Improvement of voice alarm systems in underground railway stations

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Introduction

Voice Alarm systems (VA) are an essential part of subsurface underground station emergency and evacuation systems. Their main purpose is to assist in the management of emergency situations and evacuation procedures by providing key verbal instructions to the occupants. However, these life-critical systems will be ineffective and even counter-productive if the speech messages broadcast are unintelligible.

The 1987 Kings Cross underground station disaster and more recently the July 2005 bombings on London Underground (LU), raised the awareness of the importance of an effective VA system for a safe and efficient evacuation procedure[1,2]. However, following recent research[3] it appears that more can be done to improve VA system performance and therefore contribute to safer underground stations.

Currently in many London Underground stations and particularly on subsurface platforms, the announcements broadcast by the VA system are still not adequately intelligible and often do not reach the minimum specified performance target. This lack of performance could become a contributor during a major disaster.

An increasing demand for improved acoustic performance of VA systems in underground stations should not only seek to provide audible and intelligible vital instructions during an emergency. It should also aim at assisting passenger flows and providing necessary travel/passenger information with a high degree of clarity and acoustic comfort thus conveying an increased sense of wellbeing and expected quality in the service provided.

The process of designing and implementing VA systems for underground stations is complex and depends on multiple interrelated factors: station design, operational and logistical constraints.

The system performance directly relates to its electro-acoustic characteristics as well as the space where it is installed. Underground stations often present complex P38 ▶

P37 geometrical and architectural features which severely challenge the achievement of the desired performance.

Awareness of the design environment and understanding of acoustic concepts, testing and modeling techniques can greatly assist the design to minimise the effect of inevitable external limiting factors and practical constraints.

Despite the importance of VA systems in mass transit systems, there is very little research reported in the literature providing relevant knowledge, particularly in the context of real world underground spaces. Experimental data and practical design knowledge is not released by companies responsible for the design, installation and maintenance of VA systems. Moreover it was found that contractual or custom performance specifications are often not suitably set out which can lead to ineffective designs.

The research[3,4] outlined in this article provides an insight into the practical aspects of electro-acoustic design of VA systems under real conditions found in underground stations. It is also encouraged through critical analysis to reflect on the current underrated importance of VA systems in underground stations. It suggests that attitudes should be changed and proposes technical specification changes with the ultimate aim of ensuring improved system performance to contribute to safe emergency procedures.

The research results, knowledge and insights presented in this article were obtained from practical experience in numerous test sessions and designs undertaken in real stations.

VA systems on underground platforms

Voice Alarm systems

Within London Underground, Public Address systems (PA) installed in subsurface stations are classed as Voice Alarm systems since they are an integral part of the station's fire alarm and emergency evacuation system. VA systems in that environment form the communication element of the statutory requirements under Fire Precautions Sub-Surface Railway Stations Regulations 1989. VA systems were first introduced in LU subsurface platforms in 1991 after recommendations made after Kings Cross underground station fire[5].

Overground stations do not require fire alarm evacuation systems thus sound systems installed on these stations are classed as PA systems.

The last part of a VA system (figure 1), named as the electro-acoustic transmission section, comprises three elements: the loudspeaker array (sources), the room space (acoustic transmission channel) and the listener (receiver) (figure 2).

It is in this last section of the chain where the performance of the whole system is delivered (perceived at the listener's ears or measured at a microphone).

The main function of a VA system in a space is to deliver and convey speech messages which can be satisfactorily understood by the occupants (i.e. staff and passengers) particularly in the case of an emergency. Speech intelligibility is the most important performance requirement in attaining the purposes of VA systems in underground stations and is the central performance parameter of this study. The Speech Transmission Index (STI) and its condensed version STIPA (Speech Transmission Index Public Address)[6] have been globally accepted as the de-facto industry standard metrics for the objective assessment of speech transmission quality and predictions of speech intelligibility of/from PA/VA systems.

The potential degrading factors from the input, signal processing and amplification sections are mostly of an electronic nature including electrical noise, non-linear distortions and limited bandwidth. The control and mitigation of the electronic degrading factors of the first three sections is relatively simple to attain. However, speech signal degradation in the electro-acoustic transmission section is more difficult to control and reduce. Consequently this section of the VA system is often the most critical and challenging for achieving satisfactory performance particularly in complex and acoustically difficult spaces such as underground stations.

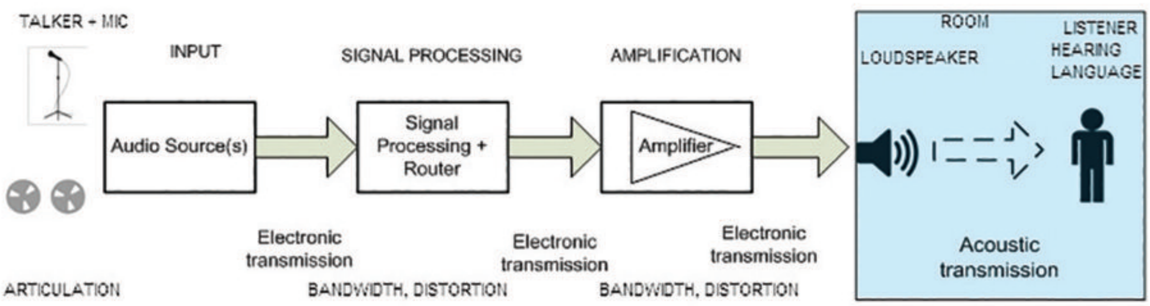

Figure 1. Basic block diagram of a Voice Alarm system and influencing factors

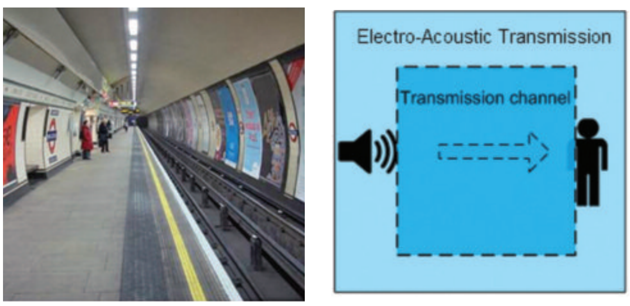

Figure 2. Electro-acoustic transmission section diagram (left) and example of an actual electro-acoustic transmission channel on an underground platform (right).

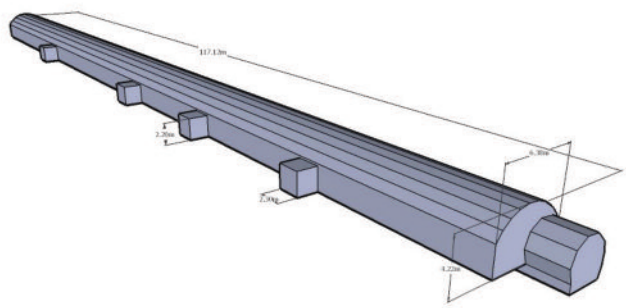

Figure 3. Main dimensions of typical London Underground subsurface station platform

This article focuses on the electro-acoustic section of the VA systems of London Underground subsurface stations. For the purpose of analysis, it is assumed that listeners share the same first language as the announcer, the hearing ability of receivers is normal and all the sections before the electro-acoustic section operate in optimal conditions. However, it should be noted that 23% of Londoners aged 16-34, and 40% of all adult Londoners have a first language other than English[7,8] Furthermore, in 2010 over 25,000 people were registered as deaf or hard of hearing in Greater London[9] and it is predicted that in the next 20 years the number of Londoners who are over 65 will increase by 33%[10].

Underground station platform characteristics

Subsurface platforms are the most challenging subsurface circulation space for quality sound reproduction in underground stations.

The majority of subsurface platforms are enclosed spaces of straight shape containing a single passenger platform and railway track. They are characterised by a large volume ($3000m^3$-$4000m^3$) of a disproportional shape in which the length (120-140m) is many times the height (~5m) and width (~6m), (figure 3). Deep platform stations are subsurface platforms which run typically at 20m below surface.

This extreme shape prevents the sound field from being diffuse when it is created from a single source[11]. Duct acoustic theory is not applicable due to the platform's large dimensions relative to the acoustic wavelengths of interest. The acoustic field in a platform excited by a single sound source is very different to the more complex field created by a multisource arrangement as it is the case of VA loudspeaker distributed systems. This fact is central in the potential design and performance prediction approaches to be employed

Platform spaces contain opening areas connecting the main volume to other spaces such as other platforms, concourses, train tunnels and ventilation outlets. Depending on the type and cross sectional size, these interconnecting apertures can act as an area of effective acoustic absorption, create local coupling effects and/or convey background noise from remote areas.

Surface materials in these platforms are acoustically characterised by being large, flat, smooth, hard and highly reflective. These boundaries tend to contain no furniture or other large fixtures. These surface qualities promote the formation of standing waves, echoes, highly reverberant sound fields, increase of background noise and the unobstructed travel of sound down the platform length, (figure 4). The long and characteristic reverberation of platforms equipped with VA systems is caused by the platform's large volume, the prominence of highly reflective surfaces and numerous other sources (loudspeakers) at a distance from a given receiver. The cross section of the volume approximates to a semi-circle. Walls and ceilings are typically concave surfaces which have the potential to cause undesired focusing effects, (figure 4).

The speech intelligibility performance of an underground platform VA system is a relatively complex phenomenon and depends on multiple interrelated factors and parameters.

The fundamental parameters affecting speech intelligibility in the electro acoustic section are the room reverberation characteristics and speech signal to noise ratio (SSNR) experienced at the listener position. They are directly determined in different measure by the interrelated factors and parameters listed below:

- Volume and shape of the space
- Sound absorption and scattering of surfaces
- Background noise temporal and spectral characteristics
- Loudspeaker–receiver distance
- Loudspeaker and receiver directivity
- Loudspeaker non-linear distortions
- Frequency response / tonality balance of the transmission channel

Other factors affecting VA design and performance

Compliance with other station operational requirements becomes a significant constraint in the design and testing. Logistical and practical considerations in a "live transit system" are numerous for each stage of the onsite processes: acoustic surveys, installation, benchmarking, commissioning and maintenance of the system. Compliance with other station operational requirements becomes a significant constraint in the design and onsite processes. These constraints typically include limited site accessibility, minimum test duration, test conditions, installation, maintenance, health and safety regulations, material/equipment certification, cost, aesthetics and heritage restrictions. P40

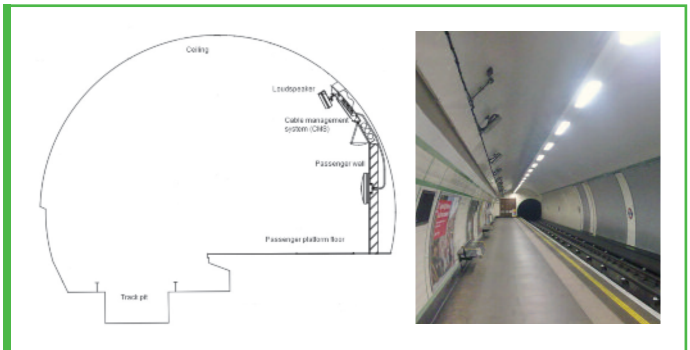

Figure 4 London Underground station subsurface platform cross section representation (left) and corresponding actual platform space.

Parameter	Performance requirement
SNR	10 dBA
Max SPL	90 dBA
Direct sound Coverage uniformity	±2dBA over 90% area
STI (CIS)	≥ 0.5 (≥ 0.7)
Frequency Response	±2dB (250Hz-6kHz) and level difference between adjacent 1/3 octave bands ≤ 5dB (100Hz to 10kHz)

Table 1. Performance parameters requirements for LU subsurface station VA systems

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Guidance on underground VA systems

Legislation and standards

In the UK except for subsurface underground stations, there is no legislation defining the requirements for the use, specification and performance compliance of PA or VA systems. However national and European standards exist, which provide detailed codes of practice and recommendations on an extensive range of aspects of sound systems applications including PA/VA. These standards do not explicitly indicate when a system is required. For instance the need for a voice alarm system is normally determined by the relevant building licensing authorities or on completion of a risk assessment by the owner[12].

Relevant standards in the PA and VA industry are often adopted as reference and/or guidance for compliance purposes[12-19].

Operator performance specifications

Railway companies, operators and/or suppliers, normally develop their own sets of technical and performance specifications. These are used for self reference and as contractual guidelines for compliance for the duration of projects. These documents are written using guidance from relevant standards and from practical experience.

It is usual practice that a supplier company responsible for the renovation and maintenance works of VA systems produces its own document as a re-definition, interpretation and expansion of the details and requirements of the parent performance specifications document handed by the railway company. The supplier document is used in turn as a contractual reference to be followed by sub-contractor companies. Table 1 shows the current electro-acoustic and speech intelligibility related performance specifications for sub surface LU station VA systems.

Findings and discussion

Electro-acoustic design

Commercial computer simulation programs are currently the most suitable and reliable prediction tool for the design of deep platform VA systems[3]. However, performing systematic acoustic surveys and acoustic computer simulations for each station VA zone can be costly and time consuming. Many platform and circulation spaces tend to have similar geometrical, architectural and environmental noise characteristics. Validated design templates based on previous surveys, computer simulation results and experience could provide a reliable and cost-efficient way to deliver VA design for qualifying spaces.

In the design of the electro-acoustic transmission part of VA systems and without the option of introducing acoustic treatment, factors relative to the loudspeaker configuration become the only controllable design variables available to overcome the inherent acoustic difficulties of the space and achieve the required system performance. However even those variables can be severely constrained by practical installation and maintenance priorities (e.g. cabling routes, vandalism protection, accessibility, aesthetics, heritage issues, cost).

Loudspeakers commissioned to be used in stations must satisfy strict minimum performance specifications for optimal speech reproduction, safety, fire and dust ingress resistance, aesthetics and other mechanical and installation requirements. Those requirements limit the selection of loudspeakers commercially available.

Moreover the loudspeaker configuration options are limited to a conventional design approach for long and highly reverberant spaces. This effective approach involves the installation of an array of low-powered and rather directional loudspeakers along the platform length, all equally spaced and connected in parallel without signal delay, (figure 5).

Using validated computer simulations it was shown that variations of the conventional configuration involving different loudspeaker positions, aim and density did not affect the reverberation in the platform space. Furthermore, variations of the loudspeaker array configuration including different types of wide dispersion loudspeaker, aim and speaker density did not significantly increase the STI/STIPA.

Assuming an optimal loudspeaker configuration under the constraints expounded above, the main degrading factors to platform VA speech intelligibility are reduced to background noise and reverberation. Background noise is, under normal conditions, dominated by occupancy noise or by distant background noise sources when the platform has minimum occupancy. If those noise levels are overcome by an adequate announcement signal level (ensured in practice by a dynamic gain system), then the only degrading and limiting factor to speech intelligibility is the platform reverberation.

From a large set of design predictions and actual measurements it was found that speech intelligibility from conventional distributed VA systems on deep platforms is limited to the maximum achievable (typically 0.40 - 0.45 STI) in the dominating reverberation condition. Only drastic approaches such as significantly reducing the loudspeaker-receiver distance, or the use of highly directional loudspeakers were able to achieve the specified performance target (0.53 and 0.50 STI respectively) in design predictions. Those configurations would present the added economic benefit that they would reduce the amplifier power requirement by a factor of 6 and ▶

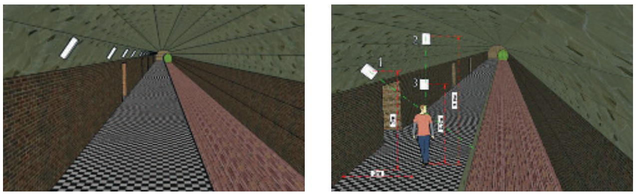

Figure 5. Conventional VA loudspeaker configuration options shown on a computer simulated underground platform

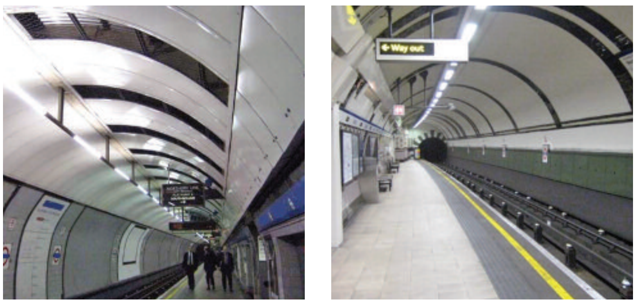

Figure 6. Station platform featuring metal panel cladding on the ceiling (left) and bare ceiling (right)

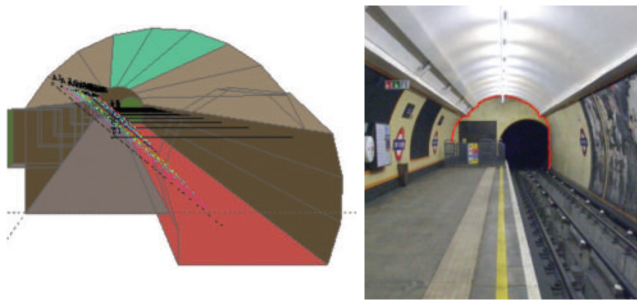

Figure 7. Left: Acoustic simulation showing the position and coverage of three strips of acoustic treatment in a deep platform. Right: Platform end wall and tunnel opening.

4 respectively. However they would reduce coverage uniformity, perceived sound quality and aesthetics.

From measurements it was also observed that metal panels forming the ceiling cladding in some deep platforms act as diaphragmatic sound absorbers, (figure 6). The significant reverberation reduction (1.0 - 1.5 sec) observed on clad platforms at low and mid frequencies (125Hz - 500Hz) resulted in measured STI scores being typically 0.05 higher than on similar platforms with bare ceilings, (figure 6).

A study on the effectiveness of the application of acoustic absorption treatment on deep platforms showed that these spaces are highly sensitive to variations in sound absorption. This fact makes the application of acoustic treatment the most effective solution to reduce reverberation and therefore enable platform VA systems to achieve the specified 0.5 STI target.

The platform end walls (figure 7) were shown to be a highly effective and efficient complementary treatment location to increase the STI score, by reducing general reverberation and strong late reflections. Furthermore, the introduction of acoustic treatment on platform areas would provide the added benefit of reducing background noise and controlling the acoustic field which would in turn enable the utilization of simple design templates.

However, until recently, the use of acoustic treatment in the design of underground stations has been discouraged due to cost constraints and installation and maintenance difficulties.

Recent research work by the author[20] has showed that assuming temperature and humidity conditions to be constant and/or negligible in the electro-acoustic design of platform VA systems can lead to performance prediction errors of up to 0.06 STI which could become critical in marginal compliance situations.

Standards and guidance

From a critical review of the relevant standards and guidance available to the station VA designer it appears that information is not well harmonised and interconnected among the different standards. Information is frequently generic, overlaps with different levels of detail and guidance is occasionally not applicable. The standards provide only limited guidance on specific aspects of the electro-acoustic design such as survey and test methodologies. Performance specifications were found too generic, imbalanced and occasionally unsuitable. These specifications require generic compliance with standards which cater for different purposes and areas of application. Attempting to meet all performance requirements as laid out in performance specifications and applicable standards can be conflicting across contractual documents, prove unattainable and counter–productive.

The specification of a minimum sound pressure level (SPL) of at least 10dBA above the average inherent background noise on subsurface platforms at the time of an announcement, is not a truly indicative ratio of effective audibility to achieve acceptable speech intelligibility since the signal measured at the receiver positions will be mostly comprised by degrading reverberant sound and background noise. On the other hand, the required operational maximum SPL level (90dBA) could be insufficient to overcome occupancy noise levels under emergency conditions (for example, crowd panic and emergency fans); hence the announcement might become inaudible and unintelligible.

Predicted uniformity of the direct field level coverage is not indicative of potential speech intelligibility or suitable to calculate useful speech signal to noise ratio (SSNR), since the direct field becomes swamped by the reverberant field in realistic situations. If knowledge of useful SPL sound coverage is needed for the strategic placement of loudspeakers, the author proposes that a direct plus early reflections level (DERL) coverage parameter would be a more relevant and realistic design indicator of useful sound energy coverage.

DERL can be defined as the SPL (dB) resultant from the useful speech energy registered at the receiver during the time window comprising the direct sound arrival and the subsequent 50ms of early reflections. From the impulse response this parameter could be calculated as expressed in Eq 1.

$$DERL = 10 * log_{10}[\int_0^{50} p^2(t)\, dt] \quad (dB) \qquad \text{Eq.1}$$

where p^2 is the square of the instantaneous sound pressure of the impulse response and t is time.

It is assumed from the relevant standards and guidance that subsurface VA systems are to be designed to provide satisfactory performance for the worst case scenarios. This currently concerns speech intelligibility predictions (STI) involving a combination of maximum possible reverberation and representative rush hour occupancy noise levels (figure 8). This scenario is simulated by synthetically adding representative occupancy noise (rush hour) levels to the intelligibility predictions (STI) undertaken for maximum reverberation[2,12]. P42

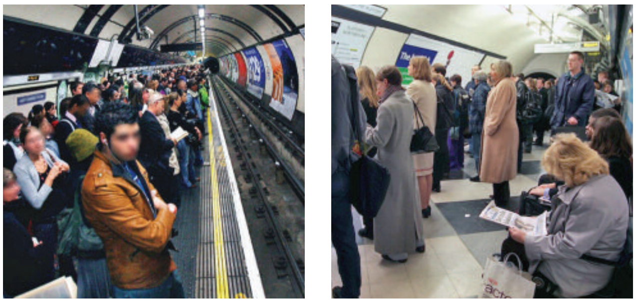

Figure 8. Examples of different occupancy density on deep platforms

P41 However this combination of conditions cannot exist in reality as the maximum reverberation occurs when the platform presents minimum occupancy, therefore this scenario is not representative of real life situations.

Also it is important to note that occupancy background noise levels under normal traffic conditions including rush hours, may not be representative of emergency situations.

Current research is being conducted by the author to determine the multiple effects and their interrelations of different levels of occupancy on platform VA performance. This study will include occupancy effects under a range of simulated emergency scenarios.

Most of the relevant standards and companies' performance specifications only mention fire and emergency evacuation as the intended applications of VA systems. However many other types of emergencies can occur equally requiring the assistance of VA systems (e.g. major accident, failure of power or air supply, entrapment, false alarm panic, stampede, terrorist attack, station kidnap/hostage situation).

Recommendations

A summary of recommendations applicable to the design and guidance documents are listed

Design

1. The design predictions should cater for the most likely worst emergency scenarios including effects caused by different levels of occupancy (figure 8) and other expected background noise sources (e.g. emergency ventilation fans).
2. Acoustic absorption treatment should be provided in all key subsurface circulation spaces where achievable speech intelligibility is limited by long reverberation (e.g. deep platforms, concourses).

If acoustic absorption treatment it is not a design option, other less effective measures could be taken to improve speech intelligibility, these include:

3. Using functional and decorative furniture/hardware/art work/ rough textured concrete/ rough textured artistic walls to increase the sound scattering properties of surfaces to help decrease reverberation.
4. Redesigning existing platform billboards (figure 8) ceiling and cable management metallic paneling as well as signage to act as tuned diaphragmatic and/or micro-perforated cavity sound absorbers.
5. Positioning loudspeakers as close to passengers' head level as possible (e.g. loudspeaker integration into cable management box panels or into acoustic treatment).
6. Consideration of limiting the low frequency response of the system. This measure will prevent long low frequency reverberation, diminish upwards masking, avoid the inefficient low frequency reproduction region of the loudspeakers' response and save significant amplification power requirements. However, although this measure can improve the perceived speech intelligibility, it can also reduce the naturalness of the announcement broadcast particularly of male speech.
7. Activation of selected loudspeakers during broadcast relative to occupancy spatial distribution (passenger presence detection (figure 9).

Standards, guidance and specifications

8. Harmonisation and rationalization of information and guidance among relevant national and international standards.
9. Performance specifications should be reviewed to produce tailored, detailed, updated and balanced requirements taking into account practical constraints and design experience.
10. Rationalising of referred standards and generic compliance involved.
11. Provision of specific and carefully balanced requirements for other interrelated VA performance parameters such as total harmonic distortion (THD), inter modulation distortion, coverage uniformity, frequency response range, frequency response flatness and maximum SPL.
12. Provision of detailed test methodology of performance parameters (including STIPA) specific for the environment, and requirements for relevant instrumentation, test equipment and operator competency.
13. Mention of RASTI as a metric of predicted speech intelligibility should be removed.
14. Harmonisation and certification standardisation of STIPA instrumentation.
15. Incorporation of a procedure to demonstrate reliability and accuracy of design predictions processes

Proposal for raising performance specification and a new standard

Underground railway transportation is the most effective and efficient mass transportation means in large cities. Many underground railway stations are currently being built, extended or renovated around the world. However underground stations are highly vulnerable and at high risk of attacks and other incidents which can develop into major disasters.

Overcrowding and the confined space of old subsurface stations (figure 10) would increase the severity of a major incident. In most types of emergency situations, the VA system will be the only means of mass communication between the emergency services and the users.

Current guidance and specifications have provisions to ▶

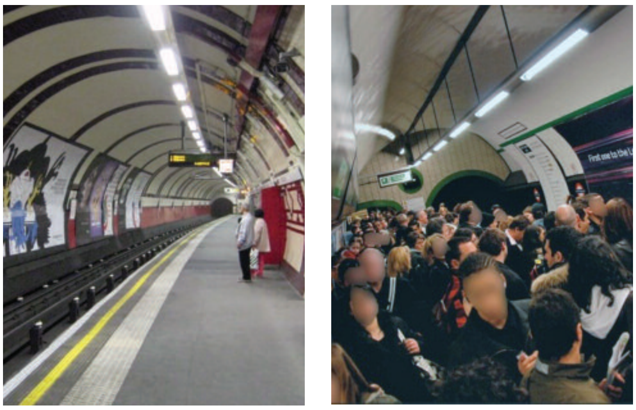

Figure 9. Minimum (left) and crowded (right) occupancy conditions on deep platforms.

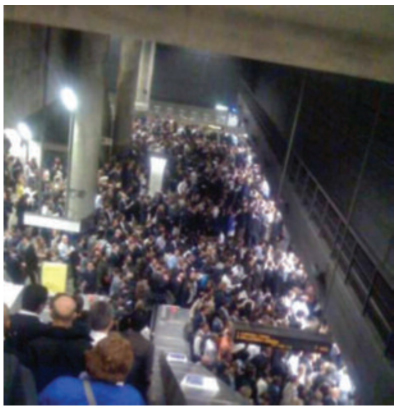

Figure 10. Underground stations exhibiting crowded conditions

relax minimum performance specifications to accommodate for the inherent difficult acoustics of the spaces. In the author's opinion this relaxation should not be contemplated for VA systems particularly those installed in high risk spaces, such as subsurface station platforms. Recognizing the critical importance of the VA systems to public safety in those spaces should prompt decision makers to raise the current minimum specification. The compliance to stricter specification then should drive the stipulation for provision of mitigating measures e.g. acoustic treatment to achieve the raised performance.

The potential life-saving and economical benefits provided by an effective VA system in case of an emergency in underground spaces should outweigh arguments of the high cost of mitigating measures. Hence it is recommended by the author to increase the current minimum speech intelligibility requirement for subsurface circulation spaces to qualification band E (0.56 - 0.6 STI)[5]. The previous minimum STI performance requirement in surface stations areas was 0.6, this was relaxed to 0.5 to minimise environmental noise nuisance. The proposed requirement aims to ensure adequate speech intelligibility and compensate for the following additional difficulties of users in an emergency situation:

- unfamiliarity with the emergency messages (pre-recorded and/or live)
- stress caused to listeners by an emergency situation which may reduce their hearing ability and concentration
- reduced message comprehension by normal hearing non-native listeners, elderly and hearing impaired users[7].

In order to facilitate satisfactory performance of life critical VA systems in subsurface underground stations, it is suggested that there is a need for the creation of a new code of practice, possibly in the form of a British Standard specific for these specific complex and high risk environments.

The new code would consolidate relevant existing guidance, address the concerns and recommendations discussed above and incorporate advice from the relevant industry so as to form a stand-alone and pioneering guidance document which could be also employed outside the UK.

The drafting of the code would also take into account practical, economic, logistical and strategic considerations so that compliance is feasible in all emergency situations.

A possible title is: *Code of practice for designing, specifying, maintaining, installing and operating Voice Alarm systems in Underground Stations*

Conclusions

The vital role of VA systems in subsurface railway stations is currently underrated. A VA system loses its intended life-saving purpose if it is unintelligible and may even become counter-productive in an emergency. Therefore it is essential that improved VA system performance is prioritised by the decision makers when a station is being designed or refurbished.

As subsurface stations are highly vulnerable and at high risk of attacks and diverse types of incidents which could lead to major disasters, particularly in crowded and confined conditions, it is not appropriate that economic considerations prevail and allow substandard VA performance.

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