DESIGN OF VOICE ALARM SYSTEMS FOR TRAFFIC TUNNELS: OPTIMISATION OF SPEECH INTELLIGIBILITY

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The design and optimisation of voice alarm (VA) systems for traffic tunnels is discussed. The acoustic conditions in traffic tunnels are generally very hostile to sound systems. The present study focuses on the improvement and optimisation of speech transmission quality under these conditions. Electro acoustic guidelines are given for the design of VA systems in tunnels on the basis of a dedicated Asymmetric Boundary Flare (ABF) horn. A new optimisation tool is introduced which measures STI using the STIPA method and calculates the required pre-filtering of the speech signal to achieve optimum intelligibility under the actual acoustic conditions in the tunnel. This optimisation algorithm has been tested by measurements on site. The results show that a significant improvement of speech transmission quality can be realised in traffic tunnels.

1 INTRODUCTION

In Europe, voice alarm and announcement systems in tunnels are often required. These systems have to meet stringent criteria with respect to speech intelligibility. Unfortunately, the acoustic conditions in traffic tunnels are generally very hostile to sound systems, caused by the long reverberation and high ambient noise levels.

In order to achieve sufficiently high levels of speech intelligibility several measures are available. Firstly, increasing the direct-to-reverberant ratio by taking room acoustic measures such as adding acoustic absorption. This is often very costly and impractical. Secondly, reducing the background noise by applying quieter ventilation systems. Technically this is possible, but not always realised in practice. Moreover, the noise caused by the traffic itself cannot be eliminated, giving a fixed lower limit for the background noise.

The alternative is to use dedicated, highly directional loudspeakers. For this purpose Duran Audio developed the Asymmetric Boundary Flare (ABF-260) horn. Due to the high front-to back ratio of the directivity pattern and the relatively low signal distortion, a significant improvement of sound quality and intelligibility can be realised in tunnels.

A well-established objective measure of speech transmission quality is the Speech Transmission Index (STI). Although speech transmission quality is not the same as speech intelligibility, it's often used as such.

In many situations the intelligibility of speech in noise may be assumed to be independent of the presented sound level and is primarily determined by the signal-to-noise ratio. However, at high speech levels, the subjective intelligibility is found to decrease. This decrease is not predicted by the original STI. For that reason, level-dependent auditory masking was introduced in the latest revision of the STI standard (IEC 60268-16:2003). As a result the objective rating of speech intelligibility by means of STI changed dramatically for PA and VA systems in tunnels. The STI of a sound system producing high sound levels (up to 105 dBA) is rated significantly lower using the revised standard, compared to the old standard (dated 1998). As a result it has become very hard or even impossible in many situations to meet the minimum STI requirements in tunnels.

To overcome these problems, in this paper a dedicated STI measurement and optimisation tool is introduced; the OpSTImizer®. Using this PC based measurement and filter optimisation tool the STI can be measured using the STIPA method and the required pre-filtering of the speech signal is calculated to achieve optimum intelligibility under the actual acoustic conditions in the tunnel.

This new method has been tested extensively by on site measurements.

2 ACOUSTIC CONDITIONS

2.1 Operating scenarios for PA/VA

A PA/VA installation will be used in various situations, like calamities, accidents and also less pressing problems such as traffic jam or car breakdown. These situations can be divided into a few, clearly discernable scenarios. Each scenario should be well described regarding:

- target audience, e.g., one person or all persons in the tunnel.
- position listeners in the tunnel, e.g., in car or next to vehicle.
- traffic speed, e.g., high speed traffic in case of a broken car on the emergency lane, or slowly moving or standing traffic in case of a traffic jam.
- ventilation active or inactive.

For each of these scenarios the minimum speech transmission quality requirements should be met. The two most important factors that affect speech intelligibility are the acoustics of the tunnels and the ambient noise spectrum of the traffic and the ventilation system.

2.2 Reflections and reverberation

The acoustic conditions in traffic tunnels are generally very hostile to Public Address (PA) and Voice Alarm (VA) systems. Speech intelligibility is often severely compromised.

Due to the low sound absorption coefficients of the acoustically hard finishes of the inner tunnel surfaces, the reflections are hardly attenuated. This leads to a long reverberation time and high reverberant level. As a result the ratio between the level of the direct sound of a loudspeaker and the excited reverberant sound field is very poor. Further, the long reverberation time also contributes to the high background noise levels in the tunnel. Both factors have a detrimental effect to speech intelligibility.

In a typical traffic tunnel with hard finishes (concrete or tiled walls and ceiling, asphalt concrete road surface) the reverberation time is usually very long and ranges from a few seconds at higher frequencies to more than 10 seconds in the low-mid frequency bands. The reverberation time and reverberant level could be reduced by taking acoustic measures such as adding acoustic absorption. However, these measures are often very costly and impractical from a maintenance point of view.

2.3 Background noise

As discussed above, speech intelligibility of PA and VA systems in traffic tunnels is also compromised by high ambient noise levels. The two main noise sources in tunnels are traffic noise and ventilation noise. The sound levels caused by the ventilation fans can be very high (up to 100 dBA), depending on the positioning and the type of fans.

The traffic noise mainly depends on the traffic speed and is caused by the car and truck engines and the tyre noise. With a traffic speed of 100 km/h the sound level is about 95 dBA. Table 1 shows some typical octave band levels for various noise sources measured in the Schipholtunnel[1], in The Netherlands.

Table 1: Some measured noise spectra in the Schipholtunnel, The Netherlands

	SPL [dB]							
Noise source	**125 Hz**	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**	**Total (A-weighted)**
Fast traffic (100 km/h)	90	85	88	92	88	74	62	95
Fans w/o deflectors	89	86	86	82	81	85	83	91
Fans w/ deflectors	94	94	94	91	84	85	82	96

From the above it's clear that in order to obtain a sufficiently high signal-to-noise ratio, high speech levels are required. On the other hand, the signal levels shouldn't exceed 105 dBA in order to avoid hearing damage. This puts severe demands on the quality of the loudspeakers that are used. Particularly, the maximum long term (RMS) SPL specifications and the distortion figures are very important.

3 SPEECH TRANSMISSION QUALITY

A well-established objective measure of speech transmission quality is the Speech Transmission Index (STI). Although speech transmission quality is not the same as speech intelligibility, the STI method can be used to predict or to measure the speech transmission quality with respect to intelligibility. The STI is expressed as a number between 0 and 1. In table 2 the STI values and the corresponding ratings are summarised.

Table 2: Rating of speech transmission quality by means of STI

Speech transmission quality	
STI [-]	**Rating**
0.75-1	Excellent
0.6-0.75	Good
0.45-0.6	Fair
0.3-0.45	Poor
0-0.3	Bad

The preferred method to measure STI in traffic tunnels is the STIPA method. This STIPA method requires a special test signal consisting of several simultaneously modulated frequency bands, having a male frequency spectrum. In contrast to impulse response methods, using MLS noise or swept sine signals, the STIPA method is able to measure the STI reduction due to harmonic distortion of the loudspeaker. Impulse response methods require a linear system, as distortion will cause undesired measurement artefacts.

With the introduction of level-dependent auditory masking in the latest revision of the STI standard[2] (IEC 60268-16:2003), the objective rating of speech intelligibility by means of STI changed dramatically. As a result, the STI of a sound system producing high sound levels (as in tunnels) is rated significantly lower using the revised standard, compared to the previous standard (dated 1998). To illustrate this effect, the (revised) STI for a single, perfect loudspeaker (with a flat frequency response and no distortion) in a reflection-free, noiseless environment (free field conditions) as a function of the sound level of male speech is plotted in Figure 1.

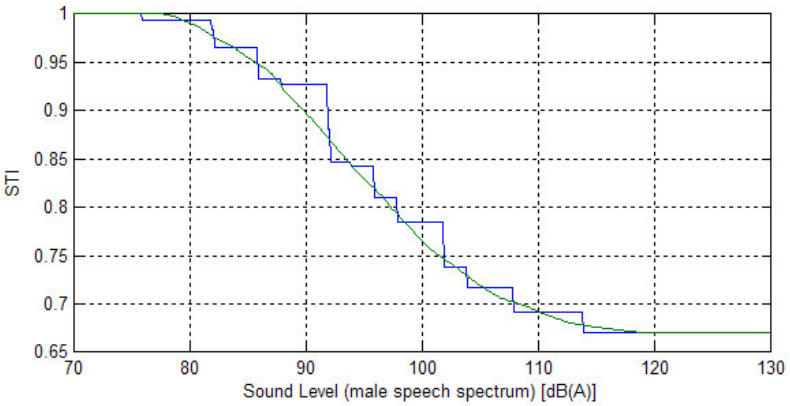

Figure 1: Revised STI as a function of the sound level of male speech (no reflections, no noise).

The 'stair cased' curve is generated using the current STI standard. The smooth one is calculated in a way which the level dependent masking is not divided into 10 dB intervals, as in the current standard, but an interpolated function of SPL.
It's clearly shown that STI is "penalised" when the sound level exceeds 75 dB(A). In fact if the system is operating at 105 dB(A) then the maximum achievable STI (i.e., under anechoic conditions) is around 0.72. According to the 'old' 1998 STI-standard the STI would be (close to) 1 for all sound levels.
Under more realistic acoustic conditions, i.e., with reverberation and ambient noise, the effect of level-dependent auditory masking on the STI is less severe but still significant. For a typical tunnel PA/VA system producing a sound level of 105 dBA at the receiver positions, the "penalty" in the revised STI is close to 0.1. From this it is evident that achieving the specified STI values under real-life tunnel conditions has become even a greater challenge. As a complicating factor, the minimum STI specifications have also become more demanding over the last years.

4 DEDICATED TUNNEL HORN

Conventional horns (e.g. re-entrant horns) exhibit a limited frequency range and a relatively high signal distortion. Moreover, as the acoustic output of a single horn is often too low, often horn clusters are used. This clustering causes causing undesirable effect in the frequency and polar response.
To improve sound quality and speech intelligibility, Duran Audio developed the Asymmetric Boundary Flare (ABF-260) horn[3], as shown in Figure 2. The ABF-260 can be used in road traffic tunnels to form a part of the voice alarm and announcement systems.

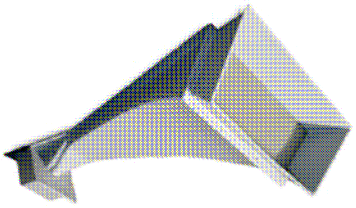

Figure 2: ABF-260 tunnel horn

The Asymmetric Boundary Flare (ABF) geometry is based on the principle of acoustical mirroring. The ABF is designed to be mounted on the ceilings of a road tunnel. The ceiling acts as a large boundary plane. As the acoustic centre of the ABF is very close to the ceiling, the ABF and its mirror image can be seen as one acoustical source with twice the sound pressure. In contrast to a conventional horn, which has to be mounted at some distance from the wall or ceiling, no sound pressure cancellations due to phase difference between the direct and reflected sound will occur over a wide frequency range. This principle is illustrated in Figure 3 and 4

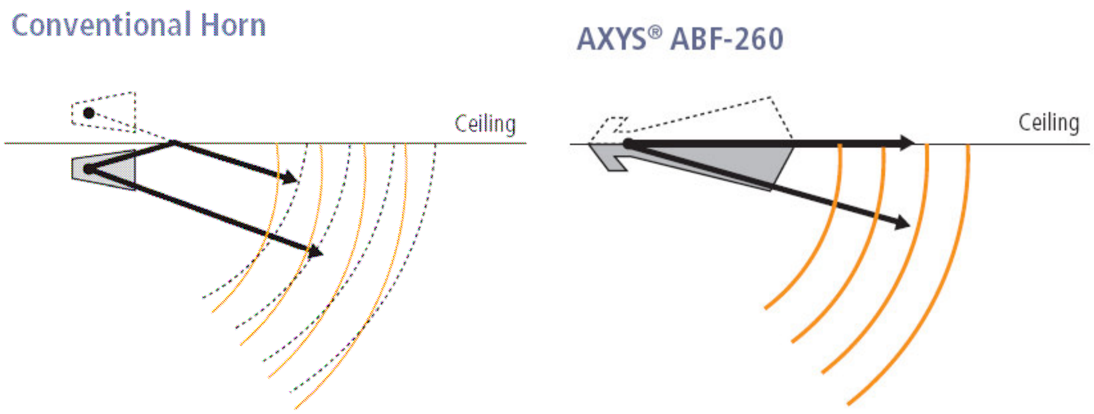

Figure 3: Acoustic mirroring of a conventional horn compared to the AXYS® ABF-260

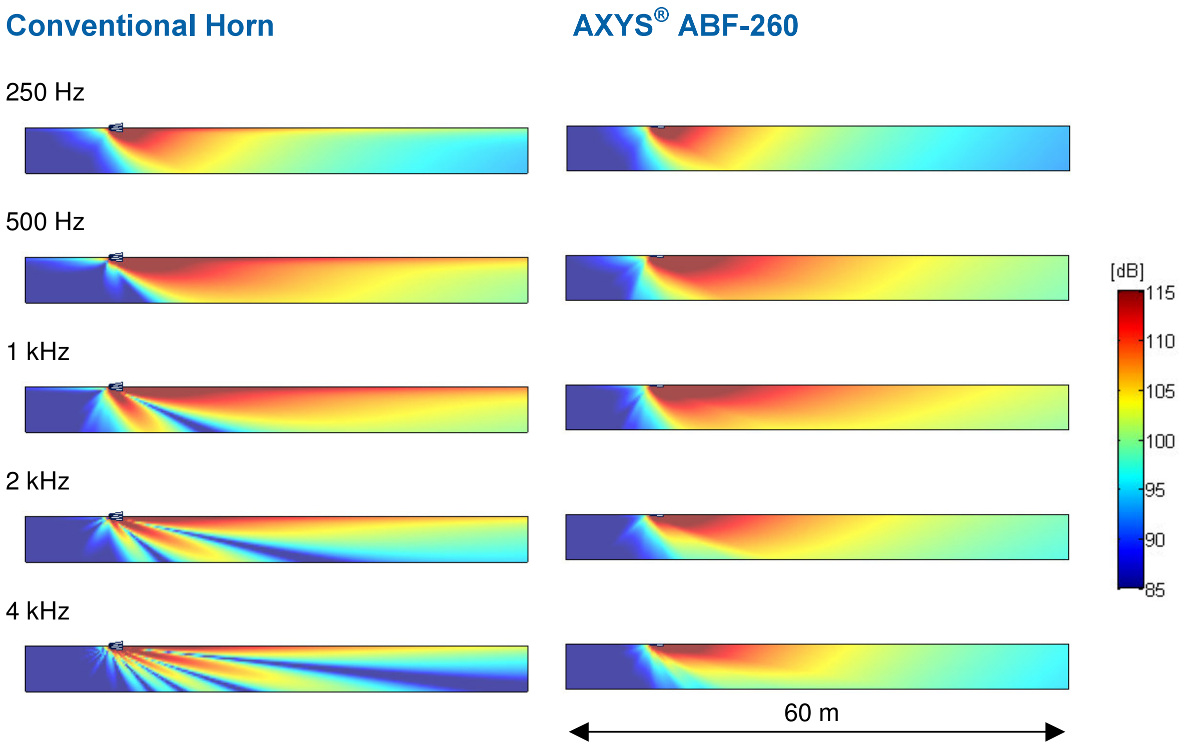

Figure 4: SPL distribution (direct sound+ceiling reflection) in the vertical plane in a tunnel for of a conventional horn mounted 0.2 m below the ceiling compared to the AXYS® ABF-260 (octave centre frequencies 250 Hz to 4 kHz)

The ABF-260 is driven either by a 50W or a 100W 2" compression driver with a 100V impedance transformer.
Figure 5 shows the measured half-space directivity balloon for the ABF-260 mounted against a horizontal boundary plane. Besides the high directivity, the balloon exhibits a very large (>30 dB) front-to-back ratio, which is a desirable feature when using multiple ABF horns in a tunnel. In addition, the ABF has an extended frequency response up to 8 kHz.

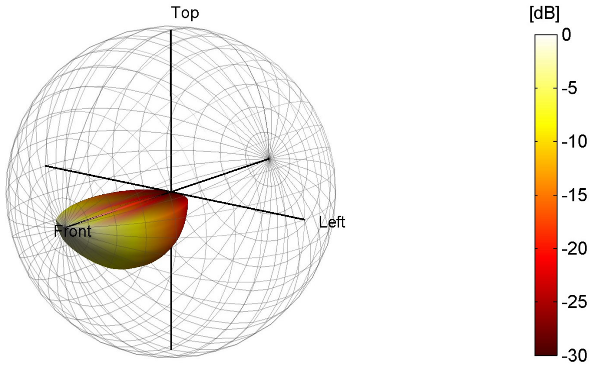

Figure 5: Measured half-space directivity balloon (500 Hz-2kHz average) for the ABF-260 mounted against a horizontal boundary plane

5 DESIGN GUIDELINES

As ambient noise can be as high as 100 dBA, signal levels of up to 105 dBA are necessary. Higher levels are to be avoided to prevent hearing damage. Although the sound level of an ABF horn in a tunnel only slowly drops with distance (typically, 2-3 dB over 50 m), the maximum spacing between ABF horns should be limited to sustain sufficient signal-to-noise ratio. Typically, a spacing of 50 m is required in most situations. A typical set-up for a "two-lane" tunnel tube is shown in Figure 6.

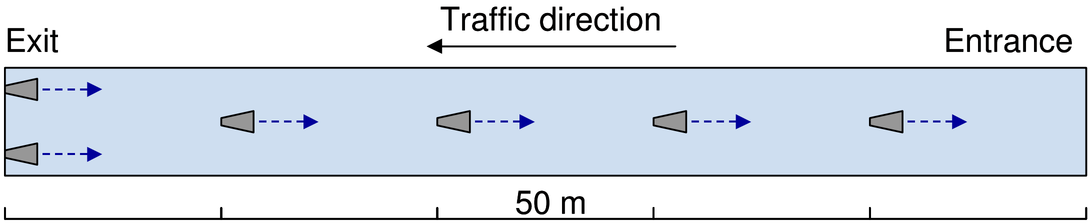

Figure 6: Typical ABF set-up for a "two-lane" tunnel tube (maximum width approx. 15 m).

The ABF horns are positioned along the centre line of the tunnel and should be aimed opposite to the traffic direction. Near the exit two ABF horns are mounted to cover the entire width of the tunnel. In order to create a coherent sound wave through the tunnel, each horn should be delayed back to the time-zero horns near the exit.
In tunnels tubes wider than approx. 15 m usually two or more ABF horns are required every 50 m in order to obtain a sufficiently high sound level and adequate coverage across the width of the tunnel. This is illustrated in figure 7.

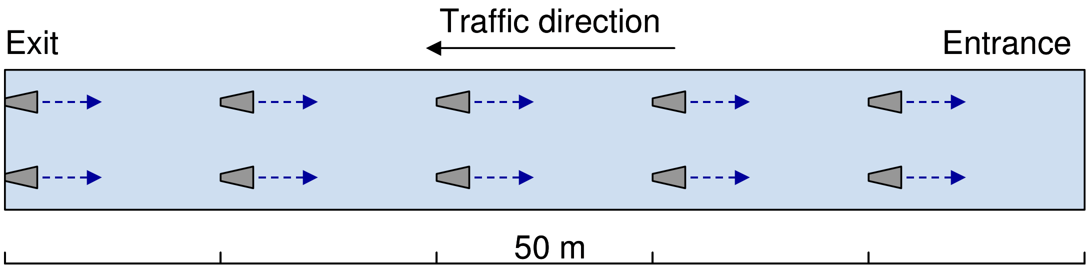

Figure 7: Typical ABF set-up for a wider tunnel tube (width >15 m).

6 OPTIMISATION OF SPEECH TRANSMISSION

6.1 The OpSTImizer

In order to obtain optimum speech transmission quality in tunnels using the ABF horns, a dedicated STI measurement and optimisation tool was developed which is introduced here; the OpSTImizer®. Using this PC based measurement and filter optimisation tool the STI can be measured using the STIPA method and the required pre-filtering of the speech signal is calculated. The optimisation procedure is as follows:

1. First, measurements are done at a number of relevant receiver positions in the tunnel using a flat EQ setting of the system. Usually 5 to 10 measurements are sufficient. Each measurement takes about 16 s. The STIPA signal should be played at the actual sound level that is required in the tunnel. In this way any degradation due to harmonic distortion and the appropriate masking levels in the STI calculation are taken into account. As the measurements are usually carried out in a "noise-free" situation (no traffic, no fan noise), the expected worst case ambient noise spectrum is added mathematically to the STI algorithm.
2. On the basis of the measured modulation transfer function including the additional ambient noise spectrum, the optimum filter for the system is calculated by the OpSTImizer algorithm. The software immediately predicts what the expected STI will be using this filter.
3. The filter settings are transferred to the Axys PB800 Amplifier, which is recommended to be used in combination with ABF. Next, the final measurements are carried out to verify the actual STI values using the optimum filter.

This new method has been tested by measurements in several traffic tunnels. The results of two of these on site measurements will be discussed.

6.2 Test set-up 1

The first test set-up was built in a 1.6 km long tunnel tube. The width of this tube was 15 m and the height was approx. 5.5 m. The inner tunnel surfaces were acoustically hard. No absorptive measures were taken. The set-up in the 15m tube consisted of four progressively delayed ABF-260/100W horns with a spacing of 50 m, as shown in Figure 8. The set-up was built in the middle of the tunnel, far away from the entrance and exit.
All four ABF horns were active, but only the STI in the last three 50m sections was evaluated. The first ABF was merely used to build-up the sound field. The measurement positions were positioned along the centre axis of the tube (row 1) and along a parallel line, 1.5 m away from the side wall (row 2). The distance between the measurement positions was 5 m. The microphone height was 1.5 m above the road surface.

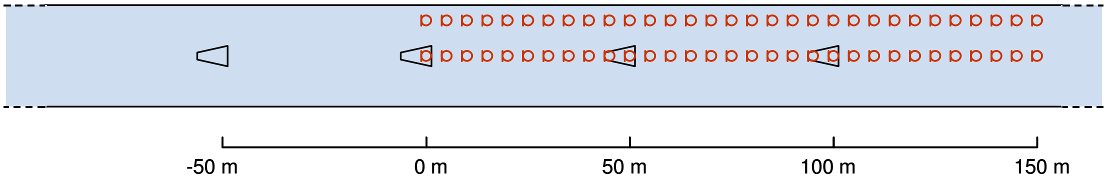

Figure 8: ABF test set-up and measurement positions in the 15m wide tunnel tube

Before the final measurements were done, the STI was measured at 10 positions in the first relevant section (0-50m) with a flat system EQ. The playback sound level was set to 103-105 dBA and for the STI calculations a fast traffic background noise of 95 dBA was assumed (see Table 1). With a flat EQ the mean (revised) STI is 0.39. According to the old 1998 STI standard the STI would have been 0.47.
On the basis of these measurements the optimum filter was calculated using the OpSTImizer algorithm and was transferred to the PB800 amplifiers. Next the STI was measured along the two measurement rows, starting at 0 m to 150 m, as indicated in Figure 8. The results are displayed in Figure 9. Using the optimised filter the mean STI for the 95 dBA ambient noise condition equals 0.49 with a standard deviation of 0.02. Without background noise the mean STI equals 0.53.
The results show that a significant improvement of speech transmission quality can be achieved by applying adequate pre-filtering of the signal.

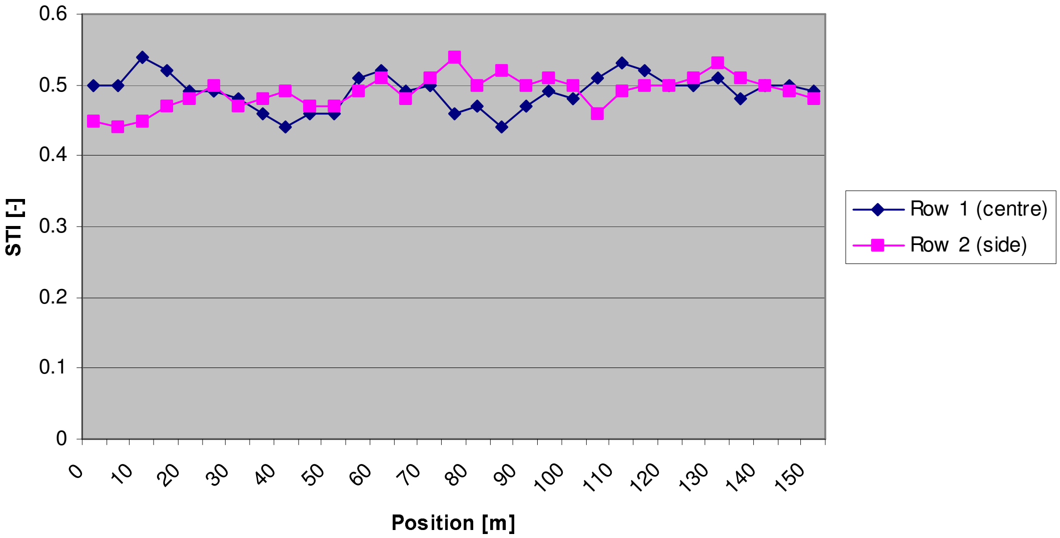

Figure 9: Measured STI values in the 15 m wide tunnel tube using optimised signal filtering and assuming 95 dBA fast traffic noise. Signal level is 103-105 dBA.

6.3 Test set-up 2

The second test set-up was realised in a parallel tube having a width of 20 m. The length and the height of the tube were identical to the previous one. The set-up in the 20m wide tube consisted of four pairs of progressively delayed ABF-260/100W horns with a spacing of 50 m, as shown in Figure 10.

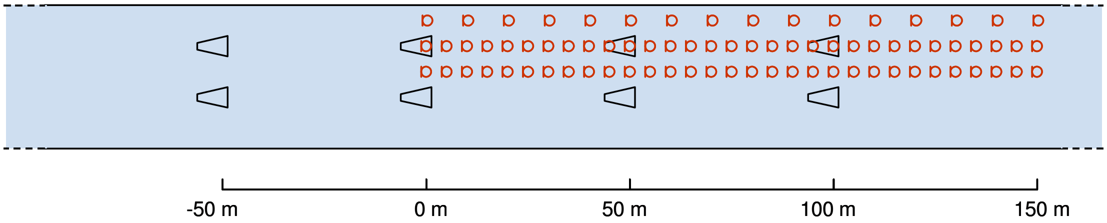

Figure 10: ABF test set-up and measurement positions in the 20m wide tunnel tube

Again, all four ABF sections were active, but only the STI in the last three 50m sections was evaluated. The first pair of ABF horns was merely used to build-up the sound field. The first measurement row was positioned along the centre axis of the tube. The second parallel row was on-axis to one of the horns in each pair. The third row was 1.5 m away from the side wall. The distance between the measurement positions was 5 m except for the third row where a spacing of 10m was used. The microphone height was 1.5 m above the road surface.
Before the final measurements were done, the STI was measured at 14 positions in the second section (0-50m) with a flat system EQ. The playback sound level was set to 103-105 dBA and for the STI calculations a background noise of 95 dBA was assumed (fast traffic, see Table 1). Using a flat EQ the average (revised) STI is 0.41. According to the old 1998 STI standard the STI would have been 0.49.
On the basis of these measurements the optimum filter was calculated using the OpSTImizer algorithm and was transferred to the PB800 amplifiers. Next the STI was measured along the three measurement rows, starting at 0 m to 150 m, as indicated in Figure 10. The results are displayed in Figure 11.

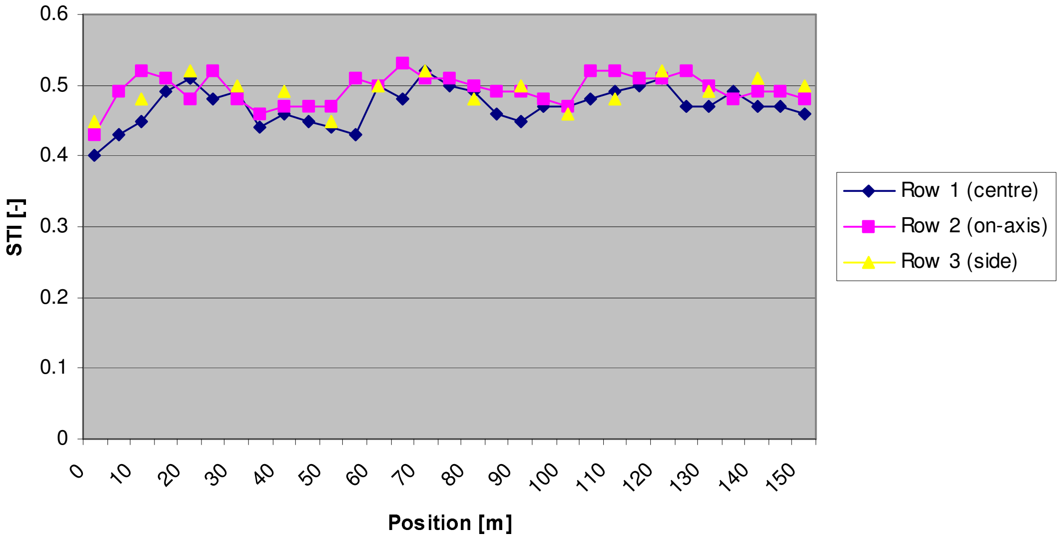

Figure 11: Measured STI values in the 20 m wide tunnel tube using optimised signal filtering and assuming 95 dBA fast traffic noise. Signal level is 103-105 dBA.

Using the optimised filter the mean STI for the 95 dBA ambient noise condition equals 0.48 with a standard deviation of 0.03. Without background noise the mean STI equals 0.51.
The results show again that a significant improvement of speech transmission quality can be achieved by applying adequate pre-filtering of the signal.

7 SUMMARY AND CONCLUSIONS

In this paper the design and optimisation of voice alarm (VA) systems for traffic tunnels is discussed. Due to the hostile acoustic environment it is very hard to obtain sufficiently high levels of speech transmission quality. With the introduction of level-dependent auditory masking in the latest revision of the STI standard (IEC 60268-16:2003), the objective rating of speech intelligibility by means of STI changed dramatically. The STI of a sound system producing high sound levels (up to 105 dBA as in tunnels) is rated significantly lower using the revised standard, compared to the old standard (dated 1998).

In this paper a new measurement and optimisation tool is introduced; the OpSTImizer®. Using this PC based measurement and filter optimisation tool the STI can be measured using the STIPA method and the required pre-filtering of the speech signal is calculated to achieve optimum intelligibility under the actual acoustic conditions in the tunnel. This approach has been verified by extensive measurements. The results show that a significant improvement of STI (+0.1) can be realised.

8 REFERENCES

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2. IEC 60268-16 3rd edition 2003-5 Sound system equipment, objective rating of the speech intelligibility by speech transmission index.
3. The AXYS ABF-260 brochure, www.duran-audio.com/pdfs/downloads/brochures/AXYS_ABF260_brochure.pdf

9 LIST OF FIGURES

10 LIST OF TABLES