Predicting Patron Noise Levels in Restaurants and Bars - An extension to J.H Rindel's Method

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ABSTRACT

The simple method that J.H. Rindel recently published to predict patron noise in eating establishments is based on a model of the Lombard effect. This method provides a substantial increase in accuracy over the commonly-used prediction method which assumes raised voices and 10*log(number of talkers). A key outcome of the Lombard model is that noise levels increase by approximately 20*log(number of talkers). Although Rindel's method is not yet widely used in Australia, it is now documented in the Patron Noise Guideline prepared by the Association of Australasian Acoustical Consultants. Rindel's statistical method has several simplifications, which can potentially lead to inaccurate results. The proposed extension to this statistical method includes the use of octave-band room constants and the contribution of the direct field of talkers, which also allow its use in situations with low reverberation such as outdoor terraces. The extended method is illustrated with a comparison of predicted and measured noise levels in two situations; the first is a busy Sydney bistro with patron numbers varying from 40 to 175 over an afternoon; the second is a busy restaurant, before and after sound absorption was installed. The effects on the predictions of the key parameters of Lombard ratio and speaking group size are also explored.

1 INTRODUCTION

Noise produced by conversations in social gathering spaces such as restaurants and bars often results in a substantial loss of acoustic comfort for patrons. This loss of comfort can be manifest as substantially degraded speech intelligibility and increased vocal effort, as conversation may only be possible a raised voice with a small distance between talker and listener. With an aging population, the extent of people with hearing loss per capita is increasing, further decreasing the comfort of older patrons in these situations.

J.H. Rindel (Rindel, 2010, 2012, 2015) proposed a method to predict the increase in noise level and required vocal effort in social situations. This method is based on the involuntary response of human talkers when speaking in the presence of noise known as the Lombard effect. Rindel's method is based on two primary equations and a Lombard ratio of 0.5 dB/dB. This ratio relates the increase in a talker's level in dB for each one dB of increase in ambient noise.

Rindel states that the Lombard effect was found to start at an ambient noise level around 45 dBA and a speech level of 55 dBA. Assuming a linear relationship for noise levels above 45 dB, the speech level can be expressed in Equation 1:

$$L_{SA\ 1m} = 55 + C(L_{NA} - 45) \tag{1}$$

where C is the Lombard ratio in dB/dB and $L_{SA\ 1m}$ is the A-weighted talker level at 1 m on axis.

Rindel recommends a Lombard ratio of 0.5, which equates to 0.5 dB increase in talker level per 1 dB increase in the ambient level. This ratio produces a 6 dB increase in sound level for every doubling of the number of people talking simultaneously and contrasts with the usually accepted rule of 3 dB increase per doubling of talkers.

A large study of talkers conducted in 1977 by Bolt Beranek and Newman concluded people increase their speech at the rate of 0.6 dB per 1 dB increase in the ambient level. Hayne et al (2011) present the list of ratios shown in Table 1 which were developed by various researchers and range from 0.2 to 1.

Table 1: List of Lombard ratios reported by Hayne et all.

Researcher	Lombard Ratio (dB/dB)
Dodd & Whitlock (2004)	0.222
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

There are three methods that can be used to predict the noise level in space with the Lombard effect: i) statistical, ii) simulation, and iii) hybrid.

2 STATISTICAL METHOD

2.1 Overview

This method assumes a diffuse reverberant field and calculates the reverberant field using standard statistically-based equations.

Based on a Lombard ratio of 0.5, Rindel develops Equation 2.

$$L_{NA} = 93 + 20\log\left(N_s/A\right) \tag{2}$$

where:

L_{NA} is the A-weighted L_{Aeq} noise level in the patron area,

A is the average absorption area in the space (S.alpha) and N_s is the number of people speaking

It is clear from Equation 2 that noise levels increase by 6 dB per doubling of talkers or decrease by 6 dB per doubling of the total sound absorption area in the space.

2.2 Uncertainties with the Statistical Method

There are five important weaknesses with the statistical method:

a) The contribution of talkers' direct field and early-arriving reflections to the overall level is not considered.

b) The effect of talker directivity is not included.

c) The Lombard ratio is not explicitly stated in the calculation and given the range of ratios published in the literature, it may be helpful to allow the ratio to be a direct input into the calculation model.

d) In many situations, the use of the total absorption term A may underestimate the amount of sound absorption in the space and the use of the room constant R may provide a better estimate. Given that a Lombard ratio of 0.5 will make the noise level vary as 20*log(R), increasing the accuracy of the sound absorption area can make a significant difference to the noise level in the room.

e) The statistical method breaks down in situations in which the reflected sound field in the space is not constant. This situation will occur when the talkers are spaced apart, or groups of talkers are spaced apart. These types of situations occur frequently in semi-enclosed, hotel beer-gardens and specific types of undercover outdoor dining areas.

2.3 Equation Details

It is helpful to understand the derivation of Equation 2, as it is not explicitly explained by Rindel and it is useful to allow changes to the Lombard ratio to explore its effect in different situations.

Equation 2 is derived from Equations 3 to 5 with *C* = 0.5

$$L_{NA} = L_{SA\,1m} + 8 + 10\log(N_s/A) + 6 \tag{3}$$

$$L_{NA} = 55 + C(L_{NAeq} - 45) + 8 + 10\log(N_s/A) + 6 \tag{4}$$

$$L_{NA} = 1/(1 - C)\{69 - 45C + 10\log(N_s/A)\} \tag{5}$$

where:

- $L_{SA\,1m}$ is the A-weighted L_{Aeq} talker level at 1m
- the 8 dB term converts sound power to direct-field pressure for a source with a directivity index of 3 dB
- the 6 dB term is part of the conversion of sound power to reverberant intensity

Replacing the total sound absorption term A in Equation 1 with the room constant (R) can provide a better match to measured levels in smaller or less reverberant areas. R can also be computed from the average reverberation time in the 250 Hz to 2 kHz range, based on the Eyring equation. The calculations can also be done on an octave-band basis.

3 SIMULATION METHOD

Rindel et al (2012) published an extension to the method to allow 3D acoustic simulation software to compute the total sound field in which talkers are immersed relative to a nominal talker level. This simulation method addresses the weaknesses in the statistical method listed in Section 2.2.

The relationship between talker level and overall noise level described by Equation 3 can be re-formulated for the simulation method as shown in Equation 6.

$$L_{NAm} = L_{SAm\,1m} + K \tag{6}$$

where:

- L_{NAm} is the modelled sound field which the group of talkers is immersed, computed from one-third or one-octave wide band levels
- $L_{SAm\,1m}$ is a nominal fixed talker level at 1 m on axis of the mouth used in the model, computed from one-third or one-octave wide band levels
- *K* is the A-weighted difference between the nominal talker level at 1m and the modelled total sound field, with a specified number of talkers

As the term *K* is derived from the acoustic model, it includes the contribution of talker directivity, direct and reverberant sound fields, and early-arriving reflections. As such, it can be considered as the room gain resulting from multiple talkers and the various source and room parameters. As there is no Lombard effect in Equation 6, *K* can be adjusted post-calculation to account for a slightly different number of talkers than was used in the model, as long as the spatial consistency of the increased talkers is similar to the modelled consistency.

When calculating the sound field using simulation method, care must be taken to create an exclusion zone around each talker so that the direct field component of the calculation is not dominated by a small distance between talker and the calculation point.

Re-arranging Equations 5 and 6 yields Equation 7, which is used to calculate the actual total A-weighted level in the patron area with the Lombard effect for a given Lombard ratio.

$$L_{NA} = (55 - 45C + K')/(1 - C) \tag{7}$$

where *K*' is the adjusted value of *K* to account for a different number of talkers and *C* is the Lombard ratio.

The actual talker level is then calculated using Equation 8.

$$L_{SA\ 1m} = L_{NA} - K' \tag{8}$$

As *K'* is computed in octave or third octave bands in the model, Equation 9 can be used adjust the room noise level L_{NA} using the speech spectrum associated with the computed talker level at 1 m.

$$L_{NA\ j} = L_{SA\ 1m\ j} + K'(j) \tag{9}$$

where *j* is the *j*th octave or one-third octave band.

4 HYBRID METHOD

The hybrid method estimates the room-gain parameter *K* by combining the calculating the statistical reverberant level with an estimate of the average direct field permeating the patron area. Although this method is not as accurate as the simulation method, it does include a number of factors that the statistical method ignores. The method calculates levels in octave-wide frequency bands, with the spectrum of a raised voice being initially used.

Features of the method to compute the reverberant component of the noise level are:

- The octave-band room constants are used.
- The directivity indices of a human talker are used to compute the sound power levels entering the room. Leishman et al (2021) present averaged one-third octave directivity indices (DI) for male and female talkers, from which octave band DIs were computed as the energy-average of each three sub-bands. Table 2 shows the resulting octave DIs.

Table 2: Directivity indices used in hybrid method (derived from Leishman).

Octave frequency band	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**
Directivity Index	0.6	2.6	1.6	1.9	4.4	4.4	5.5

Features of the method to compute the direct component of the noise level are:

- Talkers are assumed to face in every direction, which enables an average directional loss of the direct field to be computed at each frequency from the radiation patterns of the human talker in each octave band.
- Talkers are assumed to be evenly distributed over the venue floor plan, with 500 mm between any talker and the room boundary.
- Ten calculation points are randomly located in the in the patron area, with a minimum distance of 1.2 m between a talker and calculation point. The direct-field level of every talker at each calculation point is computed and the energy sum of all talkers computed.
- The energy average of the ten calculation points is computed to yield the estimate of the direct field.

5 CASE STUDIES

5.1 Large Bistro

5.1.1 Room parameters

The bistro is approximately rectangular in plan and has a ceiling that is slightly vaulted. The average dimensions of the room are 20.4 m x 14 m x 4.35 m (l,w,h).The total surface area of the room is 973 m^2 and its volume is 1246 m^3.

The reverberation times (RT) of the bistro were measured in an unoccupied state measured over a range of heights 1.5 m to 2.2 m using a bursting balloon. The times T20 and T30 of the Schroeder decay plot were computed using a WinMLS 2004 analyser. Table 3 shows the average of T20 and T30 times measured in eight positions in the room. From the RT and room data, the total absorption area A was computed from the Sabine RT equation, and the room constant R was computed from the Eyring equation. The sound absorption of patrons was added into these two room parameters according to the number of patrons in the room; (see Section 5.1.3/5.1.4.)

Table 3: Room acoustic data for bistro.

Octave frequency band Hz	125	250	500	1000	2000	4000	8000	Average 250-2 k
Average RT (unoccupied)	1.34	1.40	1.22	1.27	1.24	1.03	0.69	
Absorption per person	0.16	0.24	0.56	0.69	0.81	0.78	0.78	
A (total absorption) 90 people	178	178	231	235	250	284	391	224
R (Room Constant) 90 people	199	201	277	287	311	360	535	269

Figure 1 shows range of reverberation times over all positions and the two decay ranges.

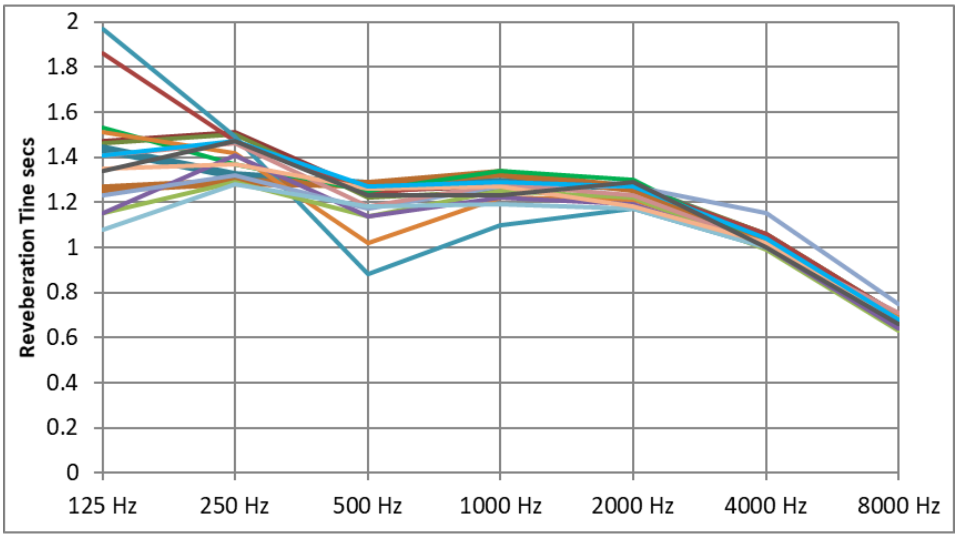

Figure 1: Range of reverberation times computed as T20 and T30 over eight positions

5.1.2 Measured levels

The noise levels and associated patron numbers in the bistro were quantified over the period of 2 pm to 6 pm on a Sunday afternoon. There was no background music, and the dominant noise source was patrons talking.

During this period, 24 measurements of patron noise levels were made at approximately equal intervals. Of these, eleven measurements were spatial L_{Aeq} measurements, made by an operator walking around the room among the standing and seated patrons. The other thirteen measurements were made with the sound level meter sitting on the author’s dining table located approximately in the middle of the patron area. The duration of each measurement was approximately 3 minutes. Patron numbers were estimated using an approximate headcount on thirteen occasions and interpolated for the times between those counts.

To quantify the contribution to the measured level of reflections from the table, a measurement of the noise level was made at 1.5 m above the table immediately before an on-table measurement and found to be 1.5 dB lower. As such, the level of the on-table measurements was reduced by 1.5 dB.

Figure 2 shows the relationship between measured level and time of measurement, while Figure 3 shows the relationship between measured level and estimated patron numbers.

To understand the change in talker spectrum as talker numbers increase, Figure 4 shows the difference between the L_{eq} level in each one-third octave band and the overall L_{Aeq} of the measurement. As a general trend, there is slightly less sound energy below 500 Hz with increasing talker numbers, showing that talkers are increasingly raising the pitch of their voices as the noise level increases.

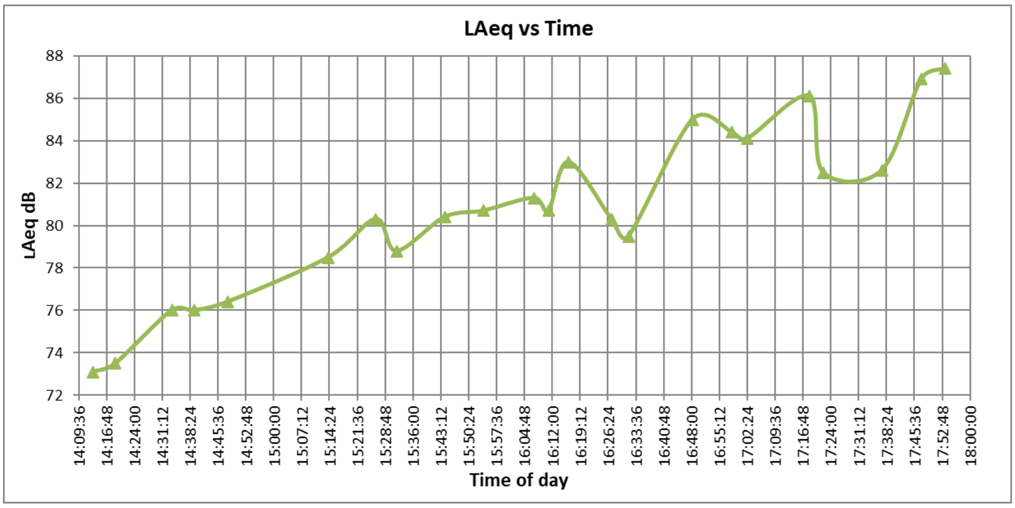

Figure 2: Internal dBA noise level vs time of measurement.

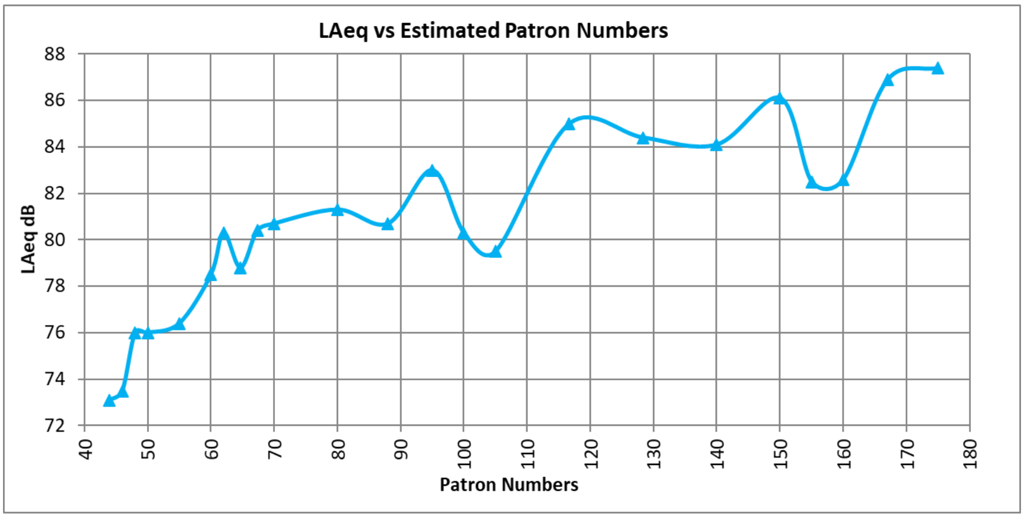

Figure 3: Internal dBA noise level vs estimated patron numbers.

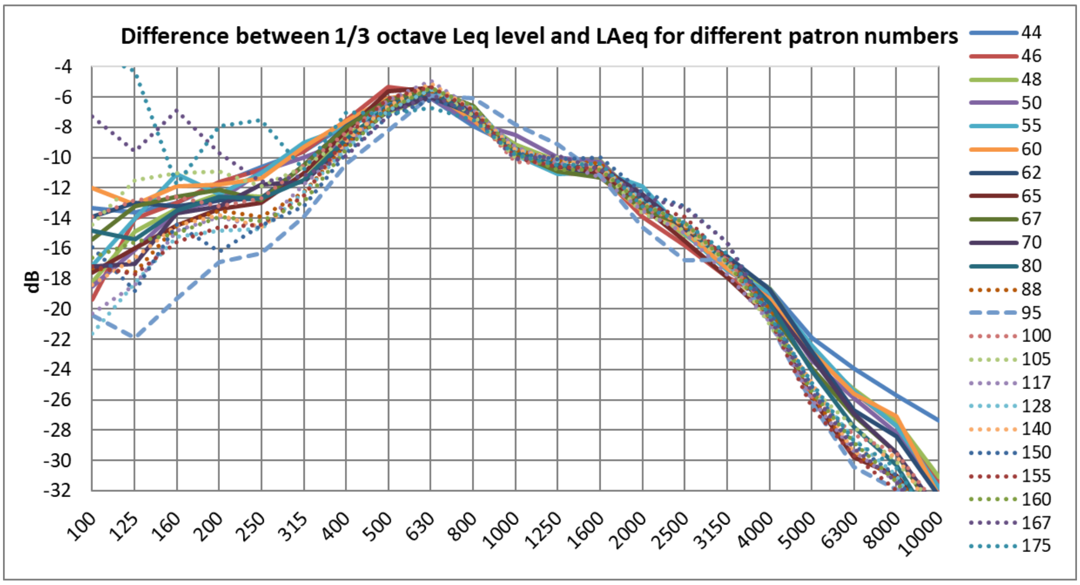

Figure 4: Spectra of each measured noise level relative to its overall L_{Aeq}.

5.1.3 Comparison of measured and predicted levels using statistical method

Predictions of patron noise were made using the statistical method with a directivity index of 3 dB for talkers (as per Equation 3) and the average room constant or absorption area computed over the range 250 Hz to 2 kHz Figure 5 compares the measured level with predictions using the room constant and a group size of 2.5 with four Lombard ratios. Figure 6 compares measured and predicted levels using the total absorption area A and a group size of 2.5 with four Lombard ratios.

When the room constant is used, the best match between measured and predicted levels with a group size of 2.5 appears to require a Lombard ratio between 0.575 and 0.6. In contrast, with the total absorption area, the best match is a ratio between 0.55 and 0.575.

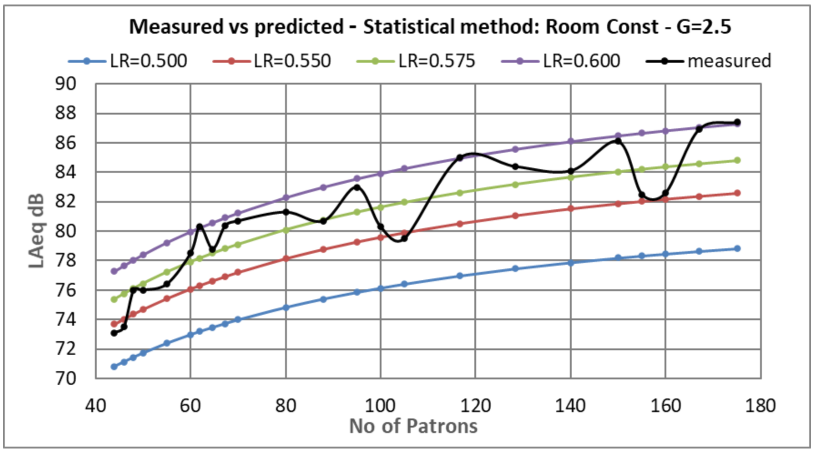

Figure 5: Measured vs predicted dBA levels (statistical method) with room constant and group size 2.5 with four Lombard ratios.

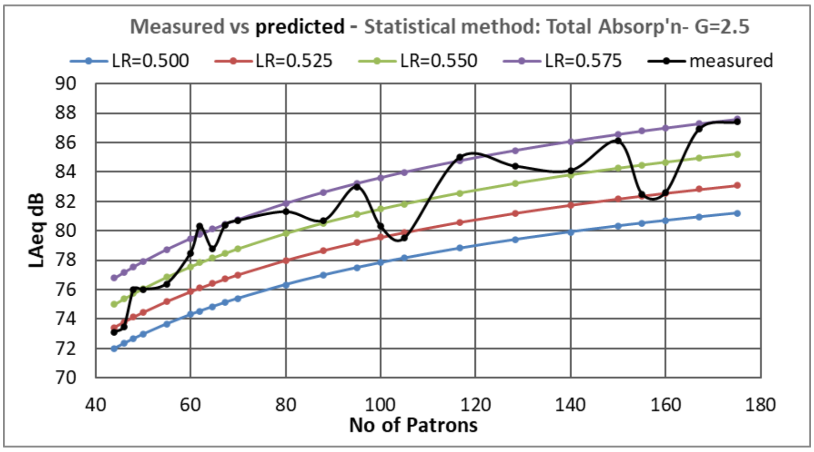

Figure 6: Measured vs predicted dBA levels (statistical method) with total absorption (A) and group size 2.5 with four Lombard ratios.

Figure 7 looks at the data in Figure 5 from a different perspective and compares the measured levels with predictions using a Lombard ratio of 0.575 and five group sizes. The best match is a group size between 2.25 and 2.5.

Comparison of Figure 5 and Figure 7 suggests that changes to the Lombard ratio have a greater effect on the levels than the number of people talking.

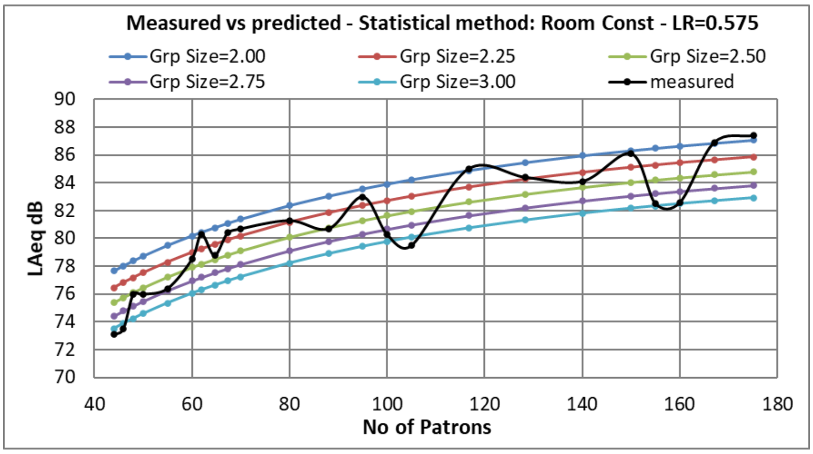

Figure 7: Measured vs predicted dBA levels (statistical method) with Lombard ratio 0.6 with five group sizes.

5.1.4 Comparison of measured and predicted levels using hybrid method

Predictions of the patron noise level were made using the hybrid method and directivity indices from Table 2. The room constants were computed for each number of patrons, an example of which Table 3 shows for 90 patrons. Table 4 lists the figure numbers and associated group sizes and Lombard ratios of the plots comparing the measured and predicted levels.

Table 4: List of figures and parameters for the hybrid method calculations

Figure	Group size	Lombard ratios
Figure 8	2	0.5, 0.525, 0.55, 0.575.
Figure 9	2.5	
Figure 10	2.75	
Figure 11	3	
Figure 12	3.5	0.55, 0.575, 0.6, 0.625

The “wobbles” in the predicted levels are due to imperfections in the method used to estimate the direct field, which include the randomised nature of the ten positions and distribution of the talkers over the patron area.

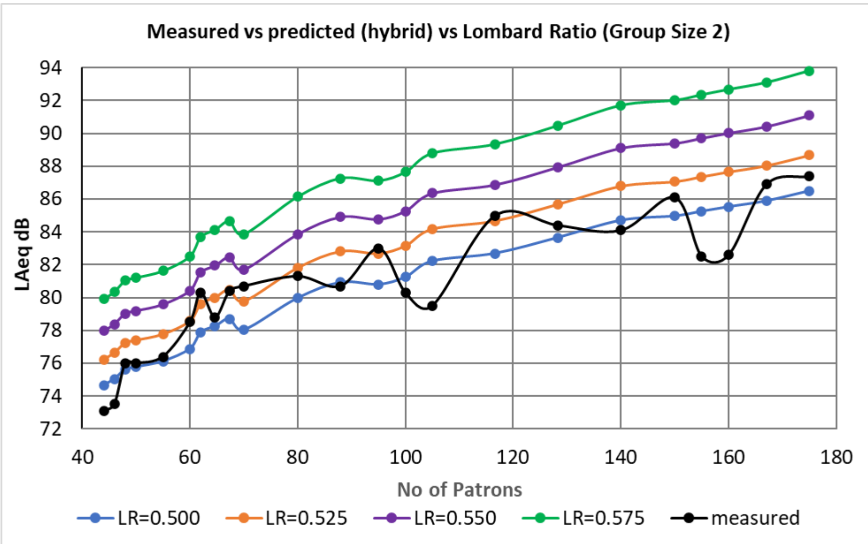

Figure 8: Measured vs predicted (hybrid method) with group size 2.0 and four Lombard ratios.

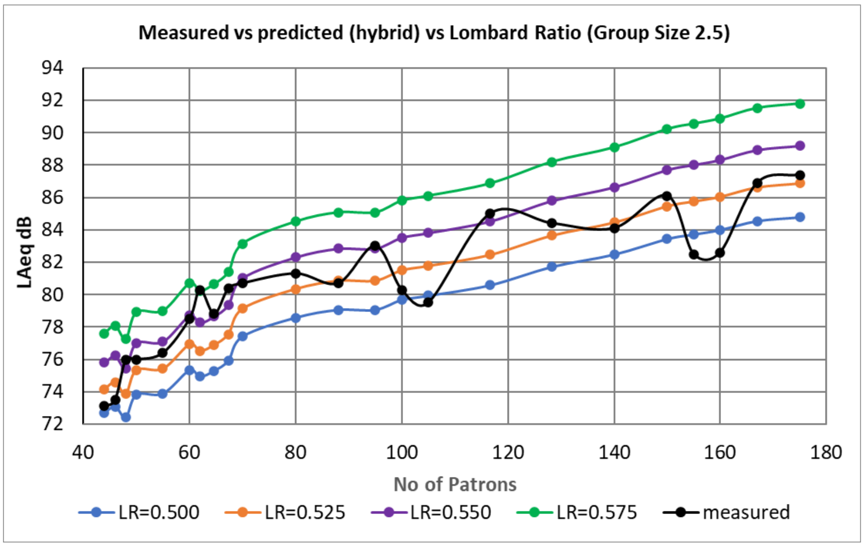

Figure 9: Measured vs predicted (hybrid method) with group size 2.5 and four Lombard ratios.

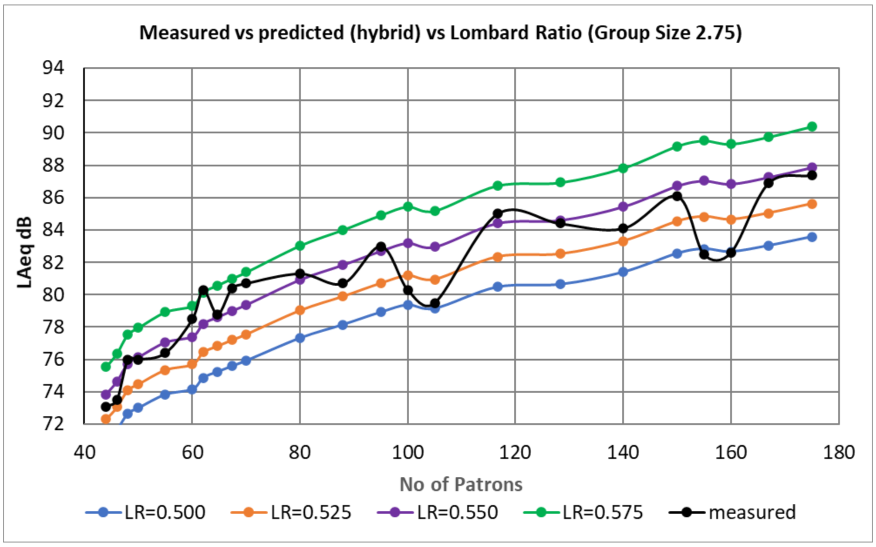

Figure 10: Measured vs predicted (hybrid method) with group size 2.75 and four Lombard ratios.

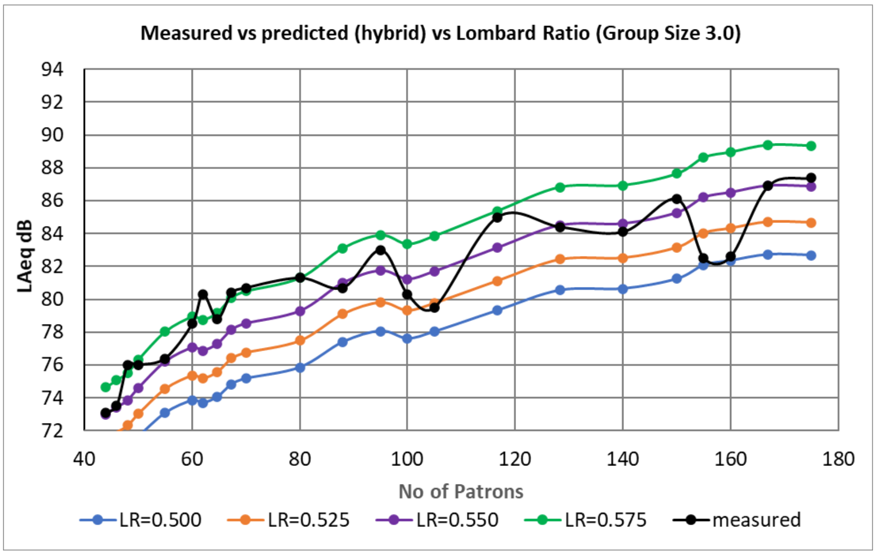

Figure 11: Measured vs predicted (hybrid method) with group size 3.0 and four Lombard ratios.

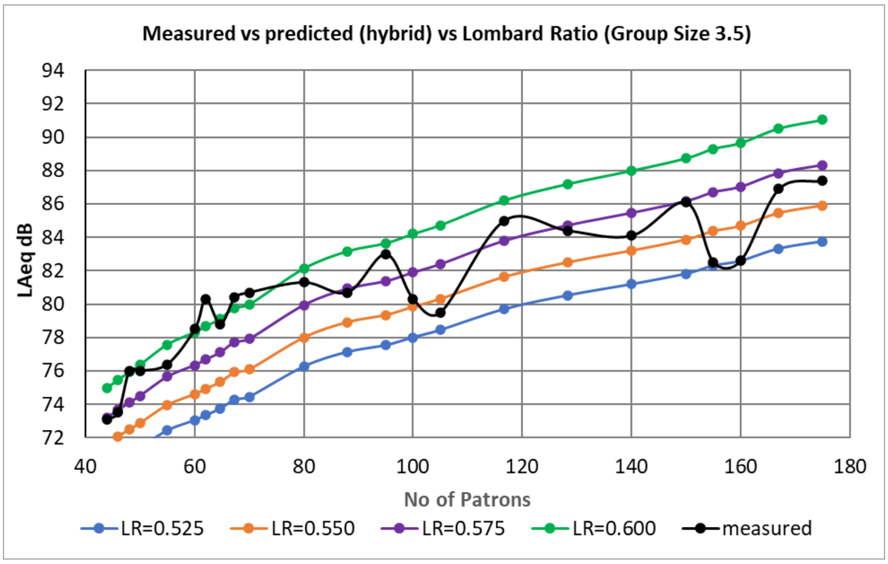

Figure 12: Measured vs predicted (hybrid method) with group size 3.5 with four Lombard ratios.

Inspection of Figure 8 to Figure 12 indicates that various combinations of group size and Lombard ratio can be used to predict the measured levels, as shown in Table 5.

Table 5. List of Lombard ratios and group sizes giving the best matches with the hybrid method.

Group size	Lombard ratio giving best match
2	0.50
2.5	0.525
2.75	0.535
3	0.55
3.5	0.575

The author's personal observations of gatherings of patrons suggest that a group size of 2 is unlikely in many situations and that group sizes between 2.5 and 3.5 are more likely. Accordingly, the Lombard ratios would lie between 0.525 and 0.575.

It appears that using the hybrid method for this bistro situation, it is not possible to obtain a good match between measured and predicted levels using Lombard ratios of 0.6 or greater.

5.2 Medium Size Restaurant

5.2.1 Room parameters

The restaurant is rectangular in plan and has a flat ceiling. The room's average dimensions are 8 m x 4.7 m x 3.6 m (l,w,h).The total surface area of the room is 166 m^2 and its volume is 148 m^3. In response to complaints by patrons, the restaurant owner approached a supplier of sound absorption panels, who recommended that a specific type of absorption panel be fitted to three walls. The author's company was asked to measure the noise levels before and after the treatment.

The reverberation times (RT) of the restaurant before and after acoustic treatment were measured in an unoccupied state measured over a range of heights 1.5 m to 2.2 m using a bursting balloon. From the RT and room data, the total absorption areas A was computed from the Sabine RT equation, and the room constants R were computed from the Eyring equation. The sound absorption of 50 patrons was added into these two room parameters.

Predictions of the noise levels were made using the statistical and hybrid methods for two group sizes and a number of Lombard ratios. For the statistical method, the absorption areas and room constants were averaged over the range 250 Hz to 2 kHz. Table 6 shows the room data before treatment, while Table 7 shows data after treatment.

Table 6: Room acoustic data for restaurant before acoustic treatment.

Octave frequency band Hz	125	250	500	1000	2000	4000	8000	Average 250-2000
Average RT (unoccupied)	0.70	0.69	0.73	0.67	0.60	0.53	0.47	
A (total absorption) 50 people	42	46	61	70	80	84	89	64
R (Room Constant) 50 people	50	57	85	105	131	138	152	94

Table 7: Room acoustic data for restaurant after acoustic treatment.

Octave frequency band Hz	125	250	500	1000	2000	4000	8000	Average 250-2000
Average RT (unoccupied)	0.50	0.49	0.38	0.40	0.40	0.37	0.34	
A (total absorption) 50 people	56	61	90	93	99	104	109	86
R (Room Constant) 50 people	69	78	145	159	181	193	207	141

5.2.2 Comparison of measured and predicted levels

The levels inside the restaurant were measured during two busy evening periods at a single point in the middle of the dining area by a seated engineer wearing a set of binaural microphones, similar to in-ear headphones. On each measurement before and after treatment, fifty patrons were present in the dining area. Background music was not present. The frequency response and level of these microphones had been calibrated on the wearer in a free field against the response of a Type 1 reference microphone located at the position that the centre of the head would have been. The audio recordings from both occasions were carefully listened to in order to extract sections for measurement that were very consistent in level without individual loud talkers.

Table 8 shows the measured and predicted levels before treatment, while Table 9 shows the levels after treatment.

Table 8: Predicted L_{Aeq} noise levels (dBA) within the patron area before treatment.

Scenario	Statistical Method				Hybrid Method	Measured
	Absorption Area (64)		Room Const (94)			
	DI=3	DI=2.6	DI=3	DI=2.6		
G= 2.5 | LR =0.55	87.1	87.9	83.4	84.1	86.2	87.6
G= 2.5 | LR =0.565	88.5	89.3	84.7	85.5	87.6	
G= 3.0 | LR =0.575	87.7	88.5	83.8	84.6	86.7	
G= 3.0 | LR =0.6	90.4	91.2	86.2	87.1	89.3	

Table 9: Predicted L_{Aeq} noise levels (dBA) within the patron area after treatment.

Scenario	Statistical Method				Hybrid Method	Measured
	Absorption Area (86)		Room Const (141)			
	DI=3	DI=2.6	DI=3	DI=2.6		
G= 2.5 | LR =0.55	84.3	85.1	79.5	80.3	82.9	82.6
G= 2.5 | LR =0.525	82.2	82.9	77.7	78.4	80.9	
G= 3 | LR =0.55	82.5	83.3	77.8	78.5	81.2	
G= 3.0 | LR =0.575	84.7	85.5	79.7	80.5	83.4	

5.2.3 Discussion

The following points are made:

a) When the statistical method is used with the following parameters, it provides a reasonable estimate of the measured levels:

- total absorption area
- a group size of 2.5
- Lombard ratio of 0.55

The higher reverberant level compared to the room constant method compensates for the absence of the direct field in the calculation.

b) The statistical method using the room constant underpredicts the measured levels, due to the absence of the direct field component of talkers' speech.

c) The hybrid method with a group size of 2.5 and Lombard ratios (LR) of 0.55 and 0.565 provides the best estimate, with only small a change in LR being required to achieve a good match with measured levels.

d) In terms of the percentage changes in Lombard ratio and group size on the predicted levels, the LR has much greater impact. For example, a change of 4.4% in LR produces a similar change in level as a 16.7% change in group size.

6 CONCLUSIONS

a) When using the statistical method in a large venue such as the bistro (Case 1), predictions using either the total absorption area or the room constant can be made to fit the measured levels using small changes in the Lombard ratio or larger changes to the group size. It can be argued that an increase in Lombard ratio is required to compensate for the lack of the direct field component.

b) In the smaller restaurant situation, the statistical method using the room constant underpredicts the measured levels, due to the absence of the direct field component of the noise.

c) With the hybrid method, the contribution of the direct field to the calculation allows a slightly lower Lombard ratio and/or larger group size (i.e. fewer talking patrons). In this context, with its ability to account for many more acoustical factors, the hybrid method appears to be more accurate.

d) With the hybrid method and a group size of 3.5 or below, it was not possible to obtain a good match between measured and predicted levels using Lombard ratio of 0.6 or greater.

e) The predicted levels are very sensitive to small changes in Lombard ratio (e.g, 0.025). In contrast, changes in group size of 20% are required to substantially affect predicted levels.

f) The statistical method using the total absorption area can be used to provide a quick estimate of the noise levels.

g) The most accurate prediction method is the simulation method, and it is the only method that can accommodate a sparse distribution of patrons or spatially-varying sound absorption in a room.

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