MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Acoustic design of voice alarm systems in an occupied underground platform

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ABSTRACT

Voice Alarm systems (VA) in underground railway spaces are life critical communication systems used to instruct occupants in case of emergency or direct them to safety. The effectiveness of these systems depends on the performance quality of the entire electro-acoustic communication chain, which speech intelligibility is the main parameter. VA are designed with the assistance of field measurements and prediction computer models. Relevant standards and industry best practice require the design and performance assessment of VA systems in unoccupied spaces. This is the most practical state to undertake acoustic measurement and is generally considered acoustically the worst-case scenario. However, the influence of occupancy on the performance of the VA remains unknown to the designer. This paper investigates the impact that occupancy can have on the acoustic performance of an underground platform VA. The sound absorption coefficients of varying densities of standing people were determined and implemented in acoustic modelling software to predict the performance of a hypothetical VA on a real underground station platform. The results showed that for a representative level of ambient noise, speech intelligibility increased notably with occupancy density.

Keywords: VA System, underground, metro, intelligibility, occupancy

I-INCE Classification of Subject Number: 76
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1. INTRODUCTION

Voice alarm (VA) systems are utilised in underground platforms of rail stations to provide critical verbal instructions to occupants in case of emergency. The acoustic performance of the systems is usually designed with the aid of acoustic modelling software which predict performance parameters as a function of input data. Since VA are life critical systems during emergencies, the acoustic models should be as accurate as possible.

The occupants on a platform have the potential to drastically alter the acoustics of the space. A small degree of sound absorption is provided by the clothes worn by a single person [1], but if the platform is occupied at various degrees, different levels of sound absorption are to be expected in the space under consideration

A large amount of research has been conducted looking into the effect of seated audiences on the acoustics of indoor spaces (particularly in auditoria) [2,3,4,5,6 & 7] but limited research, has been conducted to date on the effect of standing audiences as would be expected in an underground platform. There are a number of sources which have determined the absorption coefficients of standing people [1,8&9] but the implementation in acoustic modelling software remains very little explored. The effect of standing audience and occupancy density on the acoustic performance of VA systems has not been explored.

This study aims to investigate the effect of passenger occupancy on the acoustic performance of VA systems in underground stations to conduct the study, a hypothetical VA system will be modelled using computer simulation techniques and the effect of occupancy absorption on two performance parameters will be predicted under various occupancy densities.

2. BACKGROUND THEORY

This section will cover the general principles of acoustic design of VA systems in underground stations and the background behind the implementation of occupancy density.

2.1 Acoustic Design of VA Systems

The main electroacoustic parameter indicating performance quality for a typical VA system are: speech intelligibility (quantified in terms of Speech Transmission Index, STI), signal level (measured as the A-weighted sound pressure level SPL(A)) and signal-to-noise ratio (SNR). The speech intelligibility of a communication system, either electro acoustic or human, is the proportion of words understood by the listener and STI is the objective scale standardised in [10]. The STI method estimates the loss of modulation depth in a known signal played through a system.

In a platform VA system, a large cause of the loss of this modulation depth can come from the acoustics of the space in which the system is located, assuming that the electro-acoustic aspects of the system are distortion free [11].

Long reverberation times and high ambient noise in the space tend to mask some, or all, of the modulations in the test signal and these effects are often combatted with the introduction of acoustic treatment (sound absorption).

When designing a VA system, it often is required to meet a number of National, International and, Client Standards.

Minimum performance requirement in the UK from different guidance sources are summarised in Table 1 below. The requirements are typically targeted with the space in an unoccupied state as the industry assumption is that, this will be a ‘worst-case’ condition for the performance of the VA. In typical platforms this condition is caused by the lack of absorption allowing long reverberation in the space. An uncontrolled reverberation is one of the main degrading factors affecting the speech intelligibility from platforms VA [11]. This reference extreme condition allows for easy comparison of performance measurements of the system, which can normally only be conducted after the station is closed to the public, and the empty state has been assumed to be the ‘worst-case’ in terms of STI performance. However, this situation is not representative and during busy periods the levels of occupancy can become very high. Figure 1 below shows two images of a London Underground platform under different occupancies.

Occupancy noise level can be defined as the ambient noise level in dB measured on a platform with occupancy. The occupancy noise level is another fundamental factor in the degradation of the speech intelligibility and therefore the STI.

Table 1 – Acoustic requirements of VA systems

Source	**Acoustic Requirement of VA System**		
	STI	**SPL(A)**	**SNR**
ISO 7240-19:2007	Average 0.50 Min 0.45	>65 dB	>10 dB
BS 50849:2017	Average 0.50 Min 0.45	N/A	>10 dB
BS 5839-8:2011	0.50	N/A	>10 dB
NR/L2/TEL/30134	Average 0.50	>65 dB	>10 dB

Figure 1 – Low occupancy (L) and High Occupancy (R) in Underground Platforms

2.2 The Effect of Occupancy Density

The absorption coefficient of standing audiences has been the subject to some research [9,12] and the effect on the acoustics of varying densities of standing audiences in churches has been predicted [13].

Martellotta et al. [12], has conducted research into how the absorption coefficient of a standing audience can vary with the occupancy density. The research showed that there is a general decrease in the equivalent absorption area per person at high frequencies as the occupancy density increases.

Martellotta et al. presented the equations in Table 2 to predict the absorption coefficients of varying occupancy densities based on the area of the floor the audience occupied.

Table 2 – Equations to predict the octave band absorption coefficients at varying occupancy densities, from [12]

Frequency	Equation
125 Hz	$\alpha = 0.142d$
250 Hz	$\alpha = 0.239d$
500 Hz	$\alpha = 0.532d + 0.05$
1,000 Hz	$\alpha = 0.709d + 0.28$
2,000 Hz	$\alpha = 0.738d + 0.27$
4,000 Hz	$\alpha = 0.756d + 0.25$

Where:
d = occupancy density, people per metre square (p/m^2)
α = absorption coefficient

The above equations are based on absorption coefficient measurements of varying occupancy densities in a reverberation chamber. The equivalent absorption areas per person have been calculated by dividing the calculated absorption coefficient by the occupancy density (in terms of the number of people per metre square (p/m^2)). The resulting equivalent absorption areas per person are presented in Figure 2 below. Data at 8 kHz has extrapolated based on 2 kHz and 4 kHz values.

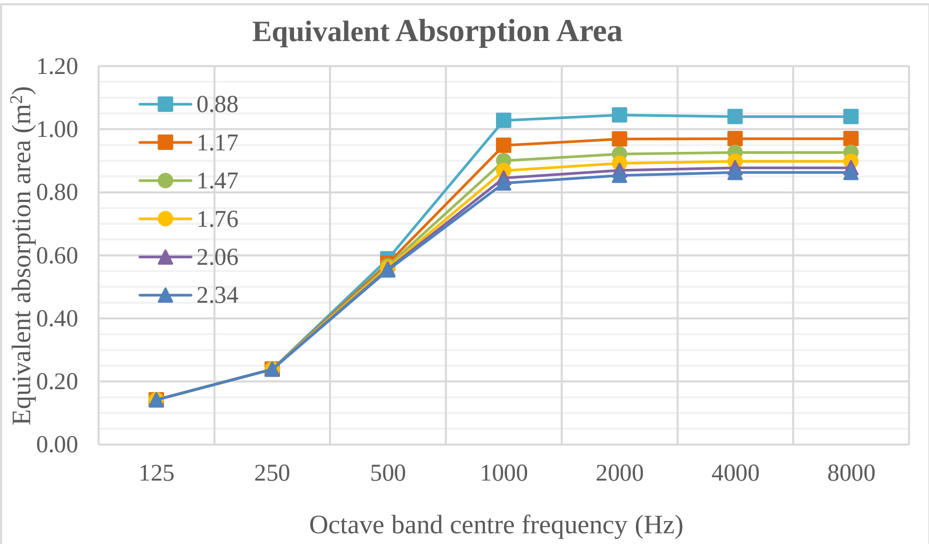

Figure 2 - Calculated absorption area per person at varying occupancy densities

As can be expected from the formulas in Table 2, there is no difference in the equivalent absorption area per person at 125 Hz and 250 Hz, and a slight decrease in absorption with increased occupancy at 500 Hz. The largest differences occur at 1, 2, and 4 kHz, where the total absorption decreases significantly at high occupancy density. This is due to the lower availability of exposed absorption area at high occupancy densities. When the density is increased the occupants are closer together and shield the adjacent person from the sound source, and therefore, stop absorption that could occur. This effect doesn’t occur at low frequencies as the wavelength is longer than the width or depth of a standing person and the waves diffract round.

3. RESEARCH METHODOLOGY

This section sets out the method for predicting the acoustic performance of the hypothetical VA system and the assumptions made within the model

3.1 Acoustic Modelling

Acoustic models are used to predict the likely performance of VA systems in underground platforms [11&14]. For the purposes of this investigation CATT-Acoustics (v.9.1) [15] computer simulation programme has been employed to create prediction models. A model of a hypothetical space has been developed to assess the impact of occupancy density. The space is based on a typical London Underground deep platform and comprises of a single approximately 150m long, 6m wide and 5m high platform with short column loudspeakers distributed evenly down the entire length.

A cross-section and a 3D projection of the platform showing the loudspeaker locations (red) and the receiver locations (blue) are shown in Figure 1.

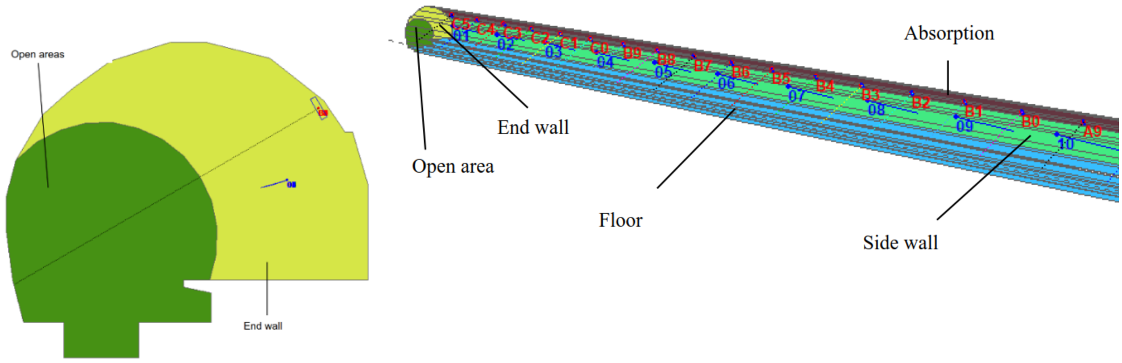

Figure 1 – Cross-section and 3D projection of the platform

Column loudspeakers are mounted at a height of 2.8m from the platform floor and have been assigned the directivity characteristics of Penton MCS20/TEN tapped at their maximum tapping of 20W. 26 loudspeakers have been used and are spaced at 5.8m intervals down the length of the platform. They are aimed with an elevation angle of 30 degrees to approximately focus on the audience average ear height (1.6m).

Acoustic panels were included in the model to represent a platform with acoustic treatment intended to increase the STI to a compliant state under the worst case (empty) scenario. Acoustic absorption is increasingly included in London Underground Stations as compliance with the Standards given in Table 1 is being sought for new stations (such as the new Crossrail Station) and stations undergoing refurbishment.

A total of 15 simulated receivers have been placed in the model at a height of 1.6m above the floor (in accordance with BS EN 50849:2017 [16]). All receivers are located along the platform length on a line located at half platform width. Simulated receivers are placed at a distance of 10m apart so that they cover areas of on axis and off axis projection from the loudspeakers.

3.3 Surface Finishes

Surface finishes have been implemented based on the materials found in a deep London Underground platform and common materials found on underground rail stations. With the exception of the acoustic treatment panels, surface materials are all largely acoustically reflective. The materials and their absorption coefficients used within the model are presented in Table 3 below. Absorption coefficients data for 8 kHz is normally not available in the literature and so, for the purposes of this study, 8kHz data has been obtained by using the extrapolation function within CATT-Acoustic as explained in the software manual [15].

Table 3 – Absorption Coefficients Used in Acoustic model

Finish	Location	Absorption Coefficient at Octave Band Centre Frequency (Hz)						
		125	250	500	1k	2k	4k	8k
Concrete	Floor, track bed, end walls	0.01	0.02	0.02	0.02	0.02	0.02	0.08*
Absorption	Wall panels	0.45	0.90	0.95	1.00	0.95	0.90	0.75*
Glazed tile	Walls	0.01	0.01	0.01	0.01	0.02	0.02	0.02*

All absorption coefficients are from [17]
Values higher than 0.99 were limited to 0.99.
*Extrapolated by CATT-Acoustic software

3.4 Occupancy Density and Implementation

Three densities have been used to predict the effect of increased occupancy based on available guidance from BS 9999:2017 [18] and London Underground Limited [19]. Table 9 of BS 9999:2017 [18] gives guidance on the design of buildings to assist in the evacuation of users of the building in the event of an emergency. Part of the design process requires and understanding of the occupancy levels anticipated during an emergency evacuation. Different design solutions will be required for different levels of occupancy, and so the Standard gives examples of typical occupancy densities. Table 4 is replicated from BS 9999:2017.

Table 4 – Occupancy Density from [18]

Density	**Floor space factor (m^2per person)**	**Example**	**Occupancy density (p/m^2)**
Very high	0.3	People queueing	3.3
High	0.5	Bar	2.0
Normal	1.0	Theatre or cinema foyer	1.0
Low	2.0	Museum or gallery	0.5

Based on this guidance, the three densities to be modelled represent, empty, normal, and very high occupancy; 0.0 p/m^2, 1.0 p/m^2, and 3.3 p/m^2, respectively.

This ties in with the London Underground guidance, LUL-S1371 [19], which has station planning requirements on platforms based on Fruin Levels of Service (LoS) [20] as follows:

Table 5 – LUL-S1371 Station Planning Requirements [19]

Category of station operation	LoS	Floor space factor	Occupancy density (p/m^2)
Normal operation	C	0.93 m^2 per person	1.1
Guidance for special events up to 3 days	D	0.28 m^2 per person	3.5

The standing audience has been implemented in the acoustic model as a single box based on the relative dimensions of a standing audience presented by Martellotta et al. [12]. The box was modelled at a height of 1.45m above the floor level with a gap of 0.5m to the edge of the platform edge and the side/end walls on the basis that passengers are not likely to stand this close to the platform edge, or walls.

3.5 Calculation of Absorption Coefficients

An absorption coefficient has been applied to the top and three sides of the audience box based on the calculated equivalent absorption area per person with the densities given above.

The calculated equivalent absorption areas per person are presented in Table 6 below.

Table 6 – Equivalent Absorption Area per Person Used in the Acoustic Models

Occupancy density (p/m^2)	Calculated equivalent absorption area applied to audience						
	125 Hz	250 Hz	500 Hz	1,000 Hz	2,000 Hz	4,000 Hz	8,000 Hz
0.0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1.0	0.14	0.24	0.58	0.99	1.01	1.01	N/A
3.3	0.14	0.24	0.55	0.79	0.82	0.83	N/A

The above equivalent absorption areas per person have been multiplied by the total number of people expected on the platform (based on the occupancy density and the area of the platform (443m^2)). The total equivalent area was subsequently divided by the surface area of the box representing the audience to derive the absorption coefficient to implement in the model, based on:

Equation 1 – Derivation of Absorption

$$\alpha = \frac{A}{S}$$

Where:

A = equivalent absorption area (m^2)

α = absorption coefficient

S = Surface area of the box

The resultant absorption coefficients for the two occupancy densities are presented in Table 7 below. The empty scenario did not have the representative audience box included in the model.

Table 7 – Audience Absorption Coefficients Used in Acoustic Models

Occupancy Density (p/m^2)	**No. people**	**Absorption Coefficients Applied Within Acoustic Model**						
		125 Hz	**250 Hz**	**500 Hz**	**1 kHz**	**2 kHz**	**4 kHz**	**8 kHz**
1.0	443	0.08	0.14	0.34	0.58	0.59	0.59	0.59*
3.3	1461	0.27	0.46	1.05	1.52	1.57	1.60	0.75*

Where absorption coefficients exceed 1.0 the coefficient was capped at 0.99
*Data extrapolated by CATT-Acoustics

Scattering coefficients have been applied based on the formula set out in Equation 2, which has been taken from the computer modelling software CATT-Acoustic Manual [15].

Equation 2 – Scattering Coefficient Prediction

$$s = 50\sqrt{\frac{d}{\lambda}}$$

Where:
s = Scattering coefficient; *d* = estimated depth of material (m); λ = wavelength of sound (m)

Table 8 shows the scattering coefficients used in the acoustic models.

The modelling has been conducted in all models with a representative temperature and relative humidity set to 20° and 50%, respectively, as the temperature and humidity can contribute to the acoustic performance of a VA system [21].

Table 8 – Scattering Coefficients used in Acoustic Models

Material type	**Scattering Coefficient Applied at Octave Band Centre Frequency (Hz)**						
	125	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Wall/floor	3	4	6	9	12	17	24
Audience	37	52	74	105	148	210	296

Values lower than 10 were replaced with 10, and values higher than 90 were capped at 90 as recommended in the CATT-Acoustic manual [20]

3.6 Occupancy Noise Level

A field survey was undertaken to measure representative occupancy noise level at a representative London Underground platform during peak rush hour. Six measurement samples of 5 minutes each ($L_{Aeq,5min}$) were measured with a calibrated class 1 sound level meter while the occupants were waiting for the train. The measurements were logarithmically averaged, and results are presented in Table 9. These values were then applied to the acoustic models as input key information for the prediction of the STI.

Table 9 – Occupancy Noise Level Applied in Acoustic Models

Measured Occupancy Noise Level (dB) at Octave Band Centre Frequency							**dB(A)**
125 Hz	**250 Hz**	**500 Hz**	**1,000 Hz**	**2,000 Hz**	**4,000 Hz**	**8,000**	
67	64	62	58	55	51	47	64

4. MODELLING RESULTS

The platform VA system performance has been predicted in terms of the total SPL and STI at each of the 15 receiver locations. The model has been calculated with all the loudspeakers operational, and the results from the receivers have been arithmetically, mean averaged to provide a spatial average VA system performance.

The resulting total SPL is presented in Figure 2 and the STI performance is presented in Figure 3. Figures 2 and 3 show the mean value and Figure 3 shows the corresponding range of values as errors bars

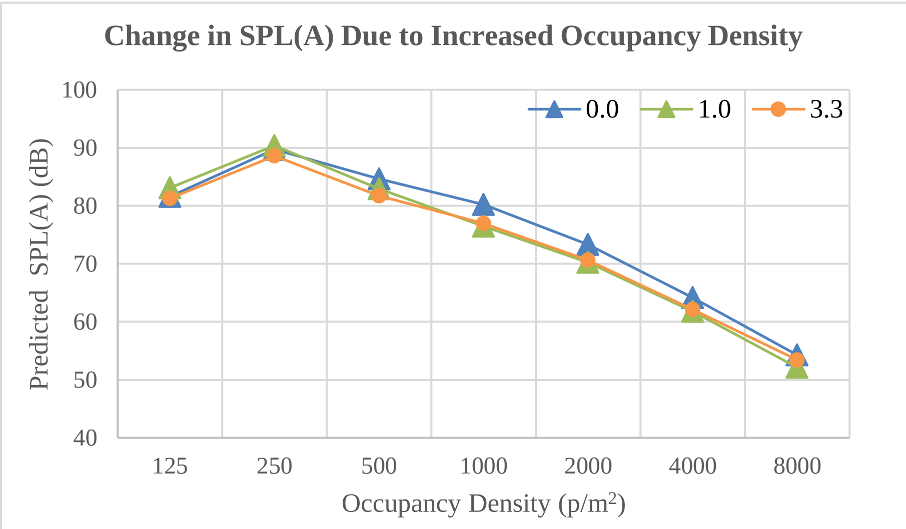

Figure 2 – Predicted SPL Under Varying Occupancy Densities

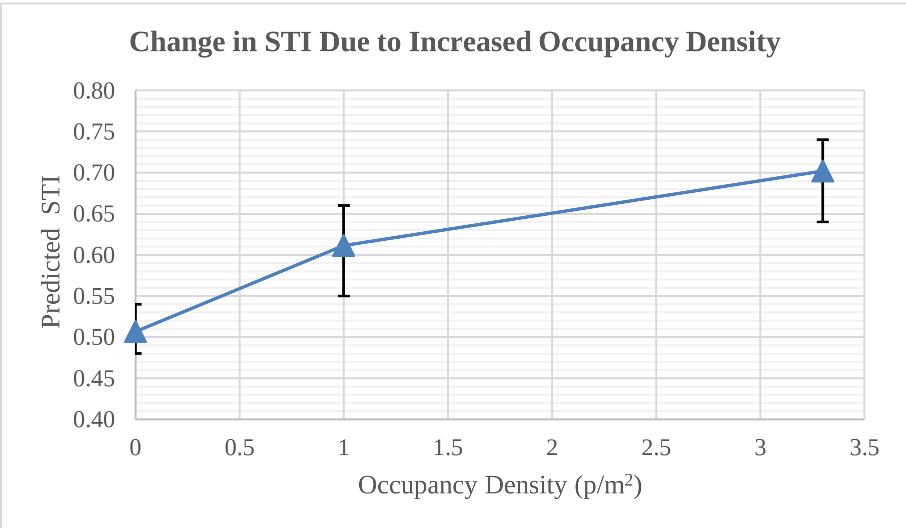

Figure 3 – Predicted change in STI due to Increased Occupancy Density

The octave band SPL results for two receivers are presented in Figures 4 and 5 below which indicate the performance for locations directly on-axis and directly off-axis.

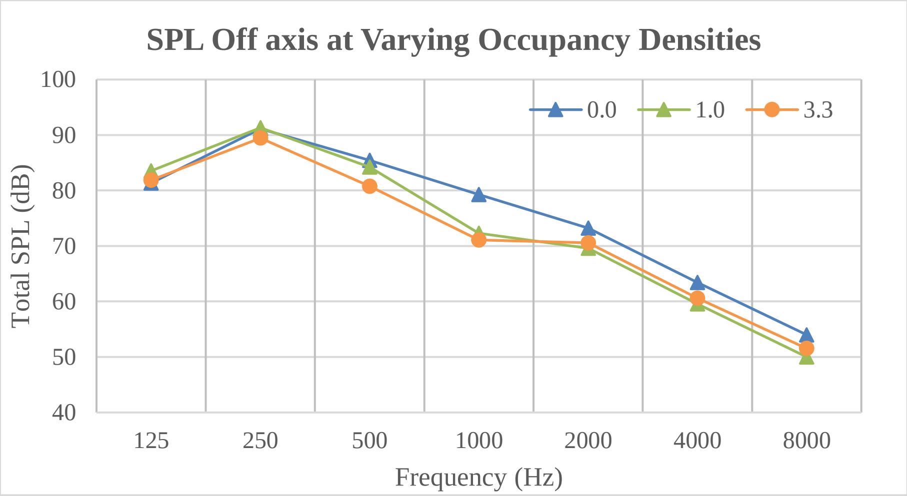

Figure 4 – Octave Band SPL – Off axis

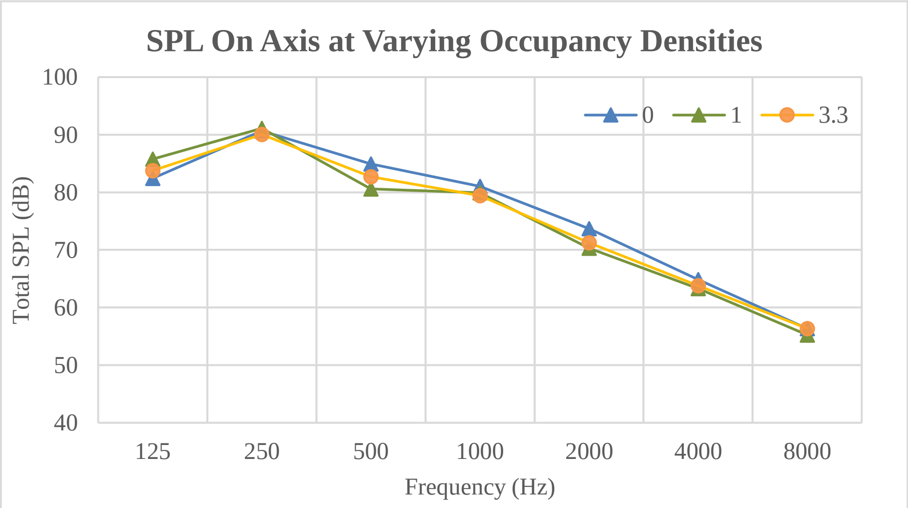

Figure 5 – Octave Band SPL – On-axis

5. DISCUSSION

The results show that there is a significant improvement on the STI performance of a VA system when a standing is audience is introduced to an underground platform, the increase was more pronounced (by approximately 0.2 STI) when the occupancy density is increased (Figure 3). This compounds the current industry assumption that the STI of a system is at its lowest in an unoccupied space and therefore, is a worst-case assessment. However, in order to comply with the current criteria given in Table 1, acoustic absorption is being installed at many underground stations. Which, under high occupancy, could be unnecessary. Although, should the platform have very few people (i.e. less than 10), the VA system would still need to be intelligible at all locations, and the absorption provided by the occupants would likely not be sufficient to create a compliant VA system.

The total signal SPL was reduced by approximately 1 dB(A) when the platform was partially occupied and by approximately 2 dB(A) when the platform was fully occupied (Figure 2). This has a major implication on the overall design of a VA system, since the total SPL is lower with occupancy, the amplification power may need to be increased to compensate for the loss in signal level and maintain the specified signal at the specified SPL level.

In a distributed VA system, the total signal SPL at the audience plane is typically increased by increasing the power tappings of loudspeakers. In this case the total power would need to be doubled to give a 3 dB increase in SPL to compensate for the effect of loss of signal SPL due to a full occupancy. This would require a doubling of amplification power, which would incur additional costs and could require additional space and cooling, which is limited in underground stations.

The SPL on axis (Figure 5) shows that there is little variation on-axis of a loudspeaker with increase density, this is largely due to the fact that the receiver on-axis will be in the direct field of the loudspeaker and the level received would have less contribution from reverberant sound affected by occupancy absorption.

There is some variation in the off-axis SPL response with a significant reduction in the level at 1 kHz for both 1.0 p/m^2 and 3.3 p/m^2 of approximately 8 dB (Figure 4). At frequencies higher than 1 kHz, the SPL was consistently 3 and 4 dB lower than the empty scenario at 1 p/m^2 and 3.3 p/m^2, respectively. This, and the lower overall SPL, could have knock on impacts in the design of the system as the 1, 2 and 4 kHz bands hold some key information which can be crucial in the intelligibility of speech.

5. CONCLUSIONS

There is no information in the literature considering the effect of standing audience and occupancy density on the acoustic performance of VA systems.

The effect of occupancy density has been shown to have a positive impact on the speech intelligibility performance parameter of a VA system in an underground platform. However, the Total signal SPL(A) was reduced by approximately 2 dB(A) with full occupancy, which could have an impact on the required amplification to recover the signal SPL to the specified level

It was found that a maximum difference of 8 dB could be experienced by receivers situated off axis from loudspeakers for different levels of occupancy at frequencies critical for intelligibility frequency. The effect was not observed for receivers on axis.

The STI has been predicted in all scenarios with the same background noise level It is likely that the background noise will vary with increased occupancy density, so a forthcoming study will investigate the impact of increased noise from higher occupancy densities.

In addition, modelling a low occupancy density with a single block over the audience area may not be appropriate. There will be a significant reduction in the volume of the space when modelling as a single block which would not be present with a low occupancy density. A new way of modelling low densities of standing audiences will also be investigated.

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