The effects of air temperature and humidity on the acoustic design of voice alarm systems on underground stations

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ABSTRACT

Sound attenuation of air due to climatic conditions is often assumed to be constant and/or negligible in the electro acoustic design of voice alarm (VA) systems. However, air attenuation variations can be significant in large underground spaces and particularly as the frequency increases to the mid to high frequencies which are the most relevant to speech intelligibility. This investigation evaluates and quantifies the impact of the variability of the most influential climatic parameters, air temperature and relative humidity, on the performance of VA systems in underground stations. Computer simulations were employed to predict the effect of varying these climatic parameters on key performance metrics. Results demonstrated a significant increase in the values of reverberation time parameters with both temperature and humidity, at frequencies critical for speech intelligibility. Consequently the values of speech intelligibility related metrics decreased with rising temperatures and humidity. Hence, the study shows how ignoring temperature and humidity effects can lead to calculation errors in the design of VA systems. These errors could cause over-specification of the absorption required of surface materials, and the inaccurate prediction of acoustic and speech intelligibility related parameters.

Keywords: Air absorption, underground station, voice alarm system, climatic condition

1 INTRODUCTION

Voice alarm (VA) systems are sound distribution systems linked to fire alarm and evacuation procedures, and are designed to distribute speech signals from a source in one or more locations to a number of other locations through a multiplicity of directional loudspeakers. They are a crucial part of the communication and emergency network in critical enclosed spaces such as underground stations, where their main purpose is to deliver effective spoken announcements which provide passenger information and more importantly assist in the safe evacuation in case of emergency.

Numerous electro-acoustic and acoustic factors may contribute to unsatisfactory intelligibility in areas of the station where the VA operate thus rendering the system ineffective.

The attenuation of sound propagating over relatively long distances caused by the sound absorption by air varies significantly and irregularly depending on climate conditions, temperature, humidity and atmospheric pressure [1,2]. The air attenuation becomes greater as frequency increases; thus the frequencies which are the most relevant for speech intelligibility (2, 4 and 8 kHz) are affected. It is therefore important to take account of these environmental factors in acoustic studies of large enclosures. However for the sake of simplicity and convenience these conditions are often assumed constant, and hence the sound absorption due to air is also considered to be constant across the frequency range [3-6].

Most room acoustic simulation programs used in the design of VA systems installed in large enclosed spaces are able to account for air absorption as a function of climatic conditions, as entered by the user. However, these variations are often overlooked by practitioners who assume that those environmental parameters will not influence the VA performance, or that they remain constant over time. Hence the usual practice is to use the climatic default values for air temperature (T, in °C) and relative air humidity (RH, in %) which are, typically, 20°C and 50% respectively.

However, on underground platforms the climate parameters may vary substantially from month to month and even from day to day partly due to outside climatic variations [7,8]. If these variations are not accounted for, there could be a negative impact on the accuracy of the design predictions and therefore in the performance of VA systems.

To illustrate typical variation of climatic conditions, Figure 1 show an example of outside temperature and relative humidity observed at a London Underground station (Heathrow) during a twelve month period. Data obtained from www.weatheronline.co.uk [9]

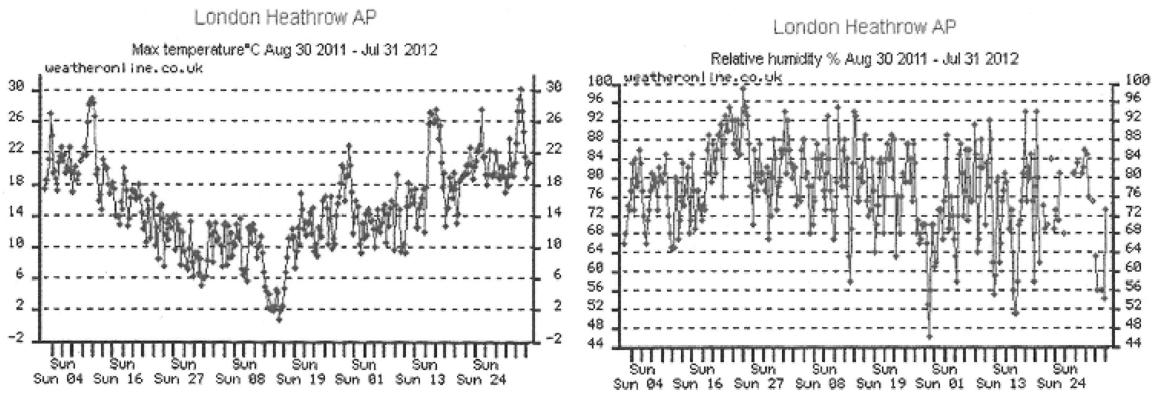

Figure 1 Maximum temperature (°C) and relative humidity variations in London (Heathrow) during 2011-2012 [9].

Gilbey et al [7] have compared measurements of air temperature on deep platforms on the London Underground with outdoor temperatures, as shown in Figure 2. It can be seen that air temperature on platforms throughout a typical year ranged from 20ºC up to 32ºC. Figure 2 presents comparatively annual average data variations for four consecutive years of outside and deep platform air temperature [7].

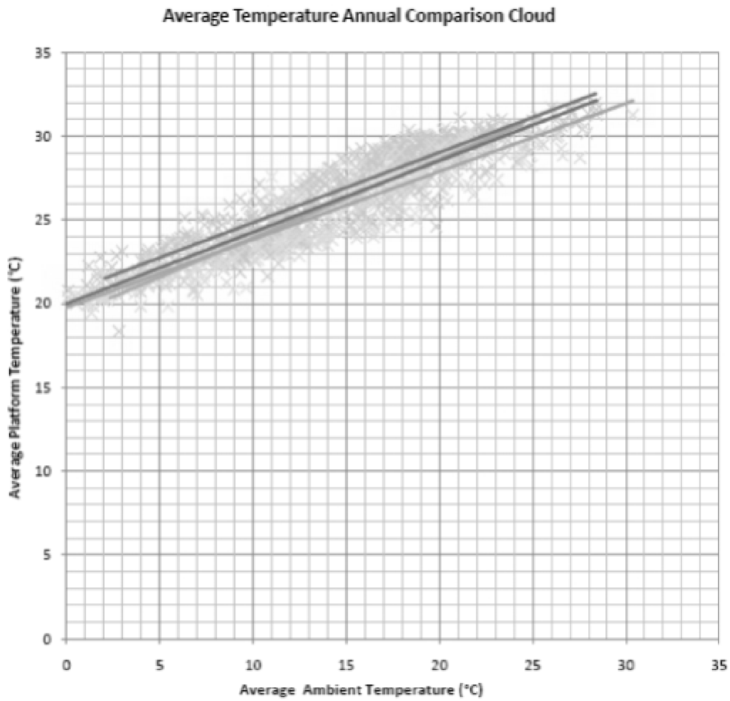

Figure 2 Scatter data plot of air temperature variations on London deep platforms against outside temperature for four consecutive years. The corresponding four best fit lines are shown. Figure adapted from [7].

Furthermore, Gilbey et al [8] found that the humidity on London Underground deep platforms follows closely the outside surface conditions..

In previous research investigating the acoustic conditions in underground stations, using mathematical models or computer simulations, most authors report results for a single and constant climatic condition [10-17]. Only Kang [18,19] has reported effects of variations of air sound absorption on acoustic parameters; however his predicted results were obtained using a single omni-directional sound source for one static climatic condition.

The study reported in this paper evaluates and quantifies for the first time the effects of the variability of air temperature and humidity on the acoustic and speech related performance of VA systems on underground platforms.

2 SOUND ATTENUATION BY ATMOSPHERIC ABSORPTION

2.1 Air sound attenuation

The dissipation of the energy of sound waves attributed to the medium in which they propagate, in this case air, is caused by three mechanisms: shear viscosity, thermal conductivity, and molecular relaxation. These represent different processes in which sound energy is converted into heat or internal energy of the air, thereby decreasing the energy of the sound wave.

The three mechanisms in free air propagation are shown to be proportional to the square of sound frequency [20]. Molecular relaxation is the major contributor to dissipation of energy in the audio frequency range, being dependant on temperature and, more strongly, on the water vapour present in the air, or relative humidity [21]. Air absorption is weakly dependent on atmospheric pressure [2]. Atmospheric pressure and air density are usually assumed constant at normal atmospheric pressure.

The estimated absorption area (A_{air}) provided by the air (or total air absorption in m^2) in a large enclosure is calculated [22] from the air intensity attenuation coefficient *m*, in m^{-1}, and the volume of air in the space, *V* in m^3, using equation (1)

$$A_{air} = 4 * m * V \qquad (m^2) \qquad (1)$$

The air sound absorption is also determined by the distance the sound has travelled**.** The attenuation due to atmospheric absorption A_{atm} in decibels (dB), can be expressed [23] as equation (2)

$$A_{atm} = 20 * log_{10}\left[\frac{P_r}{P_o}\right] = 20 * log_{10}\left[e^{(\mu * r)}\right] = a * r \qquad (dB) \qquad (2)$$

where P_o is the initial sound pressure at distance $r = 0$; P_r the sound pressure after the sound has travelled a distance *r* ; μ the pressure attenuation coefficient in Nepers per meter; and *a* the air sound attenuation coefficient in dB per metre.

The attenuation due to atmospheric absorption A_{atm}, in dB, during propagation through a distance *d*, in metres, is also given [24] by equation (3)

$$A_{atm} = \frac{\alpha * d}{1000} \quad \text{(dB)} \qquad (3)$$

where *α* is the attenuation coefficient, in dB per kilometre for each octave band at the mid band frequency. ISO 9613-1:1993 provides standardized calculated values of *α* in dB/m for pure tone frequencies at constant normal atmospheric pressure as a function of the following variables: temperature, humidity and frequency. The estimated accuracy of *α* for variables within ranges occurring in underground stations is ±10% [2].

In figure 3, part of the extensive database provided in ISO 9613-1:1993 has been compiled and presented in curves for the octave bands with centre frequencies in the speech communication range (125 Hz – 8 kHz) and relevant temperatures and relative humidity ranges. Figure 4 presents measured results of air attenuation coefficient *α* obtained by Harris [1].

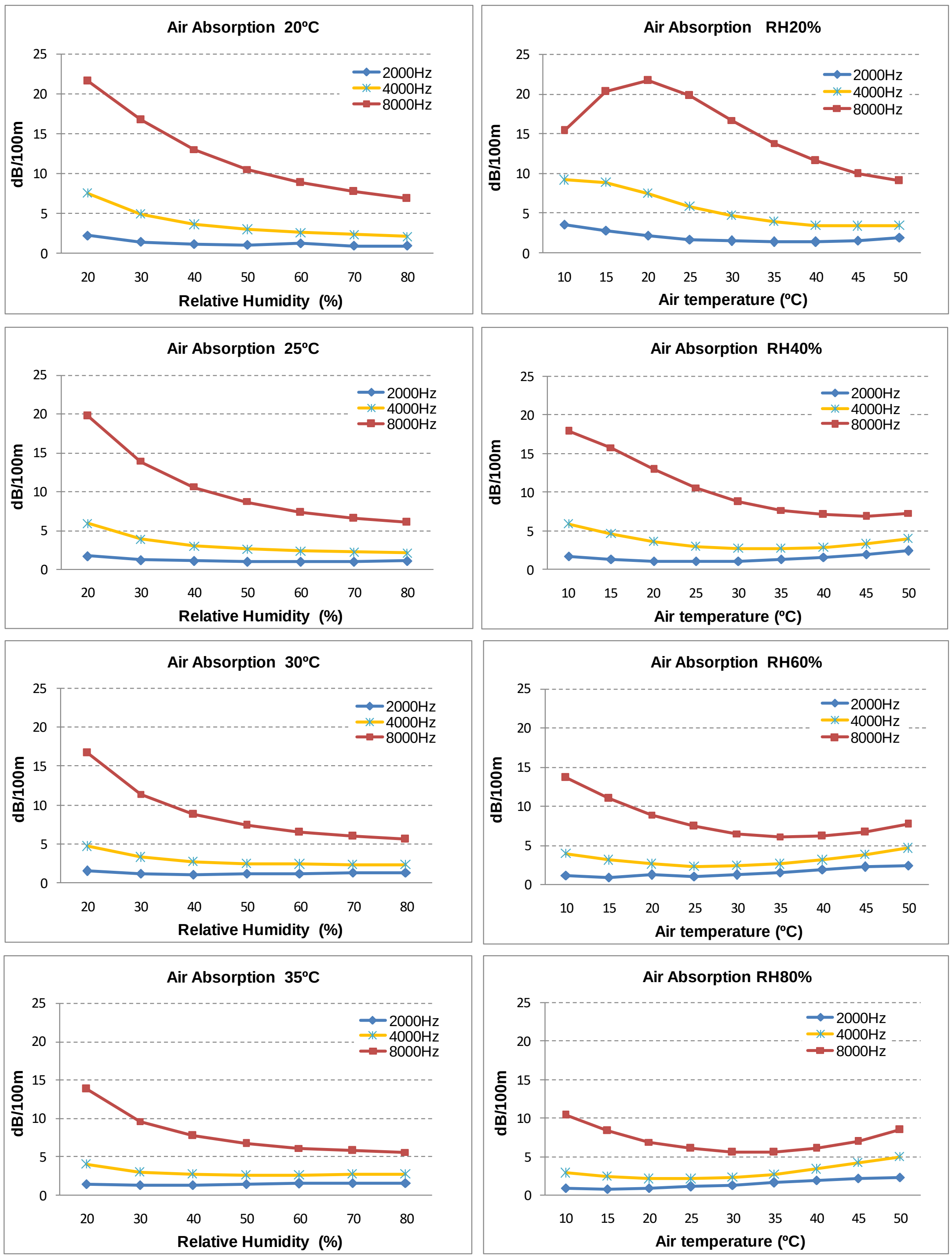

Figure 3 Atmospheric-absorption attenuation α in dB/100m according to calculation method in ISO 9613-1:1993 *plotted as a function of relative humidity (%), temperature (°C) and frequency (Hz).*

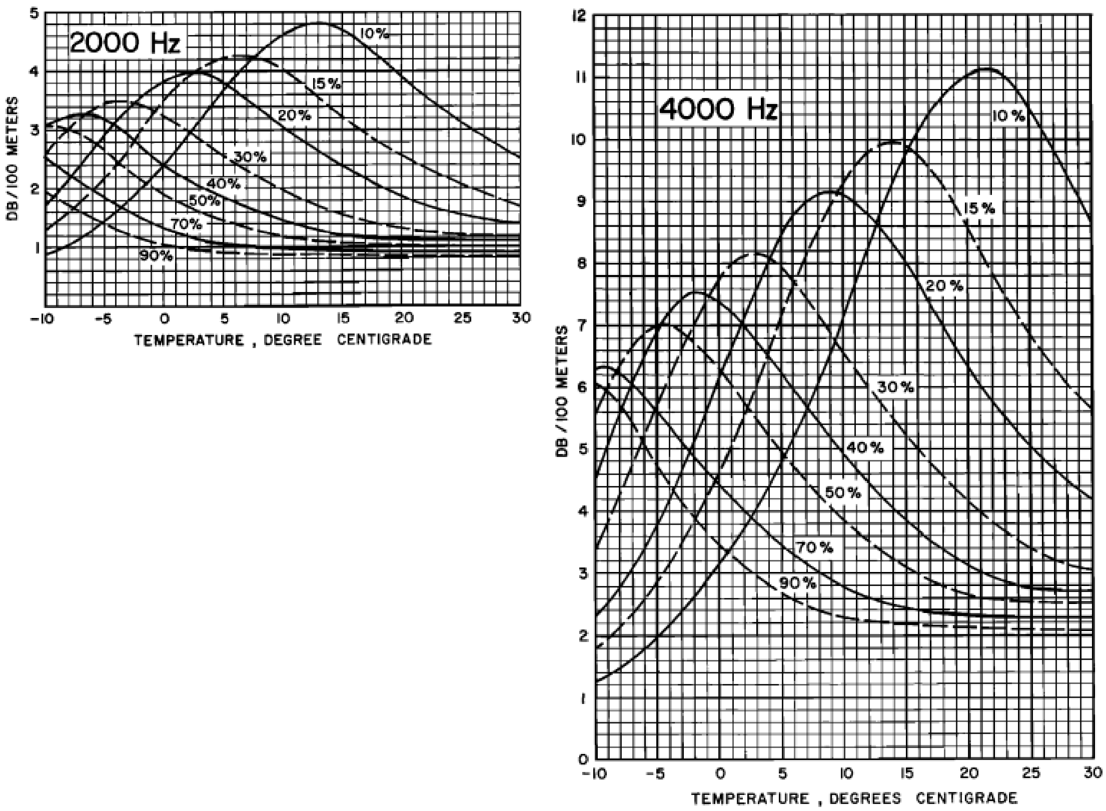

Figure 4 Air attenuation coefficient α as a function of relative humidity (%) and temperature (°C) for 2 kHz and 4 kHz, as measured by Harris [1].

From Figures 3 and 4, it can be seen that the two data sets closely agree. The data from both sources show that the air attenuation coefficient *α* increases considerably with increasing frequency and decrease of relative humidity. Figure 4 shows more clearly (due to the optimised y-axis scale) how the maximum values of *α* increase with temperature and those maxima move to a lower value of relative humidity as the temperature increases.

Another effect which is often neglected or assumed constant in practical calculations is the change of the speed of sound c_o with temperature. The speed of sound, c_o in m/s, at constant humidity is directly proportional to the square root of the temperature *t* (Cº) and is calculated according to the equation (4) [25]

$$c_o = 331.4\sqrt{1 + \frac{t}{273}} \qquad \text{(m/s)} \qquad (4)$$

The speed of sound is present in classical acoustics calculations of reverberation time such as the Sabine equation, equation (5), and it should be adjusted together with the absorption of air term for the temperature in consideration (see section 2.2). In equation (5) *A*, in m^2, represents the total absorption of the surfaces in the room and RT the reverberation time.

$$RT = 55.3 * \frac{V}{c_0.(A+4mV)} \quad \text{(sec)} \qquad (5)$$

From the above it follows that, in a large enclosed space, the reverberation time is directly proportional to the distance that the sound travels, and therefore the resultant air sound attenuation

The above formulae, values for α and methods given by ISO 9613-1:1993, are employed by commercial room acoustic computer simulation programs [25,26] to take account of climatic conditions.

2.2 Air sound attenuation in underground platforms

The large volume and long length of deep platforms on the London underground make this type of space susceptible to considerable air sound attenuation. This can result in reduced reverberation time and sound pressure level in the reverberant field, principally at frequencies above 2 kHz. The increasing reduction with frequency will, in effect, act as an undesired low pass filter unbalancing the frequency response at the receiver positions.

The surfaces inside an underground platform are typically very reflective at all frequencies of the relevant range for speech communications (125 Hz – 8 kHz). This fact makes the acoustic space highly sensitive to relatively small absorption contributions such as that provided by air. Figure 5 shows a typical London underground deep platform with a VA loudspeaker array on the passenger wall.

Figure 5 Typical London underground deep platform

2.2.1 Calculation of air absorption in varying conditions

In order to illustrate the effects of treating air absorption as constant, the air absorption in a typical deep London underground station of internal volume 3078m^3 and with a platform 120m long has been calculated using equation (1) for a range of climatic conditions, using the *m* values taken of Harris [1] for the frequencies 2 khz, 4 kHz, 6.3 kHz and 8 kHz. The five conditions and calculated air absorption for each condition are shown in Table 1.

Table 1 Contribution of the air absorption (m^2) to the total absorption in a typical London Underground deep platform as a function of frequency and five climatic conditions.

		Octave band centre frequency			
Climatic Condition	**Climatic parameters**	**2 kHz**	**4 kHz**	**6.3 kHz**	**8kHz**
1	*T* =15 °C *RH*=30%	44.1	149.6	324.9	-
2	*T* = 15 °C *RH*=50%	30.3	88.1	192.7	295.5
3	*T* =20 °C RH=50%	29.5	75.2	154.9	233.9
4	*T*= 25 °C *RH*=50%	29.2	72.4	136.8	197
5	*T* =30 °C *RH*=50%	28.4	71.8	131	184.7

For the climatic reference condition (*T* =20°C, *RH* =50%) the absorption contribution of the air to the total sound absorption estimated in the platform is 15%, 29% and 80% at 2kHz, 4kHz and 8kHz respectively.

The effects of ignoring temperature variations in speed of sound and consequently in reverberation time are exemplified by the calculation errors obtained for a range of air temperatures and octave band centre frequencies when temperature is assumed constant.

Table 2 presents calculation errors of reverberation time (*RT*) for different air temperatures (*T*) at 2kHz and 8kHz octave bands, caused by considering *T* constant at 20°C in the calculation of the speed of sound. Calculations are based on equations (4) and (5) at constant relative humidity of 50% and typical underground platform architectural parameters V= 3078m^3, $A_{(2kHz)}$=174m^2 and $A_{(8kHz)}$= 58m^2. The table shows for each temperature the calculated speed of sound (c(*T*)) and the corresponding calculated reverberation time RT(*T*). It also shows the calculated reverberation time when *T* is assumed constant at 20°C (RT(*T*=20°C)). The difference between RT(*T*) and RT(*T*=20°C) is shown as absolute error (Δ) and relative error (Δ%).

Table 2 RT calculation errors due to neglected temperature variations in the speed of sound

		2kHz				**8kHz**			
T **(°C)**	**c (*T*) m/s**	**RT (*T*) sec**	***RT*** **(*T*=20°C) sec**	**Δ**	**Δ %**	**RT (*T*) sec**	***RT*** **(*T*=20°C) sec**	**Δ**	**Δ %**
15	**340.5**	2.45	2.43	0.02	1%	1.41	1.40	0.01	1%
20	**343.4**	-	-	-	-	-	-	-	-
25	**346.3**	2.42	2.44	-0.02	-1%	1.93	1.94	-0.02	-1%
30	**349.2**	2.41	2.45	-0.04	-2%	2.01	2.04	-0.03	-2%

Although the error magnitudes seen in table 2 are small, it shows the importance of acknowledging this error contribution towards the total acoustic effect of varying climatic conditions.

3 METHODOLOGY

Computer simulations of a deep platform equipped with a VA system were employed to predict the effect of varying climatic parameters on key acoustical and speech related performance metrics.

The investigation was undertaken making use of a computer acoustic simulation model which closely replicated the geometrical, architectural and acoustical characteristics of a typical deep platform of the London underground network, such as that shown in the photograph in Figure 5 and diagrammatically in Figure 6. The room acoustic computer program employed was CATT-Acoustics v.8g [25].

It was assumed that the air in the platform was free of smoke or particles which could affect the air absorption in high concentrations. For the purpose of this investigation, site measurements and predictions were obtained without the influence of background noise.

3.1 Measurements

Prior to the construction of the acoustic model of the platform, acoustic measurements were performed during non traffic hours on a typical deep platform under unoccupied conditions.

Five receiver positions were located along the platform mid-width line of the platform in between consecutive units of the loudspeakers of the array (5 m spacing) at 1.5 m above standing platform floor. The climatic conditions at the time of measurement were as follows: normal atmospheric pressure, T= 19.2°C and *RH*= 51%.

Measurements were monoaural impulse responses obtained using the sine sweep stimulus signal method. The stimulus signal was broadcast by the platform VA loudspeaker array while a B&K 2250 sound analyser acted as the receiver recording the stimulus at each of the receiver positions. The recorded signals were later post-processed on a PC computer running the Dirac 4.0 measuring software platform to obtain the impulse responses and the derived parameters of interest.

3.2 Acoustic simulation

The measured platform geometry and architectural details were simulated in a model constructed in CATT Acoustics. In the simulation the VA system was represented by a loudspeaker array of arrangement and configuration (loudspeaker electro-acoustic characteristics, quantity, position/spacing, gain and aim) which matched the configuration found during the corresponding acoustic measurement survey. The internal surfaces of the model initially employed absorption and scattering coefficients published in the literature. Later through a selective and iterative process these coefficients were adjusted to acoustically calibrate the model against site measurements.

The platform was simulated unoccupied to match the unoccupied conditions found during the site measurements (only the researcher standing on the platform during measurements). The unoccupied condition involving one person standing on the platform represents the minimum occupancy possible in real life, i.e. one passenger. This situation determines the worst acoustic case scenarios in the design of the VA. It implies the lowest sound absorption possible, hence the highest reverberation and therefore one of the least favourable conditions for the quality of speech transmission. Further and relevant to this study, the unoccupied condition is when air absorption can have its maximum influence on reverberation parameters and therefore on speech transmission quality, particularly at low background noise levels or noiseless conditions.

Figure 6 presents two views of the simulated platform and shows the loudspeaker array and the five receiver positions along the platform length. Loudspeakers are represented with colour aim lines on the passenger wall at 3 m above standing platform while the receivers are indicated by black lines representing omni-directional microphones.

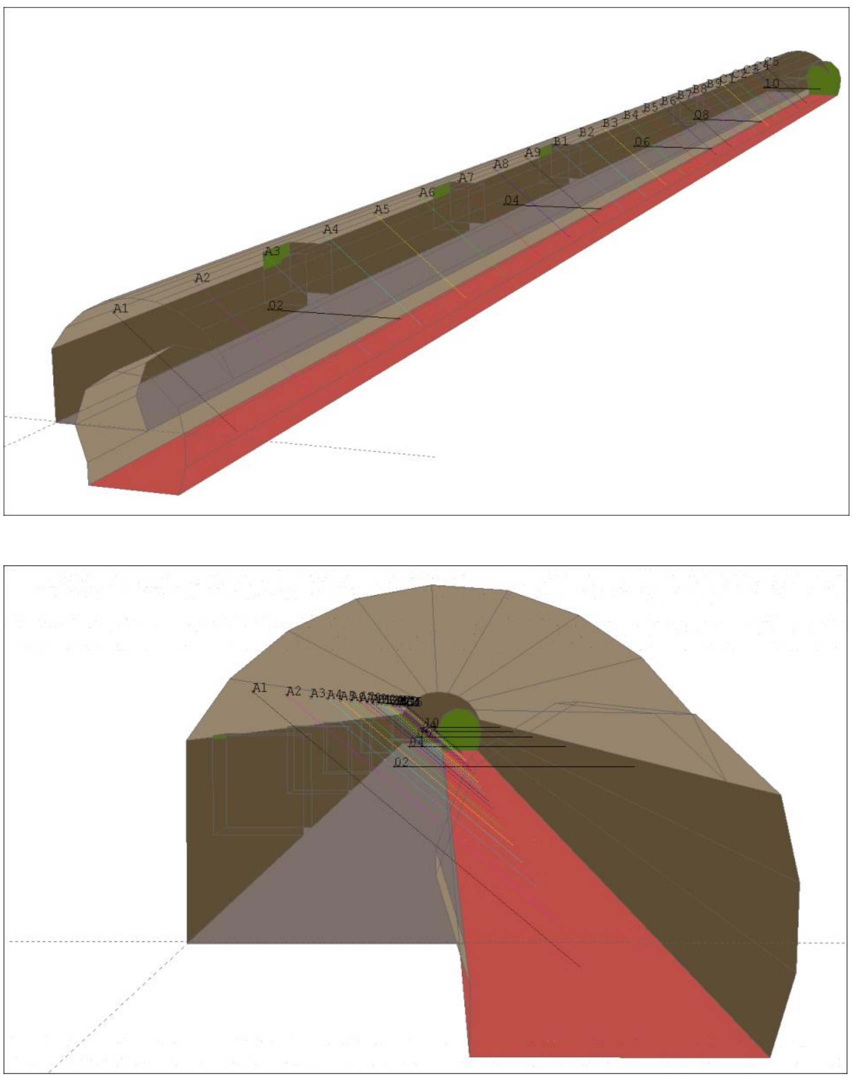

Figure 6 Views of the simulated platform showing the loudspeaker array and receiver positions

The climatic conditions found at the time of the measurements were approximated input in the program environmental setting as *T* =20°C and *RH* =50%. The air density input setting of the program was maintained constant for all simulations at the value measured on London underground platforms at 1.2 Kg/m^3 [27] which is also the program's default value. Potential fluctuations in atmospheric pressure were not considered since these are of negligible influence in air absorption.

Almost all relevant room acoustic parameters are influenced to a different extent, by changes of sound absorption due to air climatic variations. Therefore the following parameters were predicted for the different climatic conditions: RT30, early decay time (EDT), sound pressure level (SPL), definition (D50) and speech transmission Index (STI). Measured and predicted STI values in this work followed BS EN 60268-16:2003 [28].

The frequency range of octave bands used for the predictions and analysis was that relevant for speech communications in VA systems, 125 Hz-8 KHz.

The selected temperature range for the predictions and analysis was from 15ºC to 30ºC (in steps of 5ºC) while the relative humidity (RH) range was taken from 20% to 80% (in steps of 20%).

Since both temperature and humidity are interrelated in their effect on air absorption, a range of representative and realistic combinations of *T* and *RH* were used in the predictions of acoustic and speech related parameters.

Two representative case groups from a pool of possible realistic combinations were selected to illustrate the effects of variations in air temperature and humidity on the parameters of interest; in one group relative humidity was kept constant and temperature was varied, in the other temperature was kept constant and relative humidity varied. The two groups consisted of the following combinations:

Group 1 : constant relative humidity of 50% and varying temperature of 15º, 20º, 25º and 30º

Group 2 : constant temperature of 20ºC and varying air humidity levels of 20%, 40%, 60% and 80%

In order to show the maximum impact possible of the variability of air temperature and humidity conditions on evaluating acoustic parameters, results at the climatic combination of 15ºC temperature and relative humidity 20% are taken as the references values. The significance of the parameters' changes due to air and humidity variations was quantified by calculating deviations from the reference value in terms of just noticeable difference (JND) values proposed in the literature , as shown in Table 3.

Table 3 JND values of parameters suggested in the literature

Parameter	JND	Literature references
EDT	5%	[4][6][29][30][31][32]
RT30	5%	[4][6][30][31][32][33]
SPL	1dB	[30][32][33][34]
D50	0.05	[4][29] [31][33]
STI	0.03	[31][35]

The five receiver positions were distributed to cover the platform area where passengers stand. The spatial variability observed across the receiver positions for all predicted parameters was low, as indicated by the standard deviation (σ) of the results obtained for the five receiver position shown in figures 7 and 8.

As examples, standard deviations of EDT for predictions considered in case 1 were typically 0.5JND at mid and high frequencies and up to 1.2JND at low frequencies; while in case 2 were typically 1JND and up to 1.15JND for the same frequency classification. RT30 standard deviation for the both cases considered was typically 0.4JND with values at low frequencies up to 0.5JND. SPL standard deviation for both cases was up to 0.3JND while σ values for STI were up to 0.15JND.

These results confirmed the expected high spatial uniformity from a distributed loudspeaker system. The high spatial uniformity obtained allows the presentation of results and analysis to concentrate on averaged results.

4 RESULTS

This section present the prediction results for the above two case groups. Values plotted correspond to the average of five receiver positions. Error bars indicate ±1 σ.

4.1 Group 1: constant relative humidity of 50%

Figure 7 presents the prediction results for the parameters of interest as a function of frequency and temperature for a constant relative humidity of 50%

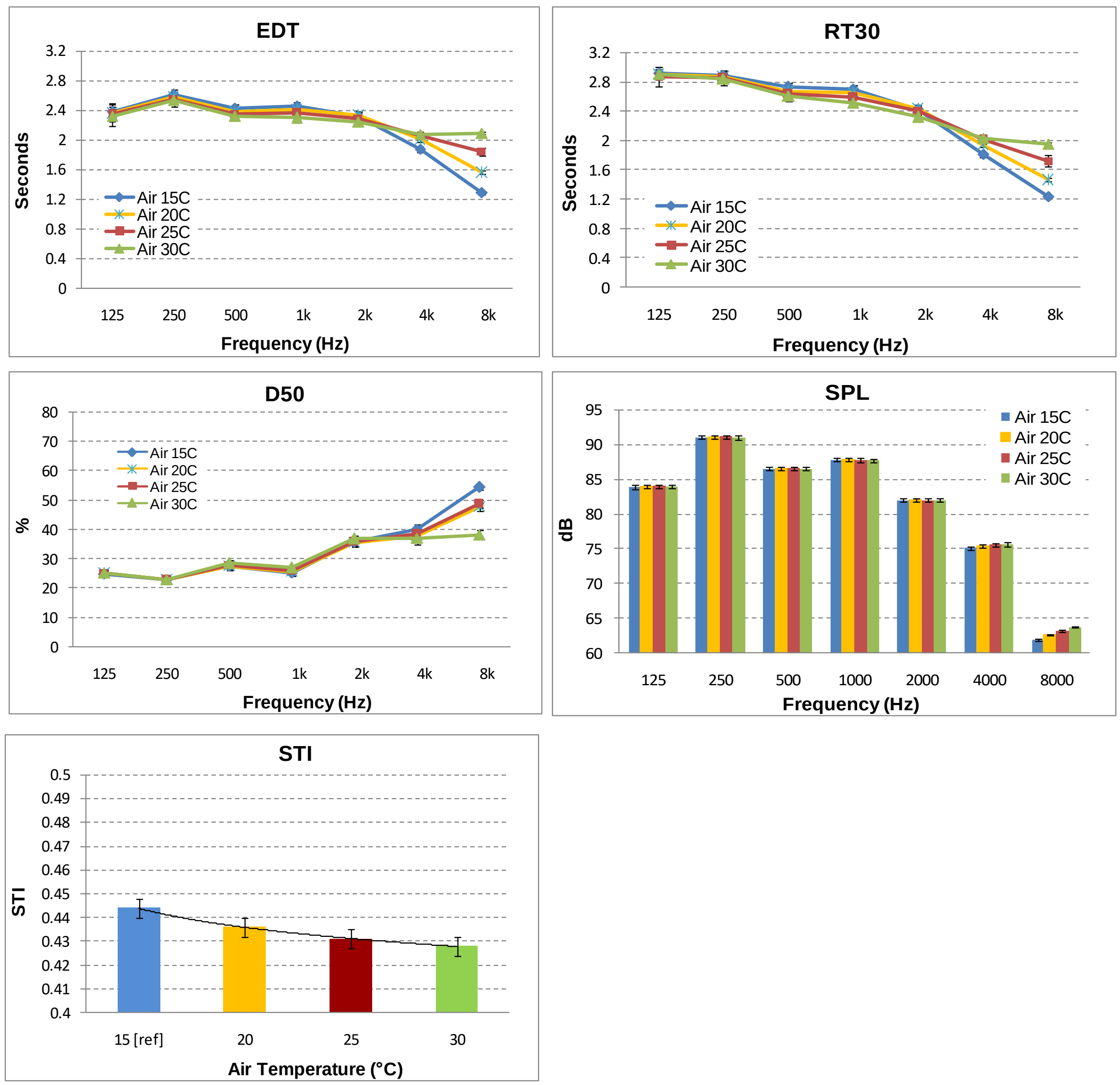

Figure 7 Group 1: Parameters predicted in octave bands centre frequencies at 50% RH for various air temperatures.

From the graphs of results in Figure 7, it can be seen that as the temperature increases, reverberation time and SPL increase, particularly at the higher frequencies, thereby reducing the speech related parameters D50 and STI.

4.2 Group 2: constant temperature of 20°C

Figure 8 presents the prediction results for the parameters of interest as a function of frequency and relative humidity for a constant air temperature of 20°C.

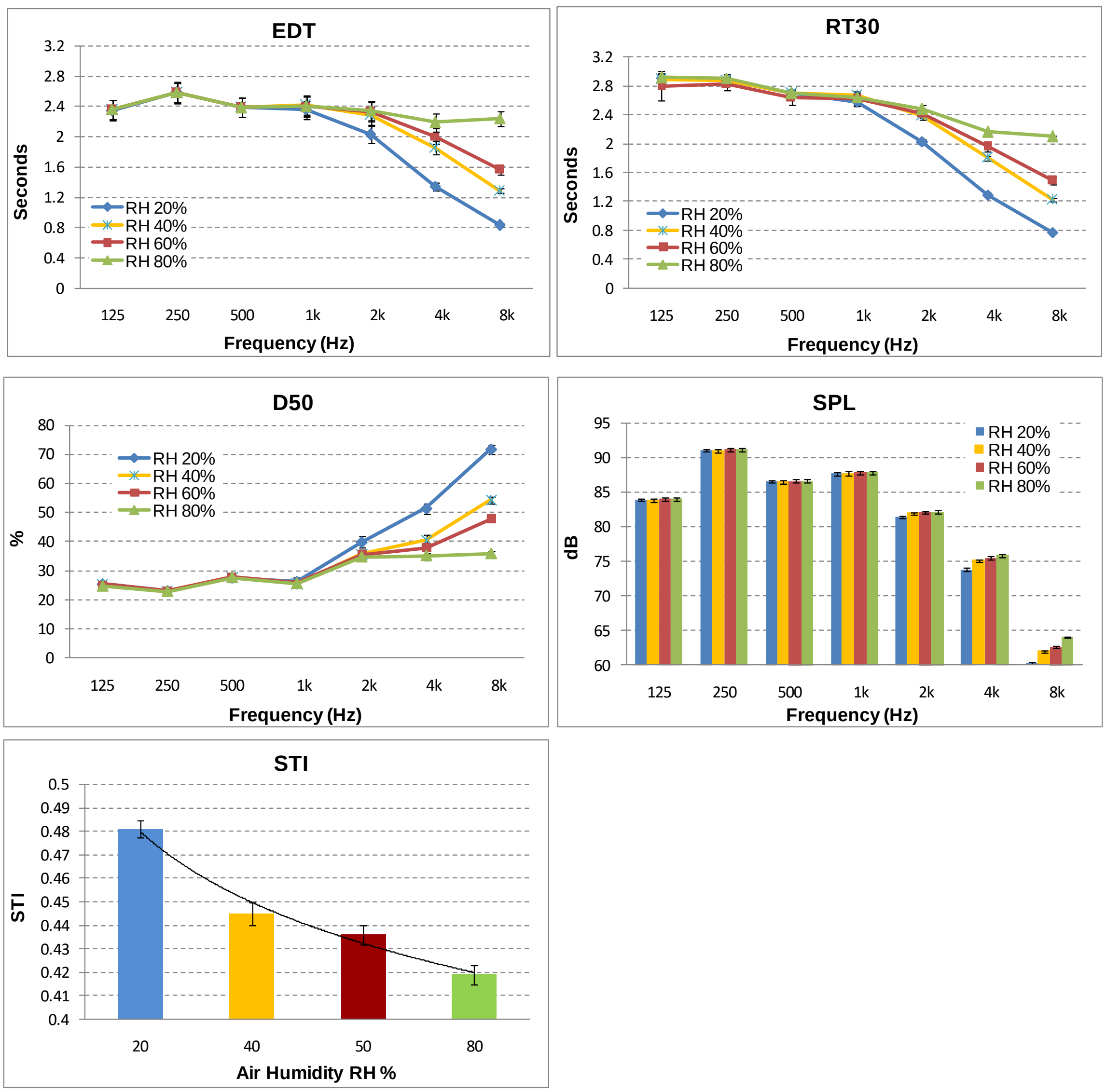

Figure 8 Group 2: Platform acoustic parameters predicted in octave bands centre frequencies at 20ºC for various air humidity values.

Figure 8 indicates that as the relative humidity increases, reverberation time and SPL again increase, especially at the higher frequencies so that the speech parameters D50 and STI are again reduced.

5 ANALYSYS OF RESULTS

This section analyses and discusses the generic air sound absorption characteristics and the results presented in the previous section for groups 1 and 2. Changes in acoustic parameters are described in relation to reference values and are analysed in terms of just noticeable difference (JND) units to assess their potential impact. Relationships between STI and temperature and relative humidity are also derived. The discussion focuses on changes in the 4 kHz and 8 kHz octave bands as these are the critical bands for speech intelligibility in VA systems where air absorption effects are most notable.

5.1 Generic air sound absorption characteristics

From the observations of the experimental data presented in Figures 3 and 4 it can be seen that the air exhibits increasing absorption at frequencies of 4 kHz and above, with a maximum sound absorption coefficient in the 8 kHz octave band, when measured at RH 20% and T= 20ºC climatic condition. The absorption maxima decrease rapidly for lower frequency bands, higher temperatures and higher humidity values. In this decreasing region, it can be seen that the changes in absorption is less for considerable changes of any of the three parameters: audio frequency, air temperature and air humidity.

5.2 Group 1: Acoustic effects with air temperature variation at constant humidity

When examining the effect of changes in temperature with constant humidity of 50% RH, the reference values are those for the situation with temperature 15ºC.

5.2.1 Reverberation

From figure 7 it can be seen that, in general, reverberation time on the platform is not affected by changes in temperature for octaves bands below 4 kHz, however at 1 kHz a slight decrease with increased temperature can be observed. In contrast, notable increases in EDT and RT30 with temperature can be seen in the 4 kHz and 8 kHz octave bands.

Table 4 present increments in reverberation time with temperature in seconds and JND units with respect to the reference values, for the 4 kHz and 8 kHz octave bands. It can be seen that the reverberation time increments are particularly high for the 8 kHz octave band where increases of EDT and RT30 above the reference values were up to 12.4 JND and 11.8 JND respectively.

Table 4 EDT and RT30 increments in seconds and in JND units relative to reference value [ref] as a function of frequency and temperature at constant RH 50%.

	15 ºC [ref]	**20 ºC**	**25 ºC**	**30 ºC**
EDT(4KHz)	1.87	2.01	2.06	2.08
Increment from [ref]	0	0.134	0.188	0.206
JND increment from [ref]	0.0	1.4	2.0	2.2
EDT(8KHz)	1.29	1.56	1.84	2.09
Increment from [ref]	0	0.272	0.556	0.802
JND increment from [ref]	0	4.2	8.6	12.4
RT30(4KHz)	1.82	1.94	2.02	2.04
Increment from [ref]	0	0.124	0.202	0.22
JND increment from [ref]	0	1.4	2.2	2.4
RT30(8KHz)	1.24	1.47	1.73	1.96
Increment from [ref]	0	0.234	0.492	0.724
JND increment from [ref]	0	3.8	8	11.8

Figure 9 shows predicted reverberation time parameters EDT and RT30 plotted against platform air temperature at a constant reference humidity RH of 50%. Regression lines are shown for the RT30 data together with their equations and coefficients of determination (R^2). The coefficients show that there is a close relationship between EDT and RT30 and temperature.

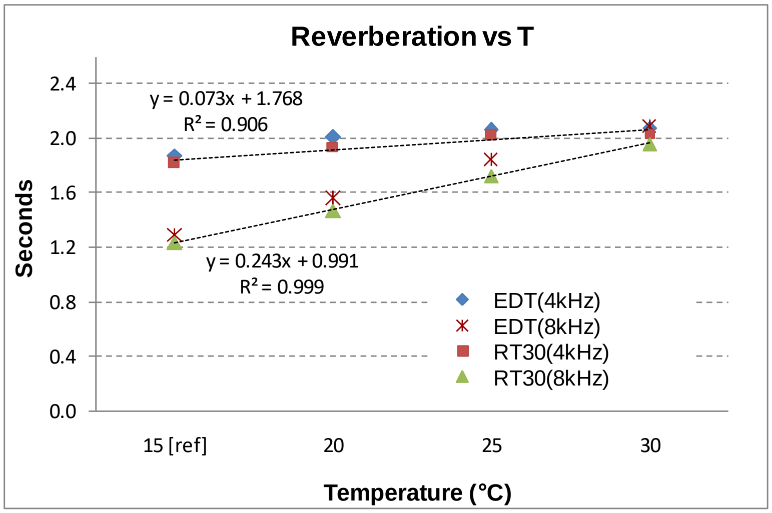

Figure 9 Predicted reverberation time parameters as a function of temperature, and regression lines for RT30 data.

5.2.2 D50 and STI

Figure 7, also shows that, similarly, D50 variations due to changes in temperature are only significant in 4 kHz and 8 kHz octave bands.

Table 5 shows the relative decrease of speech related metrics with temperature in JND units. It can be seen that increases of air temperature from the reference value resulted in decrements of D50 of up to 0.7 JND at 4kHz and a more considerable 3.2 JND at 8kHz. The reductions in STI values due to the increase in air temperature were not notable, being below 1 JND, although figure 7 and Table 5 show that there is a trend for STI to decrease with increasing temperature.

Table 5 D50 and STI decrements in JND units relative to [ref] as function of frequency and temperature at constant RH 50%.

	15 ºC [ref]	**20 ºC**	**25 ºC**	**30 ºC**
D50 (4KHz)	40.3	37.9	38.5	37.0
JND decrement from [ref]	0	0.5	0.4	0.7
D50 (8KHz)	54.4	47.8	48.9	38.3
JND decrement from [ref]	0	1.3	1.1	3.2
STI	0.44	0.44	0.43	0.43
JND decrement from [ref]	0.0	0.3	0.4	0.5

An empirical model, equation (6), was derived from the best fit trend line (R^2=0.99) obtained from plotting the predicted STI results relative to air temperature *T* (ºC) variations (see figure 7). This model is able to provide estimated changes in STI with variations of *T* for a constant *RH* condition of 50%. The input range of the model is limited to maximum and minimum temperatures typically occurring on underground platforms.

$$STI = -0.012 * ln(T) + 0.444 \quad (6)$$

5.2.3 SPL

It can be seen from the figure 7 that the variation of SPL as a function of the temperature and frequency is negligible except for the 4 kHz and 8 kHz octave bands. In these high frequency bands the effect of increasing air temperature led to corresponding increases in SPL due to the associated gradual decrements in air absorption

Table 6 shows the effect of air temperature relative increase on SPL for the two highest octave bands considered for a constant humidity of 50%. In octave bands 4 kHz and 8 kHz the SPL increases from the reference values [ref] with temperature, were up to 0.5JND and 1.8JND respectively reflecting decrements in air absorption with increasing temperature.

Table 6 SPL relative increment at 4 kHz and 8kHz as function of temperature in dB and in JND units for constant humidity of 50%.

	15 ºC [ref]	**20 ºC**	**25 ºC**	**30 ºC**
SPL(4kHz)	75.1	75.4	75.6	75.7
Increment from [ref]	0	0.3	0.46	0.54
JND increment from [ref]	0	0.3	0.46	0.54
SPL (8KHz)	71.9	72.6	73.3	73.8
Increment from Ref	0	0.68	1.32	1.82
JND increment from [ref]	0	0.68	1.32	1.82

A significant increase of air temperature from 15°C to 30°C would decrease the overall dBA level of a signal spectrally equivalent to an announcement (speech shaped noise signal) over the VA systems by less than 1JND (0.02dB).

5.3 Case 2: Acoustic effects with air humidity variation at constant air temperature

When examining the effect of changes in humidity with constant air temperature of 20°C, the reference values are those for the situation with humidity of RH 20%.

5.3.1 Reverberation

From figure 8 it can be seen that reverberation time on the platform begins to be affected by changes in humidity at frequency octaves bands above 1 kHz. Above this frequency the reverberation time increases consistently with humidity, the increases being most notable for the highest frequency bands of interest, 4 kHz and 8 kHz.

Table 7 presents increments in reverberation time with humidity in seconds and JND units with respect to the reference values. Only data for the highest frequency bands are presented. Results shows that the increments from reference values for EDT and RT30 at 4kHz were up to 13JND and up to 34 JND at 8kHz.

Table 7 EDT and RT30 increments in seconds and in JND units relative to reference values [ref] as a function of frequency and humidity at a constant air temperature of 20°C

	RH %			
	20 [ref]	**40**	**50**	**80**
EDT(4KHz)	1.34	1.85	2	2.19
Increment from [ref]	0	0.51	0.66	0.85
JND increment from [ref]	0	7.6	9.9	12.7
EDT(8KHz)	0.83	1.28	1.56	2.24
Increment from [ref]	0	0.45	0.73	1.41
JND increment from [ref]	0	10.8	17.6	34.0
RT30(4KHz)	1.29	1.8	1.95	2.16
Increment from [ref]	0	0.51	0.66	0.87
JND increment from [ref]	0	7.9	10.2	13.5
RT30(8KHz)	0.77	1.22	1.49	2.1
Increment from [ref]	0	0.45	0.72	1.33
JND increment from [ref]	0	11.6	18.6	34.4

The graph in Figure 10 shows predicted reverberation time as a function of platform air humidity at a constant reference temperature of 20°C. Regression lines are shown for the RT30 data, together with the regression equation and coefficients of determination (R^2) which show the close relationship between EDT and RT30 and relative humidity.

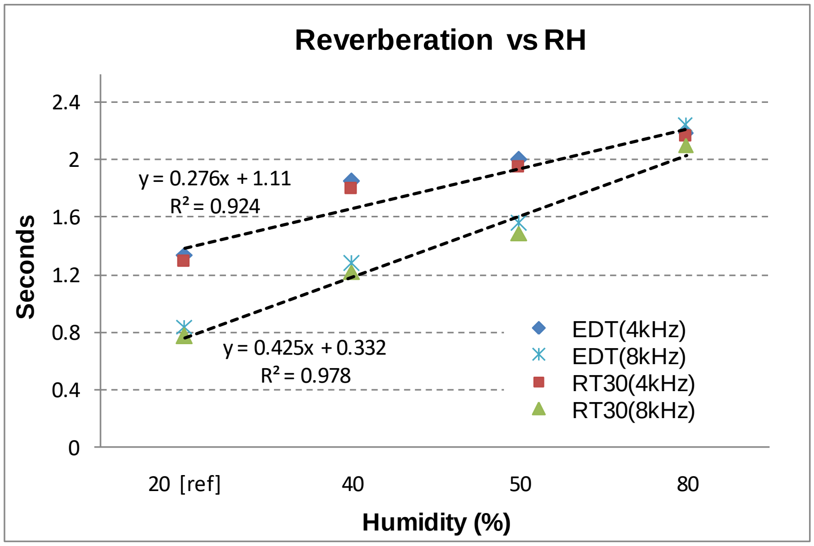

Figure 10 Predicted reverberation time parameters as a function of humidity, and regression lines for RT30 data.

5.3.2 D50 and STI

The strong influence of air humidity variation on reverberation time is clearly reflected in the graphs of speech related parameters in figure 8, which show reductions in the values of parameters with increasing humidity.

Table 8 shows the relative decrease of speech related metrics with humidity in JND units. Increases in air humidity the from reference values resulted in considerable decrements of D50 of up to 3.2 JND and 7.2 JND in the 4kHz and 8kHz frequency band respectively. Reductions in STI due to the increases in humidity were also notable, at up to 2.1JND. Both D50 and STI reductions with humidity were comparatively greater than the reductions observed with temperature changes, see table 5 and 8.

Table 8 D50 and STI decrements in JND units relative to [ref] as function of frequency and humidity at constant temperature of 20°C.

	RH %			
	20 [ref]	**40**	**50**	**80**
D50 (4KHz)	51.38	40.38	37.92	35.28
JND decrement from [ref]	0	2.2	2.7	3.2
D50 (8KHz)	71.7	54.2	47.7	35.9
JND decrement from [ref]	0	3.5	4.8	7.2
STI	0.481	0.445	0.436	0.419
JND decrement from [ref]	0.0	1.2	1.5	2.1

An empirical model, equation (7), was derived from the best fit trend line (R^2=0.98) obtained from plotting the predicted STI results relative to air humidity variations (see figure 8).This model is able to provide estimated changes in STI with variations in *RH* for a constant temperature condition of 20ºC. The input range of the model is limited to maximum and minimum *RH* typically occurring on underground platforms.

$$STI = -0.043 * ln(RH) + 0.4795 \quad (7)$$

5.3.3 SPL

Graphs of results in figure 8 show that the variation of SPL as a function of the humidity and frequency is negligible except for the 2 kHz, 4 kHz and 8 kHz octave bands. In those particular bands the effect of increasing air humidity showed corresponding increases in SPL due to the associated gradual decrements in air absorption.

Table 9 shows the effect of air humidity increments on SPL for the two highest frequency octave bands considered for a constant temperature of 20°C. These increments relative to the reference value [ref] were of up to 2.2JND and 3.8 JND for the 4 kHz and 8 kHz octave band respectively. These results are substantially higher than the maximum increments resulting from increases in temperature, see tables 6 and 9.

Table 9 SPL relative increments in dB and JND at 4kHz and 8kHz as function of air relative humidity for constant temperature of 20°C.

	RH %			
	20 [ref]	**40**	**50**	**80**
SPL(4kHz)	83.7	85.1	85.4	85.9
Increment from [ref]	0.0	1.0	1.7	2.2
JND increment from [ref]	0.0	1.0	1.7	2.2
SPL(8kHz)	70.2	71.9	72.6	74.0
Increment from [ref]	0.0	1.7	2.4	3.8
JND increment from [ref]	0.0	1.7	2.4	3.8

A significant increase of air humidity from 20% to 80% would decrease the overall dBA level of a signal spectrally equivalent to an announcement (speech shaped noise signal) over the VA system by less than 1JND (0.3dB).

5.4 Discussion

As expected from a distributed sound system in a regular shaped space, all predicted results showed a very low spatial variation.

The above analysis shows that variations in air absorption have more of an effect on reverberation parameters than on sound pressure levels. This is because the SPL parameter is mainly determined by the direct sound, whereas reverberation is determined by multiple reflections for which the air absorption is more effective due to the longer reflection path.

The stronger influence of air humidity variation on reverberation when compared with temperature is clearly reflected in the higher variations of speech related parameters D50 and STI.

The STI appeared to have low sensitivity to large variations of reverberation time.

Temperature affected EDT and RT30 almost equally due to their very similar decay rates at all octave bands. Humidity appeared to offer slightly more absorption in the calculation of EDT than in RT30 for octaves bands up to 1kHz. For higher frequencies the humidity influence on those parameters was practically the same, see figures and 8.

The increases of EDT and RT30 with both temperature and humidity in the significant octaves bands 4 kHz and 8 kHz were observed to be almost linear, see figures 8 and 9.

Climatic air variations slightly affected the SPL in the high frequency bands, which would, thus alter the tonal balance of the received signal. However those effects were not enough to significantly alter the overall SPL in dBA.

6 CONCLUSIONS

This study has demonstrated through computer simulation, that variations in air temperature and humidity can have significant effects on the electro-acoustic design of VA systems on underground platforms. Results showed increases of up to 34 JND in reverberation time parameters at high frequencies with increases in temperature and humidity. Consequently speech related parameters were seen to decrease with rising temperatures and humidity values. The 4 kHz and 8 kHz octave bands are the components of the speech frequency range most sensitive to air climatic variations while being bands critical for speech intelligibility. Variations in humidity had a greater influence on the evaluated parameters than temperature variations. A STI decrease of up to 2.1JND was observed due to humidity variations.

Two empirical models have been developed which can be used to estimate the effects of climatic conditions on STI on similar underground platforms equipped with equivalent VA system.

The neglect of temperature and humidity effects on platform acoustics and speech intelligibility predictors could lead to prediction errors in the design of VA systems which could become critical in marginal contractual compliance situations.

Thus it is important that, in future, temperature and relative humidity are regarded as key components in designing VA systems in large underground spaces and that the full range of their values, and their implications on the design, must be considered.

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