WHITE PAPER

# PAVA System For Road Tunnel Applications

EN 54-16 | EN 54-4 | EN 54-24

S4T
Safety for Tunnel

ambient SYSTEM

We make everyday life safer

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# 1. Introduction

Road tunnels with a length of 400m or more should be equipped with Public Address / Voice Alarm (PA/VA) systems according to **European Parliament directive 2004/54/EC from 29 April 2004** and the guidelines found in the German **RABT 2006 Regulations For The Equipment and Operation of Road Tunnels.** This applies as well to niches, evacuation passages and shelters.

PA/VA systems are used daily for communication between tunnel operators, drivers and passengers, but more importantly they deliver safety procedures in case of an emergency.

The goal is to deliver clear and understandable announcements. Tunnels are themselves a most challenging environment for intelligible speech reproduction.

# 2. Main challenges in road tunnel applications

### High levels of background noise

- Extreme ventilation noise
- High levels of traffic noise
- Echo

### Poor accoustics

- Long reverberation time
- High levels of reflected sounds
- Uneven distribution of direct sound

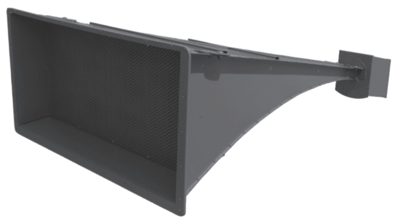
### Tunnel shape and large distances

- Extended narrow audience area
- Long distances from loudspeaker to listener
- Large distances between loudspeakers

## 2.1. Background noise

Human hearing has its limits, expecially in difficult acoustic environments. It is vital that the tunnel PA system design and performance will ensure the voice announcements are well and correctly understood, especially with the background voice present at the same time.

It is necessary that the Sound Pressure Level (SPL) of the message exceeds the SPL level of background noise by at least the recommended minimum of 6 dB – thus providing a good signal-to-noise ratio.

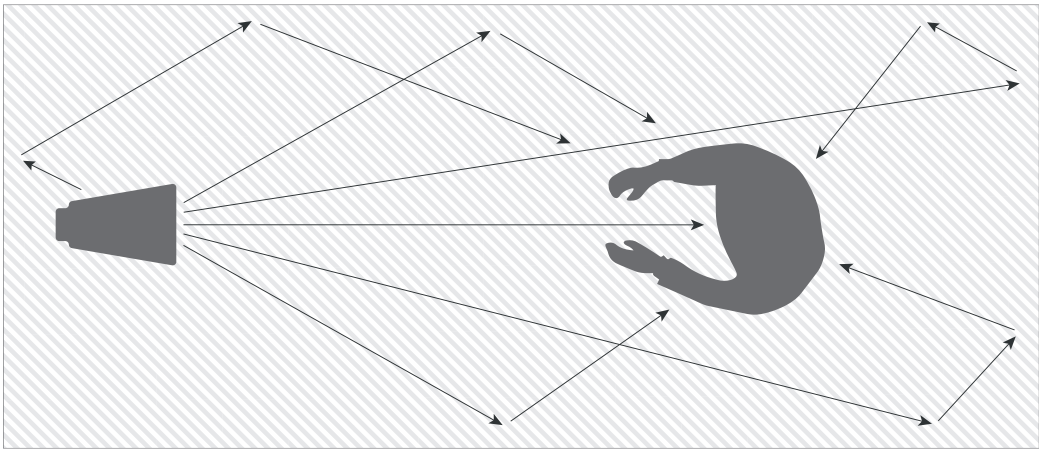
| SPL Level | Small format horn speaker | Large format tunnel horn speaker |
|---|---|---|
| |  |  |
| | Sound pressure level output @1m | |
| Sensitivity (1W/1m) | 105 dB SPL | 111 dB SPL |
| 3,75W | 110,7 dB SPL | |
| 7,5W | 113,8 dB SPL | |
| 15W | 116,8 dB SPL | |
| 25W | | 125 dB SPL |
| 30W | 119,8 dB SPL | |
| 50W | | 128 dB SPL |
| 100W | | 131 dB SPL |

**In practice:** A loudspeaker datasheet usually provides information for speaker sensitivity. For instance, if a loudspeaker has a sensitivity of 95 dB, this means that at 1 watt of power, the loudspeaker generates a sound pressure level of 95 dB at a distance of 1 meter. Each doubling of power results in a 3 dB increase of SPL. The maximum power the speaker can handle is called its rated power.

The main type of noise inside a road tunnel is the **traffic noise from moving vehicles** and **working ventilation. In extreme cases**, such as in a fire (when ventilators work at their maximum to remove smoke from the area), **the noise level inside the tunnel can reach up to 94 dB**. For this reason, **the PA/VA system must be able to provide a very high SPL level - exceeding 100 dB** consistently over a large area, which is practically impossible to achieve with small-format loudspeakers.

## 2.2. Reverberation Time

Reverberation is a natural phenomenon that describes the way a room resounds, i.e. the time needed for the sound to fade away after the sound source is silenced. A long reverberation time means that the room is prone to creating reflections. The reflected sound is perceived by the hearing with a time and phase shift in relation to the direct signal causing degradation to the intelligibility of speech. Therefore, reflected sound can be considered noise. In all cases a listener will receive a mix of direct and reflected sound and thus it is important to provide him a good Direct to Reverberant Sound Ratio.



*Picture 1. Sound propagation in a closed space*

Tunnels are characterized by long Reverberation Time. Due to the acoustically hard properties of tunnel surfaces (highly reflective materials such as concrete, asphalt, tiles etc.) most of the sound energy will be bounced back making it difficult to o achieve a good Direct to Reverberant Ratio, which is essential for achieving high levels of speech intelligibility.
To mitigate this effect and improve speech intelligibility highly directional loudspeakers must be used, allowing to reduce the number of sound reflections from the tunnel walls.

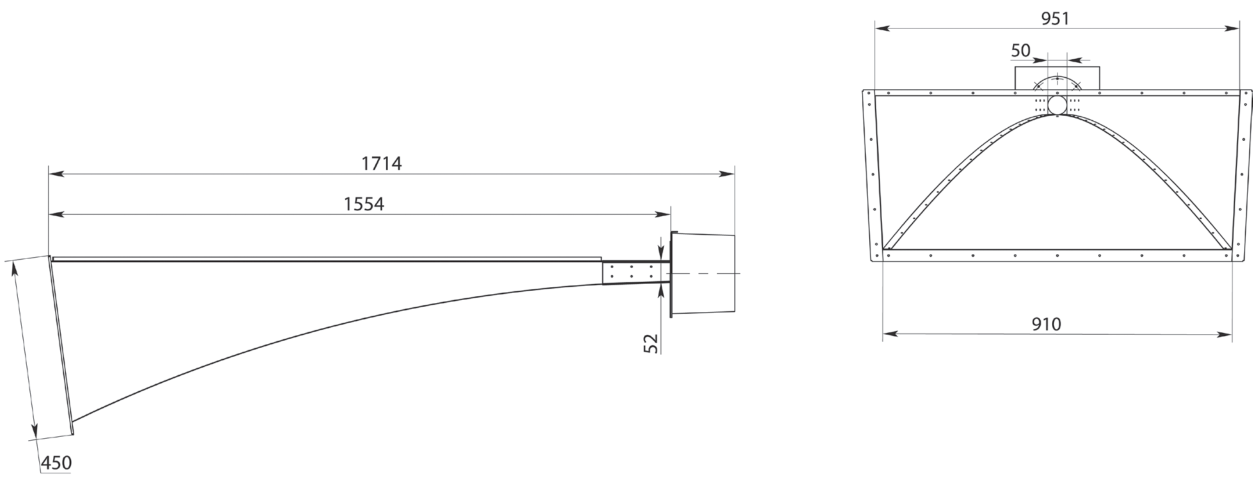
If a room Reverberation Time exceeds 2s it becomes difficult to achieve high intelligibility, because it takes too long for the sound to dissipate. In case of road tunnel Reverberation Time often exceeds 10 seconds, which is the combined result of large room volume and lack of sound absorbing materials.

It is important to understand that due to high levels of background noise the PA system must provide high levels of direct sound to ensure having acceptable SNR. At the same time increasing the level of direct sound causes an increase of reflected sound, which is considered noise.

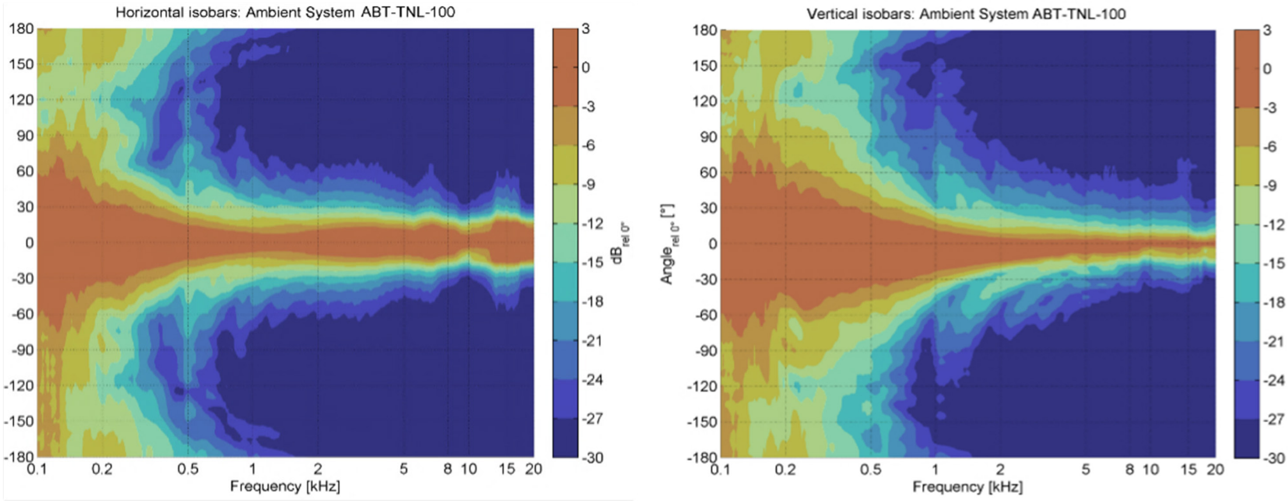
This is the main difficulty in designing a PA system for a tunnel, as the designer must search for ways to maximize the SNR keeping the best Direct-to-Reverberant sound ratio possible.

# 3. Tunnel loudspeakers

## 3.1. ABT-TNL100 Loudspeaker

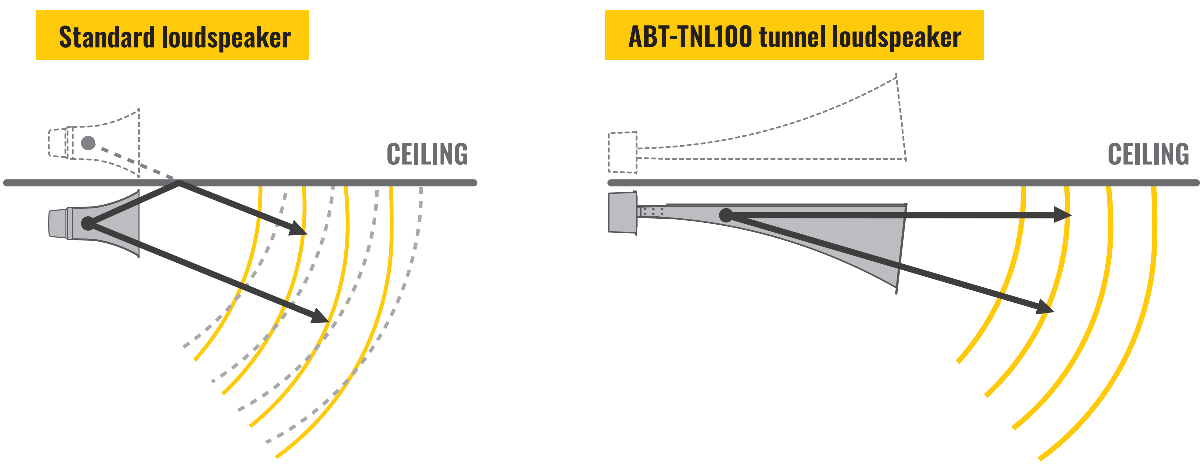

*Picture 2. Tunnel horn loudspeaker*




*Picture 3. Vertical and horizontal coverage patterns for ABT-TNL100*

PA tunnel applications require high power and highly directional loudspeakers such as the ABT-TNL100 model with a high sensitivity of 111dB SPL (@1W/1m) and rated power of 100W. It can produce extreme sound pressure levels with negligible distortion, so a single unit can cover a large section of the tunnel (50-70m). ABT-TNL100 loudspeaker is highly directional – with a horizontal dispersion angle of only 22$^0$, decreasing the sound energy directed towards the tunnel walls. Therefore, the reflected sound energy is minimized resulting in better direct to reverberant ratio and, in consequence, higher speech intelligibility. ABT-TNL100 loudspeaker's front-to-back ratio is of approx. 35 dB. This allows to minimize interference at the rear of the speaker and this helps to create a coherent wave front moving along the tunnel.

**The ABT-TNL100 loudspeaker has an asymetric flare allowing for direct mounting to the tunnel ceiling:**

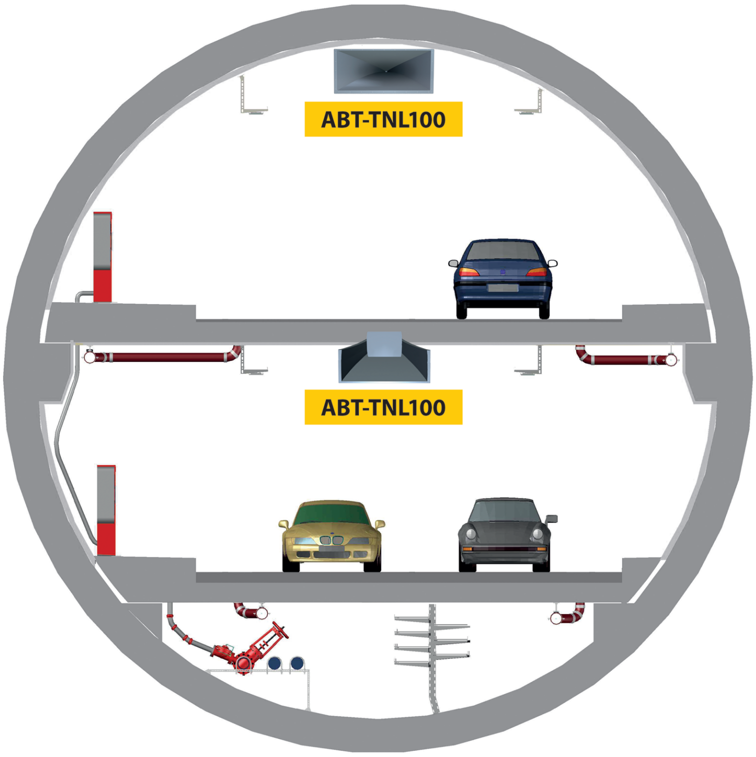



*Picture 4. Near field sound reflections for standard and tunel horn loudspeakers*

a. It can be used on either flat or curved ceilings.
b. In this case the tunnel ceiling becomes a boundary surface and acts as the waveguide of a coherent acoustic wave.
c. By limiting near field reflections, it is possible to obtain a coherent wave front, which minimizes the adverse effect of wave interference and comb filtering caused by the phase shift of direct and reflected sound in a wide frequency range.

In case of two-lane tunnels **it is recommended to use a single ANT-TNL100 horn with a speaker-to-speaker distance of 50-70m** (depending on tunnel acoustics determined by its length). **In the case of three- or four-lane tunnels it is recommended to use a pair of ABT-TBL100 loudspeakers, with a distance of 50-80m and separated approx. 6m apart**.

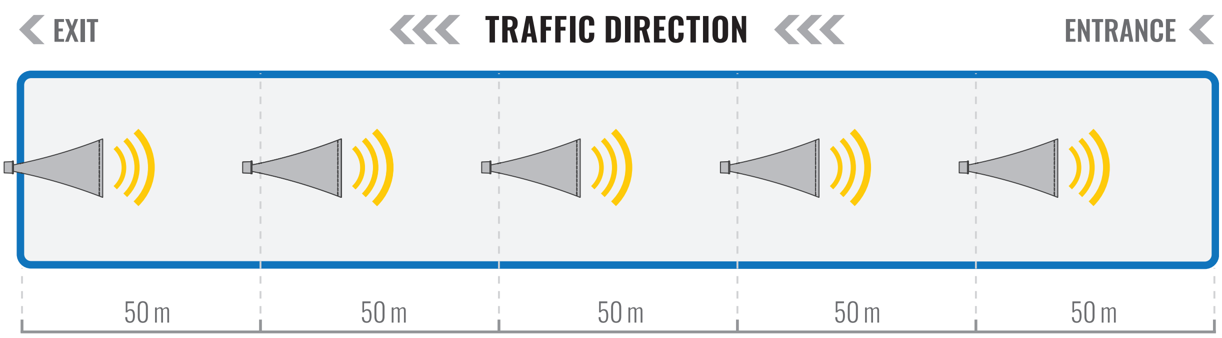
Typically the horn speaker is placed slightly offset from the tunnel main axis, so that it is close to the center of the tube, but can be serviced from a single driving lane.

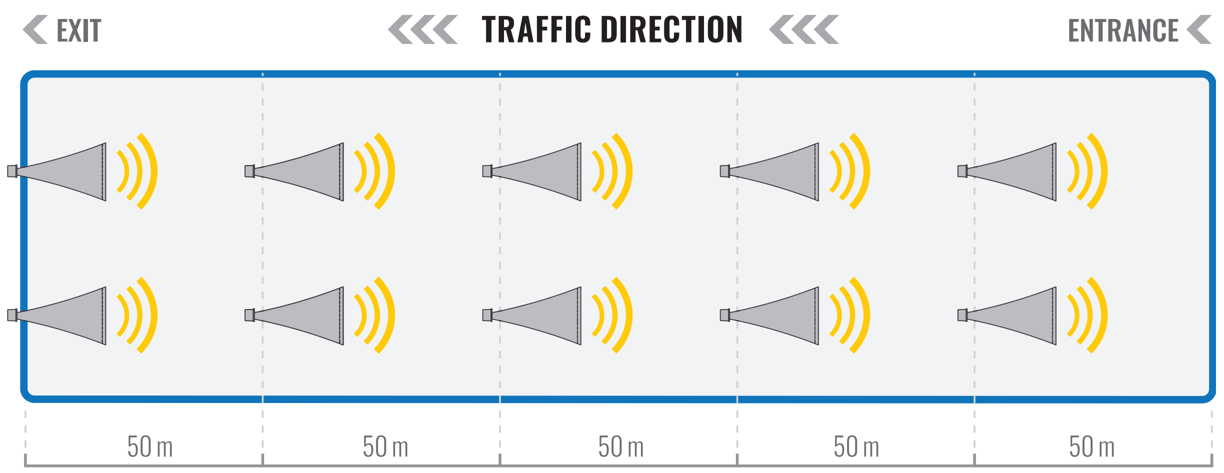



The ABT-TNL100 is designed to work in harsh environmental conditions, as can be expected in case of road tunnels in mountain areas or below rivers.

The speaker chassis is made of stainless steel covered with protective paint and offers IP66 degree of protection. The shape of the flare and front grill is designed to prevent water from entering the loudspeaker during cleaning but also to prevent birds from nesting in the exit of the loudspeaker.

The speaker connects to the speakerline via a ceramic terminal found inside of the transformer box. The speaker cable enters the chassis via a waterproof gland. The ABT-TNL100 does not require a rigging frame – the loudspeaker is rigged directly to the ceiling using M8 anchors, either through holes prepared in the housing itself, or using dedicated adapters (provided with the speaker, advised to be used in case of curved ceilings).






*Picture 5. Loudspeaker positioning in the tunnel*

# 4. The impact of tunnel shape and distances

The tunnel shape itself (being narrow and long) promotes propagation of sound along its course. As a result, the reverberation effect will be enhanced by sound reaching the listener from distant speakers - delayed by the time it takes the soundwave to travel to given point.

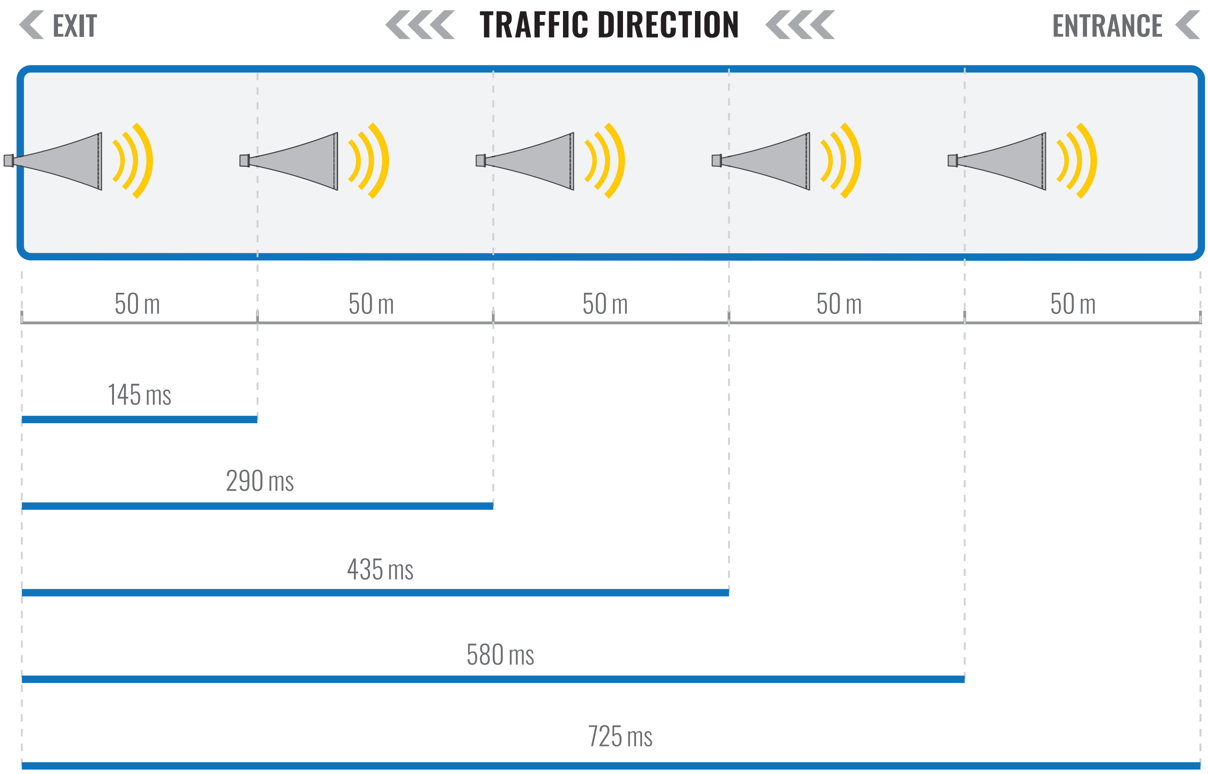
This delayed sound will decrease speech intelligibility, as it will have an effect on the human hearing similar to other random noise. The solution to this problem is to use Digital Signal Processing tools (DSP).

Introducing loudspeaker delay allows us to fine–tune the timing of the sound coming from each speaker, so that in a given point of the tunnel the listener receives time-aligned direct sound from multiple loudspeakers.

This requires a **specific system design**. As individual delay based on speaker-to-speaker distance must be introduced for each loudspeaker, this forces the designer to **power each individual loudspeaker from its own dedicated amplifier channel with accompanying individual DSP channel**. Also – all loudspeakers must be faced in the same direction.

Sound travels at a speed of approximately 344m/s. Consecutive increasing delay is applied to each loudspeaker. As a result for long tunnels the delay needed to align the system is long – for example for a distance of 2km the necessary delay is 5,8 seconds, which exceeds the capabilities of standard DSP processors.

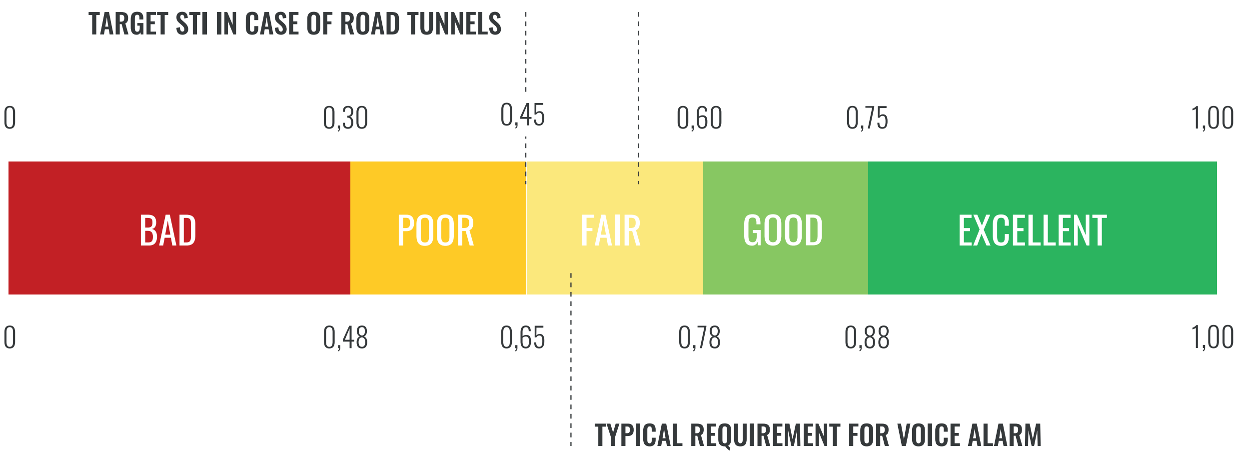
Further increase of speech intelligibility is possible using speaker EQ




*Picture 6. Concept of a time aligned sound system*

# 5. Speech intelligibility

The tunnel shape itself (being narrow and long) promotes propagation of sound along its course. As a result, the reverberation effect will be enhanced by sound reaching the listener from distant speakers - delayed by the time it takes the soundwave to travel to given point.




*Picture 7. Definition of STI based on EN 60849-16*

| STI VALUE | Quality (based on EN 60268-16) | Expected intelligibility of words [%] | Expected intelligibility of sentences [%] |
|---|---|---|---|
| 0,00 - 0,30 | BAD | 0 - 67 | 0 - 89 |
| 0,30 - 0,45 | POOR | 67 - 78 | 89 - 92 |
| 0,45 - 0,60 | FAIR | 78 - 87 | 92 - 95 |
| 0,60 - 0,75 | GOOD | 87 - 94 | 95 - 96 |
| 0,75 - 1,00 | EXCELLENT | 94 - 96 | 96 - 100 |

Even the application of the solutions described above – large speakers, time alignment and DSP does not completely eliminate the problem of difficult tunnel acoustics. In practice, it is often not possible to achieve sound quality and speech intelligibility even close to that which can be obtained in standard facilities.

For PA/VA systems the common STI requirement is defined by standards such as the EN 50849 or CEN/TS 54-32 is 0,50 (taking into account the presence of maximum noise). In case of road tunnels this requirement is extremely difficult to meet and, in many cases, not possible at all.

A much more reasonable target is 0,46 STI which is the normal lower limit for Voice Alarm Systems operating in difficult acoustic environments described in Annex G to the EN 60268-16.

1. It is worth noting that even in good acoustic conditions (such as an anechoic chamber or free field) the STI decreases with the increase of sound pressure level.
2. For a complicated project the STI should be evaluated at the design stage by performing acoustic simulations. It is important to understand that Reverberation Time and strong early reflections have significant impact on system performance and due to this fact STI simulations for tunnels should never be performed using statistical based software. It is highly advised that simulations for tunnels only be done using Ray Tracing approach software such as CATT Acoustic, EASE AURA or Odeon.

# 6. Comparison of speaker performance

In the section below there is a comparison of performance of small format horn speakers  and high-power tunnel horn speakers for a two-lane tunnel of a 1,1km length.

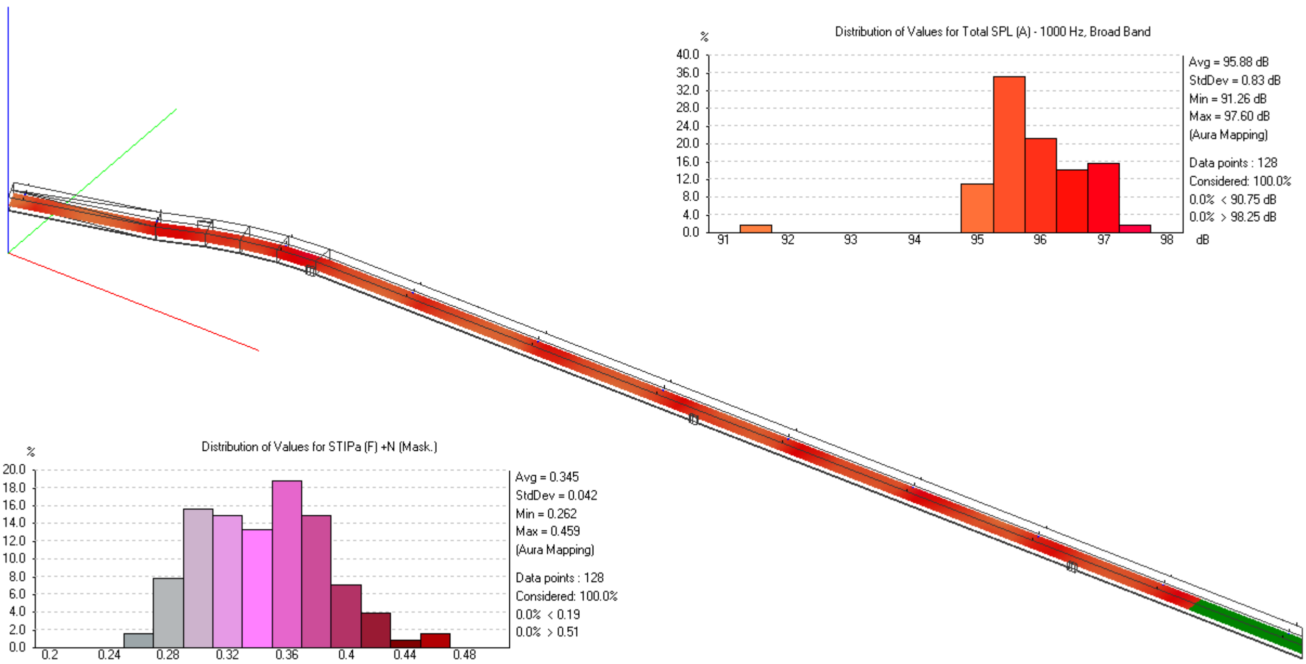
The tunnel is 5,5m high and up to 9m wide. The Reverberation Time estimated by EASE AURA in the 100Hz – 10kHz frequency range is in this case 9,14 seconds.

**CASE A1/A2:** The tunnel is fitted with a pair of ABT-T2430 horn speakers in every 50m (44 loudspeakers in total). Speakers are positioned at the sides of the tunnel. Speaker delay is introduced to each individual speaker in calculations A2.

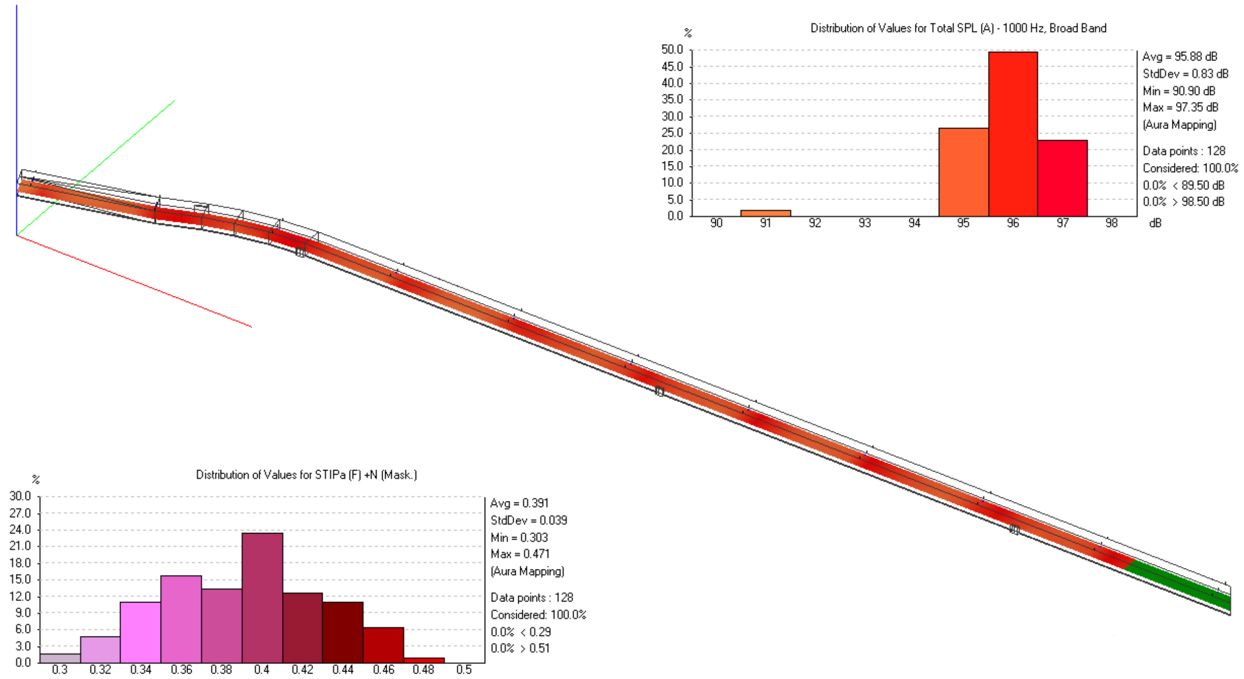
**CASE B1/B2:** The tunnel is fitted with ABT-TNL100 tunnel horn speaker, one in 50m (to a total of 22 loudspeakers). he speakers are moved to a 1m offset from  the tunnels main axis. Speaker delay is introduced to each individual peaker in calculations B2.

**NOTE:** Speaker EQ was not taken into account in the calculations. The presence of background noise was taken into account while estimating STI

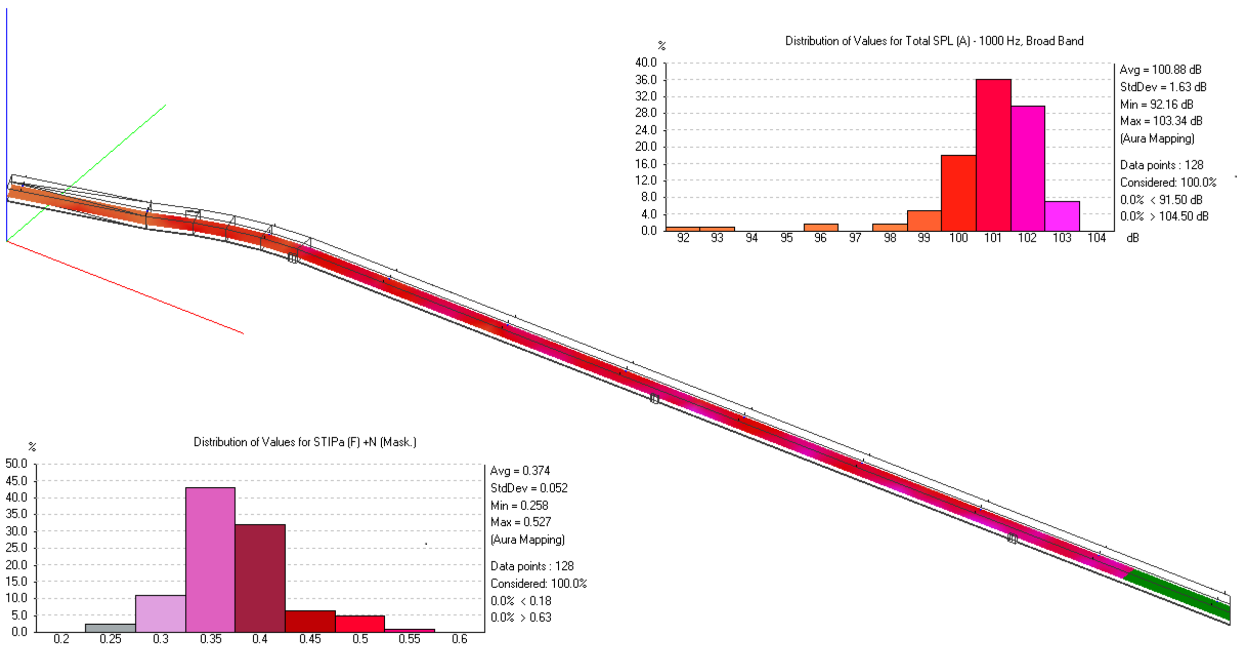
## SMALL FORMAT HORN SPEAKERS: ABT-T2430 (tapped at 30W, no delays)



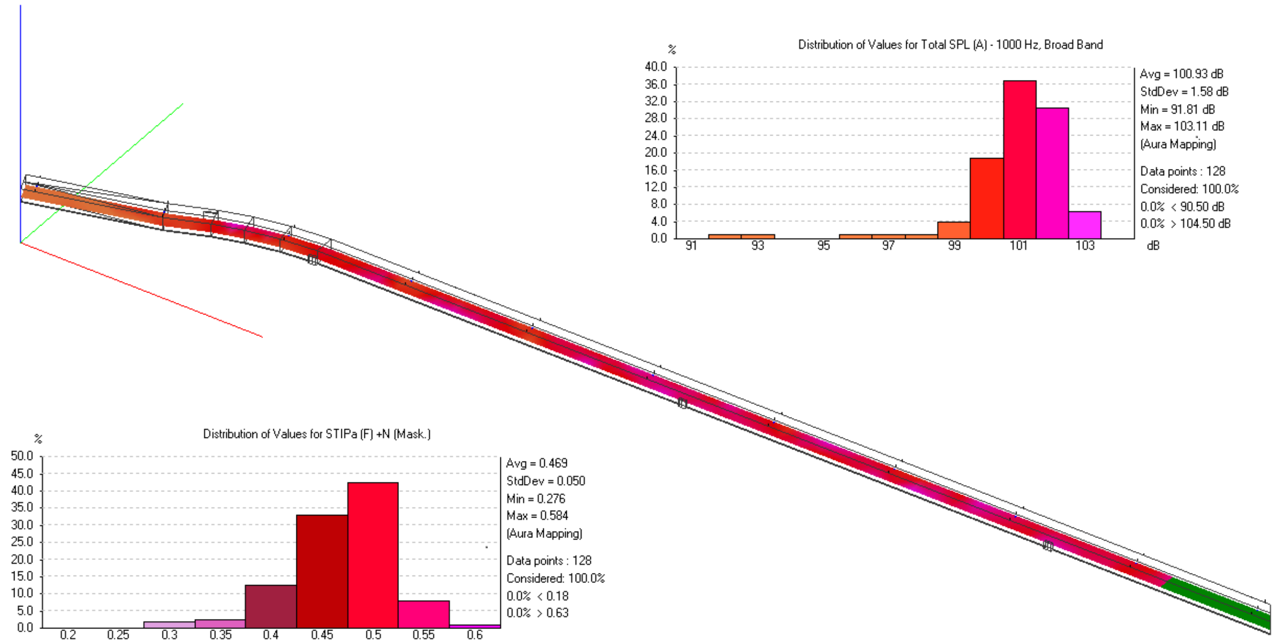
## SMALL FORMAT HORN SPEAKERS: ABT-T2430 (tapped at 30W, with delays)




## TUNNEL HORN SPEAKER: ABT-TNL100 (tapped at 100W, no delay)



# TUNNEL HORN SPEAKER: ABT-TNL100 (tapped at 100W, with delay)




## 6.1. Conclusions

The performed calculations confirm that in a tunnel environment, using large format tunnel horns powered with a system allowing for individual loudspeaker delay is the only approach allowing to achieve Speech Transmission Intelligibility required for Voice Alarm systems in the presence of high background noise. At the same time the calculations confirm that small format horns are insufficient for this type of application, as they fail to produce enough sound pressure level, for the broadcasts to have good SNR against high traffic and ventilation noise.

| SENSITIVITY (W/1m) | Parameter | |
|---|---|---|
| | Sound Level [dB SPL(A)] | STIPA (AVG; +N, +Mask) |
| A1 (ABT-T2430 without delay) | 95,88 | 0,34 |
| A2 (ABT-T2430 with delay) | 95,88 | 0,39 |
| B1 (ABT-TNL100 without delay) | 100,88 | 0,37 |
| B2 (ABT-TNL100 with delay) | 100,93 | 0,47 |

# 7. PAVA solutions - smartVES

smartES is Ambient System's solution for tunnel applications, combining advanced DSP processing capabilities (including long-distance loudspeaker delay) with multiple built-in redundancies. This ensures the highest level of system reliability and performance. smartVES is a fully digital, IP based, Public Address & Voice Alarm (PAVA) system designed to bring speech intelligibility to the next level. smartVES is the successor of the acclaimed MULTIVES system, having full backward compatibility and expanding the list of system features with new advanced DSP algorithms. smartVES is the next step in Ambient System development of Voice Alarm Systems, designed to meet the requirements of even most acoustically challenging applications.

smartVES PAVA system

## MAIN FEATURES

- ***Designed to work in large networks – scaling up to 375 IP devices and allowing to meet the requirements of even the biggest installations.***
- ***Fully compliant and EN54-16/4 certified, ensuring high performance and reliability under emergency situations.***
- ***Modular Architecture allowing to optimize system costs.***
- ***Can be configured up to No Single Point of Failure.***
- ***DSP with implemented: 3-band parametric EQ on all inputs; 8-band parametric EQ, delay, audio limiter and feedback eliminator on each of the audio outputs.***
- ***Equipped with unique proprietary DSP algorithms ensuring real-time SPEECH INTELLIGIBILITY optimization.***
- ***Easy to use configuration and management software.***

| smartVES Devices | |
|---|---|
| SMART-CU-8LCD | Stand-alone control unit with 8 control slots and touch screen GUI |
| SMART-CU-11LT | Control unit with 11 control slots |
| SMART-CU-11LCD | Control unit with 11 control slots and touch screen GUI |
| SMART-PAXXXX/E | Power amplifiers |
| SMART-PSM48/E | Power supply manager |
| SMART-DU1604 | Adaptive audio processor |
| SMART-AMAP-6 | Adaptive microphone aggregation point |
| SMART-ANSM-01 | Adaptive noise sensing microphone |
| SMART-xCtrLine-44 | Speaker line control card |

| smartVES Exchangeable modules | |
|---|---|
| ABT-xNET-1Gb/WAN/RS | Communication card |
| ABT-xLogIN-8f | Logical input card for function slot |
| ABT-xLogIN-8c | Logical input card for control slot |
| ABT-xLogOUT-8f | Logical output card for function slot |
| ABT-xLogOUT-8c | Logical output card for control slot |
| ABT-xAudIO-4/8-RS | Audio card 4 IN / 8 OUT AUDIO / RS485 |
| ABT-xAudI-8 | Audio card 8 IN AUDIO |
| ABT-xCtrLine-2 | 2 Loudspeaker line control card |
| ABT-xCtrLine-4 | 4 Loudspeaker line control card |

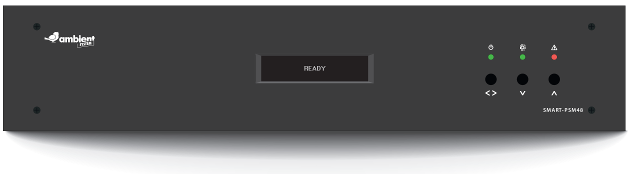
# 7.1. smartVES system components


## SMARTVES CONTROL UNITS (CU11 – LCD/LT)

- ***Control Units are net-workable audio matrix responsible for controlling the PAVA system amplifier stacks.***
- ***Modular architecture - 11 slots for loudspeaker line cards, I/O cards, etc.***
- ***Integrated DSP (EQ, delay, feedback eliminator, audio limiter).***
- ***SD flash memory card up to 32 GB dedicated for playback and recording of automatic messages (48 kHz, 16 bit).***
- ***Built-in networking: interface with 2x1Gbit Ports, 1x POE port, 2x SFP - fiber connector SC, LC, single or multimode.***
- ***Dynamic backup amplifier feature.***

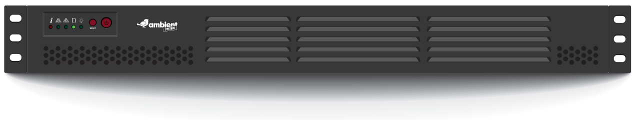

## SMARTVES POWER AMPLIFIERS

- ***100 / 50 Volt available via terminal blocks at the rear***
- ***Output channels can be linked into:***
  - *SMART-PA8080B/BE, SMART-PA4160B/BE, SMART-PA8160B/BE: 4× 160 W, 2× 320 W or 4× 320 W by daisy-chaining 50 V tapping (input on parallel).*
  - *SMART-PA2650B/BE: 1× 1300 W by daisy-chaining 50 V tapping (input on parallel).*
  - *SMART-PAXXXXB/BE series combines with the SMART-PSM48/E Power Supply Manager (charger and back-up supply).*
- ***It allows the ABT-TNL 100 loudspeaker to operate at its rated power with over 50% headroom, compensating for voltage drop and ensuring optimal speech dynamics.***




## SMARTVES POWER SUPPLY EQUIPMENT

- ***Modular power supply built around the ABT-PSC power distribution unit.***
- ***Each SMART-ABT-PSC allows to connect up to 4x smart-PS48800 PSU units.***
- ***Allows for N+1 PSU redundancy.***
- ***The system can also include a smart-PSM 48 battery charger unit and its own EN54-certified battery backup power system, ensuring reliable power supply during emergencies.***



## ISE VES SYSTEM GATEWAY

- ***The VES SYSTEM GATEWAY is an exchange server, allowing multiple smartVES system configurations to connect into a single audio network, facilitating centralized management from a Tunnel Control Center (TCC).***
- ***The VES SYSTEM GATEWAY features a SIP hotspot function, enabling the integran of PAVA systems with third-party VoIP telephony and intercom systems for seamless communication.***
- ***Additionally, the VES SYSTEM GATEWAY includes a digital message player, easily manageable through a web browser interface, offering convenient control and flexibility.***

# 8. System design guidelines

Most countries safety standards require for public transport tunnels to have an audio system to be used in emergency situations.

The system usually covers such areas within the tunnel as:

a. The main tunnel itself (for twin tunnels, each tube is considered a separate zone)
b. Evacuation galleries and staircases
c. Refuges (where people can safely wait away from the danger or wait for help)

The tunnel PA/VA system has a primary function of life-safety. The system is then being used for broadcasting of emergency and evacuation messages initiated automatically
via the Fire Alarm System and/or Supervisory Control And Data Acquisition System (SCADA).
In addition the PAVA system shall also be used to broadcast general announcements related to traffic and safety.
The system offers automated message paging as well as manual paging: from operators remote paging microphones, alarm consoles and/or a PC workstation. The system needs to offer priority paging.

The system should also offer the exchange of audio signals with the tunnel Leaky Feeder system, in a manner ensuring intelligible transmission of voice messages emitted from its memory via the LF radiating cable.
The system will transmit information about its condition and any faults to the SCADA system.
The PAVA system will also allow the SCADA system to trigger automated messages stored in its memory and route them to selected zones of the tunnel.

The system shall use:

a. dedicated high-power tunnel loudspeakers in the main tunnel

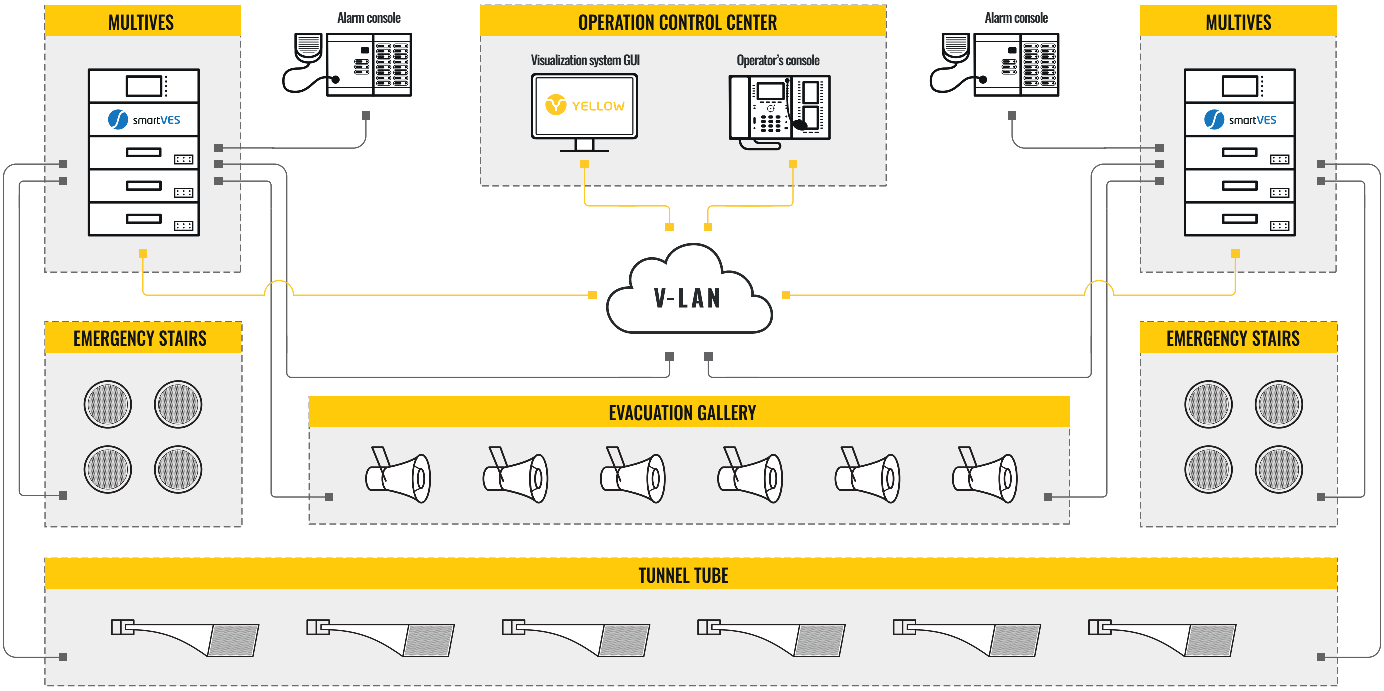
   The basic requirement is the possibility of introducing a time delay to the individual amplifier outputs, powering individual loudspeakers. This shall allow for appropriate synchronization of the loudspeaker devices. Also, for this reason, all loudspeakers in the tunnel tube shall be faced in the same direction. Alignment of the sound coming from each previous loudspeaker with the next gives higher values of the Speech Transmission Index.
b. horn speakers, sound projectors and other small format loudspeakers for escape route, staircasses and refuges

Due to the size of the tunnel the system shall be IP based, with distributed architecture:

a. the loudspeakers shall be powered from multiple locations connected via TCP/IP
b. remote management shall be possible from a remote Control Centre via WAN or fibre-optic cabling
c. alarm microphones can be placed close to the tunnel portals and/or in niches within the tunnel itself

The systems networked elements shall be connected by a dedicated TCP/IP network using a fibre optic ring (for redundancy and increased reliability). Digital audio transportation will be low latency and high resolution. Any point to point audio transmission shall not exceed 10ms latency. An advanced mechanism for audio synchronization between internal network switches based on Precision Time Protocol (PTP) shall be implemented.

## 8.1. Sample system diagram




*Picture 8. Tunnel sound system concept diagram*

## 8.2. Note on EN54

While in some countries local law does not force that the Public Address system is to comply with the EN54 standard for Voice Alarm, it is imporant to note, that many VA system features are highly desirable in a tunnel application:

a. The system shall perform continuous monitoring of its internal elements (interfaces, amplifiers, microphones, etc.)
b. The system shall monitor connected loudspeaker lines for open-, short-cicuit and groud leakage
c. The system shall have fully redundant interconnections
d. Failure of a single device shall not cause complete loss of coverage in any zone
e. Failure to a single amplifier shall automatically turn on a backup amplifier with automatic takeover

For this reason in order to ensure increased reliability and safety, the PA system is advised to be based on EN54 compliant devices and work to the standard EN 50849:2017-04/Ap1:2019-10E– Sound Systems for Emergency purposes.

# 9. Contact

## CONTACT

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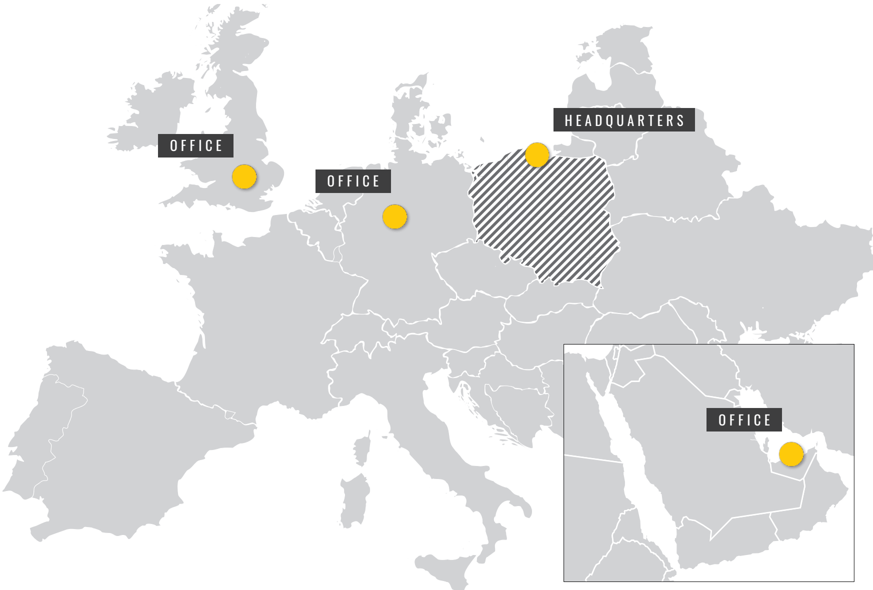
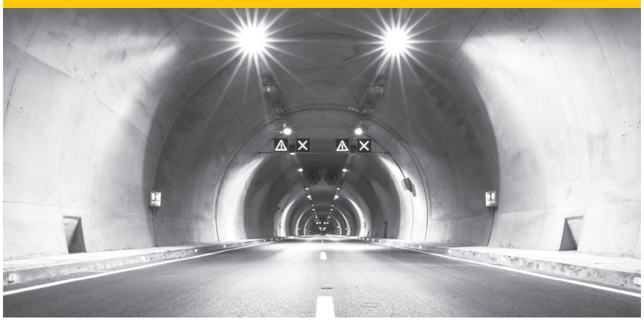



## References

### **Tunnel Żeleźnica,** Bulgaria

### **Tunnel under Swina,** Poland



### **Tunnel at Frankfurt Airport,** Germany

### **Zielonki and Dziekanowice Tunnel,** Poland

*We make everyday life safer*



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