Prediction of Noise from Small to Medium Sized Crowds

M.J. Hayne (1), J.C. Taylor (1), R.H. Rumble (1) and D.J. Mee (2)

(1) Ron Rumble Renzo Tonin, 96 Petrie Terrace, Petrie Terrace QLD Australia 4000
(2) School of Mechanical and Mining Engineering, The University of Queensland, Brisbane, Australia 4072

ABSTRACT

The prediction of crowd noise is a problem faced by acoustical consultants. Although consultants are frequently required to predict noise emissions from activities involving crowds of people, there are no reliable prediction methodologies available. In the past, reliance has been made upon the adoption of results measured at similar venues or by extrapolating the vocal effort from an individual to derive the overall level for a defined crowd size. Applying these methodologies can result in prediction errors as large as 15dB(A), indicating that they do not correctly characterise this type of noise. To derive an appropriate prediction methodology, the authors have investigated the factors that influence the generation of crowd noise such as the Lombard effect, crowd size, orientation of individuals within the crowd and whether individuals act together as a synchronised source or behave randomly. Using these factors as a basis, a series of controlled and uncontrolled experiments have been conducted in order to derive a set of equations that are suitable for use by consultants to predict the noise emissions from small to medium sized crowds (up to 100 people) located in outdoor spaces.

INTRODUCTION

The prediction of crowd noise is a problem faced by acoustical consultants and regulating authorities. Although the assessment of crowd noise is frequently required as part of development applications, there has been very little published research into the problem of crowd noise. As shown by Hayne, Rumble and Mee (2006), acoustical consultants are frequently forced to adopt prediction methodologies based upon the extrapolation of data measured at similar venues or sources. The difficulties and uncertainties of this approach are highlighted by the examination of court cases involving opposing noise experts. In such cases, differences of opinion are frequently incurred due to variations in the original source data on which these opinions have been based. This results in a less than ideal outcome for the court and community in general because the noise experts cancel each other out of consideration because of erroneous or irrelevant source data.

The lack of research into the crowd noise problem is attributed to the difficulty in isolating each of the factors known to impact upon the level of noise generated by a crowd. To reduce the level of uncertainty associated with the prediction of crowd noise, the authors have conducted an analysis of the factors influencing the generation of crowd noise. By isolating these factors, the authors have been able to conduct controlled experiments with the aim of producing a set of prediction equations for small to medium sized crowds set in a social situation.

PREVIOUS RESEARCH

An overview of the existing methods used to predict crowd noise is presented in Hayne et al. (2006). They found that very little research had been conducted into the prediction of crowd noise, resulting in consultants having to use an approach reliant upon measuring the crowd noise levels at a similar type of facility and transposing these levels over to the subject facility. This resulted in a number of descriptive parameters being used as well as a large variability in the source noise level. From observations made in their study and those of other researchers (Evans, 1990), it was determined that crowd noise cannot be characterised by a single noise parameter and that multiple descriptive parameters are required to adequately quantify crowd noise.

The ideas presented in Hayne et al. (2006) were explored further by Taylor (2008), who collated noise measurements from a variety of venues to determine what factors had the biggest influence on the noise generated by a crowd. Taylor found that, in addition to the venue type and number of people, factors such as age and whether alcohol was involved also influenced the level of noise produced by a crowd.

A study was conducted by Hodgson, Steininger and Razavi (2007) to predict speech and noise levels in 10 eating establishments. Optimisation techniques were used to determine unknown prediction parameters such as the Lombard coefficient, number of talkers per customer and the average absorption per customer. While the study of Hodgson et al. (2007) resulted in a novel crowd noise prediction model, its use is limited as:

- It only considers the A-weighted L_{eq} parameter;
- The talkers and listeners were positioned around 1.0m from each other in all of the eating establishments; and
- The prediction model is based upon diffuse field theory.

To aid acoustical consultants conducting noise impact assessments, a guideline for the consideration of patron noise from entertainment venues was prepared for the Association of Australian Acoustical Consultants by Growcott (2009). To prepare this guideline, Growcott conducted measurements of patrons using an outdoor area at a "young person"s pub" that was enclosed and surrounded by acoustically reflective walls approximately 4m high. By conducting measurements at the plane of the top of the surrounding walls, Growcott derived the following expression for the crowd noise:

$$L_{Aeq} = 21\log N + 43 dB(A) \quad (1)$$

where N is the number of patrons. The equation presented by Growcott is limited in its applicability as:

- The equation only predicts the A-weighted L_{eq} parameter
- The data used to derive the equation were obtained above a semi-reverberant space. In this type of space, the background noise level above which people try to communicate would reach a saturation level more quickly that if the crowd was located in free-field conditions.

Notwithstanding the above limitations, the observations made by Growcott accorded with the earlier observations made by Hayne et al. (2006) that:

- The situational context affects the level of crowd noise being produced;
- Alcohol and age have an influence on the level of crowd noise; and
- The level of crowd noise produced increases as the number of patrons increase.

FACTORS INFLUENCING CROWD NOISE

A schematic diagram of the factors influencing the sound power level of a crowd is presented in Figure 1.

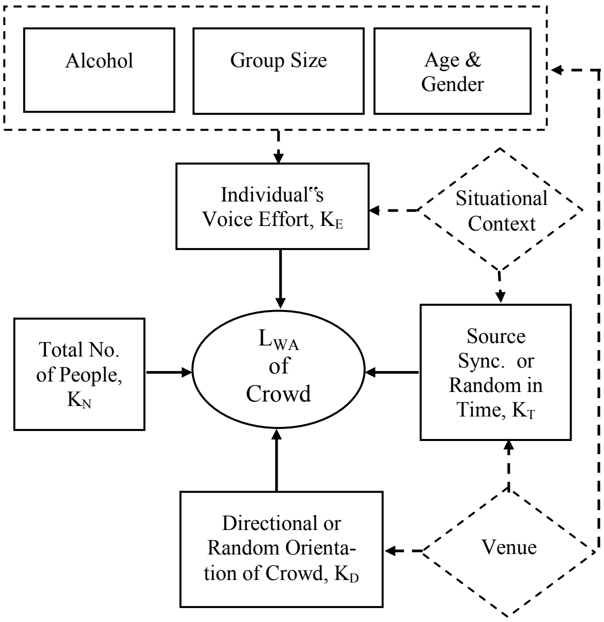


Figure 1. Factors influencing crowd noise

It can be seen in Figure 1 the overall source sound power level is a function of four variables, ie:

$$L_{WA\,(crowd)} = f(K_E, K_N, K_T, K_D) \quad (2)$$

where

1. K_E is an individual‟s voice effort;
2. K_N is the total number of people in a crowd;
3. K_T represents whether the source is synchronised or random with time; and
4. K_D is whether the crowd is directional or has a random orientation.

The venue and situational context indirectly influences the sound power level generated by a crowd. The venue determines whether the crowd has a directional or random orientation, whether it is a random or synchronised source and the group size, age and gender and whether alcohol is being consumed. The situational context impacts upon the individual‟s voice effort and whether the crowd is a random or synchronised source.

Individual's Voice Effort

The vocal effort used by individual crowd members has a direct impact upon the amount of crowd noise generated. As shown in Table 1, the range of average A-weighted sound levels ranges from 36dB(A) for whispering to 96dB(A) for a short-duration maximal shout at a distance of 1-metre in free-field conditions.

Table 1. Equivalent A-weighted sound pressure levels of speech for different vocal efforts (at 1m)

Vocal Effort	Speech Level (dB(A))
Whispering	36
Soft	42
Relaxed	48
Relaxed, normal	54
Normal, raised	60
Raised	66
Loud	72
Very loud	78
Shouting	84
Maximal shout	90
Maximal shout (in individual cases)	96

Source: (Lazarus, 1986)

A cursory examination of the crowd noise problem suggests that an individual‟s voice effort could be predicted by taking into consideration the Lombard effect. The Lombard effect is the phenomenon where talkers increase their voice effort in the presence of increasing background noise to maintain adequate conditions for verbal communication.

The ratio between the speaker‟s voice level and background noise is termed the Lombard coefficient (or Lombard slope) and is represented by the following expression:

$$\text{Lombard coefficient} = \frac{\text{increase in speech level}}{\text{increase in background noise}} \quad (3)$$

This coefficient has been analysed in a number of empirical experiments and found to vary considerably, such as those summarised in Table 2.

The large variation in the Lombard coefficients presented in Table 2 can be attributed to:

- Different types of background noise used to mask the speaker‟s voice. Ambient noise, machinery noise, white noise, pink noise and speech noise all resulted in different Lombard coefficients;

- The acoustical characteristics of the test room, which ranged from an anechoic chamber to rooms with a reverberation time greater than 1.5s;
- The spacing between the speaker and listener, which ranged from 0.4m to 5m; and
- The speech used in the experiments, which consisted of nonsense syllables, monosyllable words or sentences.

Table 2. Lombard coefficients as determined by different researchers

Researcher(s)	Lombard Coefficient (dB/dB)
Dodd & Whitlock (2004)	0.22
Kryter (1962)	0.3
Van Heusden et al. (1979)	0.3
Korn (1954)	0.38
Hodgson et al (2007)	0.69
Sato & Bradley (2004)	0.82
Pickett (1958)	1.0
Webster & Clumpp (1962)	1.0

Even without the large variation in the Lombard coefficient, the applicability of the Lombard Effect when predicting crowd noise is questionable, as the Lombard coefficient is determined based upon maintaining verbal communication. In a crowd situation, the requirement for maintaining verbal communication is not always applicable. For example, a person cheering or yelling at a sporting event would continue to do so, even though he or she knows that they are unlikely to be heard above other members of the crowd who are also cheering or yelling. In a social situation, a person affected by alcohol may continue to talk to another person, unaware that the other person cannot understand what they are saying.

Another limitation of the Lombard effect is that in many crowd noise situations, if the talker determines that the listener is unable to understand him or her, he or she will either move closer to the listener or select another person who is closer to converse with.

Situational Context

It can be observed that the overall behaviour of a crowd and its subsequent noise emissions depend upon situational context. For example, a crowd attending a funeral would be expected to behave differently from a crowd attending a sporting event. This assertion is supported by Lazurus (1986), who found that people tend to speak more quietly in private quarters where rooms are smaller and more sound absorbing, the speaker-hearer distance is shorter and the ambient noise levels are lower. In public places and workplaces, a minimum speech level of around 60dB(A) associated with a normal voice would usually be expected.

Situations where amplified entertainment exists may result in higher levels of crowd noise as crowd members would need to increase their vocal effort to talk over the entertainment and/or overcome temporary deafness caused by the periencing temporary entertainment. Black (1951) found that people experiencing temporary deafness of between 3 and 9dB raised their corresponding vocal effort by between 1 and 5dB.

Venue

The size of the venue containing the crowd indirectly impacts upon the mount of noise generated. A larger venue can contain a larger crowd that will generate a higher level of noise due to there being more people. Conversely, a larger venue with a smaller crowd may generate less noise than the same sized crowd in a smaller venue.

The cocktail party effect is the term used to describe the build-up of a sound field in a room (Long, 2006). As the background noise level increases in a space due to people talking, the separation distance at which two people can converse for the same voice effort decreases. As this occurs, the people may either talk more loudly or move closer to each other to continue their conversation.

An analysis of the cocktail effect was conducted by MacLean (1959), who found that the distance from the speaker where the direct sound pressure level is equal to the reverberant sound pressure level (termed the room radius or critical distance (Long, 2006)) was important, along with the separation distance between each group of talkers.

The acoustical properties of a venue can be characterised by the room radius. A venue which has very little absorption and is highly reverberant would have a smaller room radius than a venue with a high level of absorption that approaches the free-field conditions of outdoors. A larger room radius allows a higher signal-to-noise ratio allowing more people to talk comfortably before the cocktail party effect starts to increase the required voice effort.

Age and Gender

The age of a crowd member impacts upon his or her ability to generate vocal effort. Generally, prepubescent children and the elderly are unable to achieve the same voice effort level as a teenager or adult. Additionally, age may impact upon the ability of a person to hear sound due to age related hearing loss.

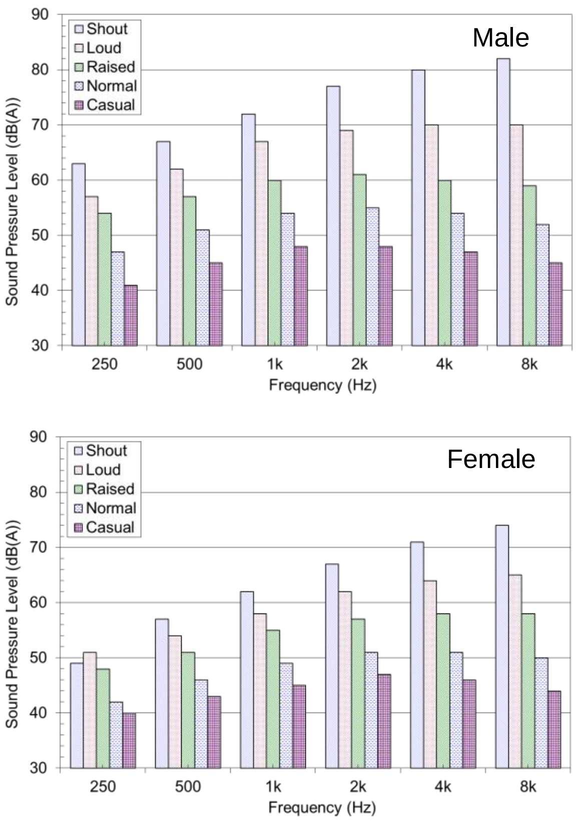
The gender make-up of a crowd has the potential to impact upon both the overall loudness as well as the spectral composition of the noise. Levitt and Webster (1997) found that the average vocal effort that can be achieved by a female is less than the effort achieved by a male. This difference ranges from around 3dB(A) for normal speaking to around 6dB(A) for shouting. A similar study conducted by Pearsons et al (1977) also found that the voices of men shouting a sentence were around 7dB higher than the voices of women. The noise from a crowd consisting entirely of men therefore has the potential to be louder than an equivalently sized crowd of females.

The variances in spectral composition between males and females for different vocal efforts are illustrated in Figure 2. The levels presented in this figure were measured at a distance of 1-metre in free-field conditions.

Alcohol

The consumption of alcohol has the potential to increase the level of crowd noise as people lose their inhibitions and become more boisterous. For example, anecdotal evidence suggests that consumption of alcohol can cause a group of females to be noisier than a same sized group of males who have not consumed alcohol.

Studies such as Upile et al. (2007) have also indicated that alcohol can affect auditory thresholds, impacting upon the ability of a person to hear in certain frequencies, including those used for speech.



Source: (Adapted from Pearsons et al 1977)

Figure 2. Variances in the spectral compositions of the male and female voices

Group Size

Crowds are comprised of a number of smaller groups within which communication can occur. At any one time, it would usually be expected that only one person within each group would be talking. The vocal effort required by a person talking would depend upon the size of the group he or she is addressing. The larger the group, the higher the vocal effort must be to communicate with all individuals within the group. This is because a larger group would result in more people being located further away from the talker. As stated in Lazarus (1986), increasing the distance between a talker and listener from 1m to 3.5m would result in the talker increasing his or her speech level by up to 5dB.

A larger group size may not always result in the speaker increasing his or her vocal effort if the spacing between group members is fixed. An example would be a couple seated each side of a table rather than next to each other. As the couple cannot sit closer to each other due to the table, they have to increase their vocal effort to communicate.

Research conducted by Hodgson et al. (2007) suggests that for a typical crowd in a social setting, the total number of people could be divided by three to obtain the number of smaller groups making up the overall crowd.

Total Number of People

Based on first principles, it would be expected that as the crowd size increases, the average sound power level would increase logarithmically. Initial test data would suggest that this relationship generally holds for the quasi-steady or babble component of crowd noise and also for events which occur in unison such as cheering at a football match. However, it does not hold for random transient noise peaks such as might occur in a crowd in a hotel or club.

Random or Synchronised Crowds

A random crowd is one in which there is no unifying influence. It would normally consist of a number of sub-sets or groups such as table groupings at a restaurant or groups of two or more at a hotel or social gathering. The identifying characteristic of such a crowd is that each group behaves independently and thus the resulting noise output is random.

A synchronised crowd is one which has some outside influence which can control and unify the noise emissions. Such influences include sporting events where crowds may cheer in unison in response to some spectacular occurrence. Concert crowds also unify at times of acclamations. A normally random crowd such as a crowd of club patrons can also produce a unified response if there is an important sporting event on a video screen.

Whether a crowd is random or synchronised will affect their noise output. However the most influence is on the peak transient events. For a random crowd, the transient noise events would initially be above the babble at low crowd numbers. As the crowd number increases, the transient events gradually become swamped by the babble after which the listener would only hear the babble with no discernable individual outbursts.

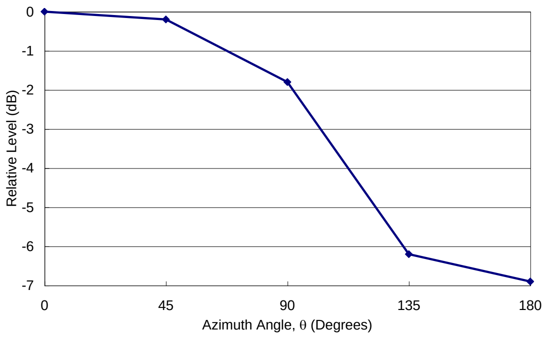
For the synchronised crowd, the unified cheers are much louder than the transient outbursts of the random crowd and would be expected to increase at a rate proportional to $10 \log N$.

Directional or Random Orientation

Each individual making up a crowd will have his or her own orientation with respect to the receiver. This orientation will range from directly facing the receiver ($\theta = 0^o$) to facing directly away from the receiver ($\theta = 180^o$). Overall, every member of a crowd could face the same direction at a certain angle to the receiver, or each member could have a random orientation.

To determine the influence of the direction an individual faces in a crowd, a theoretical study was conducted by Hayne et al. (2006) based upon the directivity and average speech spectrum of the human voice.

Using data presented in Studebaker (1985) and van Heusden et al. (1979), Hayne et al. (2006) calculated the variance in sound pressure level experienced at a receiver for different crowd orientations. The effect of all crowd members facing a certain direction is presented in Figure 3. The values are relative to the noise level at the receiver if all crowd members directly faced it. It can be seen in this figure that for a crowd facing $\pm 45^o$ to the receiver the noise level at the receiver would be approximately the same as if the crowd was directly facing the receiver. If the crowd was positioned $\pm 90^o$ to the receiver, an adjustment of approximately –2dB would be required, while adjustments of approximately –6dB and -7dB would be required for a crowd ±135° and 180° to the receiver, respectively.



(Source: Hayne et al. (2006))

Figure 3: Effect of crowd orientation (all members facing the same direction)

For a crowd consisting of individuals with a random orientation, Hayne et al. (2006) found that there would be a –3dB difference relative to the noise level at the receiver if all crowd members directly faced it.

DESCRIPTIVE PARAMETERS FOR CROWD NOISE

Previous research conducted by the authors (Hayne et al. 2006) has suggested that more than one noise parameter is necessary to adequately describe crowd noise. This is because crowd noise can be shown to be comprised of two components:

(1) A babble due to individuals in a group of people communicating with each other; and

(2) Transient peaks due to events such as people laughing, yelling and cheering.

If measured over the long-term, the babble component of crowd noise would be considered to be quasi-steady due to changes in the emission level as the number of people talking varies. This quasi-steady noise would be represented by the L_{10} and/or L_{eq} parameters.

The transient peaks are due to random events that range from a fraction of one second for a person exclaiming to several minutes for a cheering crowd. The L_{max} and/or L_{01} parameters would represent the transient peaks due to crowd noise.

CROWD NOISE MEASUREMENTS

Measurements of crowd noise were made at 11 different venues as summarised in Table 3. In most instances, multiple measurements were able to be made at each venue for different numbers of patrons.

To ensure that the measurements would be able to be analysed to determine relationships for the various descriptive parameters, all of the venues exhibited the following characteristics:

1. The patrons that comprised the crowd were interacting with each other in a casual social situation;
2. The crowd had a diffused orientation with a random noise output;
3. All of the crowds were located in external areas that were open on at least three sides to minimise reverberant build-up of the sound;
4. None of the crowds contained people that were observed to be affected by alcohol; and
5. None of the venues played music or had any other significant noise sources that raised the background noise level.

Table 3: Summary of crowd noise measurements

Venue	Number of Patrons
Hervey Bay Church	50/51
Redland RSL	25
Maroochy RSL	7/25/93
Grinder"s Cafe	15
UQ Main Refectory Al-fresco Area	20/25/30/35/40
Wordsmith Cafe	23/29/38
Private Party	10
Centenary Baptist Church	15/35/40
Caloundra RSL	13/25/30/40
Springfield Lakes Hotel	6
Pine Rivers" Bowls Club	13/15/18/20/23/25

In all instances the measurements were made in the far-field under free-field conditions. To ensure that the presences of the acoustician did not influence the behaviours of the crowd, the measurements were made unobtrusively wherever possible. As the number of patrons had the potential to quickly change, the measurements were made over 1-minute intervals.

The measured sound pressure levels were converted into sound power levels using the equation

$$L_W = L_P + 20\log d + C \qquad (4)$$

where the constant C = 8 for a hemispherical source or C = 5 for a quarter sphere source and d was the distance from the centre of the crowd to the measurement position.

Measurement Results

The measurements obtained at the venues have been averaged and converted into their equivalent sound power levels as presented in Figure 4 to Figure 7. In each instance, a least squares regression line has been fitted to the data to derive an expression for the sound power level for each parameter.

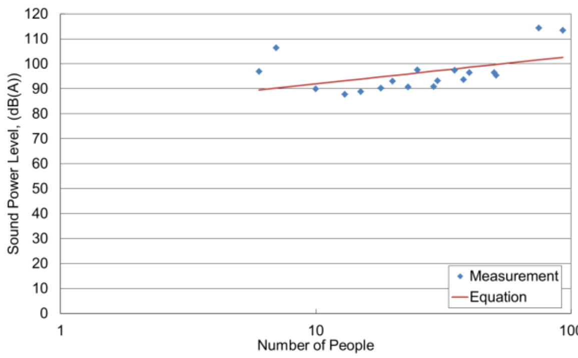


Figure 4: L_{Amax} sound power level

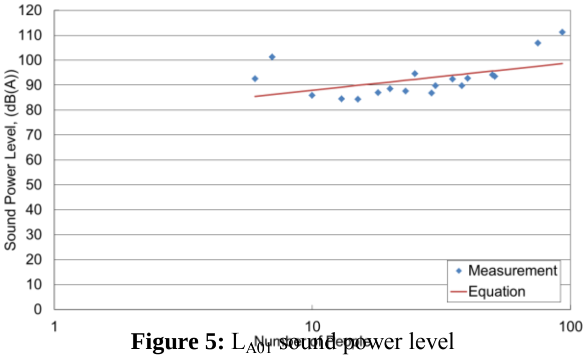


Figure 5: L_{A01} sound power level

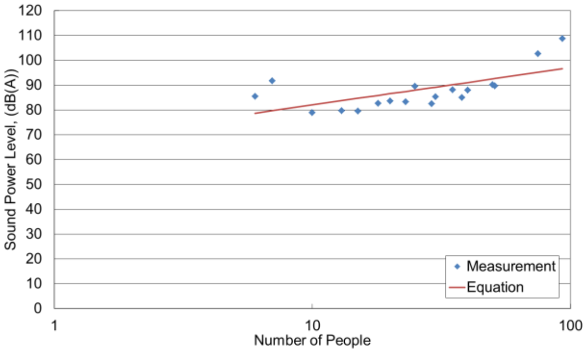


Figure 6: L_{A10} sound power level

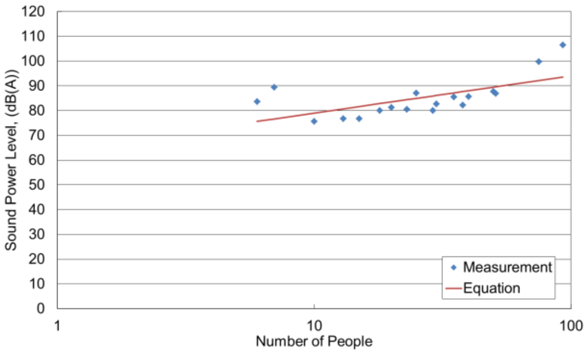


Figure 7: L_{Aeq} sound power level

The A-weighted sound power levels for a crowd size, N, can be approximated by:

$$L_{WAmax} = 11\log N + 81 dB(A) \quad (5)$$

$$L_{WA01} = 11\log N + 77 dB(A) \quad (6)$$

$$L_{WA10} = 15\log N + 67 dB(A) \quad (7)$$

$$L_{WAeq} = 15\log N + 64 dB(A) \quad (8)$$

These prediction equations would be considered applicable for a typical crowd in an outdoor social setting such as those at a bar or club. Using these source levels, it would be possible to apply adjustments to take into account factors such as the orientation of the crowd and whether it is random or synchronised.

CONCLUSION

An analysis has been conducted to determine the major influences on the level of noise emitted by a small to medium sized crowd. Based upon a simple analysis, it has been proposed that four major factors influence the noise emitted by a crowd:

(1) An individual"s voice effort;

(2) The total number of people in the crowd;

(3) Whether the noise from individuals is synchronised or random with time; and

(4) Whether the crowd noise is directional or has a diffused orientation.

Other secondary factors that influence crowd noise are:

(1) Whether or not alcohol has being consumed;

(2) The size of the smaller groups of which the crowd is composed;

(3) The average age and gender make-up of the crowd;

(4) The acoustic characteristics of the venue; and

(5) The situational context in which the crowd is placed.

By considering the above factors, measurements have been made of crowds in a social setting and simple predictive equations determined for the L_{WAmax} and L_{WA01} parameters that represent the transient components of crowd noise. Similarly, predictive equations have been determined for the L_{WA10} and L_{WAeq} parameters which represent the quasi-continuous or "babble" component of crowd noise. These equations are applicable to crowd in a social setting where people are not affected by alcohol and have a random orientation.

It is anticipated that in the future that taking into account these source sound power levels and applying the appropriate adjustments for different crowd situations, it will be possible for acoustical consultants to estimate crowd noise emissions from small to medium sized crowds of up to around 100 people in a variety of situations. Research is continuing to determine the appropriate adjustments for all of the factors discussed in this paper.

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