effects were considered, it is likely that the speech transmission would peak and then fall with increasing speaker power, rather than plateuxing as suggested by Table 13. Considering these results, the 15 dBA margin mandated by NFPA 72 may not be optimum.

IMPROVING STI

Kuttruff (2009) explains that moving as much radiated sound energy as possible to early reflections, or early receiver pickup, increases STI. Later arrival of sound is smeared with prevailing reverberation. If STI in an existing tunnel is deemed to be too low, the means by which it may be improved are;

- minimise distortion in the loudspeakers by preventing overdriving of source announcement.
- select loudspeakers with flatter more uniform response between 125Hz and 8kHz.
- use highly directional loudspeakers or line arrays in closer spacing, to maximise the direct sound which reaches the listener.
- speakers should project sound longitudinally down the tunnel.
- move loudspeakers down closer to listener's ear height, to increase the early unreflected energy reaching the listener.

In a tunnel's design stage it may be possible to make significant reductions to the reverberation time by appropriate selection of surfaces.

Use of rough surfaces (for example shotcrete) on the roof of the tunnel would reduce reverberation. Replacement of dense asphalt with open cell asphalt would also significantly improve absorption and thus reduce reverberation at speech critical 800-1kHz region. However open cell asphalt is not preferred as it holds liquid fuel in the event of a spillage and combustion area. There is a trend toward a grooved concrete road surface.

Reduction of jet fan noise is also of critical importance. Running multiple fans at reduced speed (rather than a single fan at full speed) can give the same aerodynamic thrust but at considerably reduced noise levels.

CONCLUSION

It was clear from the measurements made in the Sydney Harbour Tunnel that some improvements could be made to the measurement technique. The reverberation time measured from the sudden termination of pink noise was successful. Attempts to measure impulse response using swept sine excitation were less successful due to inadequate exciation levels at low frequencies. Good agreement was obtained between the pink noise method and the impulse response method for frequencies above 500 Hz. Measurement of sound absorption and reverberation variation down the tunnel could have been improved significantly with a larger range of measurement location distances, preferably up to 500 m. The model used to predict the speech transmission from first principles, based on simple design inputs, seems adequate for the task.

At this stage we are not certain whether the tendancy of the model to under-predict reverberation time is inherent to the model or to an inaccuracy in the absorption coefficients which were used in the model.

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