Practical Considerations for designing Road Tunnel Public address Systems

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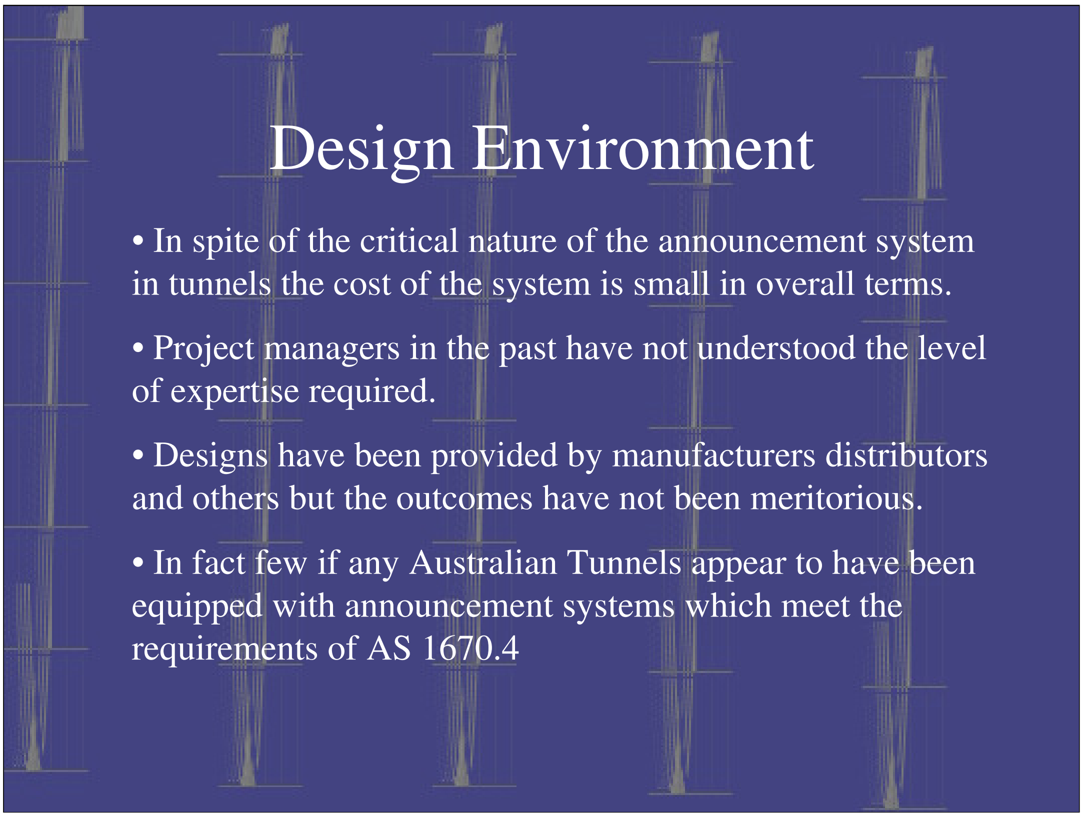
Genesis

Governments world wide have legislated intelligibility into the requirements for audio announcement systems for emergency / evacuation control.

This applies to all situations and locations - including public road tunnels, bus-way tunnels and associated egress tunnels

- The western world has generally accepted an intelligibility standard and legislated a requirement into evac system performance.
- Whether government process' encourage or impede the inclusion of high quality design practice is debatable.
    - We have in place a system that requires certification by suppliers but then favours the lowest price bid.
    - If a Fire Alarm systems supplier includes the cost of professional design and commissioning in a bid is the bid compromised on price ??
- Intelligibility depends heavily on prevailing acoustic conditions but often the design process is enacted by people untrained in the field and unaware of the interaction between sound source and it's acoustic environment.
- Project construction plans and Architectural designs are usually completed in the complete absence of any concept of impacts on intelligibility. The prevailing notion appears to the author as being - "Here's your constraints - DESIGN a sound system that works here.
- The concept that an acoustic environment can be so hostile that intelligibility is impossible is not widely understood by the civil engineering and project design and management strata.



• Project managers are keen to contain the cost of all components of a tunnel. Anecdotal information provided to the author indicates the cost of the 'architectural panels' beside the roadway in the Airport Link tunnel system is of the order of $25,000,000.

• The announcement system not only has significant cost impacts related to the need for high performance loudspeakers but is also impacted substantially by the requirement for very high levels of reliability delivered in part by comprehensive redundancy

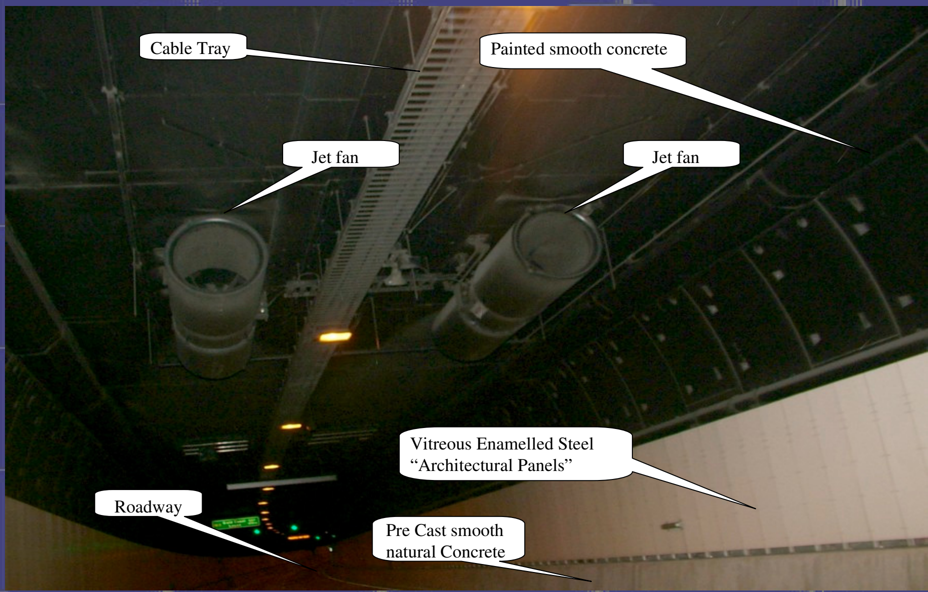
• All this puts the system designer under significant pressure to utilise mass market budget level components - regardless of the small contribution made to overall cost of the tunnel.

• The cost of the design work itself has been carried mostly by manufacturers or contractors who recover costs from sales made. The notion that the project management team should hire independent expertise is not well established in respect of audio systems.

• The manufacturers designer has then an extra level of pressure not only to maximise return to the employer by utilising the most profitable devices but also to configure the system so as to minimise installation costs

•To date failure to meet announcement system standards does not seem to have had serious consequences although levels of interest may be increasing.

The Tunnel itself

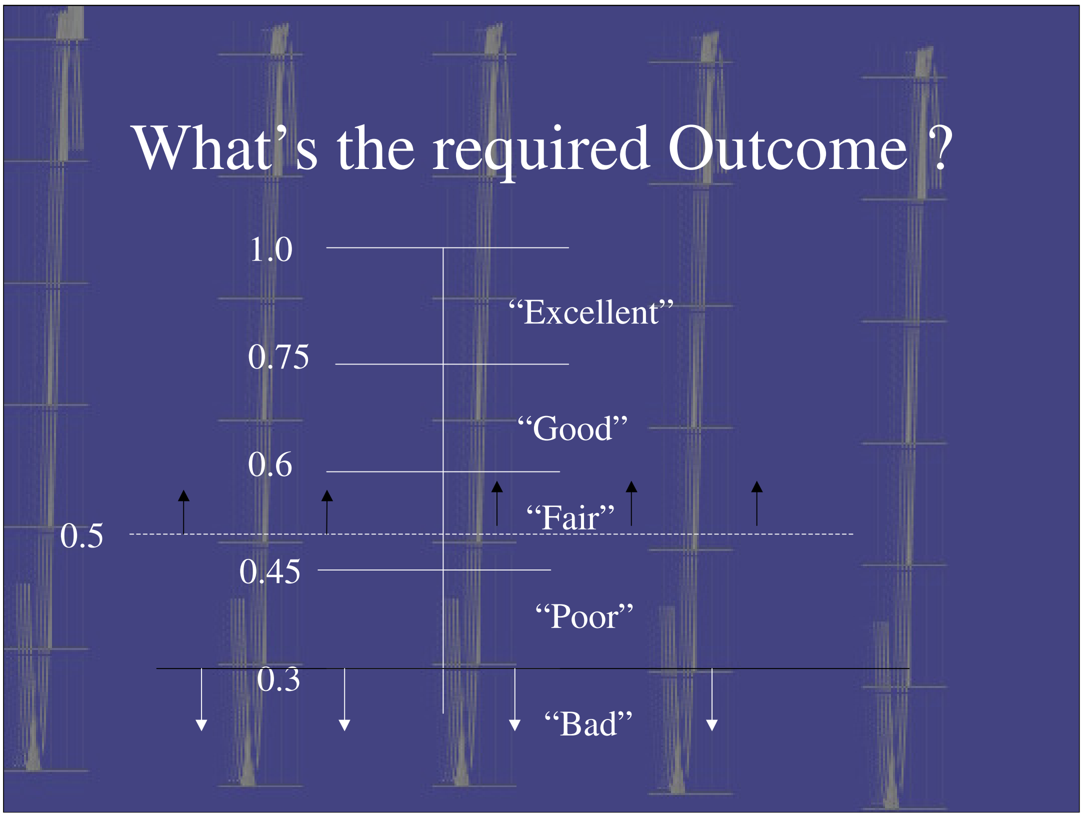


Construction materials are selected for durability and minimal recurring maintenance costs. The pre-cast concrete crash barriers for example, are fitted with so called “architectural features” which appear to be galvanised steel framed walls. The manufacturer's data on the surface sheeting shows it is steel with vitreous enamel finish. The absorption coefficients of this product are unknown in precise terms but extremely unlikely to assist the sound system designer. The construction materials are selected for civil, structural, architectural and possibly lighting criteria well in advance of any input from any acoustician and remain fixed regardless of acoustic impact.

The precise nature of the performance criteria for the ‘architectural panels’ is not known to the author but is does seem likely that a specially designed porous concrete block made from selected silica sand or similar could provide good light reflectivity and add a substantially beneficial acoustic effect.

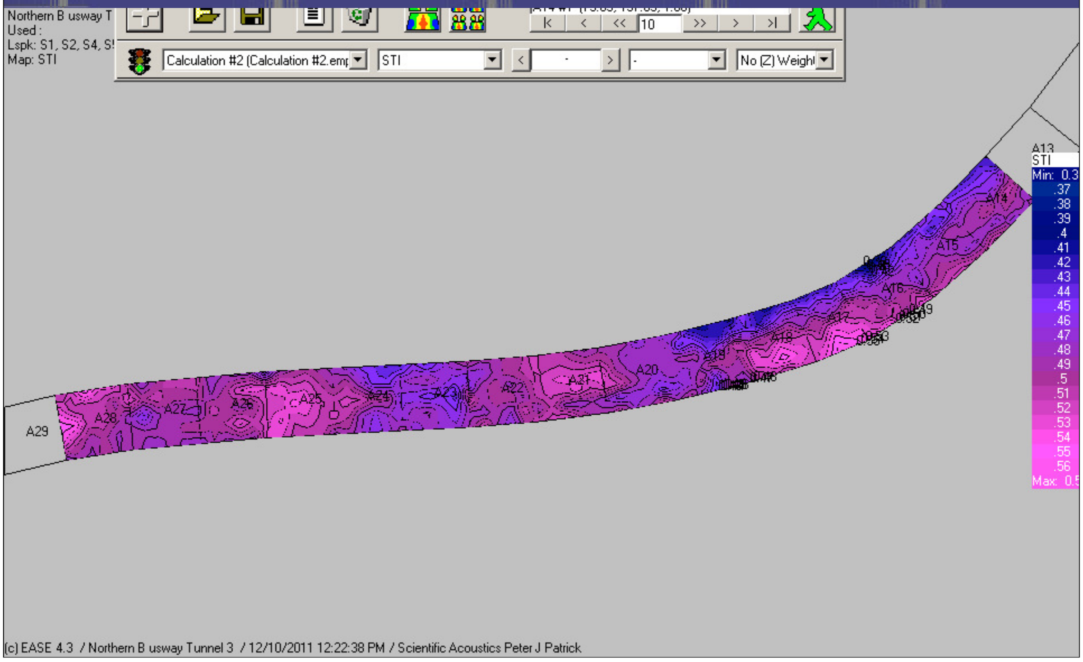
The notion that the sound system designer must simply ‘design’ a system to operate in whatever environment is provided seems to prevail.

The concept that an excessively hostile acoustic environment renders the task impossible does not have widespread acceptance in the realm of the architectural design team.

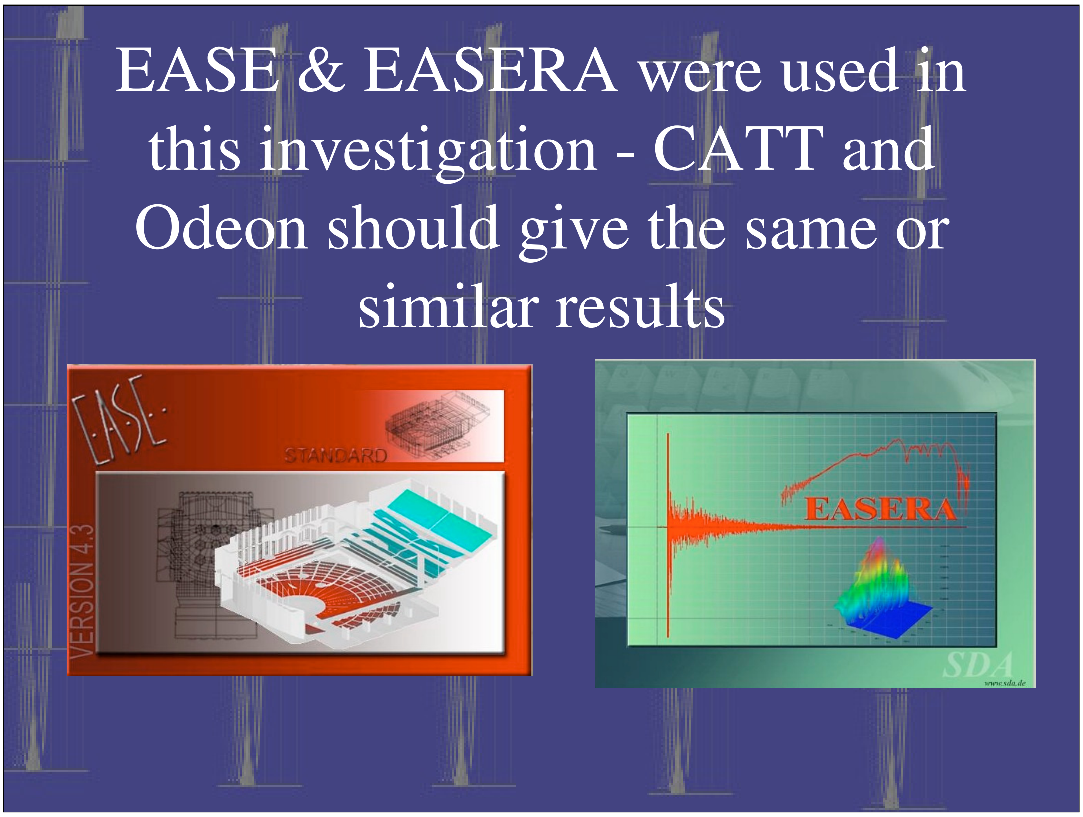


Specifications may call for a Speech Transmission Index (STI) of 0.5 or greater in the presence of 85 dB (A) noise or greater.

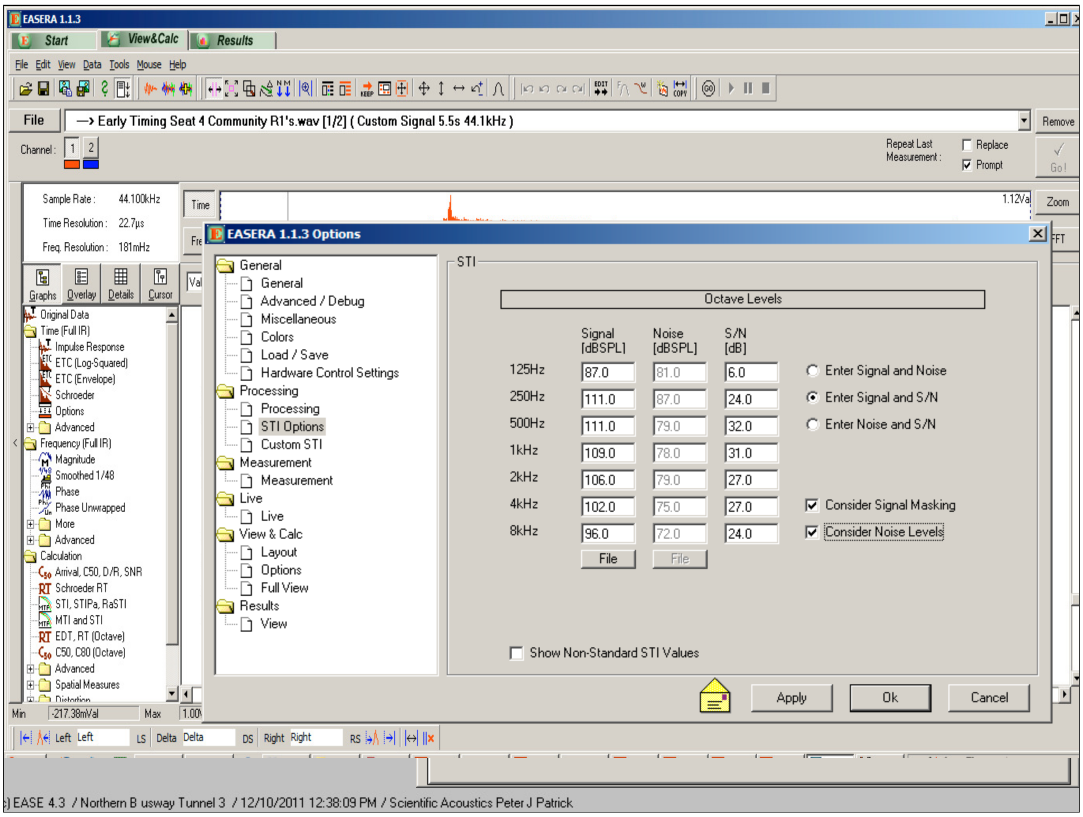
Design Procedure in common use



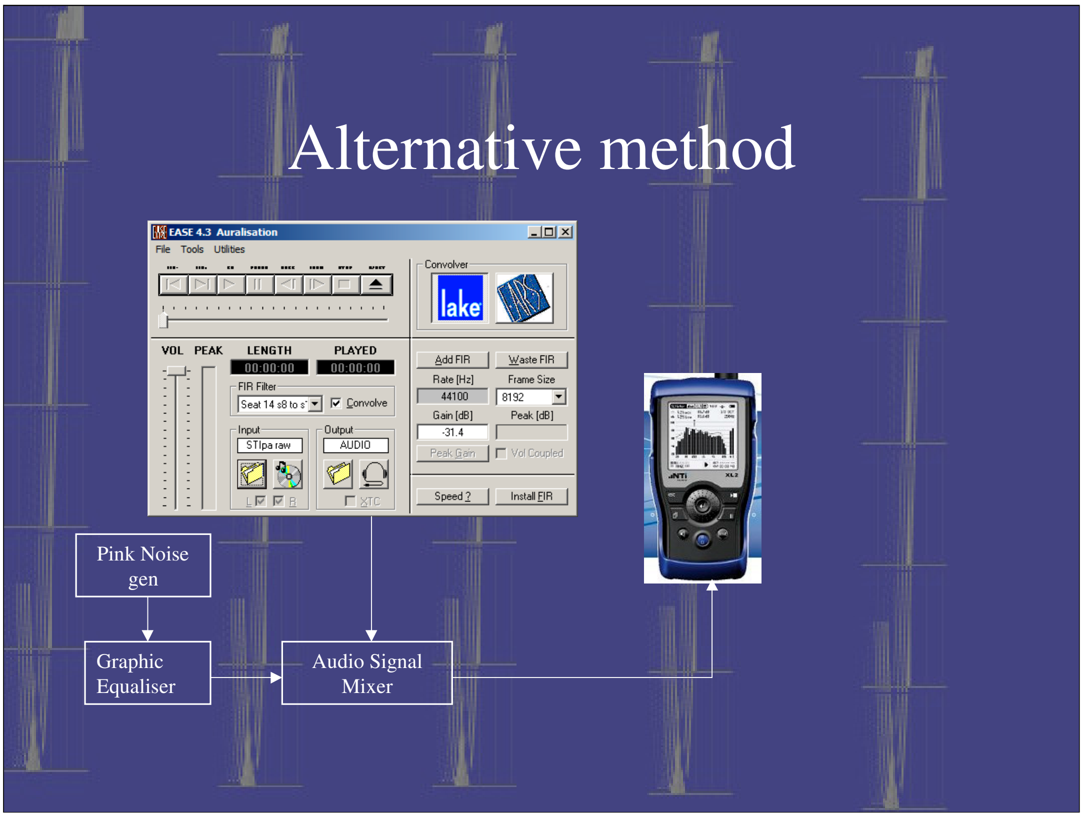
. Loudspeaker system design has typically done using Ease, Catt or Odeon style 3D modeling programs often done by loudspeaker manufacturers technical specialist staff on pro-bono basis. Outcomes appear to be as variable as the number of design sources with few examples of fully compliant installations to be found. The design process involves the creation of a 3D model of the enclosed space which replicates the acoustic nature of the tunnel and populating the structure with loudspeakers selected for their acoustic output & directivity from the range available to the designer (often those manufactured by the designers employer). The software then calculates the quality of sound produced and displays it either on a calculation plane or 'audience area' or in more detail form at a particular single point or listener seat placed by the designer for the purpose of the test. Budget level packages of the generic kind of software packages used for this purpose use statistical calculations to derive the outcomes. That is – they consider all absorption evenly distributed over the entire surface of the model, the reverberant field is considered evenly distributed, specula reflections are not included and late arrivals not well catered for (Ballou, 2005).



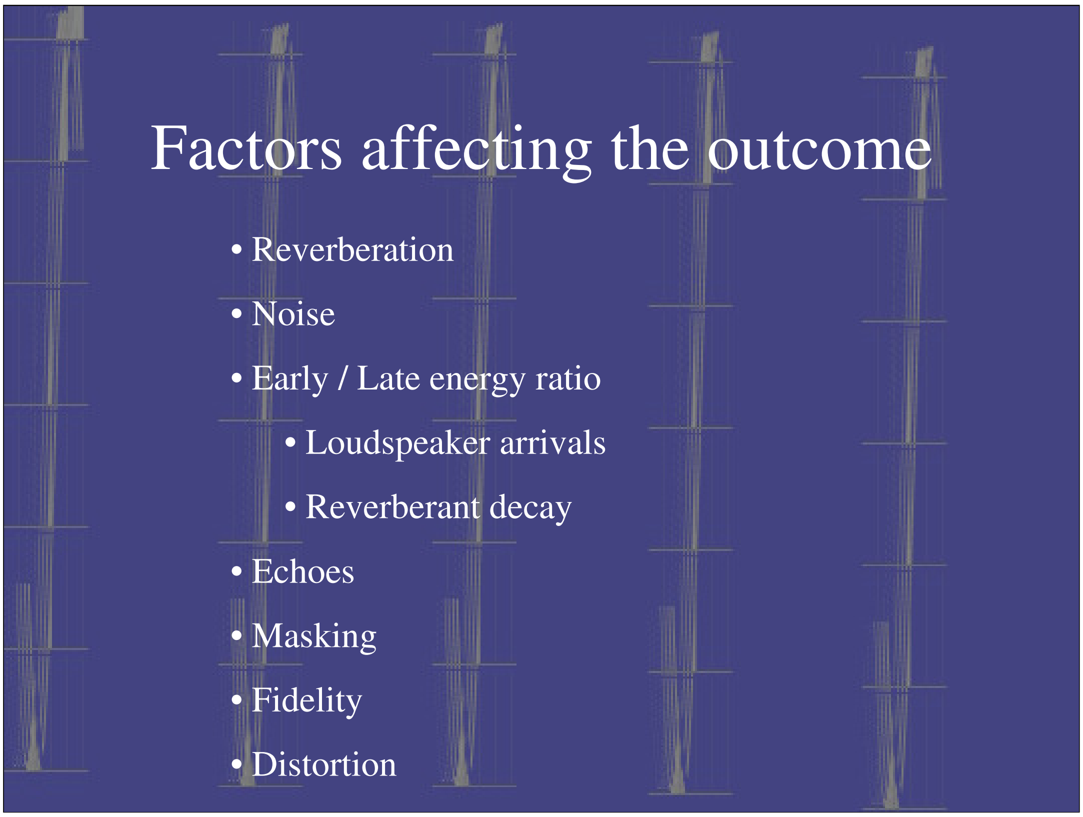
EASE (Enhanced Acoustic Software for Engineers) software, with all available options, has been used by the author since 2000 and is used extensively throughout the investigations presented in this paper. There is no reason for the choice other than the author's familiarity with the software and a number of other analysis and measurement packages from the same supplier.



The inclusion of high level background noise in the calculations in EASE is best done by either using the hybrid ray trace engine ‘AURA’ to derive the STI outcome and add the noise via a table or by deriving an impulse response and exporting that to an analysis package, Easera, where the noise can be added from an Octave band table.



Another option available to the designer is to derive the impulse response of the sound system in the tunnel and convolve the STIpa test signal through the Impulse response to produce a simulation of the test signal from the loudspeakers at the test location in the model. This simulation can be played directly into the STIpa analyser or mixed with a recorded or simulated noise signal at the correct signal to noise ratio and measured directly by the analyser.



Taking these factors individually:- The reverberant level, which related directly to the direct / reverberant ratio at any point in the space, is related not only to the tunnel's acoustic behavior but also to the number of loudspeakers and the directivity of each which means selection of loudspeaker and layout is critical (Ahnert & Stefan, 1999; Davis & Patronis, 2006). Noise is generated by large axial fans and road traffic. The noise level also depends on the tunnels acoustic behavior. The location of discreet arrivals from loudspeakers at a distance from the one nearest the listener on the temporal scale has a marked effect on clarity measures such as C35 and C50 and depends on the designers attention to signal processing detail. Finally, the STI test includes seven octave bands from 125 Hz to 8 KHz which implies fidelity, or frequency response, is a serious matter depending on choice of loudspeaker and signal processing under IEC60268-16.

The topic covers a very wide range of technical disciplines each of which have been addressed, and continue to be addressed, by authors focussed on the individual subject. In keeping with the paper's title - "Practical considerations …" none of the various disciplines are discussed in great detail but rather examples of the work method are provided. Test results from various software and hardware test systems are provided throughout with descriptions of the process used.

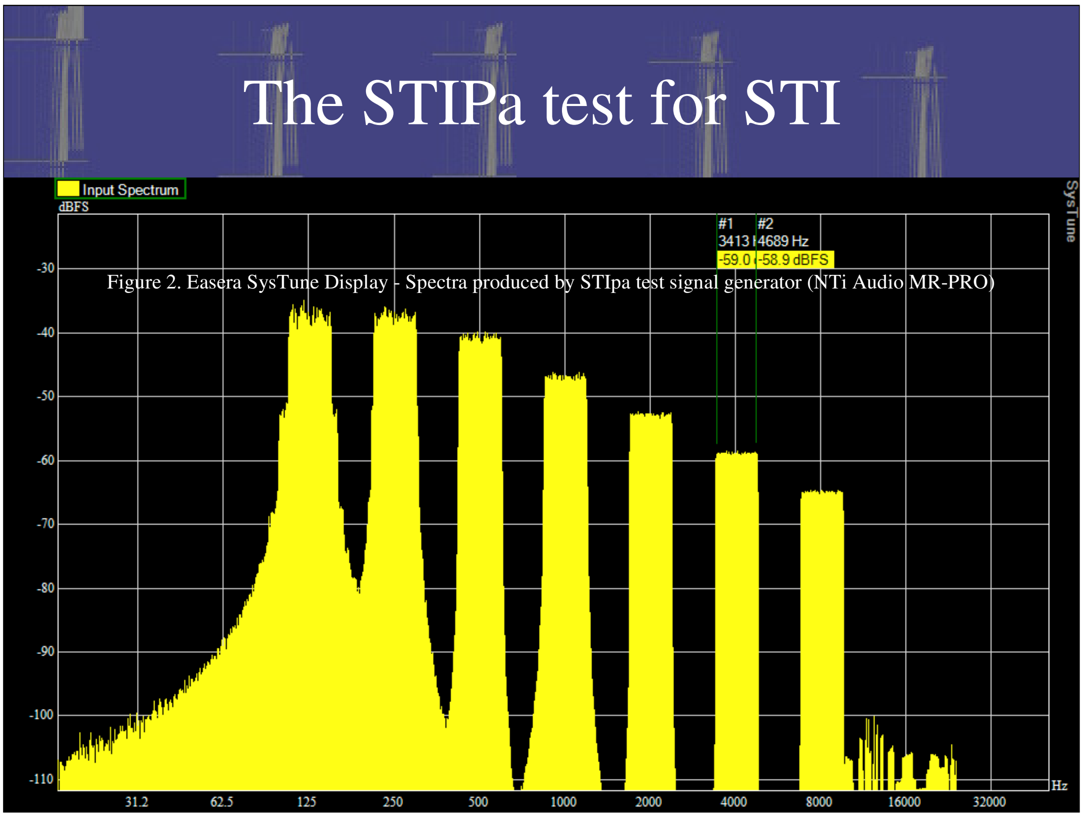


Figure 2. Easera SysTune Display - Spectra produced by STIpa test signal generator (NTi Audio MR-PRO)

The STI and STIpa test is defined in IEC 60268-16, fourth edition 2003-05 The full STI test requires the measurement of modulation transfer indices at 14 frequencies from 0.63 Hz to 12.5 Hz in seven octave bands from 125 Hz to 8 KHz. The STIpa test applies only two modulating signals to each octave carrier so the simultaneous measurement can be made in typically 10 to 15 seconds.

IEC 60268-16 defines numerous measurement regimes such as masking, octave weighting and redundancy factors which are not within the scope of this investigation. The document also describes differences between male and female voice signals (the female voice test excludes the 125 Hz octave) which are not considered individually in this text.

An STIpa test signal generator produces a test signal that embodies half octave wide 'noise' spectra set at octave band centres from 125 Hz to 8,000 Hz. Figure 2 shows the spectrum produced by an NTi Audio MR-PRO set to generate the STIpa signal. The gaps in the spectrum are a deliberately included feature to assist in the design of effective filters in the analyser device.

The spectral response of the test signal means that a well smoothed frequency response is not entirely necessary to garner a good reading - maintaining a constant SPL at each octave centre is important.

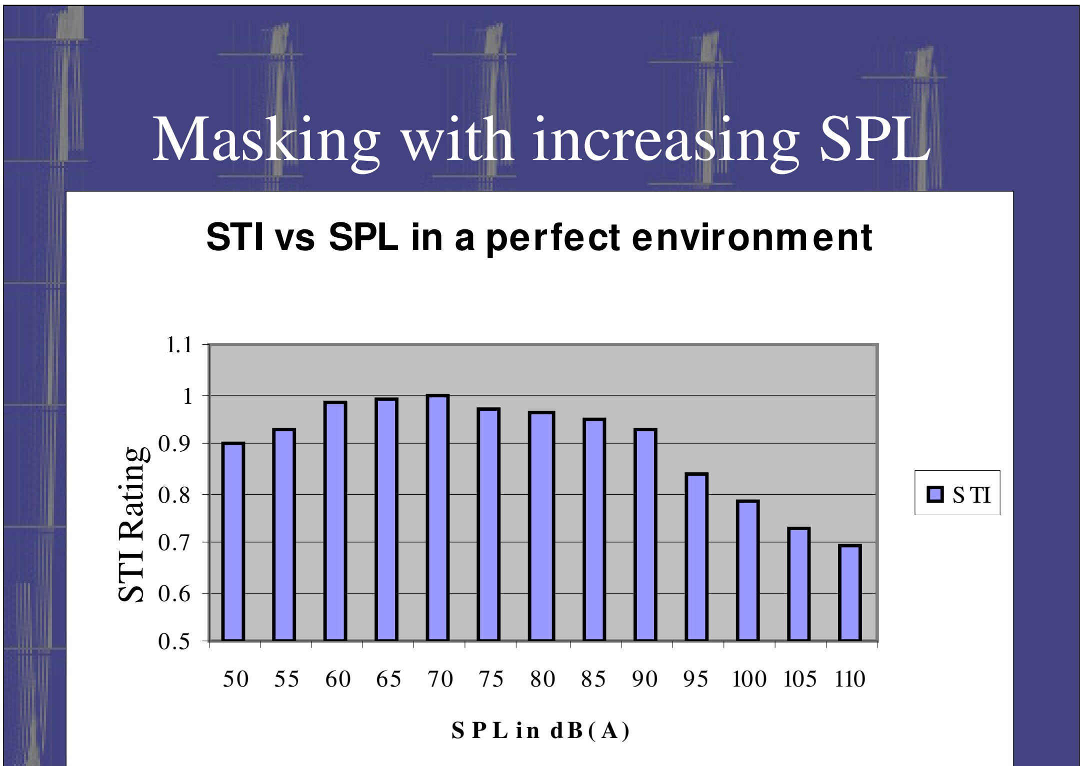
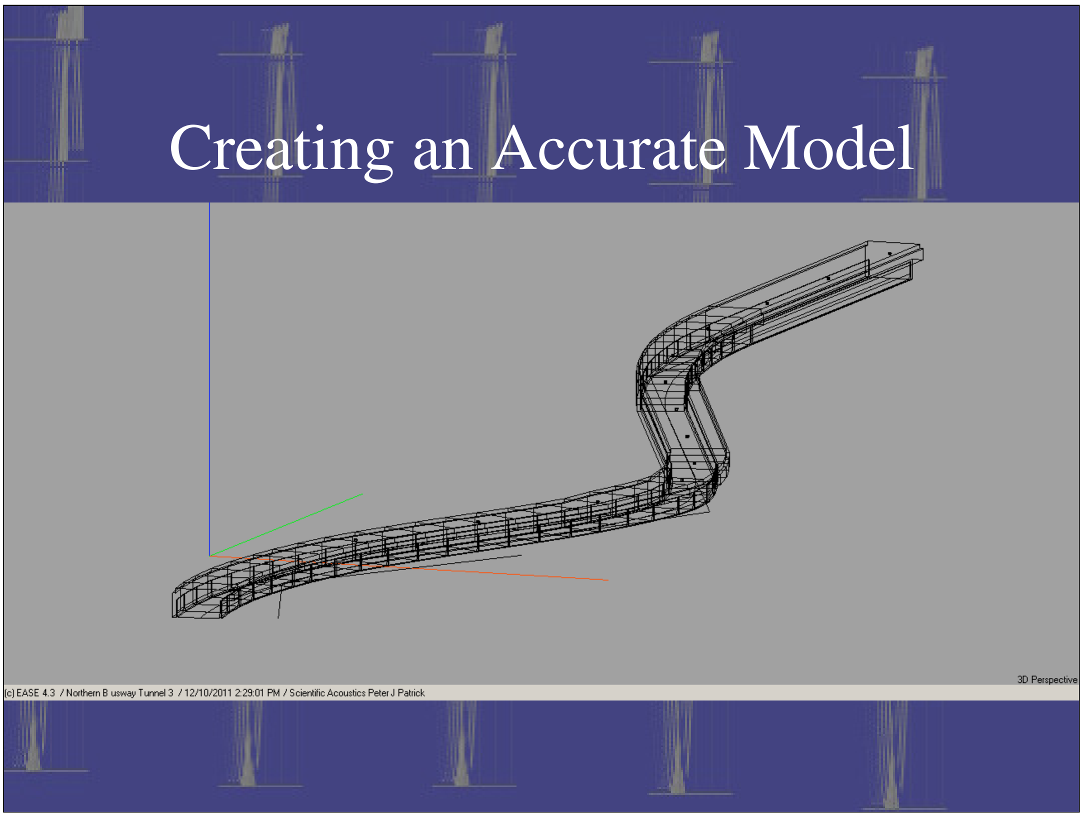


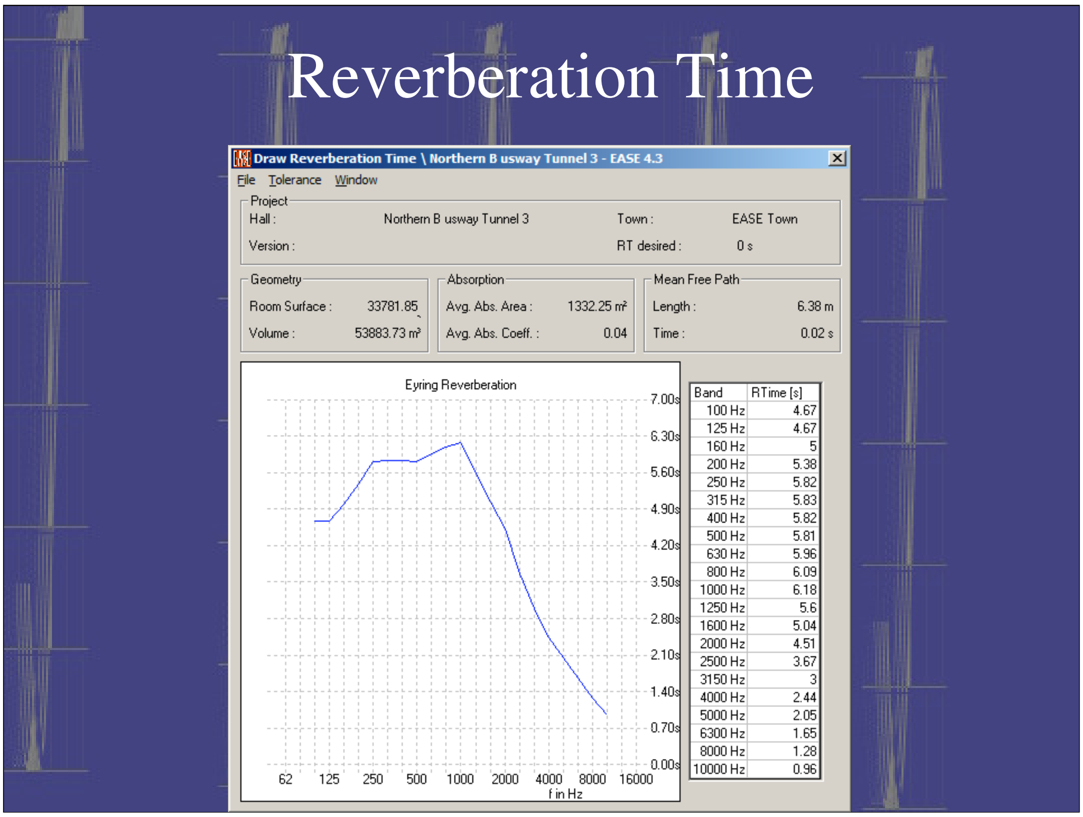
Figure 3. SPL vs STI reading according to NTI Audio, XL2

The STI weighting for Sound Pressure Level (SPL) produced by the NTi Audio, STIpa measuring system is shown in figure 3. The measurements were obtained by directly linking the MR-PRO generator to the XL2 Analyzer with a cable and adjusting the generator output to produce the SPL rests at which the columns are centred. It shows that at high SPL's required to deliver a useful signal to noise ratio in a noisy environment the intelligibility rating is substantially reduced on account of the high SPL itself without beginning to consider the detrimental effects of the background noise, reverberation, distortion or any other interference



> The modeling and design process presumes that all the input parameters are correct and optimised as necessary. That is – the model accurately reflects the real world acoustic conditions and physical dimensions, the loudspeaker locations are compatible with the building, the calculation parameters have been correctly set and the noise spectra accurately imposed. The quality of the outcome then depends on the designer's ability to select the most appropriate loudspeaker, loudspeaker spacing and location as well as appropriate time delay or signal processing (Ballou, 2005).

Computer limitations generate a desire to model only a portion particularly of long tunnels - usually with both ends open and modeled as totally absorbing surfaces. The sheer size, number of surfaces and number of loudspeakers placed in the model directly affect calculation time. For example a model of one of the Northern Bus-way tunnels created by the author is 600 m in length with 724 faces and 14 loudspeakers. It takes approximately 1 minute for a modern Intel i7 processor based computer to calculate and display a direct SPL plot on a standard audience area using the simplest statistical calculations available. A comprehensive ray Trace routine may take more than 7 days. Testing a full replica of a long road tunnel can be challenging. The author has been made aware of system designs based on sections of tunnel less than 200 m in length, far less than the complete tunnel, in an effort to minimise calculation time.



The first item of interest in producing an accurate acoustic replica of the real tunnel is the calculation of the correct reverberation time. Long reverberation times in excess of 3 seconds present increasingly challenging environments for loudspeaker system designers on two fronts: - (a) The reverberant sound pressure level behaves as noise thereby reducing the signal to noise ratio presented to the listener and (b) The total noise level produced by a noise source such as a fan is elevated by natural reinforcement. Long reverberation times reduce the direct to reverberant ratio and elevate fan and traffic noise further reducing signal / noise ratio which in turn requires higher sound pressure levels from the loudspeakers which of itself reduces the intelligibility again.

Long reverberation times also extend the calculation time in high performance computer programs.

This generates the desire to model only a sample length of the tunnel so that calculation times are much shorter

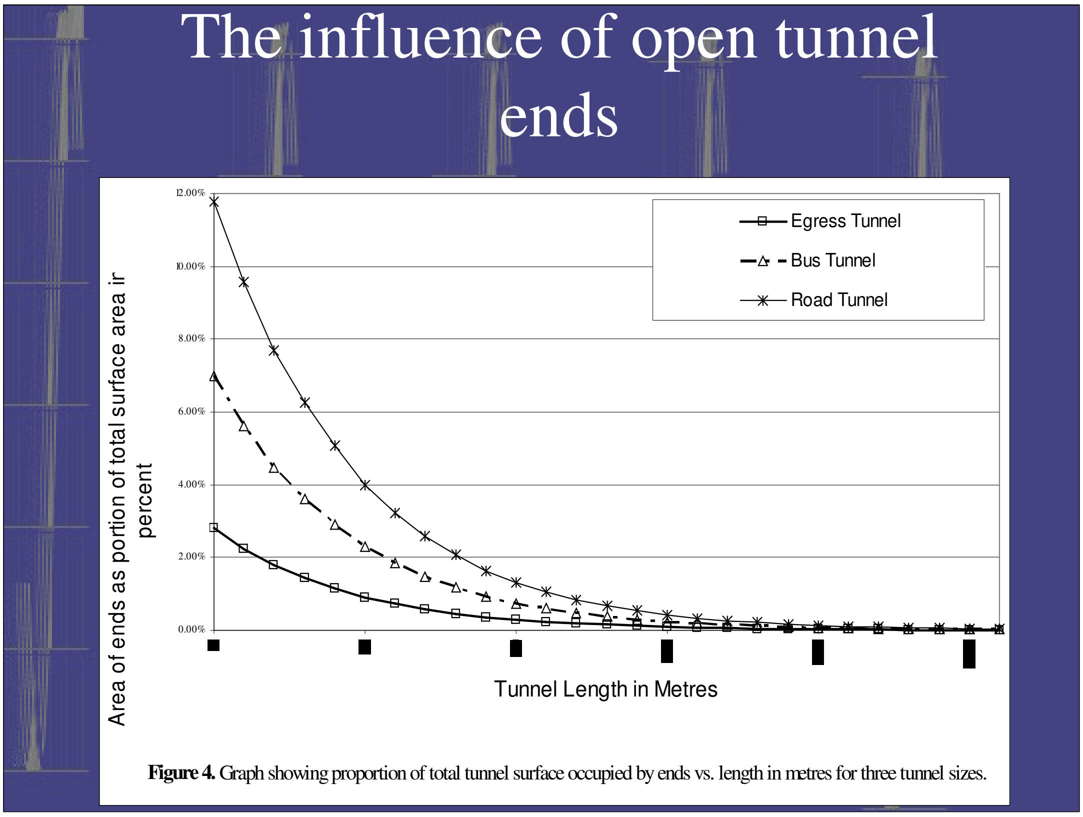
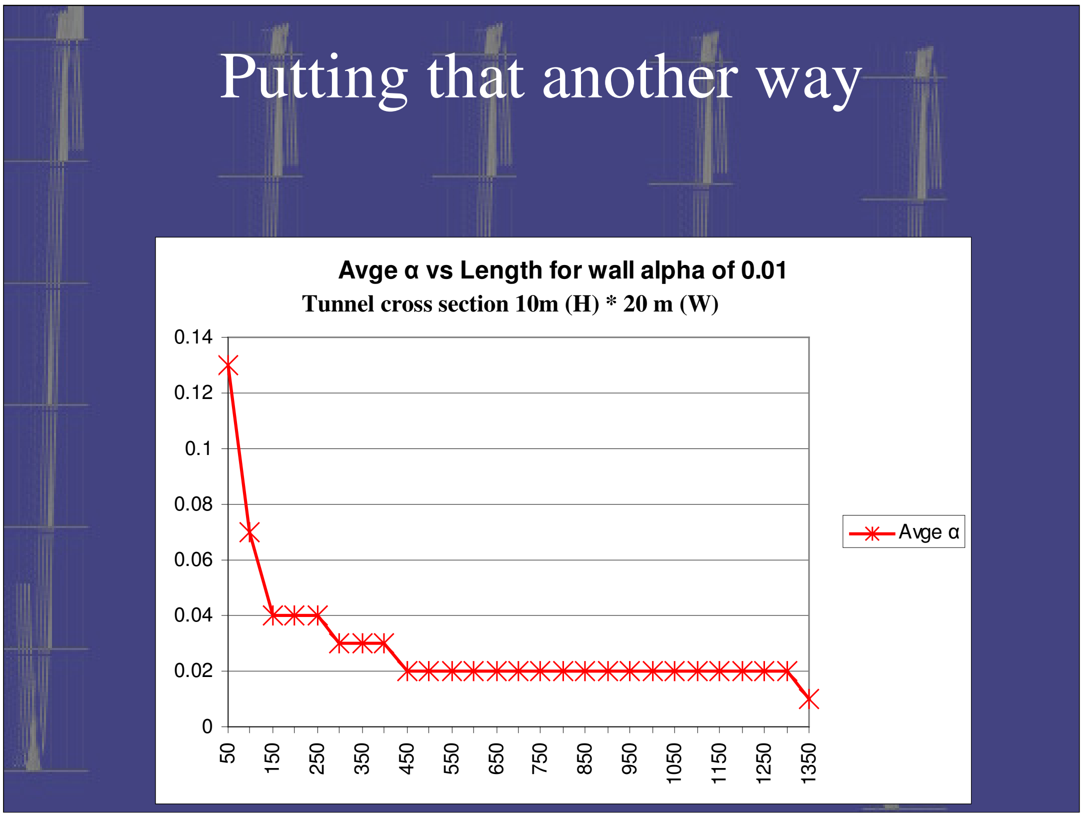


Figure 4. Graph showing proportion of total tunnel surface occupied by ends vs. length in metres for three tunnel sizes.

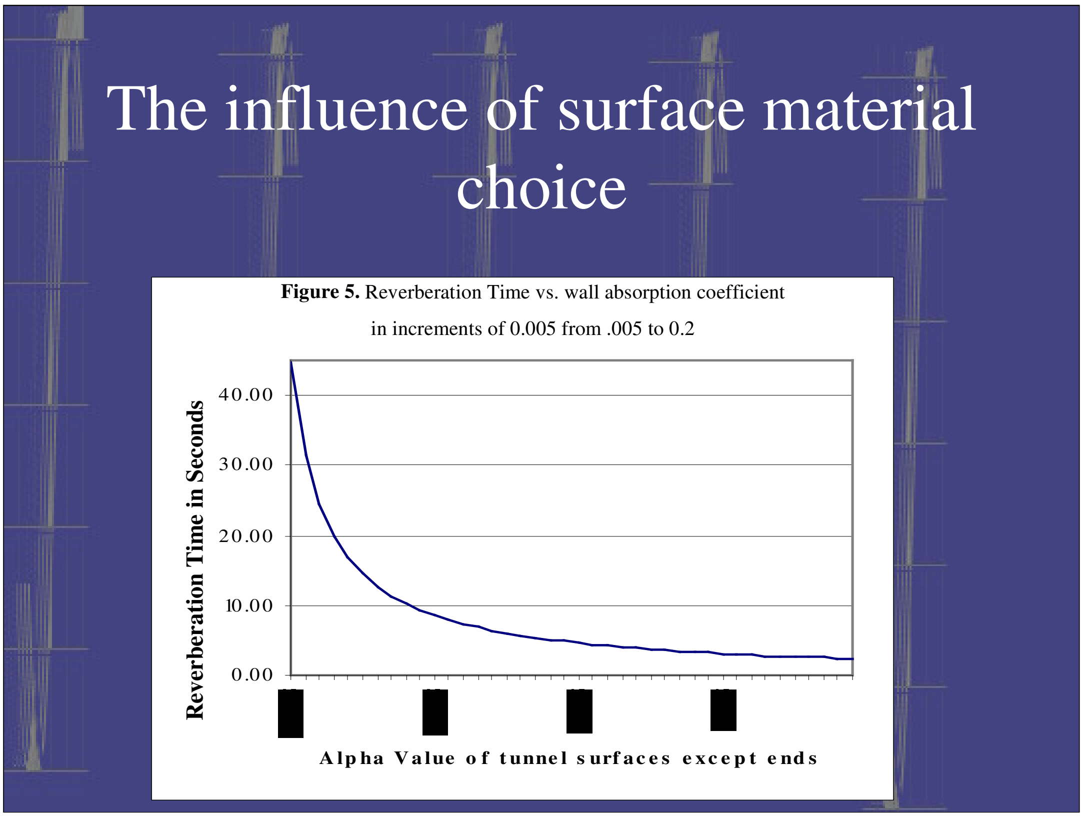
The effect of modeling only a sample length of tunnel skews the reverberation time calculation when the ends of the tunnel are assigned ‘absorber’ properties. The cross section area of the open end remains constant regardless of tunnel length so a shortened tunnel embodies an incorrect ratio of end area (total absorption) to wall area (highly reflective). The effect of increasing the proportion of surface area occupied by the ends depends on the ratio of the area of cross section to tunnel length.

The reason for the erroneous outcomes produced by abbreviated tunnel lengths is demonstrated in figure 4 which shows the ratio of surface area of tunnel end to total surface area for the three tunnel sizes used in this document.



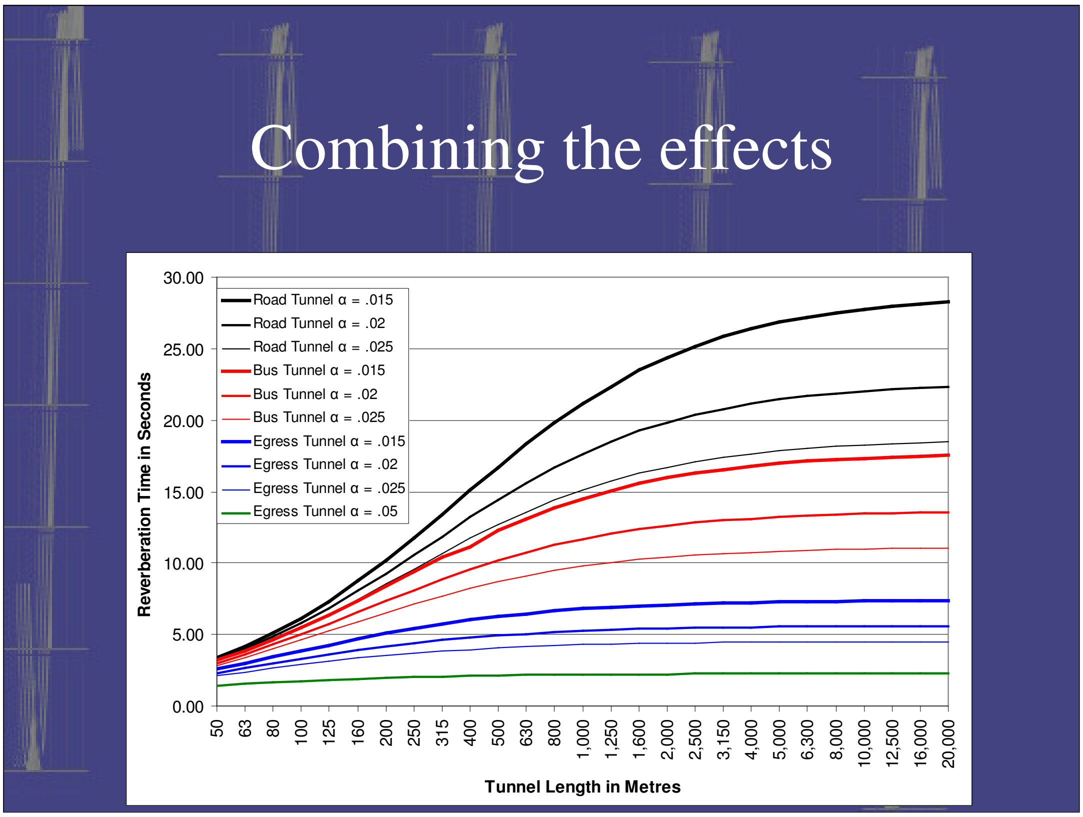
Here we can see the average absorption coefficient rounded to two decimal places vs length of a tunnel with wall coefficients of 0.01 with ends made of ‘absorber’ material.

If the tunnel is 2,000 m long the average is close to 0.01. But if we make the model just 100m long we have an average of 0.07



Typically a model of a tunnel is created using absorption coefficients for concrete and similar materials taken from a database provided by the software authors. Coefficients as low as 0.01 and 0.02 are shown in the generic dataset. Other construction materials used in tunnels are not much more friendly – vitreous enameled steel for instance as used on the architectural features. It should also be noted that the figures for smooth concrete are most likely natural concrete. Painted concrete, which is used extensively in tunnel construction, is likely to exhibit even lower absorption across the spectrum. Absorption coefficients are usually measured in reverberation chambers constructed of smooth concrete. Measuring the behavior of vitreous enameled steel in such a space can hardly be assigned high levels of reliability given the probability that the material under test has similar to, or lower absorption coefficients than the materials comprising the test chamber itself.

Figure 5 shows the effect of wall absorption coefficient vs. reverberation time in a 2,000 m long road tunnel with a 200m^2 cross section modeled with 'absorber' or 100% absorbing ends.

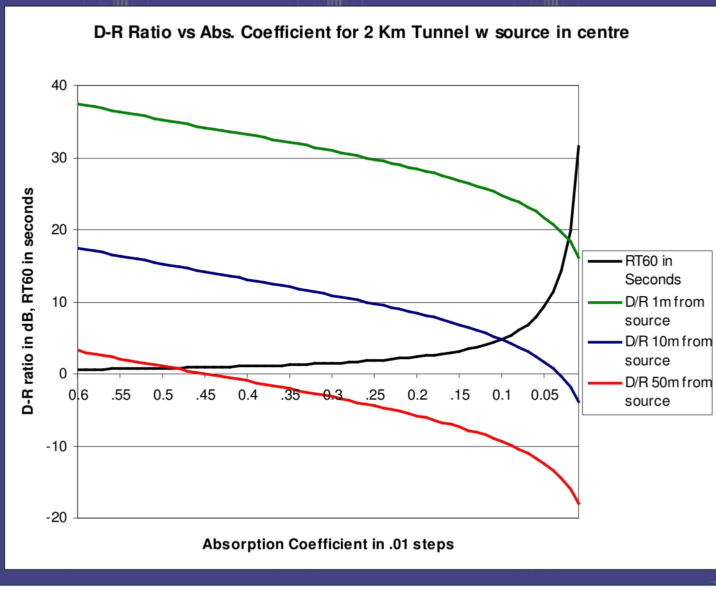


The reader's attention is drawn to the steep nature of the curve in the region of absorption coefficients in the order of smooth concrete (0.01 to 0.02). Reverberation times in the order of 20 seconds have been reported by others (Yokohama et al., 2007) who were able to test a real tunnel thereby adding credence to the graph in figure 5. The point of interest here is that it is extremely unlikely that highly accurate predictions can be made regarding the reverberation time of such a tunnel unless absorption coefficient data, which is accurate to at least three decimal places, becomes available. Given that such data is impractical or impossible to collect it is not possible to verify the precise shape of this portion of the graph by measurement.

The author is aware of at least one paper which tests the accuracy of calculations derived from software models against measured outcomes positively. In the paper known to the author tunnel lengths of 200 metres and less were tested. Under these conditions the open ends of the tunnel are the dominant sound absorbers thereby providing reliability to reverberation time calculations and the following calculations.

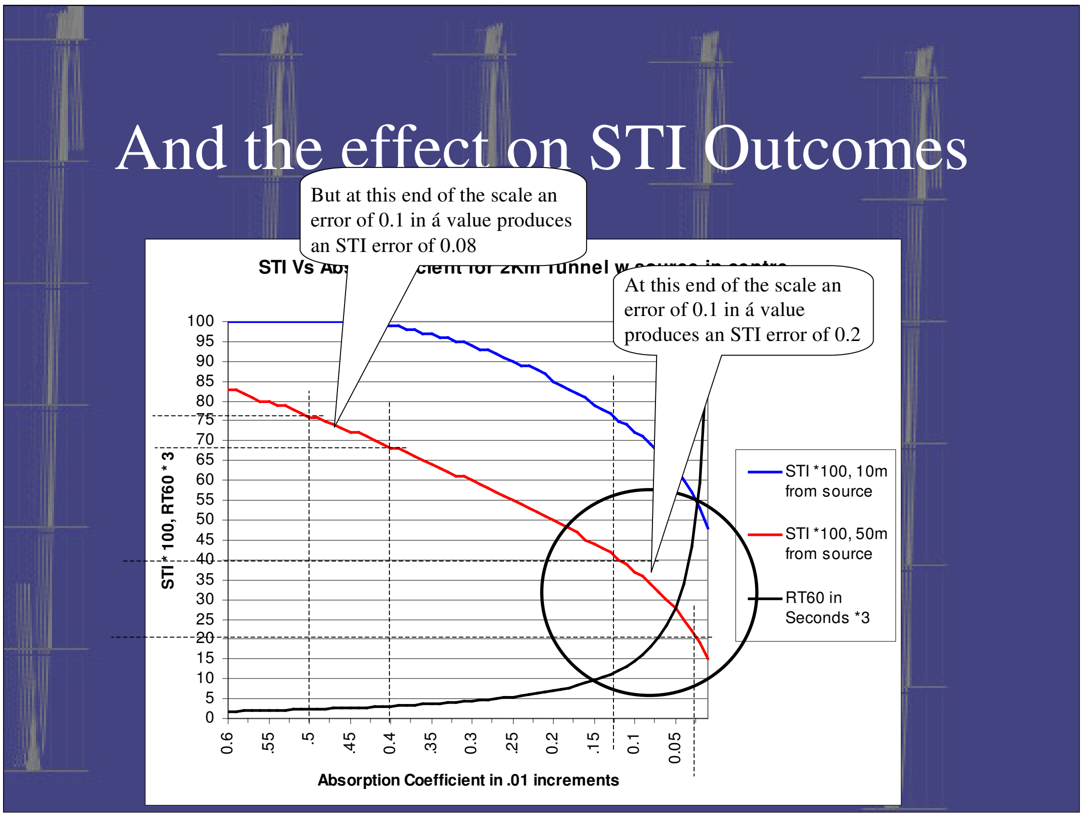
The combined effects of variable or inaccurate absorption coefficient data and incorrect tunnel length are as shown in graphical form in figure 6. The legend is repeated here for clarity – Black = road tunnel, Red = Bus Tunnel, Blue = Egress Tunnel & Green = Egress Tunnel reverberation vs. length with .05 alpha value. (Compressed Clay Brick) Note that the effects of the open ends are significantly diminished when a degree of sound absorption approaching that of compressed clay brick construction is applied. An unpainted concrete block wall in an egress tunnel would deliver a much less hostile loudspeaker system design environment. The same condition would apply in amplified form in a large tunnel.

Translating Absorption coefficient to Direct/Reverberant outcomes



Here we can see that the reverberation time has a direct effect on direct to reverberant ratio which changes linearly with absorption coefficient. Interestingly the linear relationship appears to decline at the right hand end of the graph where very large swings are seen in reverberation time associated with less severe changes in direct / reverberant ratio.

The change in direct to reverberant ratio nonetheless changes quite rapidly with small changes in absorption coefficient



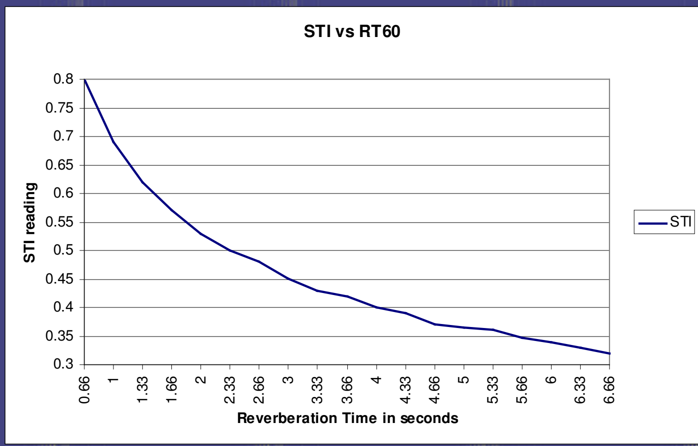
Here we see that the blue graph associated with a shorter source / listener distance is unaffected until the direct/reverberant ratio reaches a critical level.

The red graph shows the same linear relationship as the previous graph.

The dashed line is set at a point representing 5 seconds reverberation time and 0.35 STI at 50m

Increasing the number of loudspeakers only makes matters worse. The outcome of 0.71 at 10 metres in a 5 second reverberation time environment is optimistic too a degree - these figures were taken from a statistical calculation engine with a single source in a tunnel 2,000m long which is obviously producing a reasonable direct / reverberant ratio of about 5 dB at 10 m.

A closer look at the relationship between RT60 and STI



Here we can see that the STI value is flattening out in an exponential manner as reverberation time increases in a linear fashion.

The trouble is that the reverberation time at the low absorption coefficient end of the scale is changing in an upwardly exponential curve with small changes in absorption coefficient

Noise Data

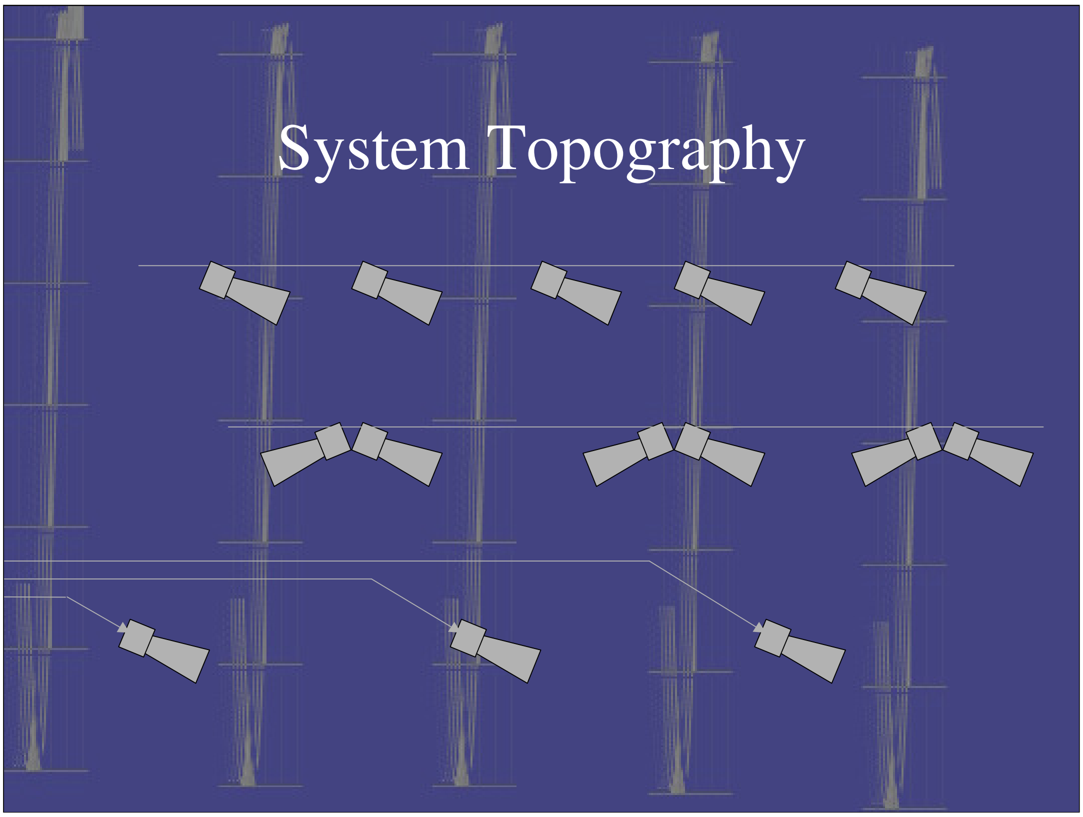
Octave	In Shed	Corrected for Free Field
63 Hz	80.1	78.4
125 Hz	81.1	81
250 Hz	85.6	86.6
500 Hz	77.4	78.8
1,000 Hz	79.5	78.2
2,000 Hz	78.9	78.5
4,000 Hz	75	75.2
8,000 Hz	70.1	71.8

Table 1. Noise data provided by client showing octave band noise levels for a typical axial fan

Table 1 replicates a data set provided in good faith by a tunnel construction team member for use in calculating a loudspeaker systems performance and ability to deliver an acceptable STI in the presence of fan noise. The original measurements seem to have been made in a factory shed of some kind and then converted to “free space” using an unknown formula. The data was used at the clients insistence and is presented and used in the calculations in this paper in order to illustrate the outcome it produced in the modeling process. It is not presented as factual data to be relied upon by others.

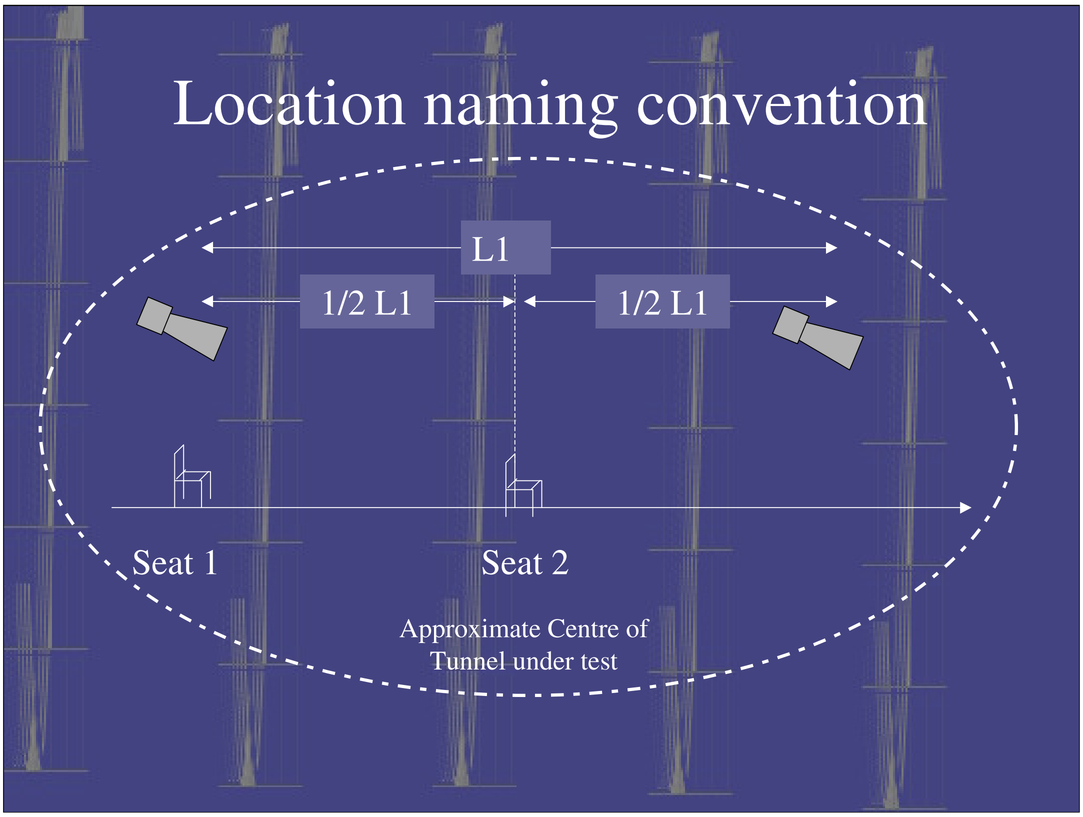
In follow up conversations with tunnel project engineers no fan noise data has been discovered that can be shown to have been measured under standard measurement conditions

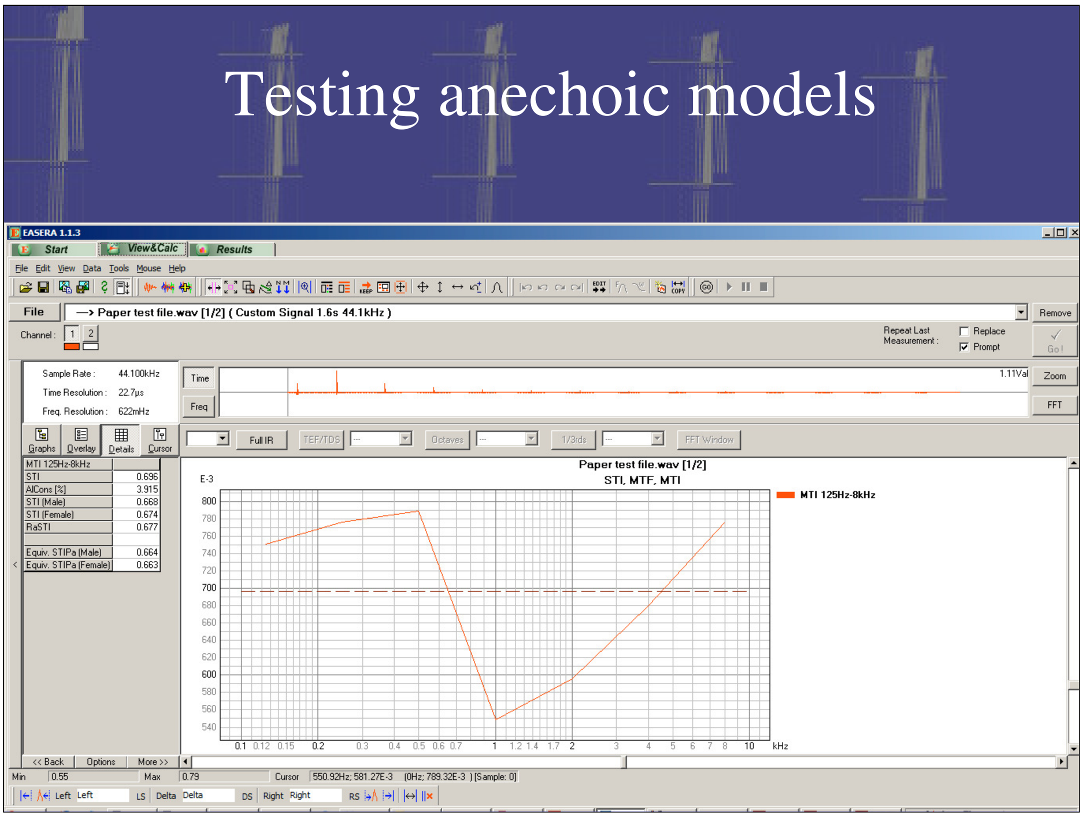
The conclusion reached by the author is that shortening model tunnel lengths to accommodate computer resource constraints, surface material information of insufficient accuracy and lack of reliable noise level data can conspire to produce a highly unreliable design environment.



There is a wide range of system topography options available to the loudspeaker system designer. Simple distributed systems comprised of individual loudspeakers, distributed clusters of loudspeakers and sequentially delayed arrangements all have been utilised. Critical parameters include (a) Loudspeaker performance (b) distance from loudspeaker to listener (c) number of loudspeakers.

The simple distributed system using individual loudspeakers without signal delay processing has application in egress tunnels where the loudspeaker to listener distance can be managed and kept quite short. In such cases the direct sound path length can be kept short enough to ensure the direct sound pressure level is quite high compared to the reverberant sound pressure level. Further, the short distance from loudspeaker to listener means that quite low sound pressure levels from the loudspeaker will generate useful sound pressure levels for the listener. For example small loudspeakers generating 90 dB (A) @ 1.0m in a distributed system with 5.0m spacing and 1.2m above the listeners head will produce approximately 84 dB (A) near the mid point between loudspeakers. A similarly simple situation (isotropic loudspeakers) in a large tunnel with 40m loudspeaker spacing requires approximately 108 dB (A) @ 1.0m for the same listener level. The dense spacing in a small tunnel thereby requires a lower total acoustic power to deliver 85 dB (A) to the listener thereby generating a lower level of reverberant energy for the same listener sound pressure level. The relationship is governed to a degree by the inverse square law in that the direct sound increases by 6 dB when the distance to listener is halved but the reverberant field strength only increases by 3 dB with every doubling of the number of loudspeakers. This means in effect that the designer can always make gains in intelligibility by increasing the number of loudspeakers provided that when doubling the number of loudspeakers the distance from loudspeaker to farthest direct field listener is halved.


Location naming convention
L1
1/2 L1
1/2 L1
Seat 1
Seat 2
Approximate Centre of
Tunnel under test



One seldom considered aspect of system design however, is the aggregated effect of multiple direct sound arrivals. Loudspeaker spacing has a very direct bearing on the interval between arrivals of loudspeaker sound at increasing distance from the listener. The effect of loudspeaker spacing was tested in an anechoic model dimensioned for an egress tunnel 3.0m (H) * 2.8m (W) * 100m (L). Isotropic loudspeakers (spheres) were set at 2.95-m height and listening points at 1.7m for a standing human. One listening directly below a loudspeaker at or very near the centre of the 'tunnel' and another set at the halfway point between two loudspeakers. Ease software allows the user to collect a sample impulse response from individual locations, in this case seat 1, directly below the central loudspeaker, and seat 2, centrally located between the two loudspeakers nearest the centre. Figure 7 shows a graph from the software displaying the direct sound arrivals from one of a sequence of tests undertaken for this document. The software also provides an option to export the impulse response in a number of forms including a 44.1 KHz sample rate *.wav file, Binaural Impulse response (BIR) and several other options. The exported file can then be imported into the analysis package 'Easera'.

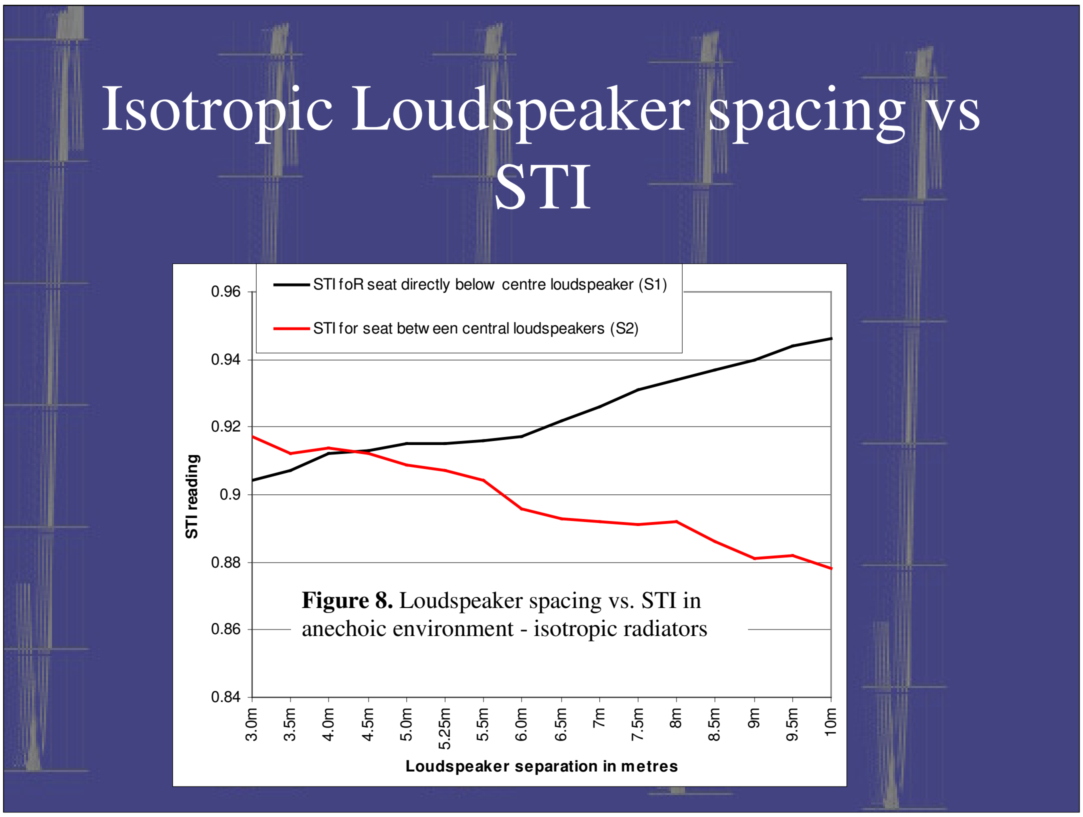


Figure 8. Loudspeaker spacing vs. STI in anechoic environment - isotropic radiators

Figure 8 shows the calculated STI results for various loudspeaker spacing for both the seat below the central loudspeaker (seat 1) and the mid point listener (Seat 2). This convention is used for anechoic and echoic tunnel test measurements throughout this paper.

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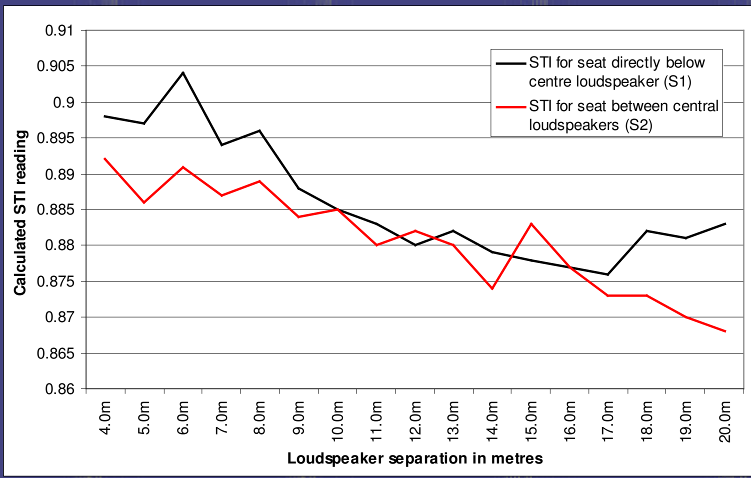
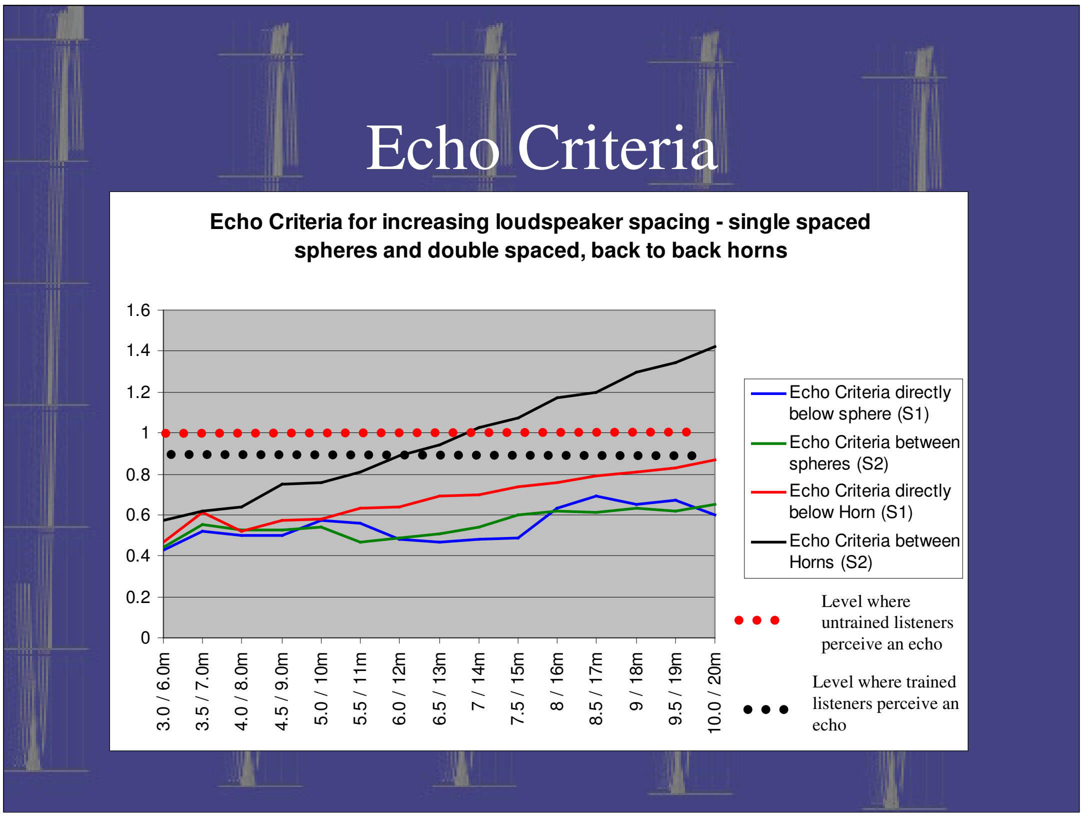
The roll off in STI calculated for the mid-point between loudspeakers with increasing spacing relates to the strength of first arrivals compared to later arrivals from loudspeakers 10m more distant in sequence. The increase in STI value with increased spacing for the seat directly below the central loudspeaker relates simply to the increasing ratio of direct sound from this loudspeaker to the direct sound pressure from increasingly more distant ‘next’ loudspeakers. It is proposed that the point where the two graphs cross (4.5) is the optimum spacing for the physical conditions in the model. That is, with loudspeakers set on a 3.0m high ceiling for a standing listener. In this case the STI delivered to the listener is the most evenly distributed and of the highest order.

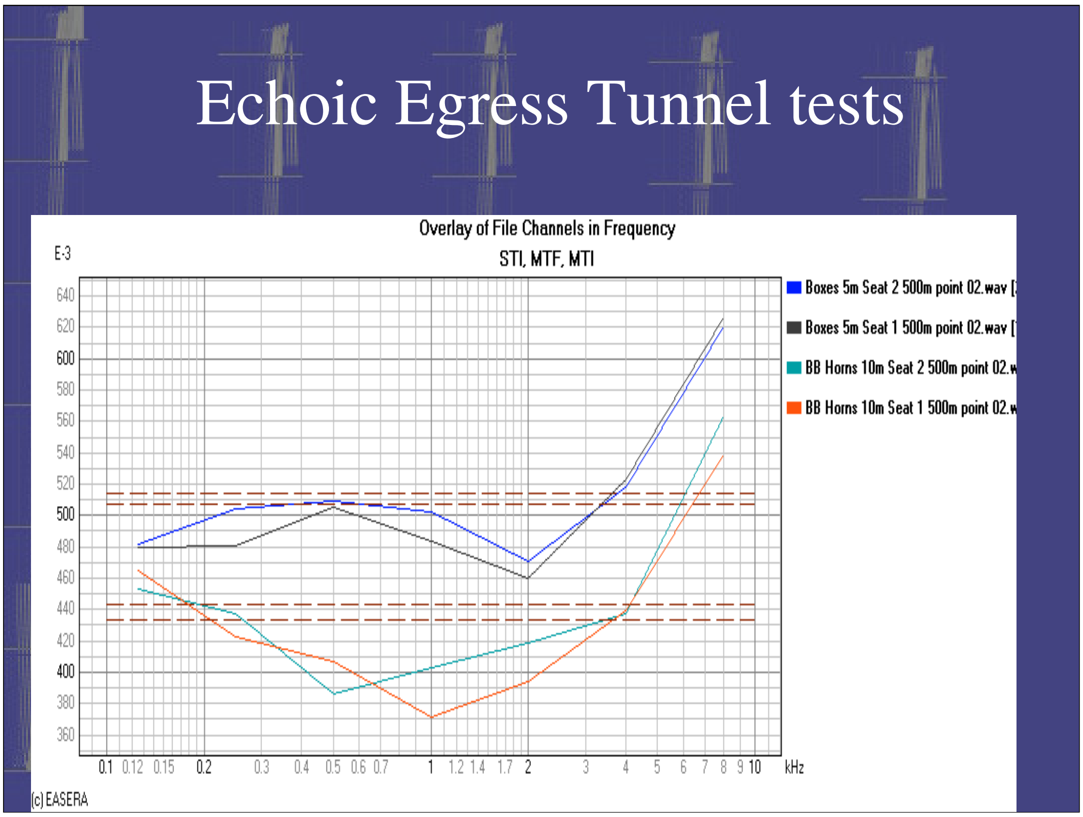
STI vs spacing for horn speakers





Another measure of sound quality is the Echo Criteria developed by Dietsch and Kraak and implemented in the Easera analysis package. [1], [5], [8]

Figure 10 shows the graphed outcomes for isotropic radiators and double spaced back to back horns. It shows that double-spaced horns in back to back configuration (Black curve) produce increasingly distinct echoes between loudspeakers at distances greater than 14 metres.



A 500m long egress tunnel model was assigned absorption values of 0.02 for all walls, ceiling and floor. The ends were assigned absorber values or 100% absorption, which gave a 1 KHz reverberation time of approximately 5.0 seconds. Two loudspeaker systems were assessed using a hybrid ray trace routine. The systems tested were (a) Commonly used horn speakers set back to back 10.0 metres apart and (b) Commonly available indoor/outdoor cabinet loudspeakers with a cone driver and dome tweeter individually placed and set at 5.0m spacing. The listener seats were placed (a) directly below a pair of horns or single cabinet (Seat 1) and at the half-way point between loudspeaker mounting points. (Seat 2)

The STI outcomes for all four combinations are shown overlaid in figure 11. (Upper traces cabinet speakers @ 5.0m centres, lower traces horn speakers @ 10m centres) The restricted fidelity of the horn speakers (a) prevents the 125 Hz octave being heard and therefore restricts the real world intelligibility for the male voice [6] (b) renders calculations for horn speaker's invalid below 200Hz. Figure 13 shows the centre time outcomes for the 10m spaced horn speaker pairs is the major cause of poor performance [8] compared to the 5.0m spaced cabinet speakers which deliver the shorter centre times.

The Y axis of figure 11 is displayed as mili units or 300 thousandths of a unit to 560 thousandths of a unit which means STI values from 0.3 to 0.56 on a scale of 0 to 1.0

The X axis of figures 11 and 12 are scaled from approximately 100 Hz to 15 KHz in the frequency domain. The Y axis of figure 12 extends from approximately 40 to 260 ms.

Echoic Egress Tunnel tests

Anechoic Road Tunnel System Tests

Arrangement		Spheres	Small Horns	Medium Horns	Large Horns	Premium Horns	Infinite Boundary
Loudspeakers in 20m spaced line no delay	Echo Criteria Seat 1	1.15	1.58	1.33	1.36	1.16	0.92
	Echo Criteria Seat 2	1.32	1.7	1.33	1.34	1.23	1.15
	STI Seat 1	0.663	0.608	0.587	0.584	0.576	0.75
	STI Seat 2	0.735	0.64	0.608	0.593	0.572	0.696
	Centre Time Seat 1	52ms	85ms	113ms	116ms	118ms	31ms
	Centre Time Seat 2	37ms	60ms	89ms	93ms	94ms	47ms
Loudspeakers back to back in 40m spaced line no delay		Spheres	Small Horns	Medium Horns	Large Horns	Premium Horns	Infinite Boundary
	Echo Criteria Seat 1	2.14	2.75	2.52	2.55	2.07	1.65
	Echo Criteria Seat 2	2.36	3.41	2.56	2.52	2.26	2.37
	STI Seat 1	0.862	0.737	0.71	0.69	0.646	0.872
	STI Seat 2	0.77	0.739	0.685	0.686	0.705	0.755
	Centre Time Seat 1	17ms	72ms	125ms	137ms	144ms	18ms
	Centre Time Seat 2	40ms	45ms	55ms	55ms	59ms	44ms
Loudspeakers in 40m spaced line 118ms delay		Spheres	Small Horns	Medium Horns	Large Horns	Premium Horns	Infinite Boundary
	Echo Criteria Seat 1	2.92	3.83	2.94	2.76	2.45	1.14
	Echo Criteria Seat 2	2.97	4.27	3.43	3.17	2.81	0.55
	STI Seat 1	0.887	0.873	0.928	0.93	**0.918**	0.963
	STI Seat 2	0.576	0.813	0.878	0.898	**0.923**	0.998
	Centre Time Seat 1	44ms	35ms	22ms	20ms	**17ms**	27ms
	Centre Time Seat 2	108ms	45ms	19ms	16ms	**13ms**	11ms

Road Traffic Tunnel loudspeaker system tests for an anechoic environment were conducted in three main arrangements. (1) All loudspeakers facing the same direction set at 20m intervals (2) Loudspeakers set in clusters of two facing in opposite directions with the clusters set at 40m intervals (3) All loudspeakers facing the same direction at 40m intervals with a sequential delay time of 118ms. Six loudspeaker types were tested (a) Isotropic radiators or ‘spheres’, (b) Small Horn speakers approx. 15cm diameter (c) medium size horn speakers approx. 35cm diameter (d) Large horn speakers approximately 50cm diameter (e) premium horn speakers approx. 60cm diameter (f) Loudspeakers set on an Infinite baffle producing no dispersion to the rear.

The convention used for egress tunnel calculations was continued with seat 1 directly below a loudspeaker or cluster near the half way point in the tunnel and seat 2 at the mid point from seat 1 to the next loudspeaker. The road tunnel model was 1,050m in length, 10.0m in height and 20.0 m in width with loudspeakers set on the ceiling. All loudspeakers were set at a down-tilt of 10 degrees in all tests.

The first set of tests were derived by saving the direct arrivals from all loudspeakers at each seat as a *.wav file then opening the file in Easera where the system performance was calculated in complete absence of consideration for signal to noise, sound pressure level or frequency response. The loudspeaker system temporal behavior and loudspeaker directivity are the determining factors. The results are given in Table 2

The sequential delay system offers a clear advantage when the delay time is critically adjusted and high directivity loudspeakers used. Where non-directional loudspeakers are used the sequential delay actually degrades performance. The ultimate performance is obtained from a sequential delay system when the loudspeaker has an infinite front to back ratio.

Effects of Added Noise I

	20 m spaced	Back to back 40m	118ms Sequential delay		
	Medium Horns	Medium Horns	Medium Horns	Large Horns	Premium Horns
STI Seat 1	0.505	0.617	0.736	0.732	0.751
STI Seat 2	0.533	0.595	0.686	0.698	0.758

Table 3. STI from anechoic tests with octave band noise

Five cases were selected for further examination by exporting the direct arrival impulse response as an Ease Binaural Impulse Response file. This type of file conveys sound pressure level directly to Easera thereby permitting the introduction of fan noise into the STI calculation. The Fan noise octave band data for ‘free space’ from table 1 was transcribed into the Easera STI Options data sheet along with the loudspeakers calculated octave band SPL. All loudspeakers were set with the same output SPL over the stated operating band: - 95 dB lin. in each 1/3 octave band. The results are shown in Table 3 where it can be seen that that at seat 2 the premium horns deliver an audible improvement in intelligibility.

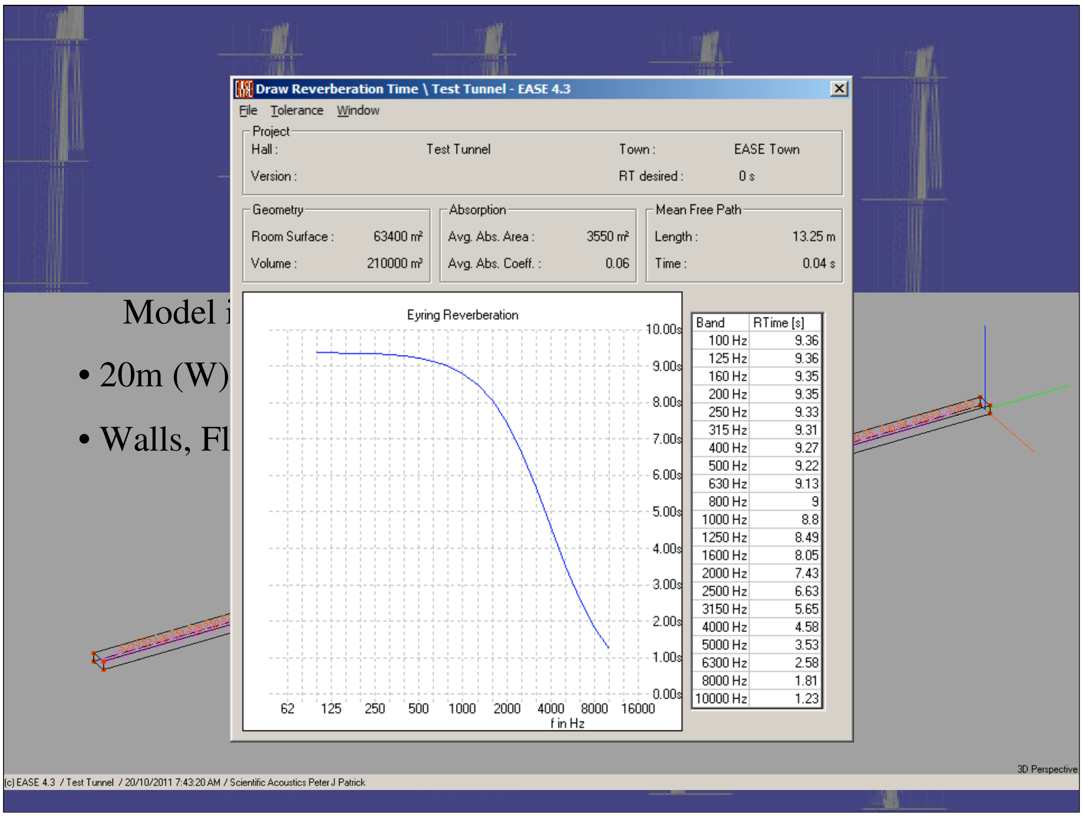
Comparison of test methods

20 m spaced medium horns				
	No Noise Easera calc	No Noise XL2 Meas	With Noise Easera Calc	With Noise XL2 Meas
STI Seat 1	0.587	0.57	0.505	.5 *
STI Seat 2	0.608	0.57	0.533	.51 *
40 m spaced Back to back medium horns				
	No Noise Easera calc	No Noise XL2 Meas	With Noise Easera Calc	With Noise XL2 Meas
STI Seat 1	0.71	0.64	0.617	.57 *
STI Seat 2	0.685	0.65	0.595	.61 *
40 m spaced sequential delay premium horns				
	No Noise Easera calc	No Noise XL2 Meas	With Noise Easera Calc	With Noise XL2 Meas
STI Seat 1	**0.918**	0.93	**0.751**	0.76 *
STI Seat 2	**0.923**	0.94	**0.758**	.86 *
* - readings obtained by adding signal and noise and adjusting total level to ~ 70 dB(A)				

Table 3. STI from anechoic tests with octave band noise

A second method was applied as a crosscheck. Binaural Impulse Response files (BIR) were used in a process whereby STIpa source signal from an NTi Audio MR-PRO was convolved through the BIR to produce a *.wav file of a kind used for 'auralisation'. The convolved signal was fed into an NTi Audio XL2 Analyzer and the signal level adjusted for a chosen level in dB (A). The STIpa measuring mode is then selected and a reading obtained. The same convolved signal was also mixed with a noise signal shaped according to the 'free field' column of table 1, to simulate a signal to noise ratio chosen to simulate real conditions. The outcome is shown in Table 4

The correlation between methods is reasonable. The noise loaded readings using the NTi Audio system required a total signal + noise level of ~70 dB (A) at the input of the XL2. Significant differences were found to relate to the NTI systems use of a continuous variable formula for STI vs SPL whereas the Easera system utilised the formula from IEC 60268-16 Third Edition 2003 – 05 which is not continuous.

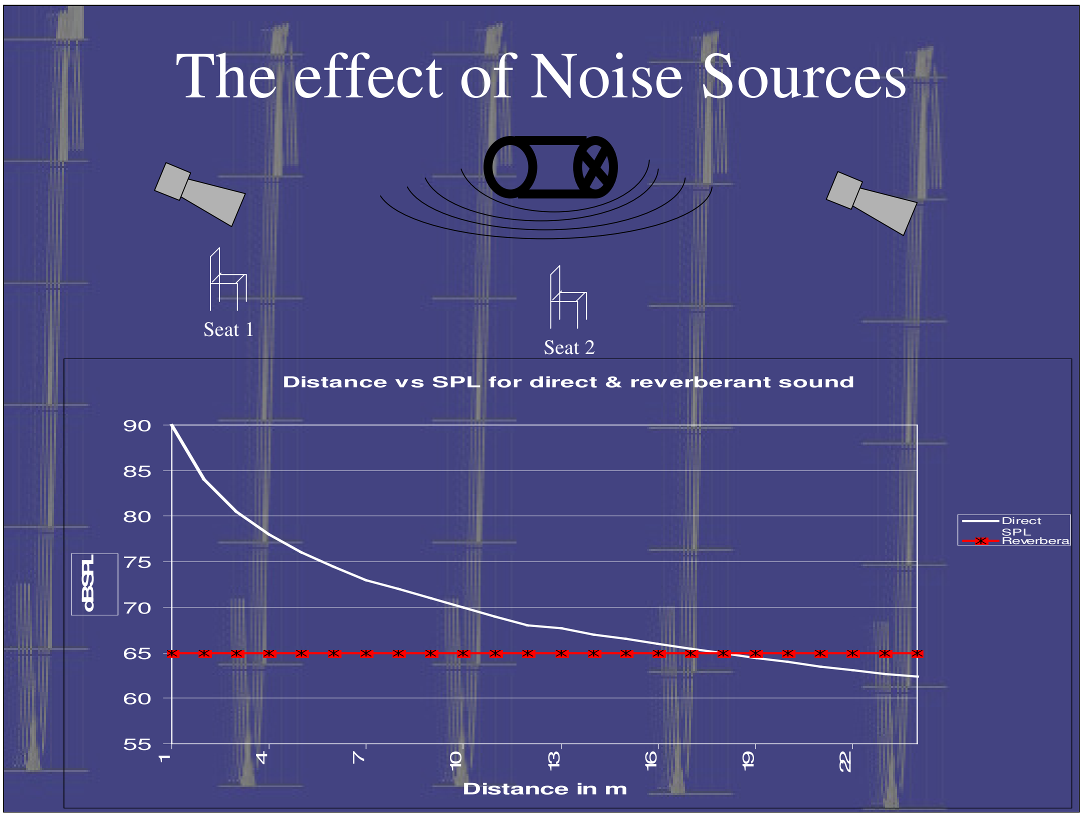

Draw Reverberation Time \ Test Tunnel - EASE 4.3
File Tolerance Window
Project
Hall : Test Tunnel
Town : EASE Town
Version :
RT desired : 0 s
Geometry
Room Surface : 63400 m²
Volume : 210000 m³
Absorption
Avg. Abs. Area : 3550 m²
Avg. Abs. Coeff. : 0.06
Mean Free Path
Length : 13.25 m
Time : 0.04 s
Eyring Reverberation
10.00s 9.00s 8.00s 7.00s 6.00s 5.00s 4.00s 3.00s 2.00s 1.00s 0.00s
62 125 250 500 1000 2000 4000 8000 16000
f in Hz
Band RTime [s]
100 Hz 9.36
125 Hz 9.36
160 Hz 9.35
200 Hz 9.35
250 Hz 9.33
315 Hz 9.31
400 Hz 9.27
500 Hz 9.22
630 Hz 9.13
800 Hz 9
1000 Hz 8.8
1250 Hz 8.49
1600 Hz 8.05
2000 Hz 7.43
2500 Hz 6.63
3150 Hz 5.65
4000 Hz 4.58
5000 Hz 3.53
6300 Hz 2.58
8000 Hz 1.81
10000 Hz 1.23
Model i
• 20m (W)
• Walls, Fl
3D Perspective
(c) EASE 4.3 / Test Tunnel / 20/10/2011 7:43:20 AM / Scientific Acoustics Peter J Patrick

Road Tunnel Echoic test results - same loudspeakers - three topographies

	20m horns		40m B-B		40m sequential delay	
	Seat 1	Seat 2	Seat 1	Seat 2	Seat 1	Seat 2
STI	0.23	0.24	0.31	0.27	0.62	0.61
EkGrad	1.43	1.1	1.21	0.98	0.68	0.67

Each Echoic test took ~ 7 days in a standard ray trace routine. That’s three weeks testing for six listener seats and three system designs.

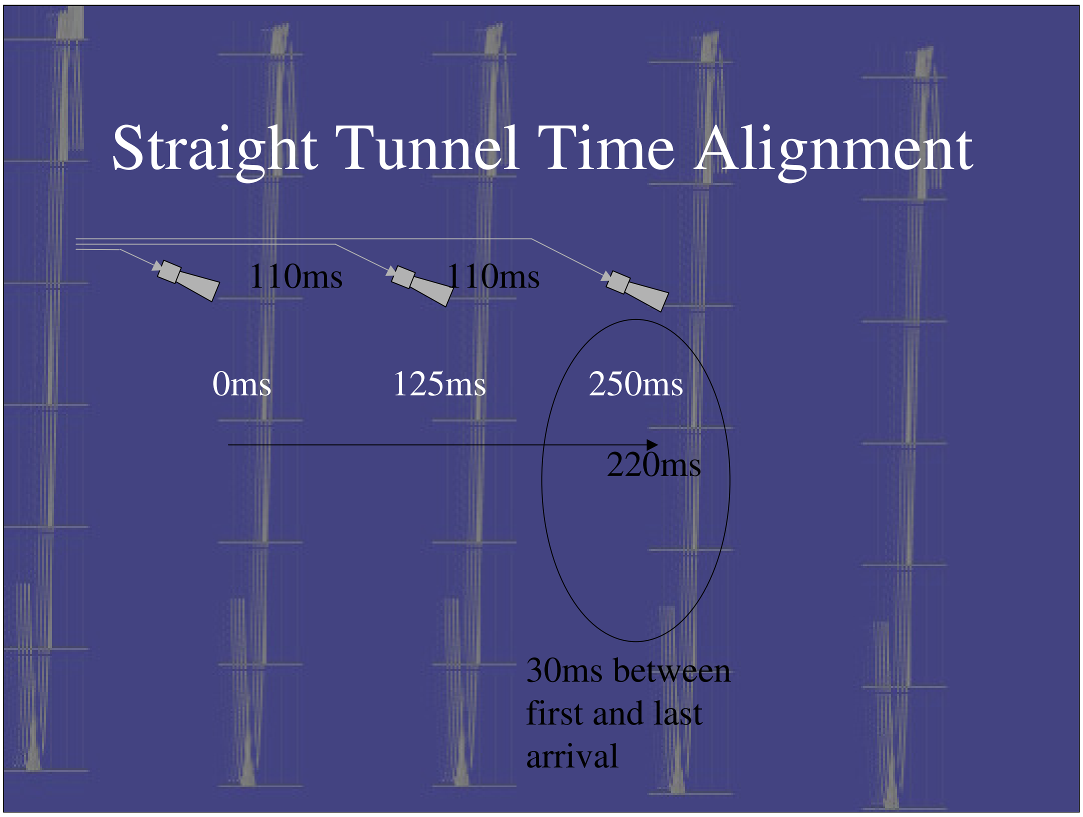
The absolute values for STI are irrelevant but comparisons are valid. The change from figures circa 0.3 in the plain distributed system to 0.6 for the sequential delay system align well enough with the findings from the Japanese study (Reference [7] where the sequential delay improved STI readings from 0.15 to 0.3



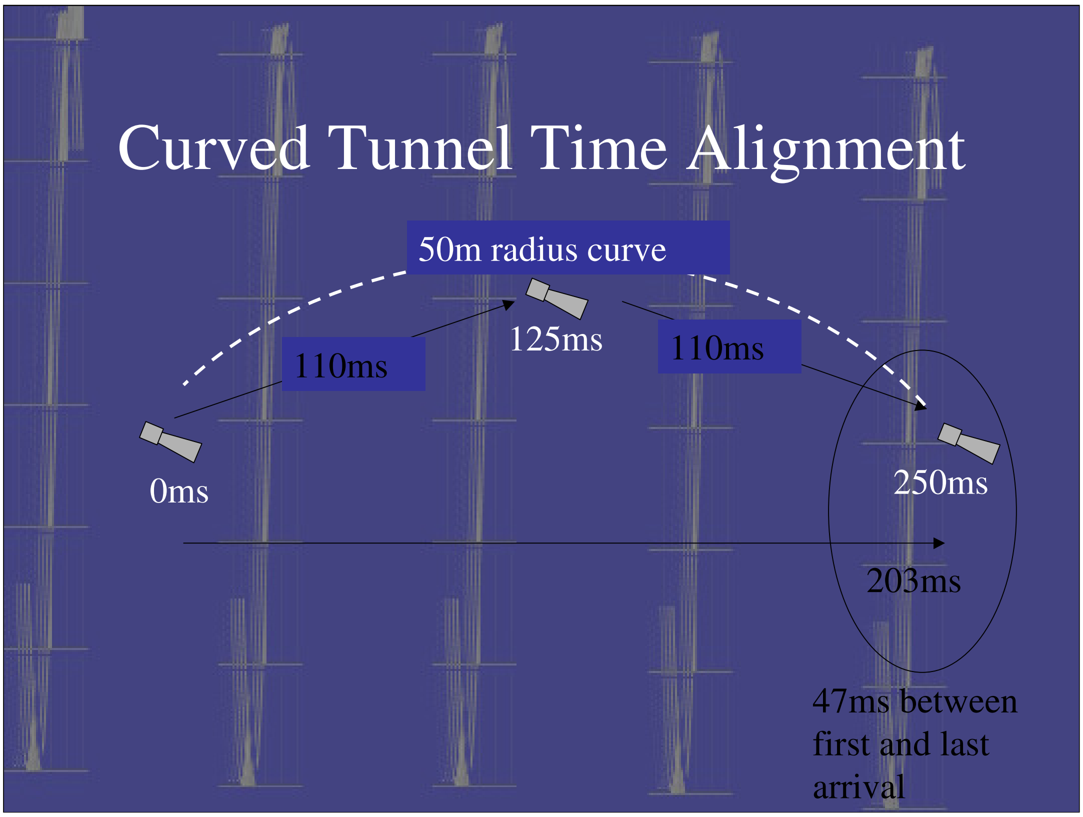
THE EFFECTS OF NOISE SOURCES

It is expected that the readings at seat 2, the mid point between loudspeakers, will suffer significant degradation in consequence of degraded direct to reverberant sound level ratio compared to seat 1, directly below a loudspeaker.

The location of a noise source, such as a large axial fan, in the region of seat 2, where the direct to reverberant ratio is degraded, will result in further degradation of an already challenged outcome. The location of fans therefore indicates a requirement for a companion loudspeaker, placed within a few metres of each fan.



The time alignment of the loudspeaker system for sequential delays is a simple task when the tunnel follows a straight line. Large radius curves however, present an increased level of difficulty. The sum of all individual delays in a curved line of loudspeakers in a replica of a real tunnel was approximately 537 ms. The direct path from first to last however, is 506ms. Signal delay settings which satisfy Haas effect requirements for a straight line of loudspeakers will incur an extra 31 ms spread in arrival times at the destination loudspeaker which in turn compromises the system STI. Careful alignment of time delays is required to optimise STI outcomes.


Curved Tunnel Time Alignment
50m radius curve
110ms
125ms
110ms
0ms
250ms
203ms
47ms between
first and last
arrival

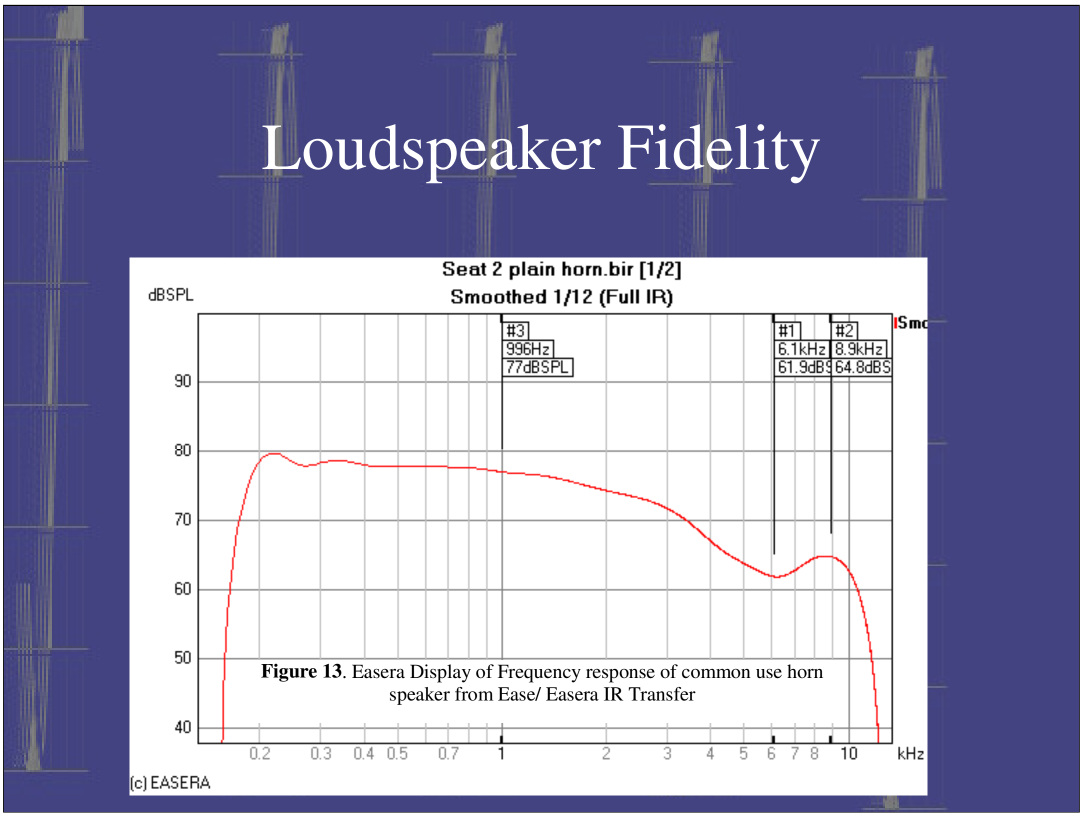
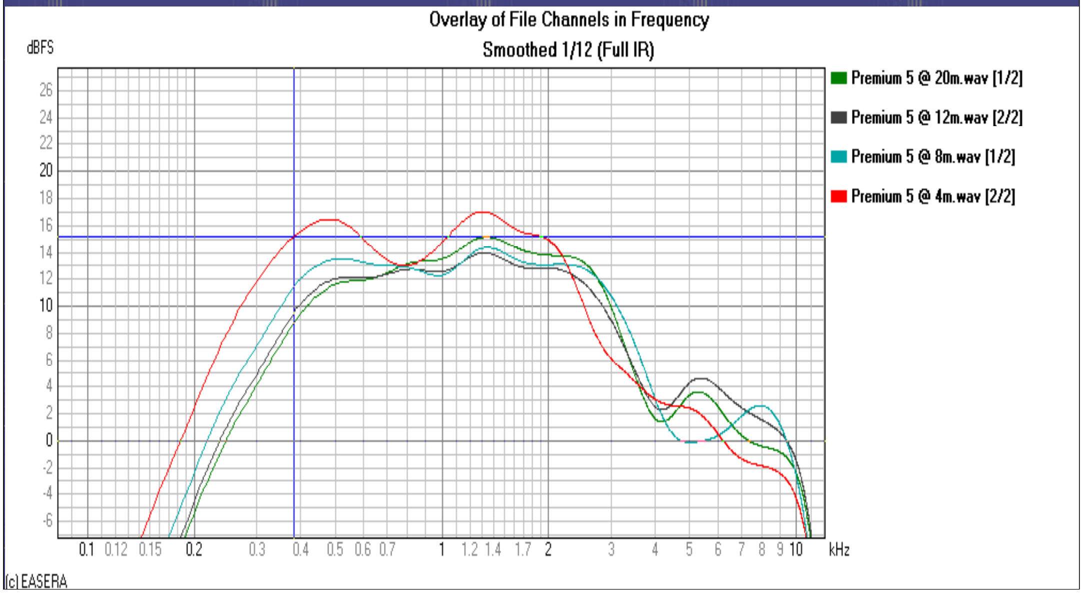


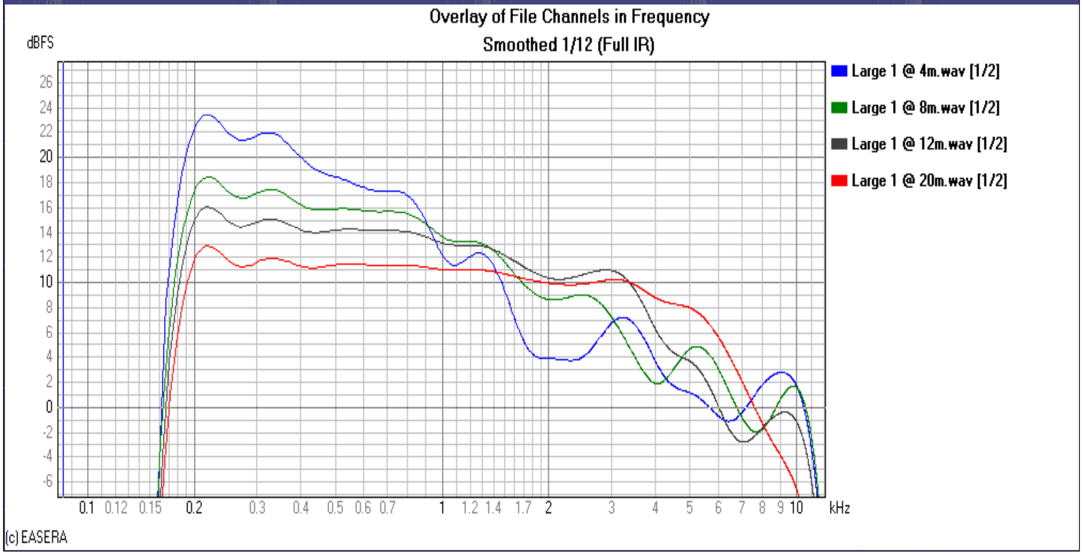
Figure 13. Easera Display of Frequency response of common use horn speaker from Ease/ Easera IR Transfer

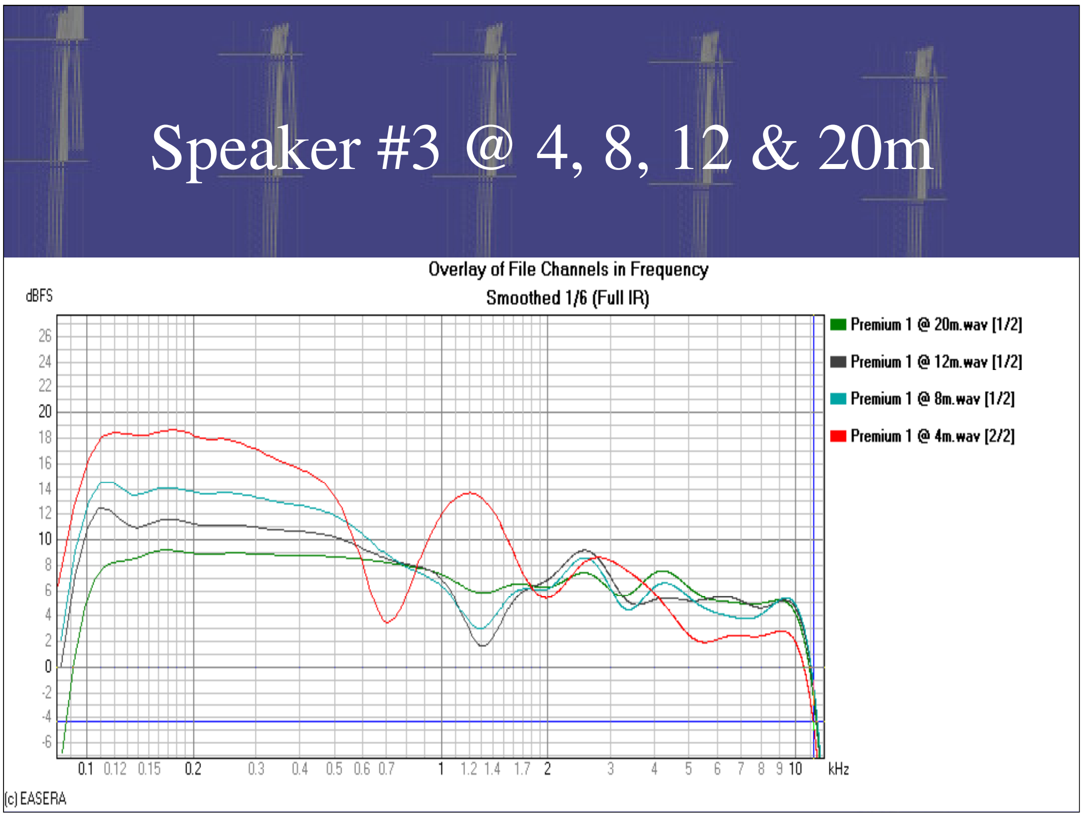
Figure 13 shows a frequency response plot from a commonly used horn speaker derived by exporting the impulse response from Ease into Easera. Here we can see firstly that the Ease data was gathered from 1/3 Octave smoothed pink noise bands because the response curve shape is unusually smooth for a loudspeaker response resolved to 1/12th Octave. It shows however that the speaker response rolls off at approximately 24 dB / Octave below 200 Hz and that the HF response rolls off by approximately 18 dB at 6 KHz. Manufacturers printed data for the same product in higher resolution shows a 30 dB change in output from a peak at around 1,600 Hz to a trough at around 8 KHz. The male voice STI measure includes the 125 Hz and 8 KHz octave bands which common horn speakers do not reproduce well at all. Further the process of equalising a 30dB range in response in an electronic system generates extreme requirements on system dynamic range.

Speaker #1 @ 4, 8, 12 & 20m



Speaker #2 @ 4, 8, 12 & 20m





A frequency response which is flat within a few dB across the register of interest and across the range of listening distances is simply undeliverable because:- (a) variations of 30dB if they exist, can not be equalised without over stressing system dynamics and (b) the response changes with distance. Figure 14 shows a comparison of frequency response measured at four set distances from the loudspeaker, for three loudspeakers generically suitable for tunnel announcement system installation.

Equalising a frequency response aberration requires a deal of averaging for a flat overall outcome at the octave band centres of interest

• The native behavior of any sound system topography should be first proven in an anechoic environment before implementing in a tunnel environment.

• Each large, fixed noise source, should be complemented with a nearby companion loudspeaker. to maximise signal to noise ratio. The distance between these companion loudspeakers should then form the basis for the rest of the design so that the string of intermediate loudspeakers is set at equidistant intervals between fans.

• Whilst the down-tilt of the loudspeakers was treated arbitrarily in this document it is nonetheless a critical feature to be optimised in any design to suit the height of the loudspeaker and geometry of the tunnel

• Any model of a tunnel should include the full dimensions, particularly tunnel length, wherever possible. The reliability of calculations made relate to the proportion of tunnel length modeled as shown in figures 4 & 6. Significantly truncated tunnels will produce significantly optimistic calculated outcomes.

• It is unlikely that highly reliable calculations can be made in the presence of the hostile acoustic environment found in long tunnels as currently built. Calculations based on structures composed of material data sets of insufficient accuracy as described in figure 5 and associated text, are likely to render outcomes at substantial variance with the final result.

• Computer resource restrictions remain a serious obstacle to the derivation of detailed design work. The statistical analysis calculation engines deliver reasonable outcomes in a short space of time for plain distributed systems but can not accommodate a sequential delay system. Detailed analysis of sequential delay systems may take months to conclude using common ray trace technology. Computer cloud systems where a subscriber uploads a model to a large networked computer system may be available in the near future.

• Time alignment of sequential delay systems must be critically adjusted where road curvature is encountered.

• Loudspeaker selection should include examination of frequency response to reconcile equalisation needs with system dynamics and STI requirements. Equalisation must be done by measuring at several locations.

Finally

In general it is unlikely that ‘good’ levels of intelligibility will ever be delivered in a road tunnel audio system until some measure of control over reverberation time is available. The use of sound absorbing concrete, unpainted blockwork or some similar product with absorption coefficients of the order of 0.1 would add a significant measure of sabins to the quota presently found, substantially improve the outcome, and improve the reliability of the modeling process.