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Studying Acoustical Characteristics of Occupied Restaurants

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Studying Acoustical Characteristics of Occupied Restaurants

by

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Studying Acoustical Characteristics of Occupied Restaurants

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Sound level data and occupancy data have been logged in five restaurants by the research team at the University of Nebraska – Lincoln. Sound levels and occupancy at 10 second intervals were documented over time periods of roughly two hours during active business hours. Noise levels were logged with dosimeters distributed throughout each restaurant, and occupancy was obtained from images recorded by infrared cameras. This work presents data on average sound levels and statistical metrics, such as L10 and L90 values as well as on each restaurant's Acoustical Capacity and Quality of Verbal Communication, as introduced by Rindel (2012). Acoustical Capacity is a metric describing the maximum number of persons for reasonable communication in a space, calculated from the unoccupied reverberation time and the volume of the space. Quality of Verbal Communication is a metric describing the ease with which persons in the space can communicate at a singular point in time, depending on the reverberation time, the volume of the space, and the number of occupants in the space. This work also aims to confirm the validity of Rindel's predictive model (2010).

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Chapter 1

Introduction

Restaurant noise is often cited as a nuisance by patrons. The noise affects patrons' ability to communicate with group members and serving staff. In Zagat's 2018 Dining Trends survey, noise was reported to be the most bothersome aspect of the experience by 24% of survey respondents, followed closely by poor service at 23%. For places often used as a primary social gathering point, the inability to carry a conversation is annoying and may cause patrons not to return to a restaurant.

1.1 Motivation

Researchers at the University of Nebraska-Lincoln aim to independently validate a predictive model developed by Jens Holger Rindel in his 2010 paper, and to study several other relatively new criteria related to acoustics of indoor spaces such as Acoustical Capacity and Quality of Verbal Communication (QVC). These criteria are attempts at simplifying acoustical data in an easy to use format. After much more validation, these metrics could be very helpful for engineers and architects designing the restaurant, as well as the owner marketing the restaurant. Seeing a restaurant with a QVC rating of "very good" could easily tip the scales over a restaurant with a "insufficient" or "very bad", especially for customers with any amount of hearing loss.

Currently, there are no guidelines or performance standards dealing with acoustics in restaurants specifically. In the recent decades, both the healthcare industry and K-12 education have developed guidelines for acoustical performance in their respective spaces, such as ANSI 12.60 for classrooms and ANSI 12.70 for speech privacy in healthcare. It is not hard to imagine many other industries including the restaurant industry developing their own voluntary guidelines within the next several decades.

1.2 Overview

This thesis covers the measurement and analysis of five Omaha-area restaurants. Impulse response and background noise level measurements were carried out before the restaurant opened for service on a regular day of operation. The sound levels were measured over a roughly 2-hour period using noise dosimeters and occupancy levels were recorded using IR cameras to preserve subject privacy. This data was analyzed using a variety of relevant criteria, including mean A-weighted equivalent noise level (LAeq), n-th percentile levels (Ln), quality of verbal communication (QVC) and acoustical capacity. The data was also compared to predicted levels calculated using Rindel's mathematical model.

Chapter 2

Literature Review

This chapter discusses previous work on restaurant acoustics done by a variety of authors in different fields. It begins with an overview of the phenomena that occur in restaurants, discusses research on the effects of restaurant sound fields on human perception, and presents a summary of previous predictive models proposed for restaurants.

2.1 Acoustical Phenomena

The effect responsible for the high ambient noise levels found so frequently in enclosed public spaces and restaurants in particular is the Lombard effect. The Lombard effect is the propensity for a speaker to raise their voice in a space to overcome the ambient noise, often impacted from other people in the space, leading to a feedback loop in which everyone raises their voices. The effect is named after a French doctor who first observed the effect as early as 1909 [Rindel, 2015].

Distinguishing between and understanding voices also becomes much more difficult at higher noise levels due to a lower signal-to-noise ratio (SNR). This effect is called the “cocktail party effect” and refers to the ability to segregate different stimuli and decide which ones to focus on [Rindel, 2015]. Focusing on a single string of stimuli is much easier when the SNR is high; however, when the stimuli is similar in level to the background noise or the stimuli begin

overlapping in pitch, the desired information is much more difficult to pick out. Additionally, the cocktail party effect is much more effective as a binaural effect due to 3D localization cues in the stimuli. The "cocktail party effect" name was first coined by Cherry in a study he performed focused on a listener's ability to distinguish between two conversations- a test later termed "dichotic listening" [1953].

2.2 Restaurant Sound Fields and their effects on Perception and Behavior

Several papers have been published in the past 25 years dedicated to measuring the acoustic environment of restaurants encompassing a wide variety of locations and restaurant types. A summary table is presented in To and Chung [2018]. These studies reported the noise levels of the venues and a few of them reported survey responses from customers; however, occupancy numbers were not commonly reported. In their summary, sound levels in restaurants range from 50 dB to 88 dB. The limitations of this aggregation however are the wide variety of types of spaces. Comparing measurements of semi-formal and formal restaurants to a food court does not always result in meaningful data. Measurements from two nightclubs were included as well. They had mean LAeqs of 91 dB and 97 dB; these measurements were excluded from the range presented above.

Recent papers from several researchers indicated there is an effect of the acoustic environment on taste and enjoyment of food. Yan and Dando found a correlation between acoustic environment and the stimulation of specific flavors, in this case a diminution of sweetness intensity and an augmentation of umami flavors [2015]. Their focus was on airline cabins

specifically; however, the conditions are applicable to similar loud venues. Alamir and Hansen conducted a similar investigation in which they had participants rate their liking of the food presented in three different noise conditions: relaxing music, road traffic noise, and restaurant noise [2020]. They found that the type of noise affected the liking of food, with both restaurant noise and traffic noise decreasing the liking compared to the background noise of the room, while the relaxing music increased it. In addition, increasing the volume of the noise also decreased the liking regardless of the noise type.

It is also important to consider the effects of the background noise level being too low. Patrons could become equally uncomfortable in an environment that is too quiet. Just like in offices and hospitals, speech privacy could become a concern if the levels are decreased too much.

While the acoustic effect on taste is important, the noise levels of a venue also have a direct effect on the willingness of patrons to spend money and time in a restaurant [Bottalico 2018]. Bottalico discovered that subjects began to be disturbed by noise at 52 dBA, and began raising their voices in accordance with the cocktail party effect at 57 dBA. Participants also became less likely to spend time and money at 52 dBA.

Battaglia reported that 0.5-0.7 sec. was the range for optimal reverberation times based on patron surveys [Battaglia 2014]. The patron surveys gathered subjective data in four categories, quietude, communication, privacy, and comfort. The comfort metric showed a high level of correlation with the reverberation time. A variety of other metrics were compared, such as the background noise level, however none had any significant correlation with patron comfort. The privacy scores also showed correlation with reverberation time, albeit less so than comfort.

2.3 Previous Work on Predictive Models

The research interest into data-driven models of restaurant noise is continuing to grow. One possible outcome criteria to use in models is subjective customer satisfaction. Having customers rate noise sources, as well as the quality of food, staff interactions, and other qualities of the restaurant can give researches data to use in creating statistical models of how satisfied a customer would be [To and Chung 2018].

Quality of Verbal Communication (QVC) is a labeling system characterized by the SNR at a distance of one meter from a talker in the space [Rindel 2012, Lazarus 1986]. The SNR as defined can be calculated by subtracting the ambient noise in the room from the direct sound from the talker. The level of the talker is assumed to be 55 dB above a background noise level of 45 dB, and is extrapolated using a slope of 0.5 dB/dB. This slope is known as the Lombard slope and was predicted and verified experimentally by Rindel. The SNR of the space is directly related to the unoccupied reverberation time, the volume, absorption area, and number of occupants. This metric changes based on the number of occupants in a space, so the QVC of a restaurant at full capacity is likely to be drastically less than a restaurant with only a few occupants. QVC designates a category based on the SNR, as shown in Table 2.1.

Quality of Verbal Communication	SNR Lower Limit (dB)	SNR Upper Limit (dB)
Very Good	>9	
Good	3	9
Satisfactory	0	3
Sufficient	-3	0
Insufficient	-9	-3
Very Bad		<-9

Table 2.1 QVC Categories as suggested by Lazarus [1986]

The SNR can be calculated by Equation 2.2 where A is the equivalent absorption area (in m^2) of the room, g is the group size factor, and N is the total number of occupants. The group size factor will be different for every space and event, but good compatibility between the data and model can be achieved by adjusting the value. The group size factor can be estimated to be the average number of people at a table or booth in the restaurant. There are a number of factors that could modify this estimate, such as a single large group. Large groups often have more than one person speaking at a time. It is also possible that no members of a group are talking at a specific moment. During the meal itself, patrons will be eating, lowering the possible number of talkers.

$$SNR_{1m} = -14 + 10log\left(\frac{A * g}{N}\right) \qquad (2.1)$$

Due to the nature of the logarithmic relationship, doubling the number of people in the space will lower the SNR by 3 dB.

QVC can be also presented as a function of the unoccupied RT and the volume per person of a space, as shown below.

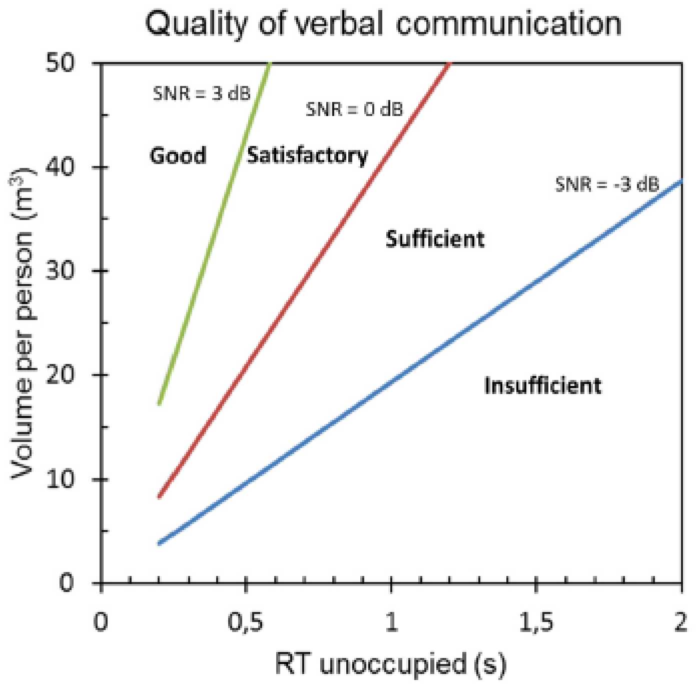

Figure 2.1 QVC as a function of unoccupied RT and volume per person [Rindel 2015]

Acoustic capacity N_{max} is a metric designed to indicated the maximum number of people in a room to allow a sufficient level of verbal communication [Rindel 2015]. The equation Rindel suggests to calculate acoustic capacity is:

$$N_{max} \cong \frac{V}{20 * T} \tag{2.2}$$

where V is the volume (in m^3) of the space, and T is the reverberation time (in seconds). This equation is the result of simplifying an equation to predict the ambient noise of a space combined with the assumption that sufficient QVC requires an ambient noise level of 71 dB or less [Lazarus 1986].

Acoustical capacity could be used both in the design phase for building a new restaurant, but it could also be used as part of the operation guidelines. Self-limiting the number of guests in the

restaurant would increase the level of verbal communication, and would likely decrease the noise complaints.

Leccese et al. used the same N_{max} metric along with physical characteristics of the space to model the useful and excess noise in a dining room with an emphasis on ensuring speech intelligibility [2015]. The analytical model they developed indicated levels within 1 dB of the field measurements, indicating a good initial estimate of the acoustic environment. The researchers suggest that their model would be helpful in initial design phases for acoustically sensitive venues.

Rindel developed a mathematical model in his 2010 paper that can be used to calculate the noise levels in a space based on a number of the same variables as the previous equations. His model can be expressed as the following equation:

$$L_{N,A} = 93 - 20log\left(\frac{A*g}{N}\right) \tag{2.3}$$

Where A is absorption area of the room (in m^2), g is the group size factor, and N is the total number of people in the space. As with the equation for QVC, the group size factor is generally an unknown, but good compatibility of the model and data can be achieved with an estimated guess and careful adjustment.

Rindel proposed this model for use on banquet halls and other large venues; however, the model could be applied to any indoor space in which guests gather and communicate verbally, such as a museum or a mall.

2.4 Summary

Restaurant acoustics is a growing field of interest. A variety of new acoustical metrics have been developed to help investigators objectively assess restaurants. In addition, efforts have been made to create mathematical models to predict the acoustics of a restaurant before designs are completed. All of this work, along with the work presented in this thesis will help designers, architects, and engineers in the future to create better acoustical environments for restaurants and their patrons. However, more validation of these models is needed.

Chapter 3

Methodology

This chapter describes the procedures for identifying restaurants, making measurements, and analyzing data, utilized for this thesis.

3.1 Identification of Restaurant Partners

Restaurant partners local to the Omaha area were recruited through several means. Some were visited in person, while others were contacted by email or phone. The Omaha Chamber of Commerce website was used extensively to contact local restaurants. By March 2020, 17 restaurants had agreed to participate in the study, although only five were able to be tested before the COVID-19 pandemic.

The research team submitted a proposal to the University of Nebraska Institutional Review Board (IRB). The IRB determined that because the restaurant patrons’ identifying data would not be collected, this project was not considered human subject research. Because of this, the team did not need to collect permission from any patrons. The research team presented this information, along with a description of the measurement processes in a flyer that was sent to the restaurant managers upon first contact.

3.2 Measurement Procedures

The first part of a measurement was unoccupied measurements. The team would go to the restaurant during a time when the restaurant was not open to customers to document dimensions of the space, surface materials, furniture layout and seating arrangements, and to identify potential noise sources. Background noise levels and impulse response (IR) measurements were also taken. A Larson Davis Model 831 Type I Sound Level Meter was used to measure the background noise level over a duration of one minute. From this measurement, the A-weighted equivalent sound level (LAeq) was the primary metric of interest. Other potential noise sources, such as background music, kitchen noise, or talking, were quieted during the measurement.

The IR measurements were conducted in one of two ways, using either balloon pop measurements or a swept sine method. In the first threee of the five restaurants measured, the balloon pop method was used while the swept sine was used in the latter ones.

The balloon pop method was used during the first phase. Balloons were 15 in. in diameter and three balloons were popped at each source location around the restaurant. The pops were recorded and analyzed using the software included on a BSWA sound level meter.

During the second phase, the team used EASERA software to run the IR measurements using the equipment setup shown in Figure 3.2.1. A laptop was connected to an RME Babyface Audio Interface via USB which managed the lines in and out. The line out was connected to Larson Davis BAS001 Omnidirectional source and a Larson Davis BAS002 Amplifier, while the line in was attached to a Larson Davis Model 831 Sound Level Meter.

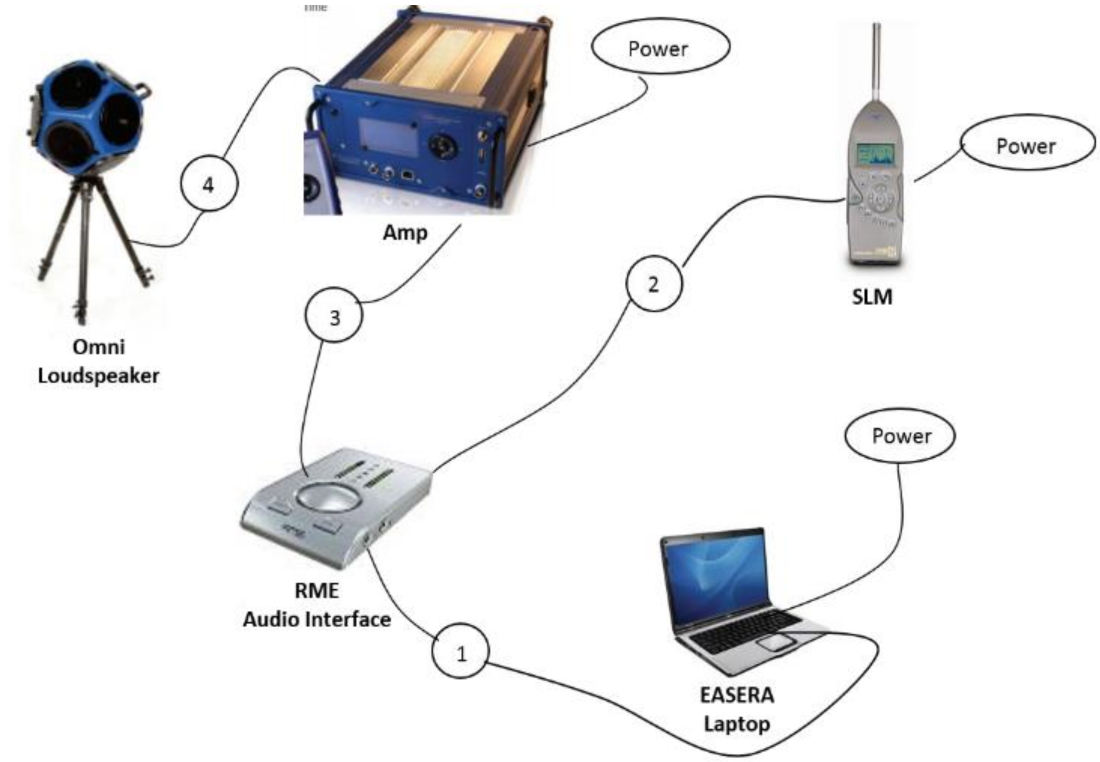

Figure 3.1 Impulse Response Measurement Diagram from the UNL IR measurement instruction packet

Sine sweeps with a pink noise frequency weighting were used to measure the impulse responses. The sine sweeps were set to 5.9 sec. and 8 sweeps were conducted and averaged. 5.9 sec. sweeps were used because they were longer than the expected decay values. EASERA then processed the results to obtain the IR of the space, and the software was used to determine the T20 from the impulse response.

Typically, later in the same day, the team would set up the occupied measurement testing equipment. This portion of the testing involved setting up between three and ten Casella dBadge2 dosimeters around the space depending on the layout, as well as a BSWA Type 2 Sound level meter to obtain octave band data. These were placed in such a way as to obtain sample readings across as much of the restaurant's sound field as possible. The dosimeters were

attached using a combination of the clips and gaff tape. Typical examples include being clipped to a chandelier or taped to a wall. These dosimeters were sometimes placed directly against reflective surfaces, which could alter the measurement by up to 3 dB. The dosimeters were time synced before being activated and set to record a measurement every second. To protect subject privacy, no sound files were recorded in the restaurants.

The team also set up infrared video cameras in the space to allow researchers to count the number of occupants in an unidentifiable way, thereby protecting privacy. FLIR camera attachments for mobile phones were first used for the first three restaurants, before transitioning to Seek Thermal Cameras. The FLIR devices were capable of recording for up to 2 hours due to battery life issues. The Seek Thermal Cameras were theoretically able to record for longer, however due to other unresolved technical limitations, the measurement runs were still kept at around 2 hours. The goal was to leave the camera recording for a block of time when the restaurant experienced both busy and not busy periods of time. The cameras were placed in the space to capture views of the entirety of the space. At the end of the measurement period, the team would retrieve the equipment and return to the lab for further data processing.

3.3 Data Processing

To process the impulse response measurements, the octave band T20 data from EASERA were copied into Microsoft Excel sheets along with the background noise level measurements from the Larson Davis 831 SLM. The 10-second LAeq data from the dosimeters was also exported to individual excel sheets and compiled into a single sheet. With this data it was important to line up the time codes between each of the dosimeters.

The thermal imaging video files were exported to the computer and the researchers used 10-second fast forward and rewind functions to count manually the number of occupants at each point in time, as well as an estimated average group size in the space. Figure 3.3.1 shows a sample thermal image from one of the restaurants. The data were compiled into the same excel spreadsheet as the dosimeter data.

Figure 3.2 An Example Image from an IR Video

A script written in R was then used to read the data from the spreadsheets and to output usable graphs and other metrics for analyses. Packages used prominently in the R script include “ggplot2”, “dplyr”, and “lubridate”.

Chapter 4

Analysis

This chapter presents the results and analysis of the data collected from the five restaurants. First the processing methods are discussed, followed by the output of the various metrics. While not all of the collected data from every restaurant is discussed in this section, everything is presented in Appendix A.

4.1 Initial Processing

The research team conducted measurements in five Omaha-area restaurants, all with a capacity of between 50 and 100 people. The restaurants had volumes ranging from 180 m^3 to 800 m^3. The mean group size was estimated by researchers while analyzing the IR videos. The physical characteristics are summarized in Table 4.1. Restaurant floorplans and dosimeter location maps are located in Appendix A.

Restaurant	Volume (m^3)	Room Shape	Capacity	Mean Group Size	Seating Type	T20 (sec)	Number of Dosimeters
Restaurant 1	780	Quadrilateral	100	2.5	Tables and Booths	1.84	3
Restaurant 2	230	Quadrilateral	50	2	Tables and Booths	1.00	5
Restaurant 3	800	Quadrilateral	75	1.5	Tables and Booths	1.20	3
Restaurant 4	700	Quadrilateral	60	3	Tables	1.24	4
Restaurant 5	180	Quadrilateral	50	4	Tables	1.41	7

Table 4.1 Chart Summarizing physical characteristics of participating restaurants and relevant measurement details

The raw data was downloaded from the various instruments as discussed in the last chapter and compiled into Microsoft Excel spreadsheets. The spreadsheets were used to calculate a variety of values and were also read by a script written in R to create graphs to assist with data visualization.

4.2 Room A-weighted Equivalent Sound Levels

The mean A-weighted equivalent level (LAeq) of the room was determined by taking an energy average of the dosimeter readings logged every 10 seconds. The measurements ranged from 63 dBA at the lowest to 77 dBA at the highest, and are summarized in Figure 4.2. Additionally, the standard deviation of the logged sound pressure levels was calculated and is displayed as well.

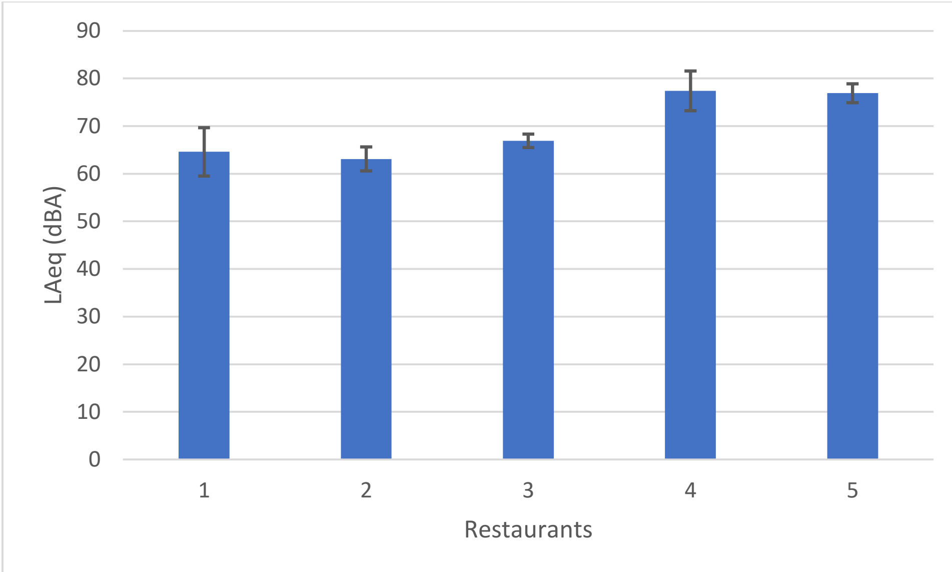

Figure 4.1 Chart showing average noise levels and standard deviations measured in the five restaurants

Restaurant 4 has the highest noise levels, closely followed by restaurant 5. Both of these restaurants had relatively low capacities of 50 and 60 respectively; however, Restaurant 4 had a volume of 700 m^3 and Restaurant 5 was much smaller having a volume of only 180 m^3. Their reverberation times were both in excess of 1.2 seconds, two of the highest reverberation times measured.

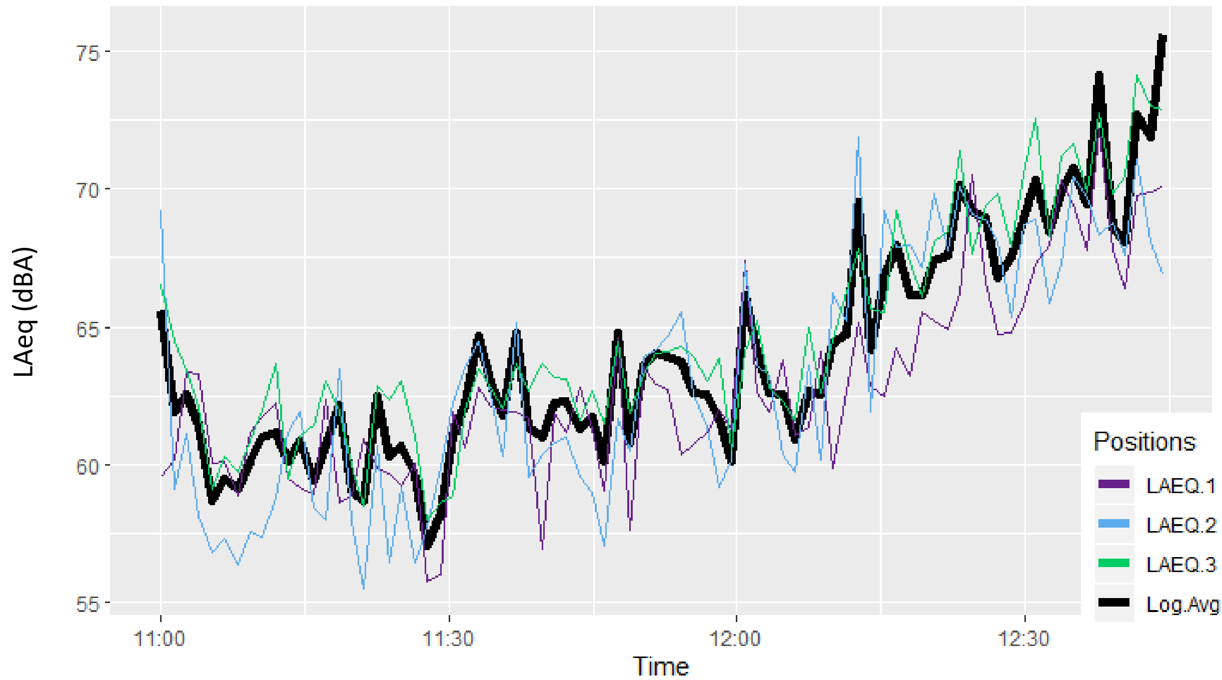

Figure 4.2 Noise levels from individual dosimeters and the average in Restaurant 1

4.3 Percentile levels

The percentile levels tell a similar story as the average LAeq, but they show a clearer picture in regards to the extreme values on either end of the spectrum. Percentile levels are presented as Ln where n is a number between one and one hundred and indicates the sound level exceeded n percent of the time. For example, L10 indicates the sound level exceeded 10 percent of the time. L10, L50, and L90 are the most common percentile measurements used to summarize a space, and are presented in Figure 4.4. The dosimeter data was compiled into a comprehensive spreadsheet for each restaurant and the function “PERCENTILE.EXC” in Excel was used to find the n-th percentile level.

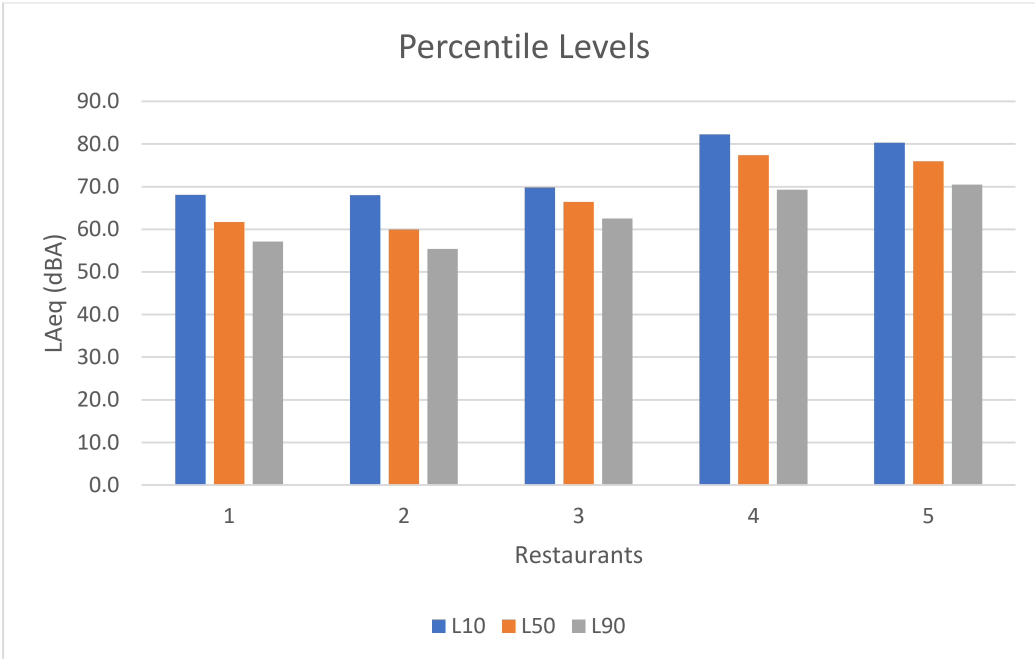

Figure 4.3 Percentile Levels for L10, L50, and L90 for each of the five restaurants

	L10	L50	L90	L10-L90
Restaurant 1	68.1	61.7	57.10	11.00
Restaurant 2	68	60	55.40	12.60
Restaurant 3	69.8	66.4	62.50	7.30
Restaurant 4	82.3	77.4	69.30	13.00
Restaurant 5	80.3	76	70.5	9.80

Table 4.2 Percentile Levels and L10-L90 spread

Like the mean LAeq, Restaurants 4 and 5 exhibit higher values for L50, which behaves similarly to the mean LAeq. Additionally, the spread between the L10 and L90 is larger for Restaurant 4 than for Restaurant 5, demonstrating the correlation with the standard deviation. The L10-L90

spread is detailed in Table 4.2. Restaurants 1 and 2 had nearly identical L10 values, sitting at 68 dBA, while the L50 and L90 values were 1.7 dBA higher for both metrics in Restaurant 1. This seems to indicate a much more consistent environment in Restaurant 1 vs Restaurant 2. Restaurant 3 appears to have an even more consistent environment than Restaurant 1 according to this metric. The spread between L10 and L90 for Restaurant 3 is only 7.3 dB, as shown in Table 4.1. This means that for 80% of the time that the restaurant was open and being monitored, the space was between L90 of 62.5 dBA and L10 of 69.8 dBA.

It is also possible to plot the Percentile Levels as a continuous threshold, resulting in an Occurrence Rate plot, as shown in Figure 4.4. Metrics based on this method of calculation are not in common use currently; however, the graph could be a useful tool to compare multiple spaces. Additionally, creating a criterion to specify what percentage of the time a space is above n-th level would also be useful in classification. Bottalico reported that patrons began raising their voices in accordance with the cocktail party effect at 57 dBA, so specifying what percentage of the time a restaurant is above that value would be useful not only for research, but for patrons of the restaurant as well [2018]. Only Restaurant 2 was below the 57 dBA threshold for more than 10% of the time. Other restaurants had periods below the 57 dBA threshold, however the total added up to less than 10% of the total time period measured. Using 57 dBA as the threshold could create a cluster of values that would be unhelpful for comparison. Alternatively, a larger value could be chosen such as 70 dBA.

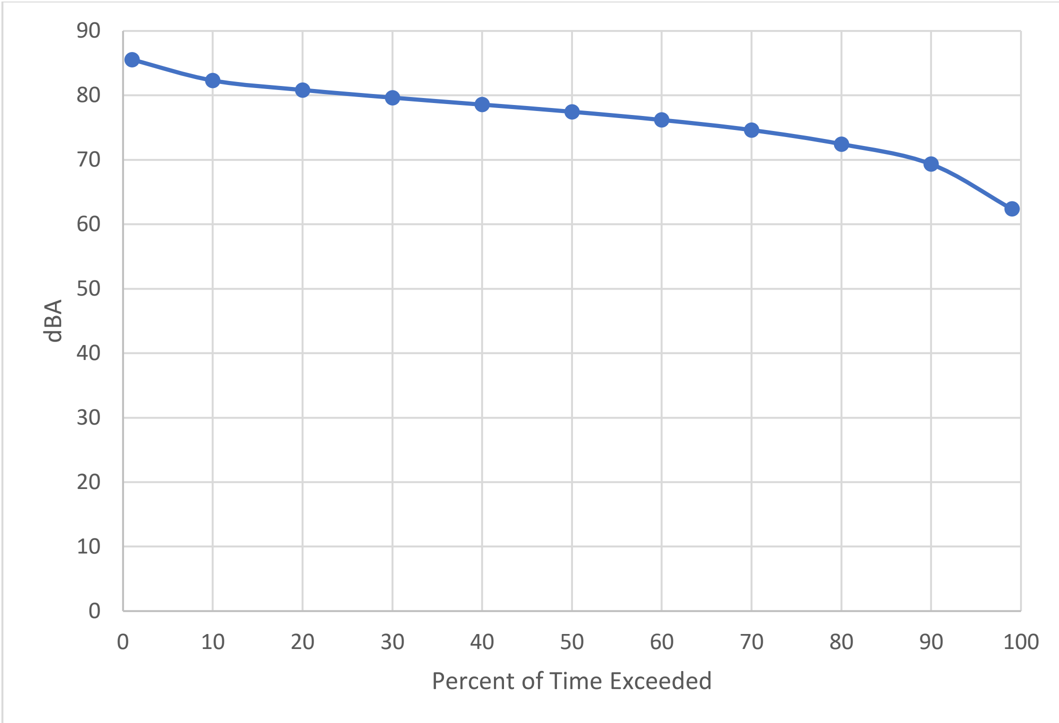

Figure 4.4 Occurrence rate plot for Restaurant 4

4.4 Occupancy and Measured Sound Level

Plots were created to compare the measured sound levels to the number of occupants across time. It is clear that as the number of occupants increases, the sound level tends to increase as well. Figures 4.5 and 4.6 plot examples of this trend, showing an upward trend in sound levels as the number of occupants increased. The data was normalized using the standard procedure of subtracting the overall average from each data point and dividing by the standard deviation.

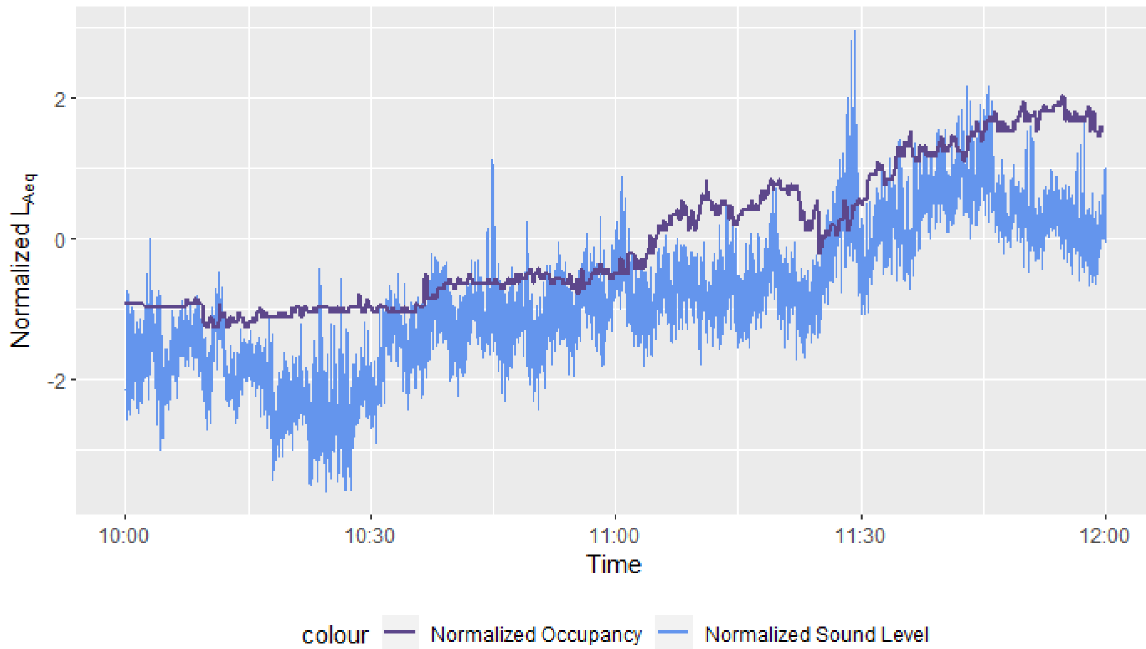

Figure 4.5 Normalized sound level in Restaurant 4 compared to the normalized number of occupants

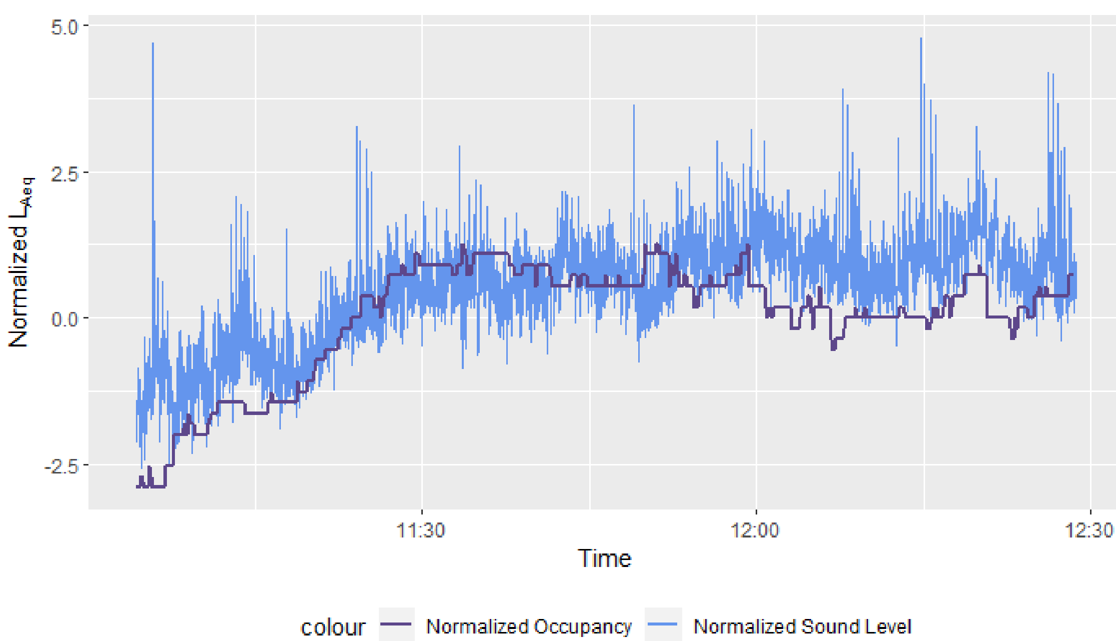

Figure 4.6 Normalized sound level in Restaurant 5 compared to the normalized number of occupants

For all of the restaurants, there are obvious peaks in the data. These events most likely correspond to a door slamming or a burst of kitchen noise. The noise of the customers tended to stay consistent over longer periods of time. There are cases in which this might not be true, however. For example, during a televised sporting event, a crowd watching the television might cheer all at once, creating an event that cannot be explained by occupancy.

Another interesting observation about Restaurant 4 is that the sound level data appears cyclical. While the overall change is roughly one standard deviation, that only equates to 4.2 dB, an amount barely perceptible to humans, especially over the several minutes that the cycles take. These cycles did not appear in the data of any other restaurants so there is no solid hypothesis, but one possible theory is that it could be due to cycling mechanical equipment in the restaurant.

4.5 Measured and Predicted Sound Levels

Rindel presented a mathematical model to predict sound level based on occupancy in his 2010 paper, previously discussed as Equation 2.3 in Chapter 2. The expected level $L_{N,A}$ at a particular point in time is based on the number of occupants in a space. A is absorption area of the room (in m^2), g is the group size factor, and N is the total number of people in the space. The absorption area of the room was calculated using a modified Sabine equation to include the contribution of a variable number of occupants.

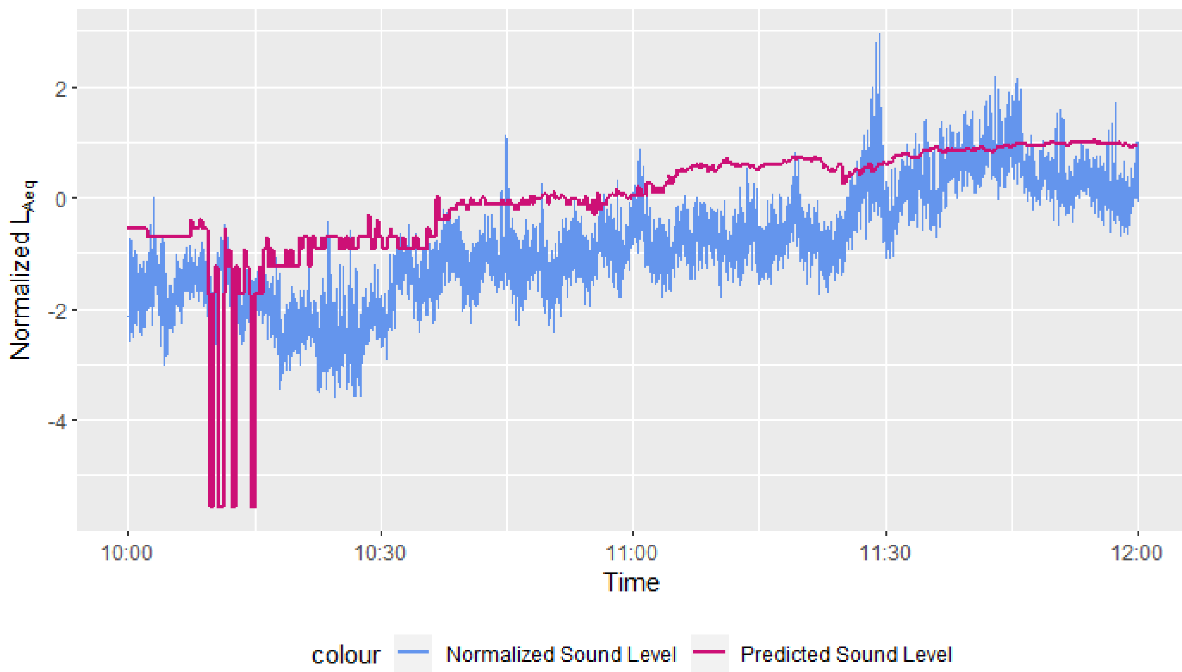

Figure 4.7 Normalized measured sound level compared to normalized predicted sound level of Restaurant 4

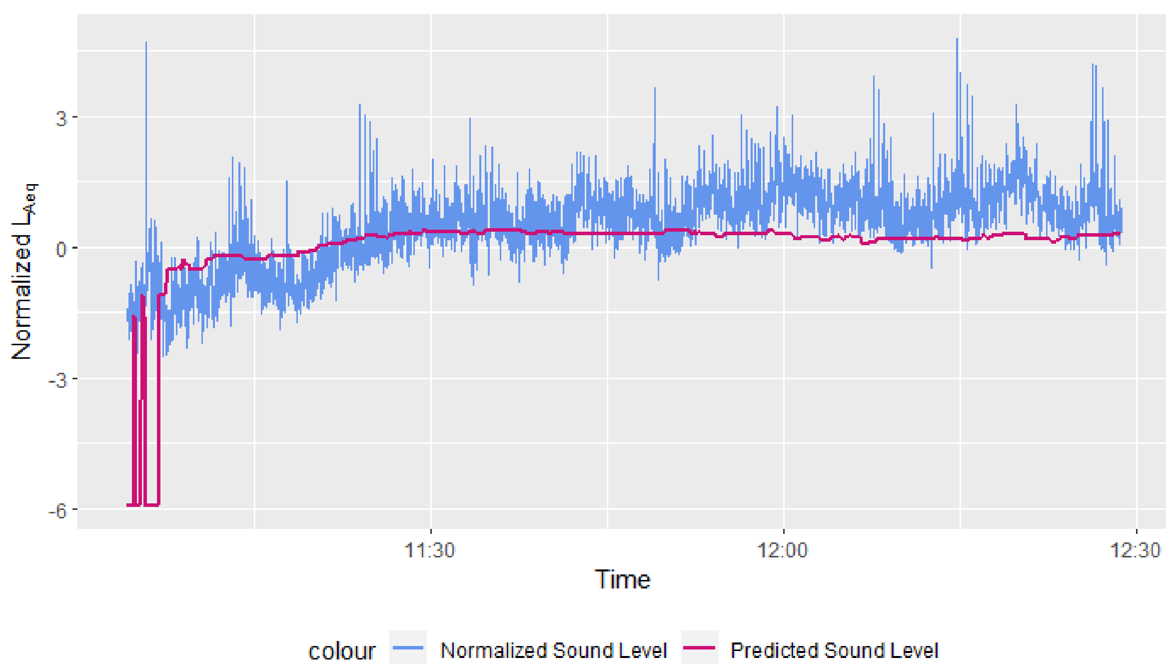

Figure 4.8 Normalized measured sound level compared to normalized predicted sound level of Restaurant 5

As seen from Figures 4.7 and 4.8, the equation appears to track with the measured data. Rindel specifically notes that the model is more suited towards large spaces with larger numbers of people. The model also does not handle having zero occupants well, given that it has to divide by zero. This mishandling can be seen in the beginning of both plots, where the predictive line drops off the bottom of the graph.

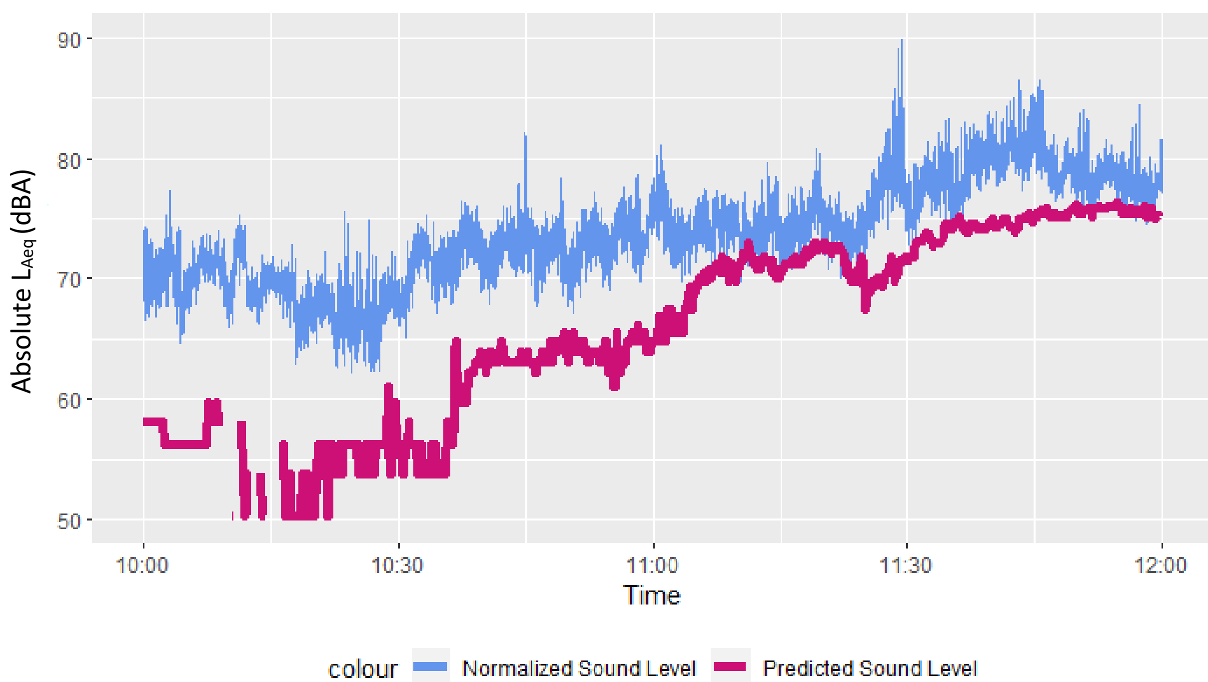

Figure 4.9 Absolute measured sound level compared to absolute predicted sound level of Restaurant 4

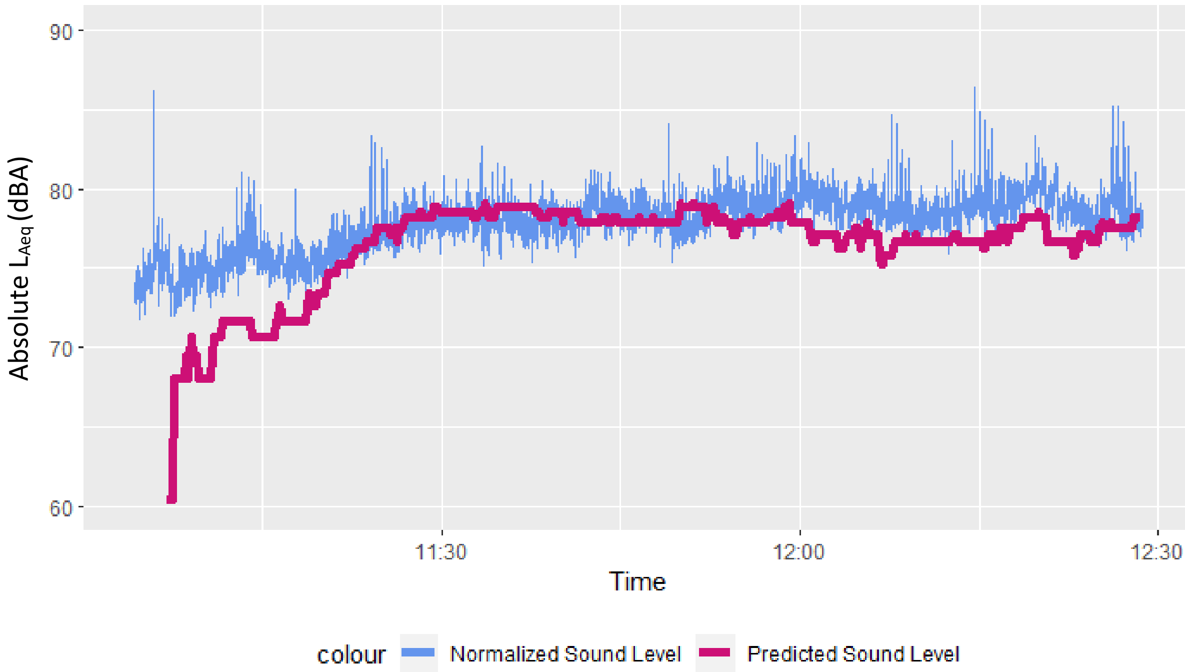

Figure 4.10 Absolute measured sound level compared to absolute predicted sound level of Restaurant 5

In Restaurant 4, the equation severely underestimates the noise levels in the restaurant, while in Restaurant 5 it does a much better job. In both examples however there are major drop-offs at the beginning of the measurement when there are few or no occupants in the space. The model does not account for the background noise levels of a space, and while they would not make a difference for predicting levels when there are large amounts of people, accounting for it would create a much more comprehensive model.

These misgivings aside, the model does a good job providing a rough estimate for the sound levels. Additionally, there are a few constants that could be tweaked to more accurately model the space, such as absorption per person and the group factor. For the sake of this study, the average absorption per person was set at 0.35 m^2, and the group factor was an estimate based on the thermal camera footage. Though this factor in actuality changed whenever a group entered

the space, the chosen value was held constant. Absorption per person ranges from 0.2 to 0.5 m^2, so the midpoint of the range was selected as an average value [Rindel 2015].

A chart of the average rms deviation of the predicted noise levels compared to the average of the measured levels depending on the group size factor is presented below as Table 4.3.

Group Size	2	3	4
Restaurant 1	9.09	11.09	12.91
Restaurant 2	7.41	5.19	4.7
Restaurant 3	15.6	12.1	9.62
Restaurant 4	11.68	8.34	6.09
Restaurant 5	18.51	15.01	12.53

Table 4.3 RMS deviation of the predicted model dependent on group size factor

In a perfect execution of the model, the deviations would be zero, indicating the prediction is identical to the measurements. The closer to zero the deviation, the more accurate the model is. The chart shows that for Restaurant 2, a group size estimate of 4 would be more accurate than the estimate of 2 used. It is important to consider the other variables in this instance however, because during analysis of Restaurant 2, researchers did not see a group any larger than two people.

This model is a tool that could be easily utilized to formulate estimates of sound levels during preliminary design talks with architects, or to quickly compare options for different materials in the space.

4.6 Acoustical Capacity

Acoustical capacity is another metric proposed by Rindel [2015]. This metric aims to define the maximum number of people in a space to preserve effective communication. Rindel notes that sufficient quality of verbal communication requires a background noise level of 71 dB or less. Previous discussion of this metric is present in Chapter 2. The important variables for this equation are the volume of the space and unoccupied reverberation time.

Acoustical Capacity	Number of People
Restaurant 1	21
Restaurant 2	12
Restaurant 3	33
Restaurant 4	28
Restaurant 5	6

Table 4.4 The recommended acoustical capacity for effective communication, as calculated by Equation 2.1 for the five measured restaurants

For the five measured restaurants, the acoustical capacity was less than half of the actual capacity, and in the case of Restaurant 5, the acoustical capacity was only 12% of the actual capacity of 50 people. The major factors contributing to this reduction is the lack of absorption in the space. If the reverberation time could be lowered, the acoustical capacity would increase.

4.7 Quality of Verbal Communication

The quality of verbal communication is closely related to acoustical capacity. It aims to describe the ease of interpersonal communication in a space based on unoccupied reverberation time, volume, absorption area, and the number of occupants. QVC was previously discussed in Chapter 2. The QVC is a qualitative label assigned based on the quantitative value of the vocal SNR at a distance of one meter assuming a talker level of 55 dB at that distance and a background level of 45 dB. The QVC of each restaurant at full capacity, half capacity, and one-quarter capacity were determined by plotting the reverberation time and volume per person on Figure 2.2. At full or half capacity, every restaurant rated as insufficient or very bad. At one-quarter capacity, only Restaurants 3 and 4 were rated as sufficient, the rest rating again as insufficient.

Using the characteristics of a space to determine what the QVC would be helpful when designing, but it is also possible to measure over time as the restaurant is operating. Graphs can be created by entering the occupancy and sound level data into the model, such as Figures 4.13, 4.14, 4.15, and 4.16.

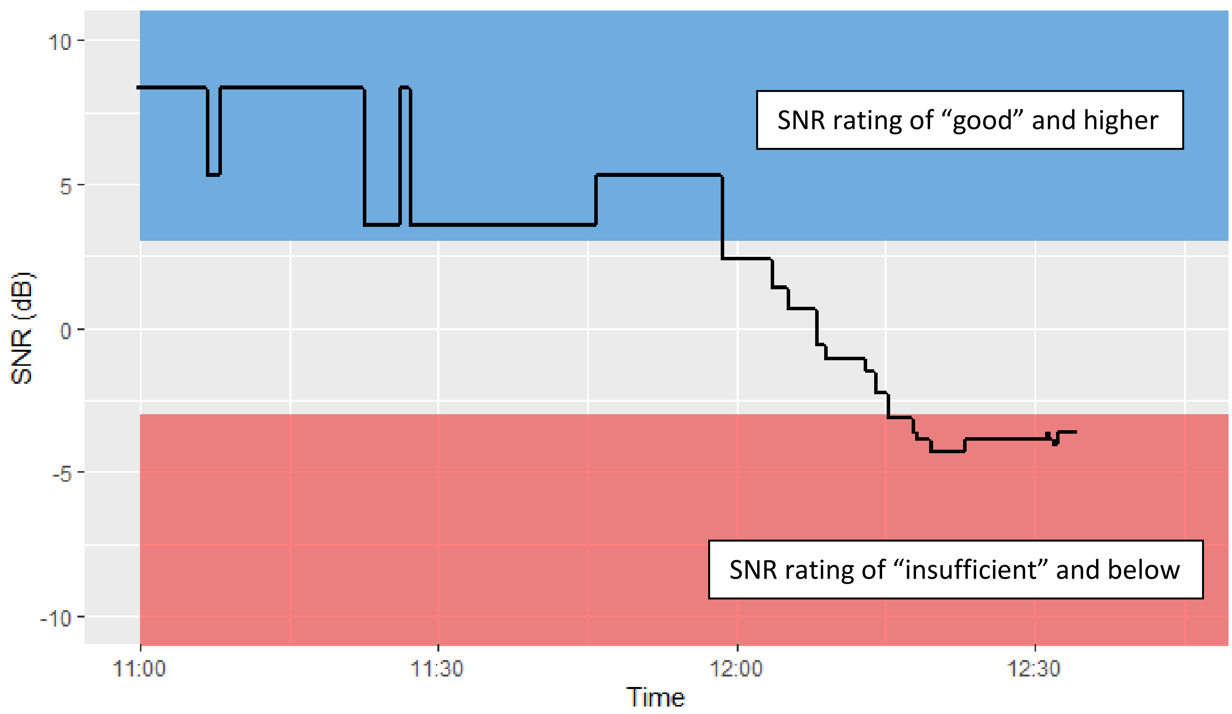

Figure 4.11 The Vocal SNR of Restaurant 1

Although the restaurants all did poorly when calculated at full capacity, Restaurant 1 performed fairly well during the beginning of its lunch hour. The restaurant was not particularly busy, and only had a BNL of 58.1 dBA, allowing the QVC to be good for the first hour of operation. After that, occupancy increased and slowly lowered the QVC to satisfactory and sufficient by 12:00 PM, and finally into the insufficient range by 12:15 PM. This trend is also seen in the graph of Restaurant 2. It starts out less busy, before becoming the busiest around 6:45 PM. The dinner rush then quickly dissipates and the QVC returns back up to satisfactory.

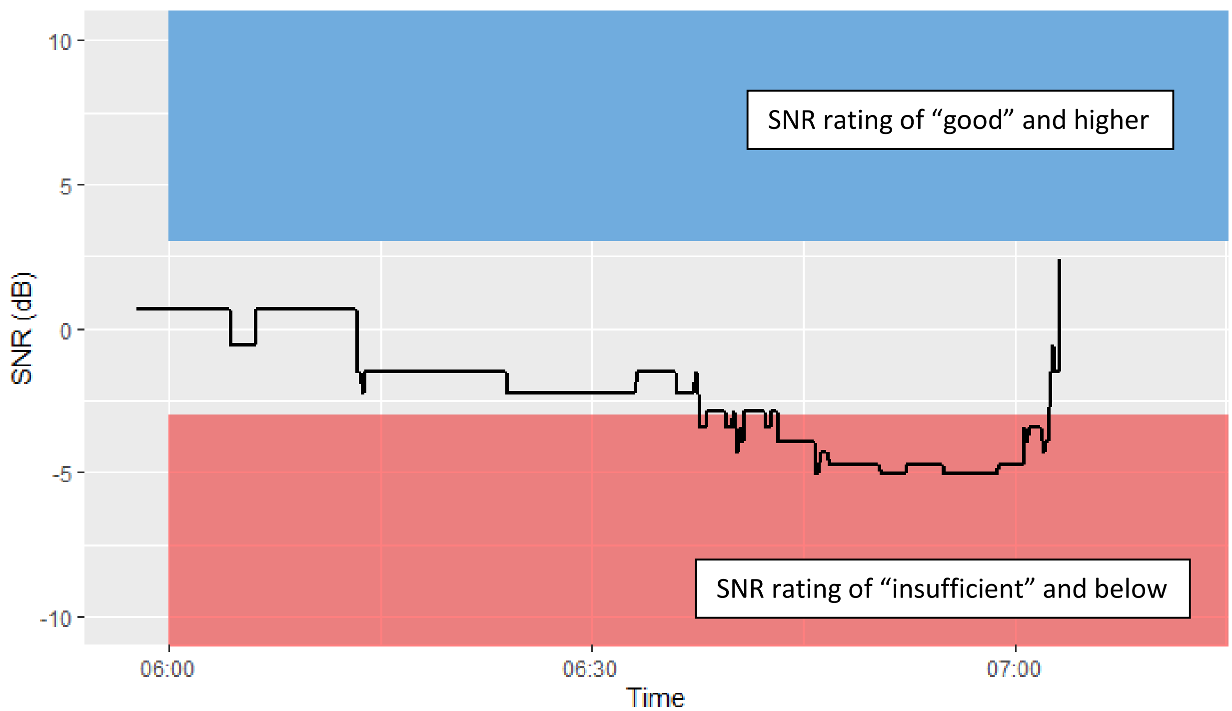

Figure 4.12 The Vocal SNR of Restaurant 2

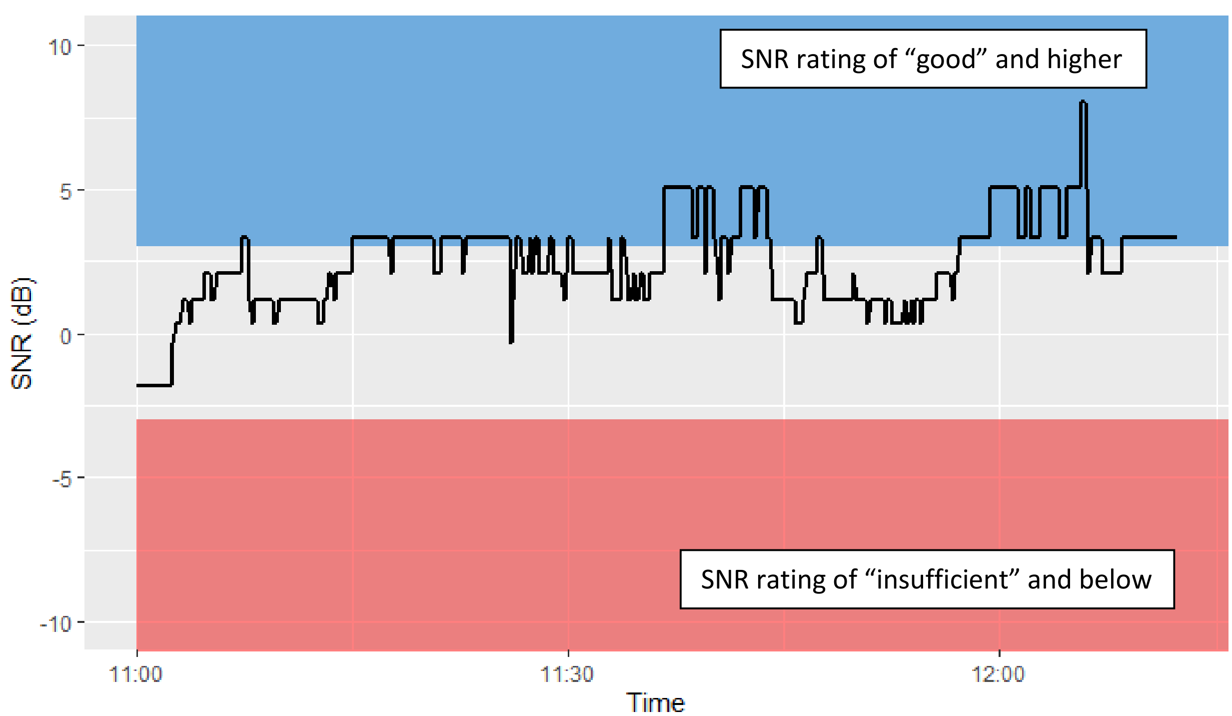

Figure 4.13 The Vocal SNR of Restaurant 3

Restaurants 1, 2, and 3 showed the most promise for the application of this metric. Restaurants 4 and 5 present fairly stagnant graphs. They hover between -5 dB and -10 dB and never change any meaningful amount. For Restaurant 4, the occupancy was very high for the entirety of the measurement period, making impossible for the sound levels to decrease any amount. Restaurant 5 wasn't nearly as busy as restaurant 4 during the measurement period, however the reverberation time of 1.41 seconds is very high, especially for a space of only 180 m^3, again preventing the Vocal SNR and by extension the QVC from being a reasonable value.

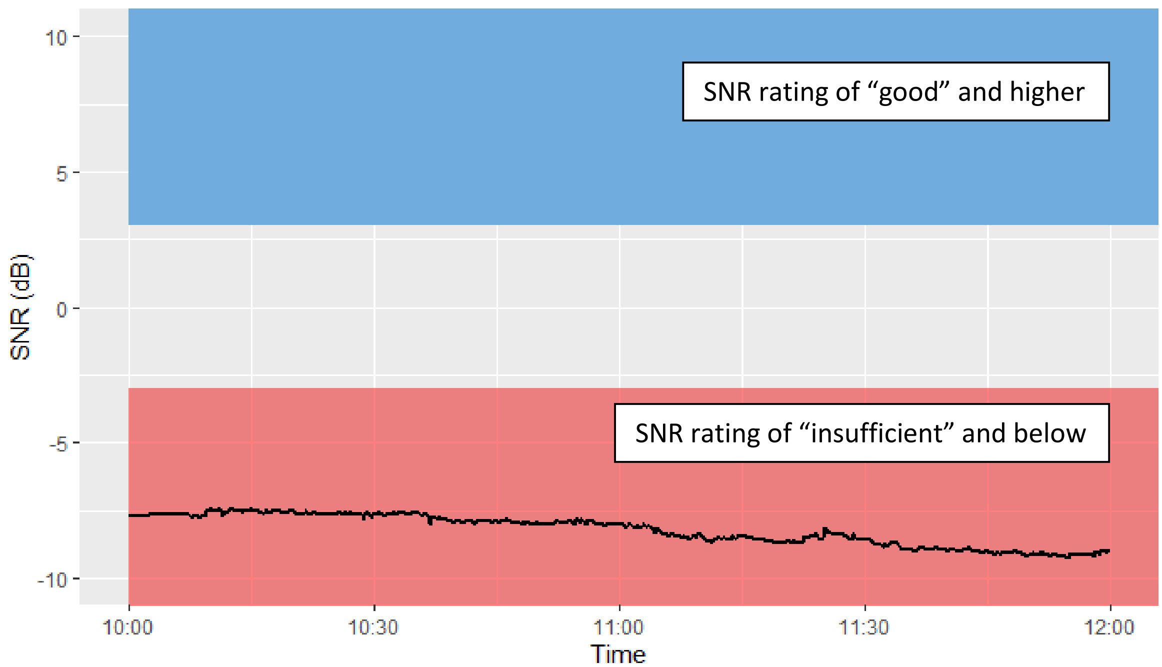

Figure 4.14 The Vocal SNR of Restaurant 4

4.8 Summary

Many acoustical metrics have been presented in this chapter, including mean LAeq, n-th percentile levels, QVC, and acoustical capacity. Additionally, occupancy was compared to

measured and predicted sound levels. Generally, the model performed well. It tracked well with the measured data, however it had issues with precisely predicting levels. It does not perform well in low occupancy situations. The low vocal SNR and QVC of the five restaurants is a direct result of exceeding the acoustical capacity of the space. This "acoustical overcrowding" is the cause of many noisy restaurants and the complaints that patrons lodge against them. QVC and acoustical capacity are useful tools to assist architects and engineers with designing restaurants and will help convey what needs to be done to a space when meeting with an owner or restaurant manager.

Chapter 5

Conclusion and Recommendations for Future Work

5.1 Conclusion

This thesis reported on measurements at five Omaha-area restaurants. The noise levels and occupancy were measured during operating hours, as well as reverberation time and background noise levels while the restaurants were closed. The results were then compared to the predicted levels from a model proposed by Rindel (2010). The data were also used to validate some proposed acoustical metrics called acoustical capacity and quality of verbal communication. Acoustical capacity is a property of a specific space that limits the number of patrons in a space to keep a sufficient level of verbal communication. All five of the restaurants tested had acoustical capacities much lower than their actual capacity. Acoustical capacity is closely related to quality of verbal communication. QVC assigns a category to a space based on the verbal SNR at a distance of one meter from the talker. This verbal SNR is affected by the reverberation time, volume, absorption area, and the number of occupants. This metric is designed to easily convey the difficulty of communication in a space.

The restaurants had mean LAeqs of between 63 dBA and 77 dBA and T20 reverberation times of between 1.00s and 1.84s. The unoccupied background noise levels due to mechanical systems and kitchen noise varied from 58 dBA to 64 dBA.

The modeled levels trended similarly to the measured levels; however, the model begins to perform poorly at low occupancy levels due to logarithms and the potential for dividing by zero. In its current state, the model is best suited for predicting levels in large spaces with large capacities where the noise levels are dominated by the occupants in the space. The accuracy of the model was also impacted by the estimate of group size for each restaurant. The rms deviations showed that some of the group size factor estimates were not quite accurate; however, a few of them also indicated much higher group sizes than actually occured, such as Restaurant 5. The average rms deviation indicated that group size should be closer to 7, however this contradicts the thermal footage that showed smaller sized groups. One possible explanation for this behavior is that there are large periods of time where no one in a group is speaking. Either way, the model gives a good general idea of the worst-case performance of a space.

None of the restaurants measured met any QVC targets when occupied by more than a few patrons. Patrons have a reasonable expectation to be able to communicate with other members of their group, and it is on restaurants to create environments to fulfill this need. The ways to increase the QVC of a space are to increase the amount of absorption area and to decrease the background noise level. Because QVC and acoustical capacity are closely linked, these methods also result in a much higher acoustical capacity of the space.

5.2 Future Work

First and foremost, future work on this topic should gather more data to understand the broad range of acoustic conditions in restaurants and continue to use these to validate proposed models for predicting sound levels in restaurants. Many restaurants have expressed interested in

participating due to the growing concerns of excess noise in restaurant environments. Sixteen additional restaurants in the Omaha area are willing to participate once the world returns to a pre-pandemic situation. Gathering data for longer periods of time in each restaurant would also help. Additionally, dosimeters would not be placed on reflective surfaces, or the reflective effects should be accounted for to reduce error. Ideally the entire day could be measured if the technical limitations regarding occupancy measurements could be worked out. Another helpful tool would be to use machine learning to estimate occupancy and group size from the thermal recordings. Metrics other than those based on time-logged LAeqs could also be evaluated, such as psychoacoustic metrics and peak and max values. Octave band data could be clustered using machine learning techniques such as k-means clustering and explored using other metrics.

A future study could also attempt to optimize the mathematical model to account for low occupancy situations. Adding the assumed background noise level to the predicted levels could be a way to help account for no occupant noise. More accurately predicting the group size factor for each restaurant would also help the model. In this study, the group size factor was treated as a constant value, consistent for a single restaurant over the entire course of the measurements; however, in practice this value is always changing. Determining the source of the background noise could also be informative. Whether the noise is mechanical noise or kitchen noise or something else makes a difference in which mitigation strategies are applied.

Another suggestion for future study is to validate the QVC predictions by obtaining subjective information on how patrons feel about the quality of verbal communication. Using surveys would be one possible way to see how patrons feel about certain environments. Depending on the demographics of the restaurant, surveys could be conducted in a variety of ways. Paper copies, google forms, and apps such as Soundprint or Hush City are all possible options.

Alternatively, the spaces could be recorded using 3D microphones. This recording could be reproduced by a speaker array in a sound booth and would allow researchers to accurately control the environment and to receive feedback from a single participant on multiple spaces.

Bibliography

Alamir, Mahmoud A., and Kristy Hansen. “The Effect of Type and Level of Background Noise on Food Liking: A Laboratory Non-Focused Listening Test.” *Applied Acoustics*, vol. 172, Jan. 2021, p. 107600. *DOI.org (Crossref)*, doi:10.1016/j.apacoust.2020.107600.

Andrews, Betsy. *New Research Is Causing Restaurant and Bar Owners to Rethink Noise Control in Their Venues*. p. 9.

Astolfi, A., and M. Filippi. *Good Acoustical Quality in Restaurants: A Compromise Between Speech Intelligibility and Privacy*. p. 4.

Battaglia, Paul L. *Achieving Acoustical Comfort in Restaurants*. 2015, p. 9.

Bottalico, Pasquale. “Lombard Effect, Ambient Noise, and Willingness to Spend Time and Money in a Restaurant.” *J. Acoust. Soc. Am.*, 2018, p. 7.

Culling, John F. “Speech Intelligibility in Virtual Restaurants.” *The Journal of the Acoustical Society of America*, vol. 140, no. 4, Oct. 2016, pp. 2418–26. *DOI.org (Crossref)*, doi:10.1121/1.4964401.

Lazarus, H. “Prediction of Verbal Communication in Noise- A Review: Part 1.” *Applied Acoustics*, vol. 19, no. 6, June 1985, pp. 439–64, doi:https://doi.org/10.1016/0003-682X(86)90039-3.

Lazarus, H. “Prediction of Verbal Communication in Noise- A Review: Part 2.” *Applied Acoustics*, vol. 20, no. 4, June 1985, pp. 245–61, doi:https://doi.org/10.1016/0003-682X(87)90062-4.

Leccese, Francesco. “An Analytical Model to Evaluate the Cocktail Party Effect in Restaurant Dining Rooms: A Case Study.” *Applied Acoustics*, 2015, p. 8.

Meng, Qi. “Effects of Typical Dining Styles on Conversation Behaviours and Acoustic Perception in Restaurants in China.” *Building and Environment*, 2017, p. 10.

Rindel, Jens Holger. *2 Restaurant Acoustics – the Science behind Verbal 3 Communication in Eating Establishments*. 2017, p. 17.

Rindel, Jens Holger. *Acoustical Capacity as a Means of Noise Control in Eating Establishments*. p. 8.

Rindel, Jens Holger. *Noise Problems in Restaurants*. 2012, p. 6.

Rindel, Jens Holger. *Restaurant Acoustics – Verbal Communication in Eating Establishments*. no. 1, 2019, p. 14.

Rindel, Jens Holger. *The Acoustics of Places for Social Gatherings*. 2015, p. 8.

To, W. M., and A. Chung. *Describing Sonic Environment of Chinese Restaurants Using a Mathematical Model*. 2018, p. 10.

Woods, A. T., et al. “Effect of Background Noise on Food Perception.” *Food Quality and Preference*, vol. 22, no. 1, Jan. 2011, pp. 42–47. *DOI.org (Crossref)*, doi:10.1016/j.foodqual.2010.07.003.

Yan, Kimberly S., and Robin Dando. *A Crossmodal Role for Audition in Taste Perception*. p. 9.

Appendix A

A.1 Restaurant Layout Drawings

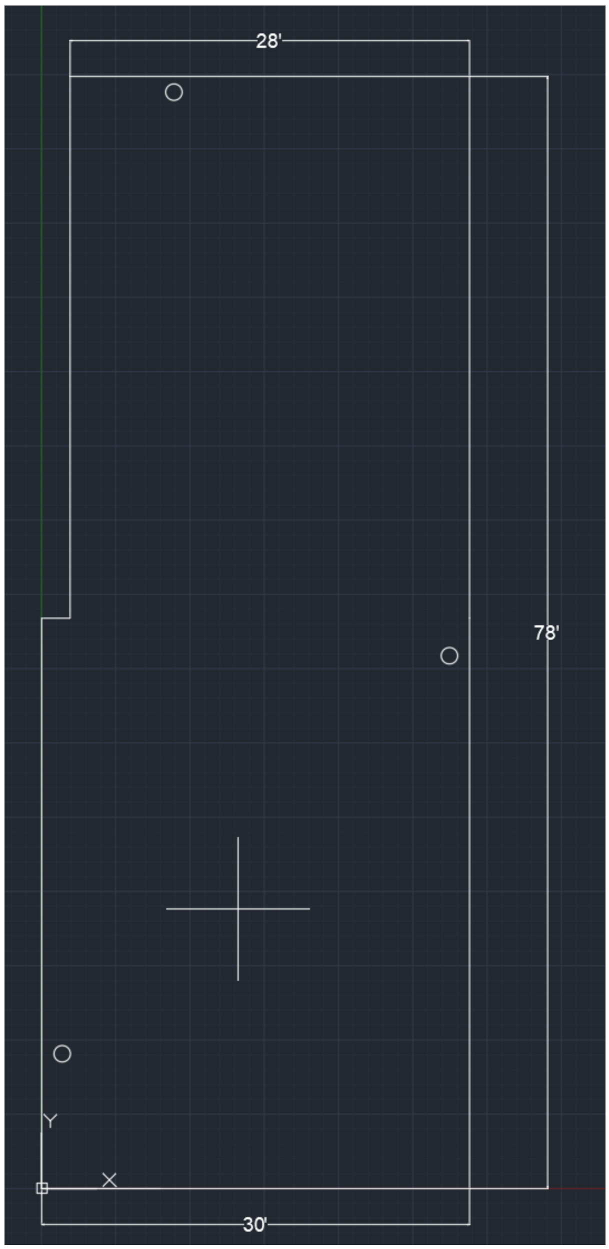

Figure A.1 Layout of Restaurant 1 with Dosimeter locations marked with circles

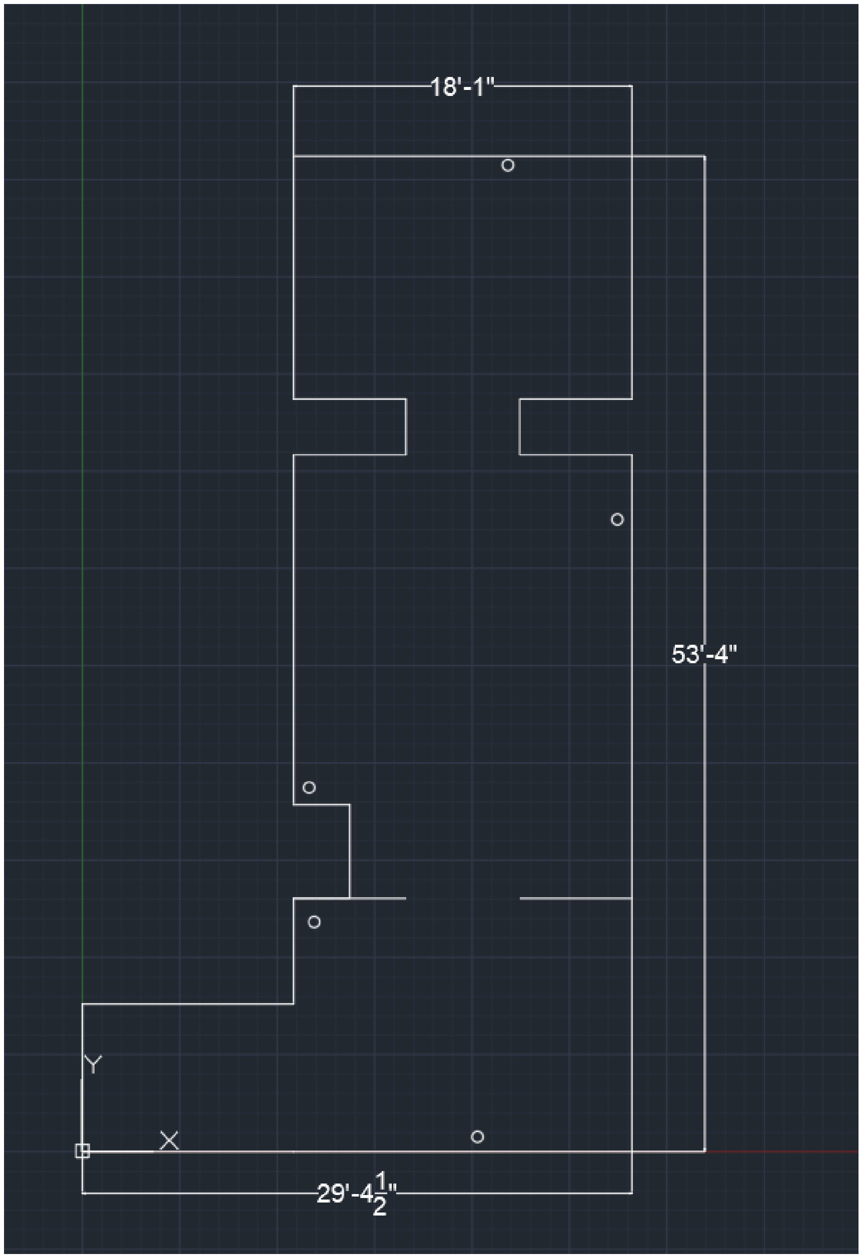

Figure A.2 Layout of Restaurant 2 with Dosimeter locations marked with circles

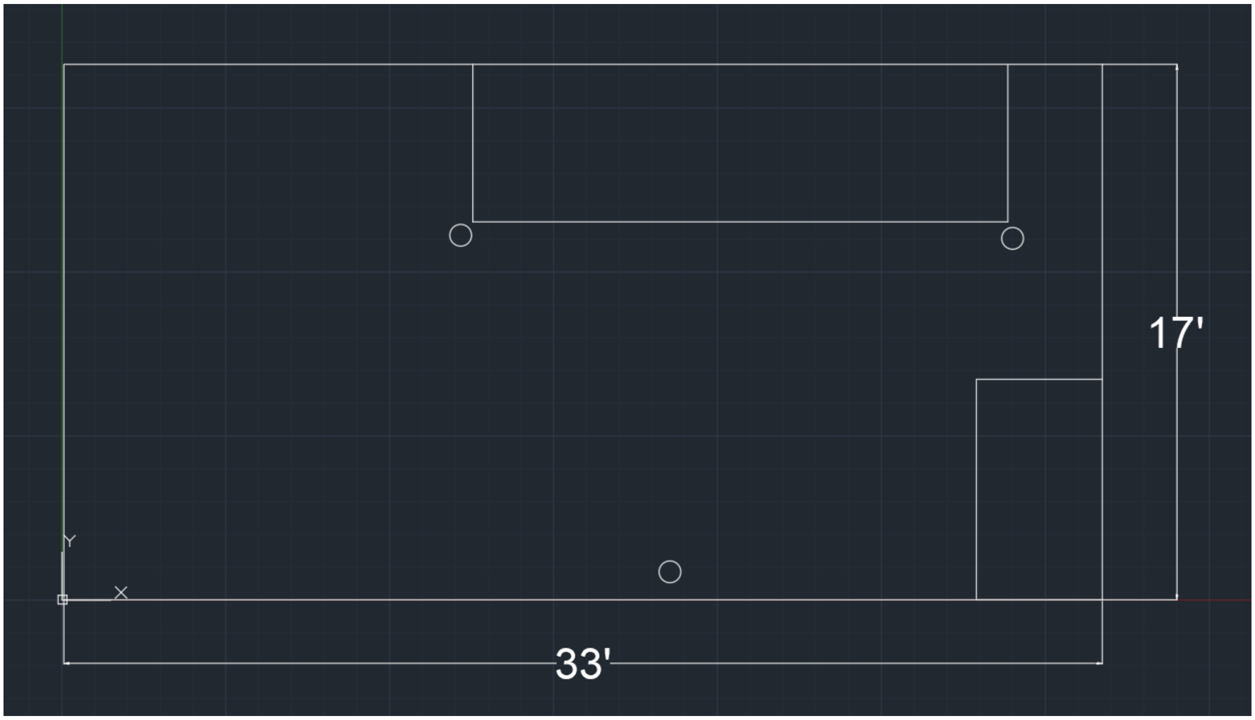

Figure A.3 Layout of Restaurant 3 with Dosimeter locations marked with circles

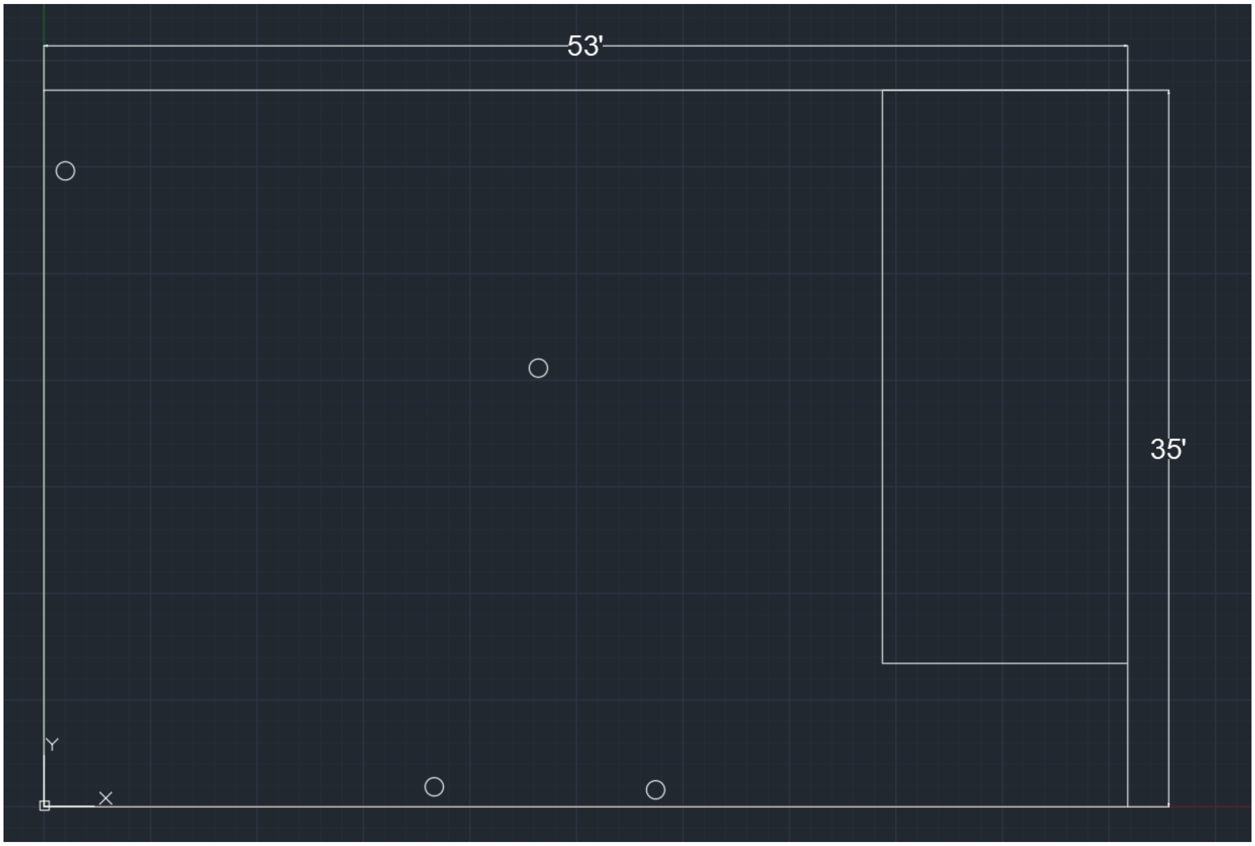

Figure A.4 Layout of Restaurant 4 with Dosimeter locations marked with circles

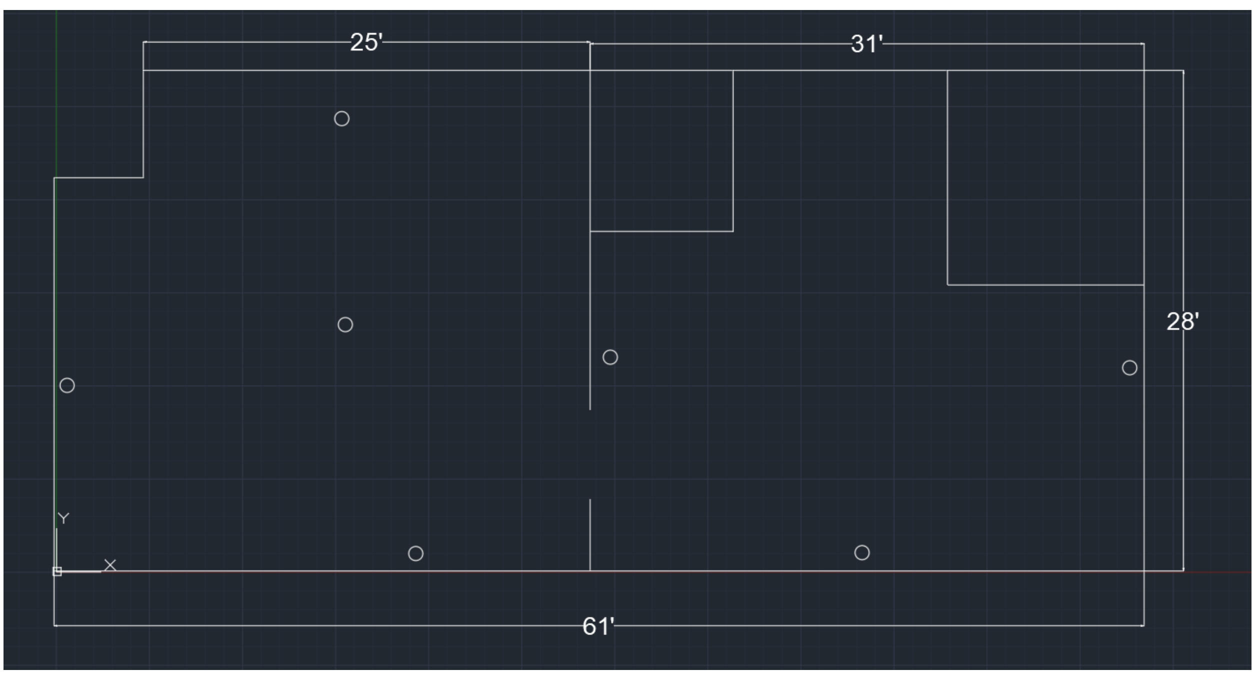

Figure A.5 Layout of Restaurant 5 with Dosimeter locations marked with circles

A.2 Noise Levels

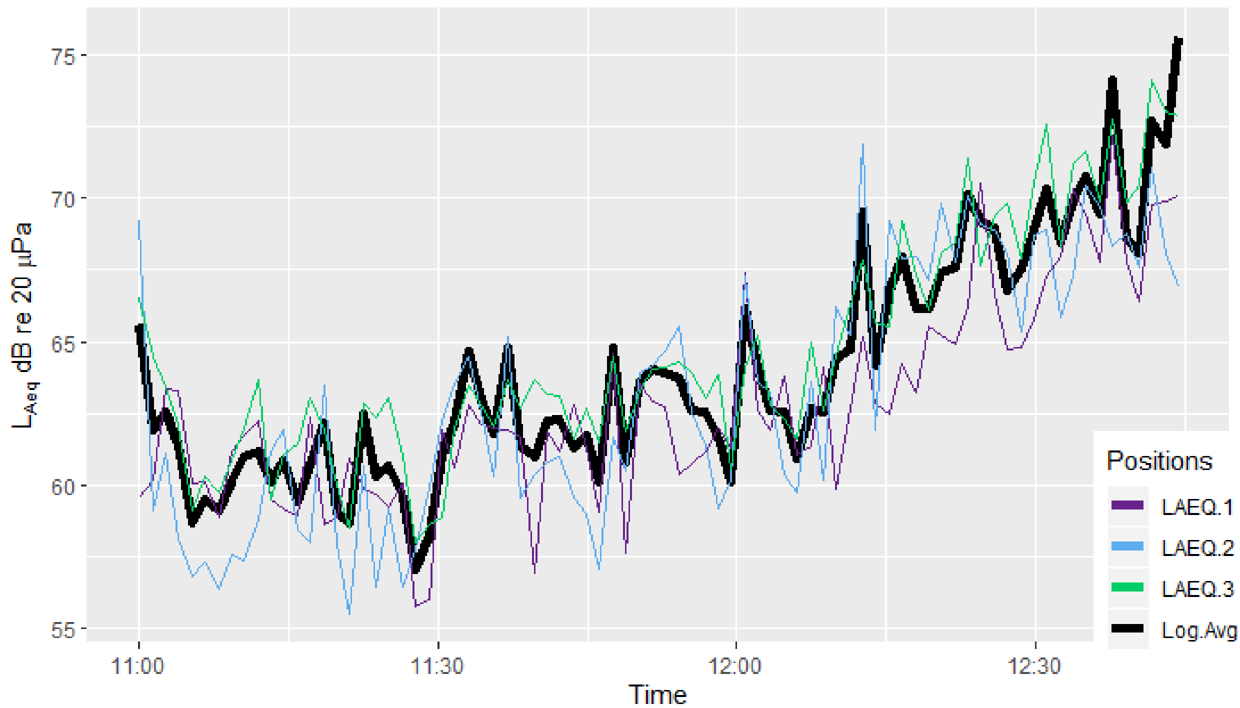

Figure A.6 Noise Levels of Restaurant 1

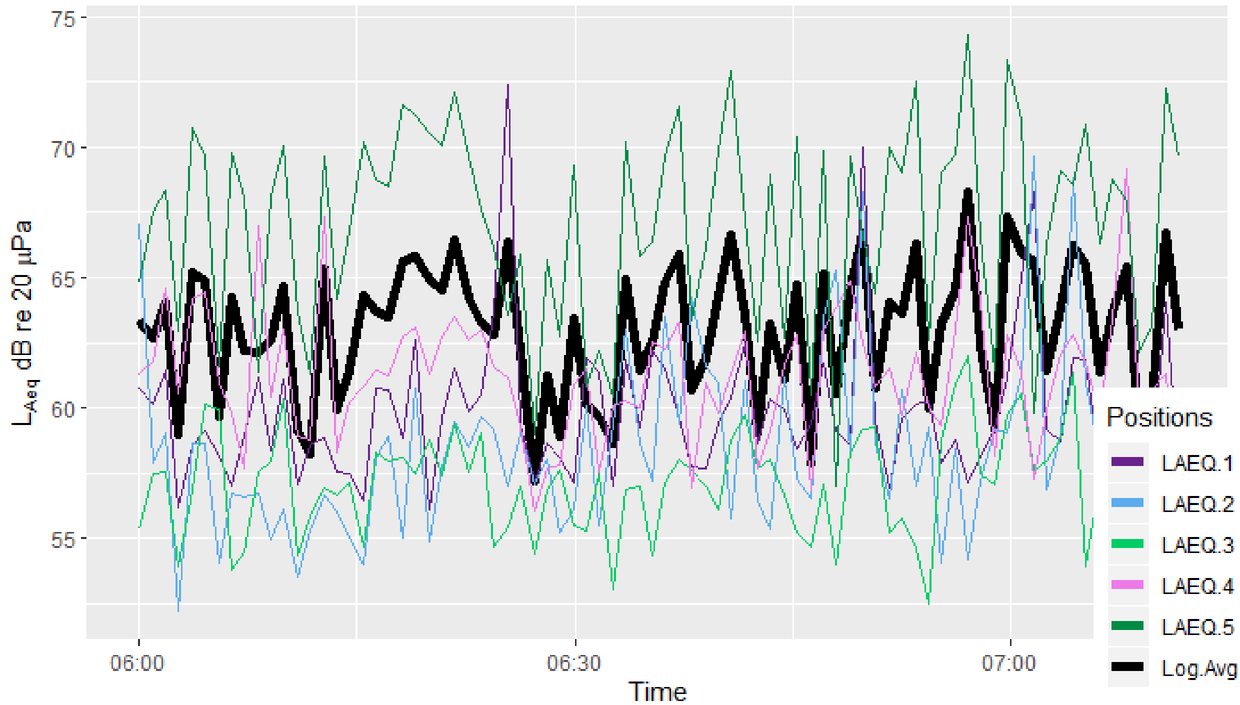

Figure A.7 Noise Levels of Restaurant 2

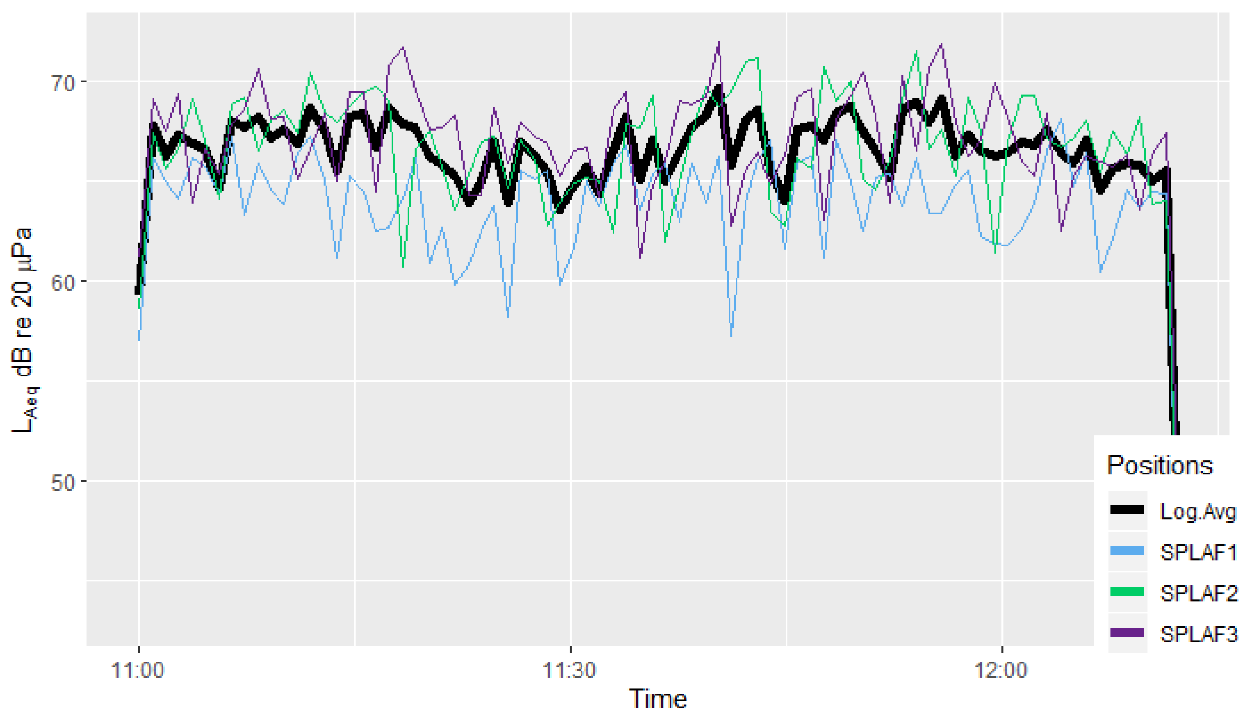

Figure A.8 Noise Levels of Restaurant 3

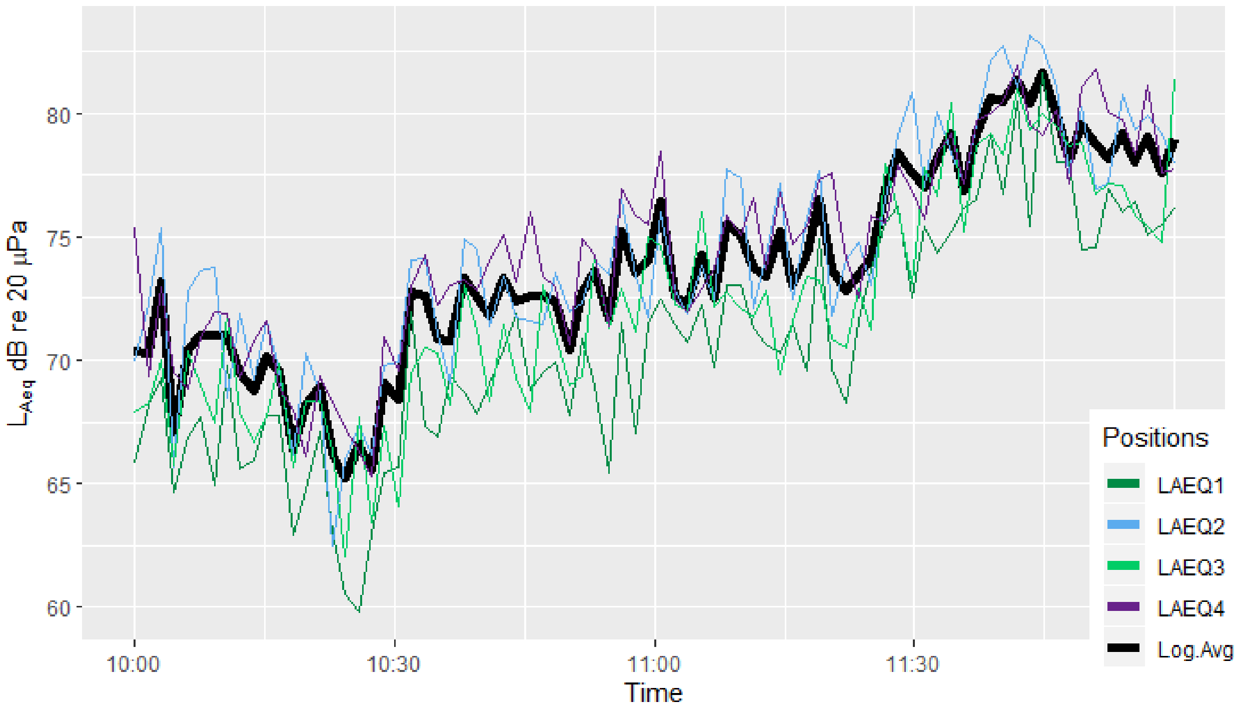

Figure A.9 Noise Levels of Restaurant 4

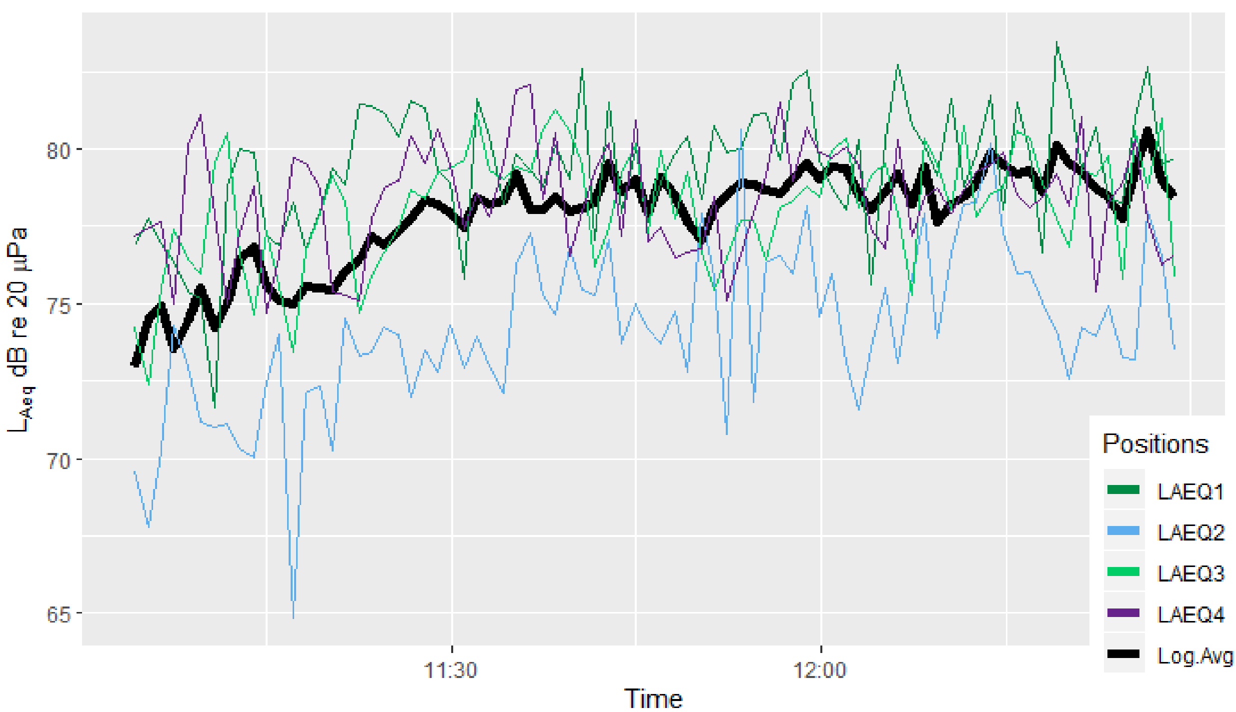

Figure A.10 Noise Levels of Restaurant 5

A.3 Occurrence Rate

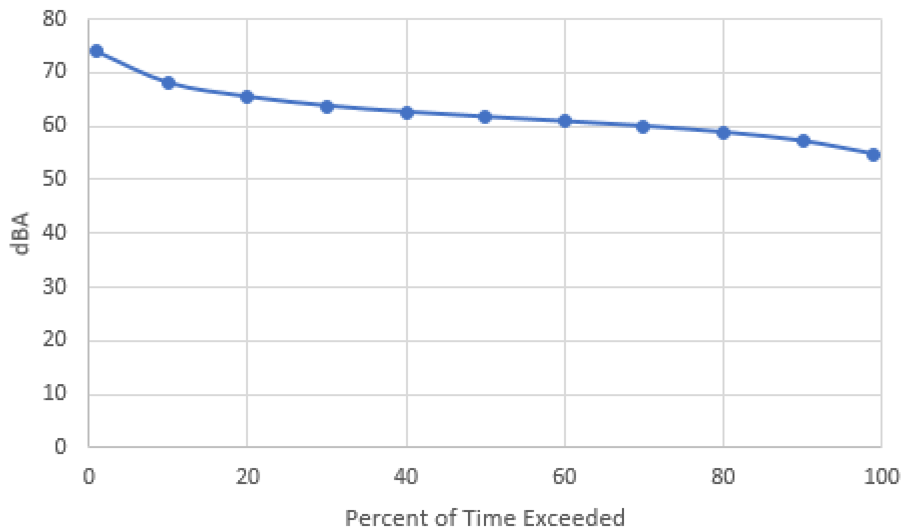

Figure A.11 Occurrence Rate of Restaurant 1

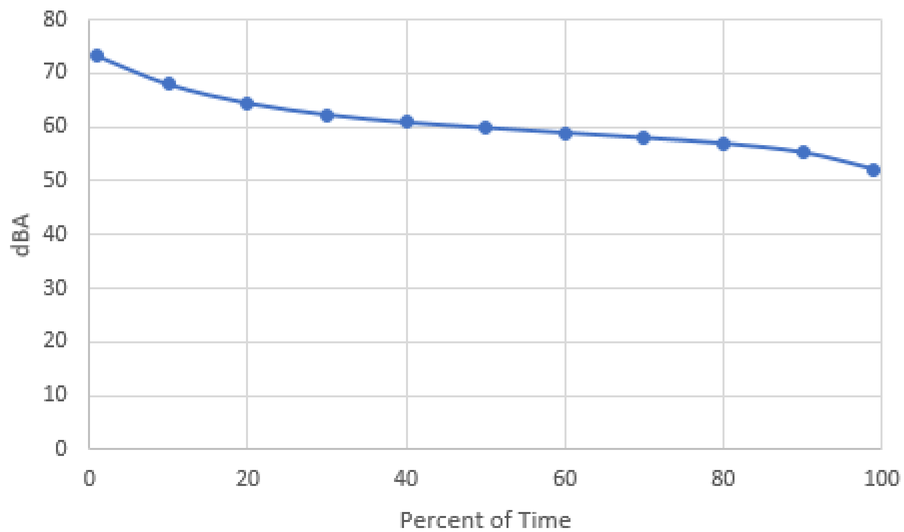

Figure A.12 Occurrence Rate of Restaurant 2

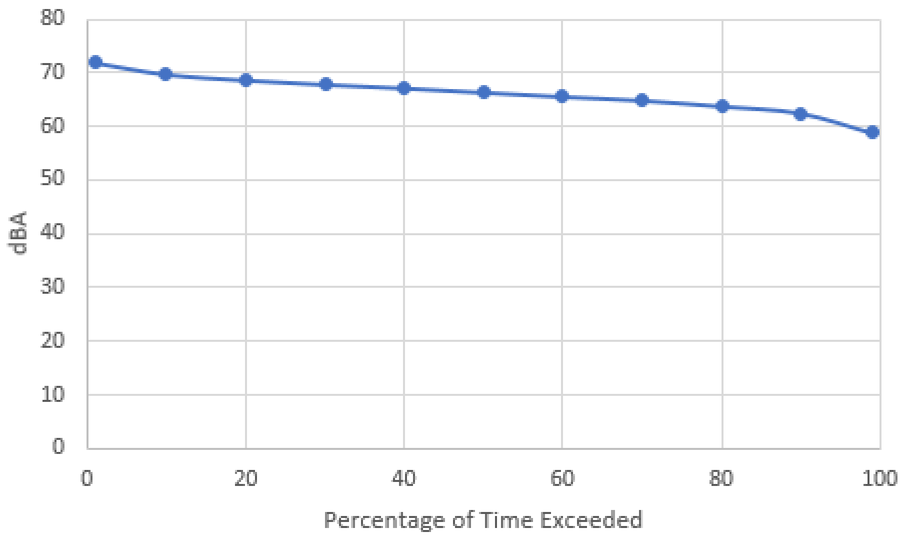

Figure A.13 Occurrence Rate of Restaurant 3

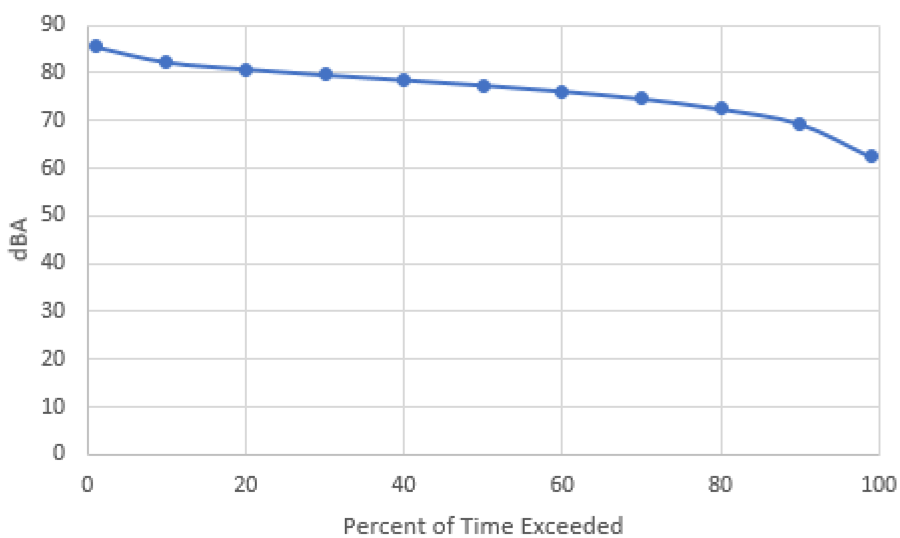

Figure A.14 Occurrence Rate of Restaurant 4

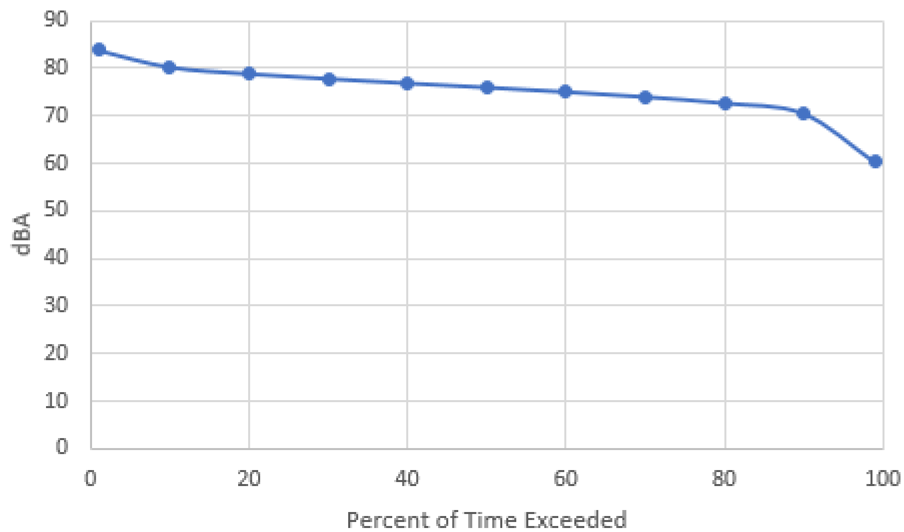

Figure A.15 Occurrence Rate of Restaurant 5

A.4 Normalized Sound Levels vs Normalized Occupancy

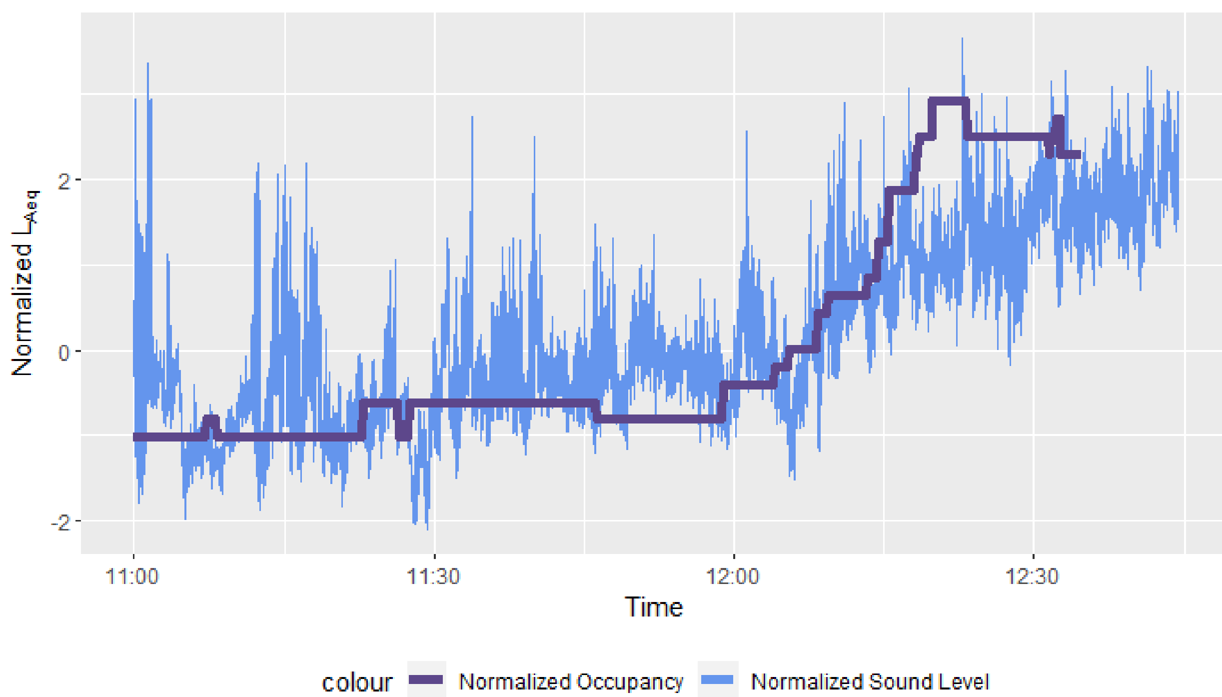

Figure A.16 The sound level vs number of occupants in Restaurant 1

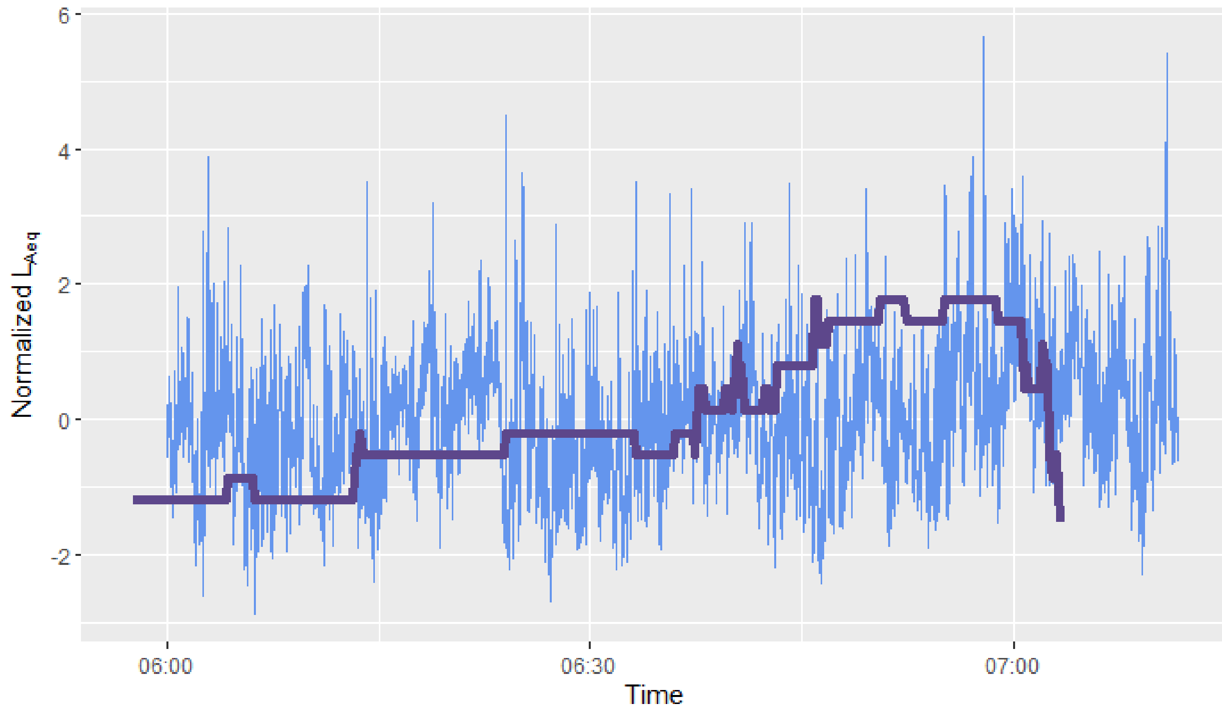

Figure A.17 The sound level vs number of occupants in Restaurant 2

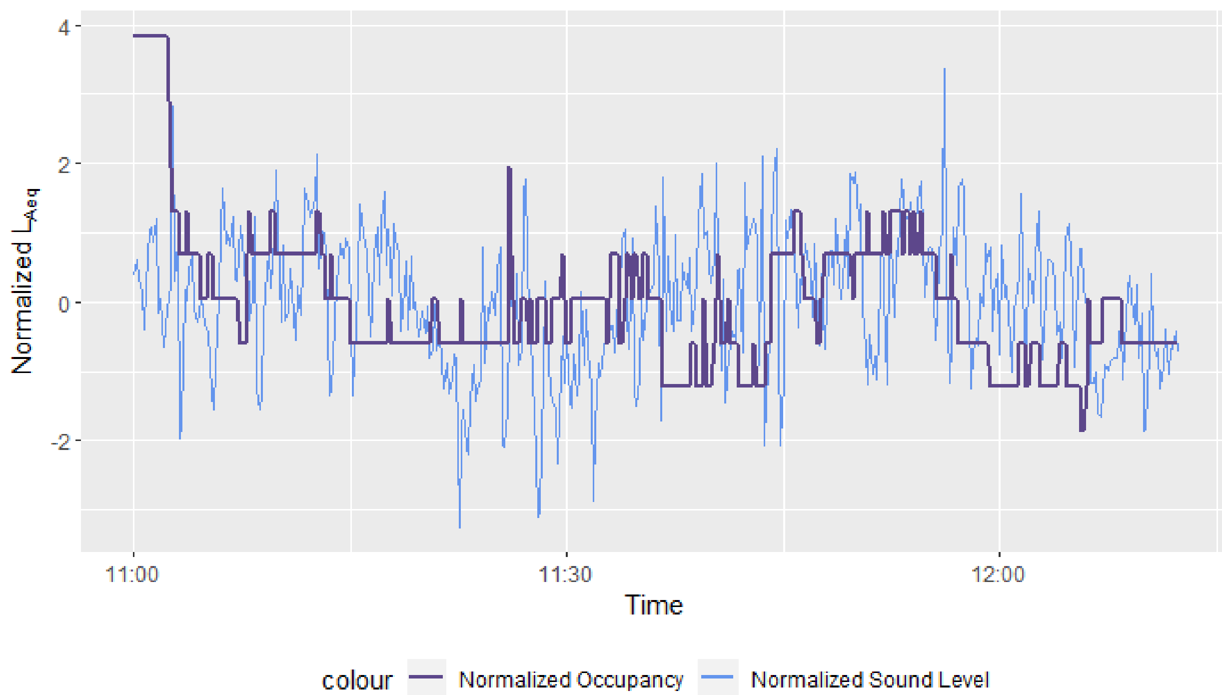

Figure A.18 The sound level vs number of occupants in Restaurant 3

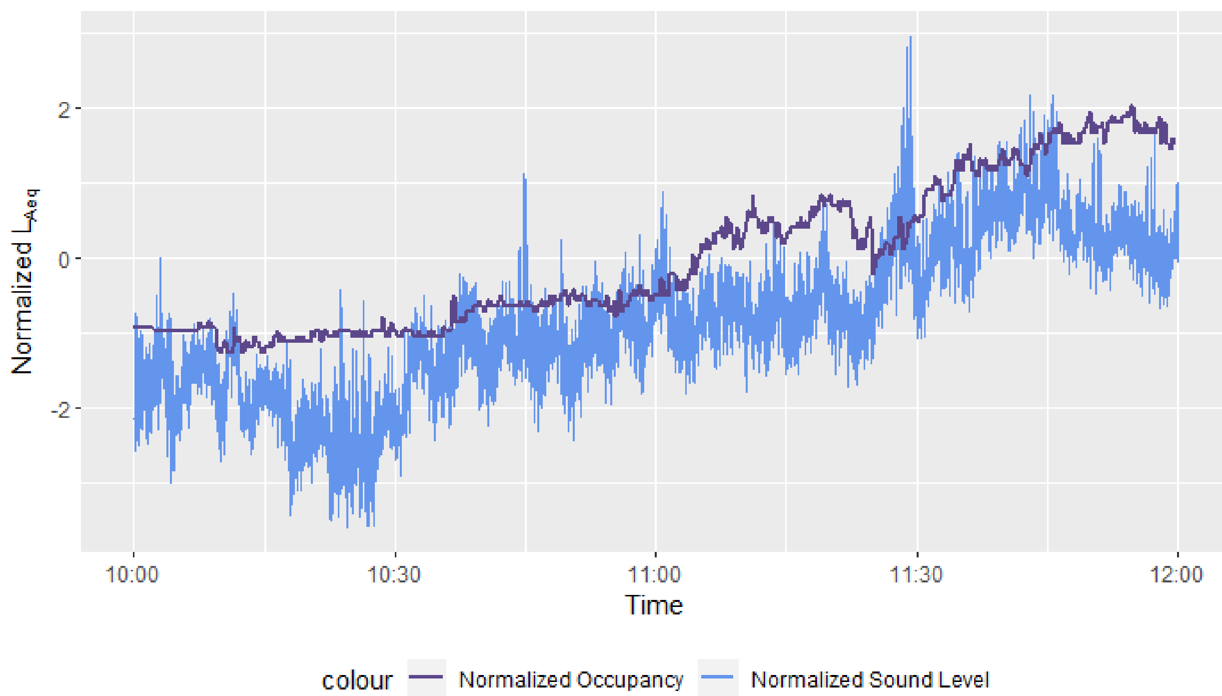

Figure A.19 The sound level vs number of occupants in Restaurant 4

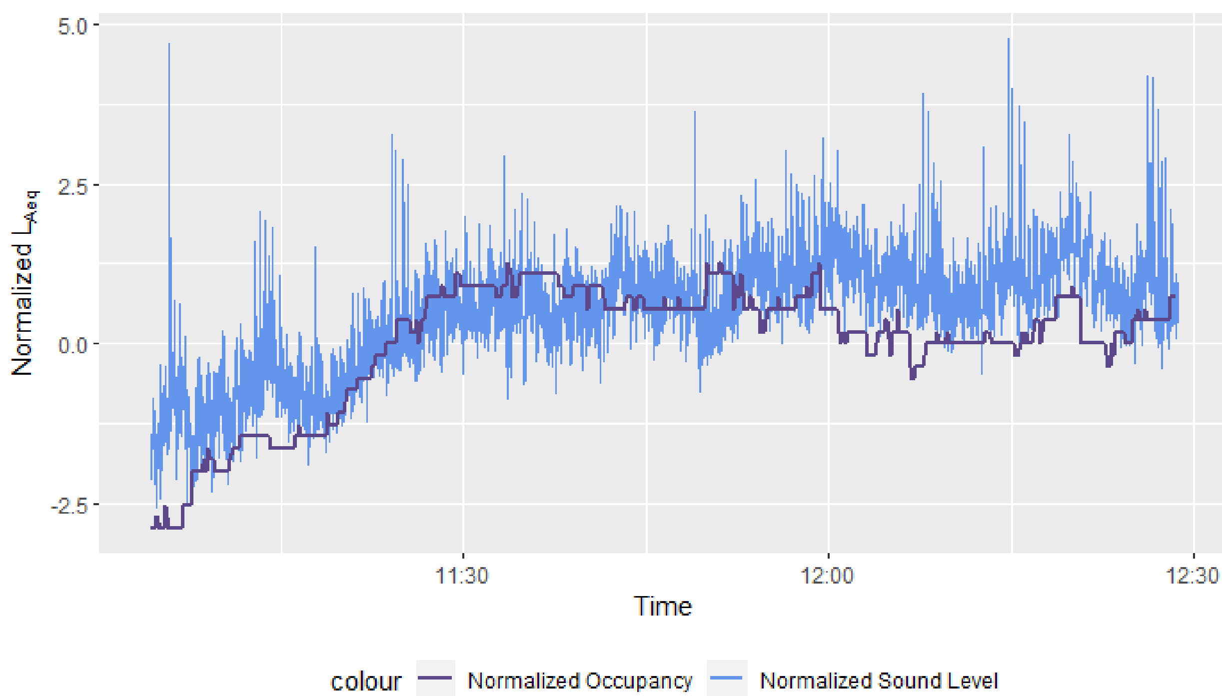

Figure A.20 The sound level vs number of occupants in Restaurant 5

A.5 Predicted Absolute Levels

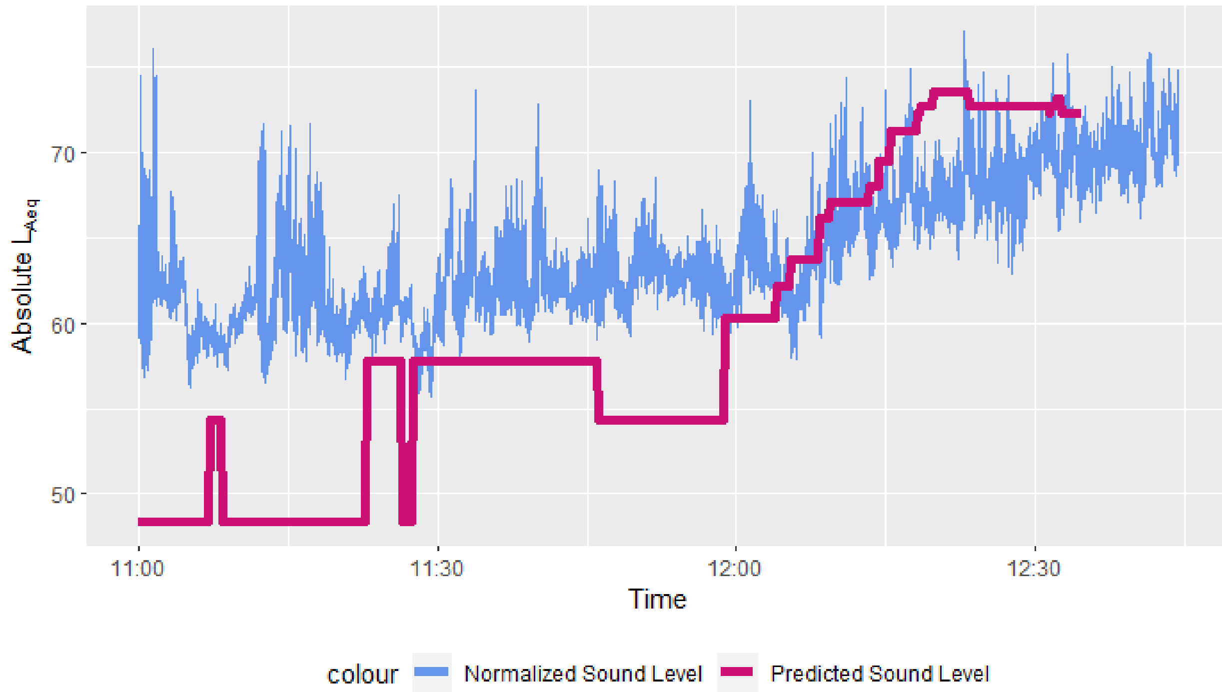

Figure A.21 The sound level vs the absolute predicted levels in Restaurant 1

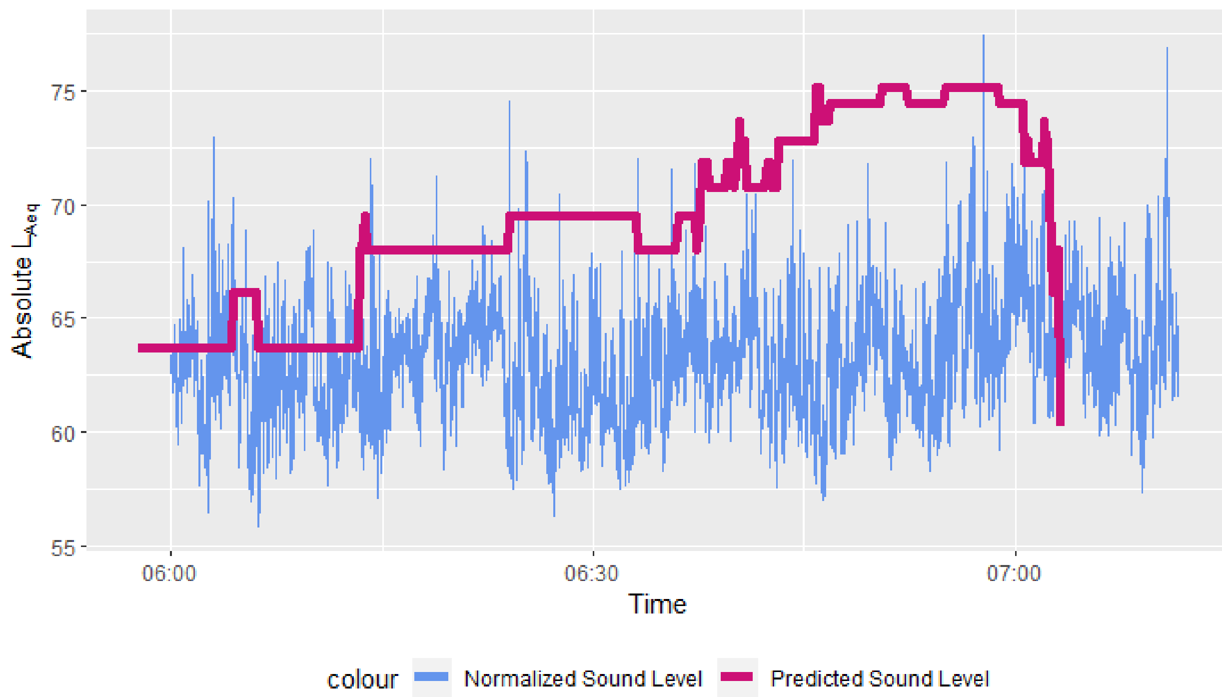

Figure A.22 The sound level vs the absolute predicted levels in Restaurant 2

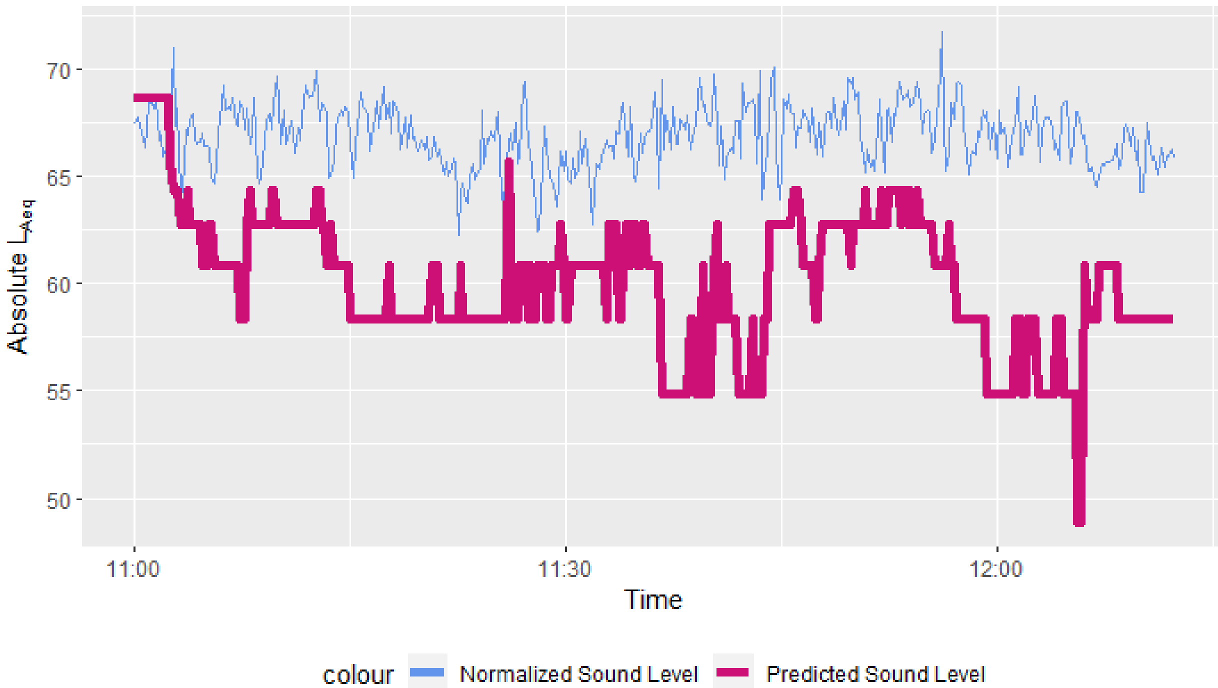

Figure A.23 The sound level vs the absolute predicted levels in Restaurant 3

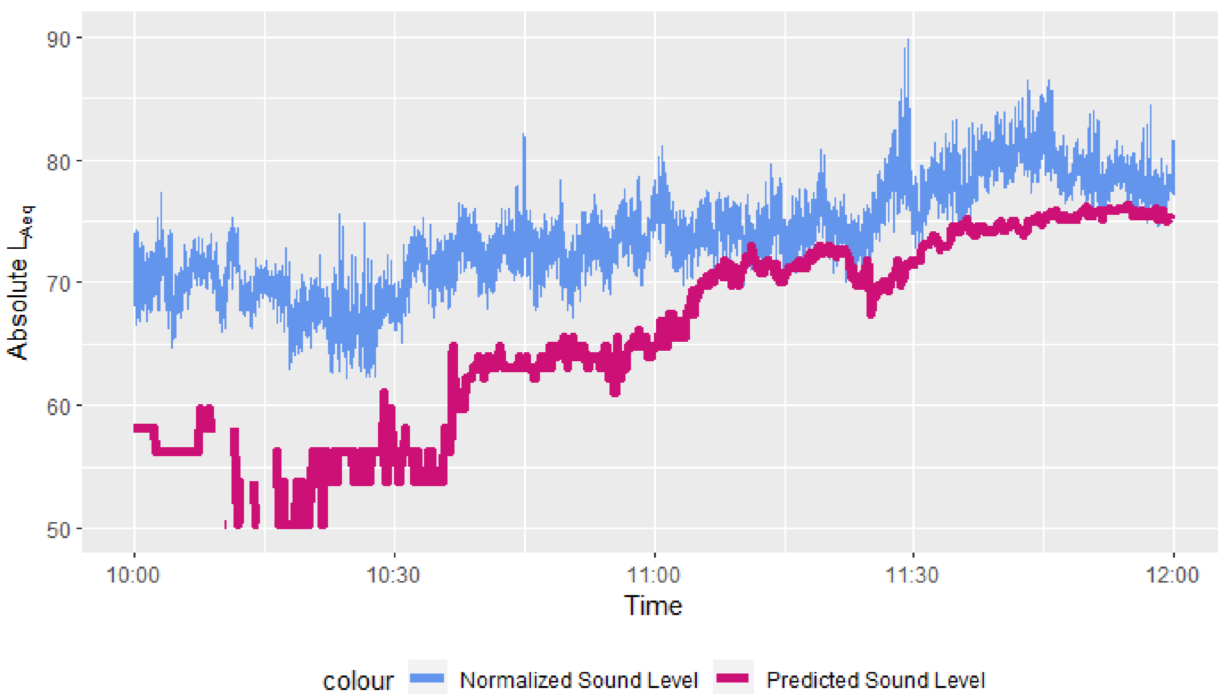

Figure A.24 The sound level vs the absolute predicted levels in Restaurant 4

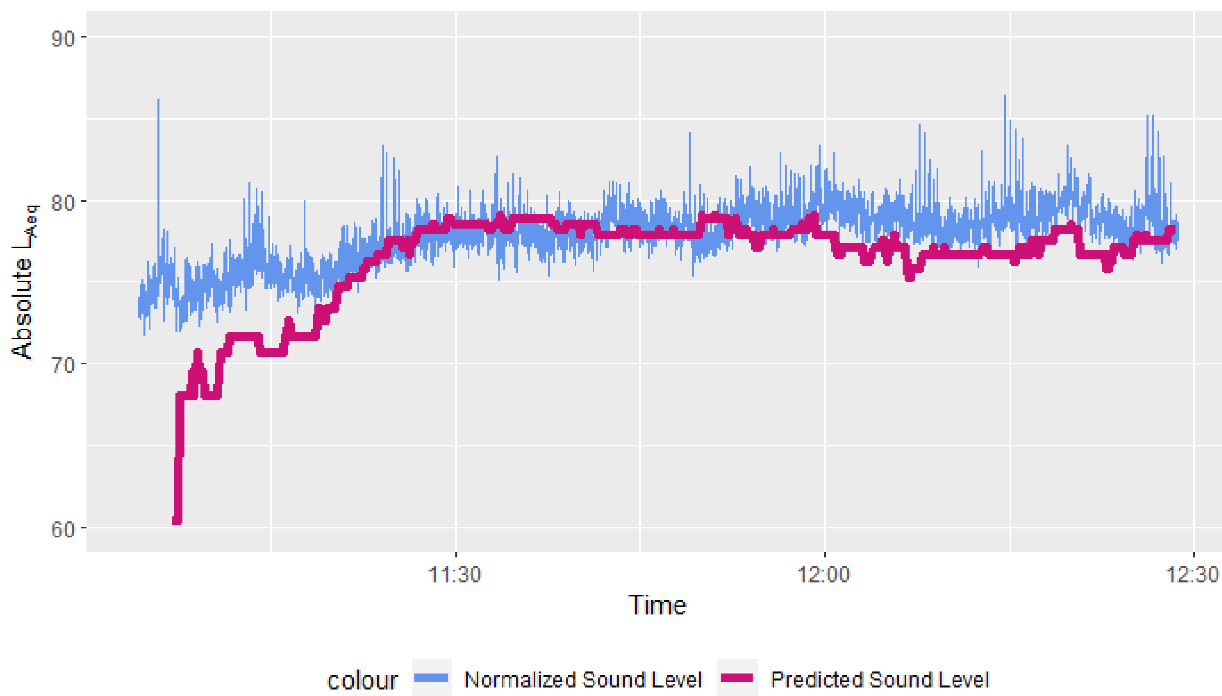

Figure A.25 The sound level vs the absolute predicted levels in Restaurant 5

A.6 Predicted Normalized Levels

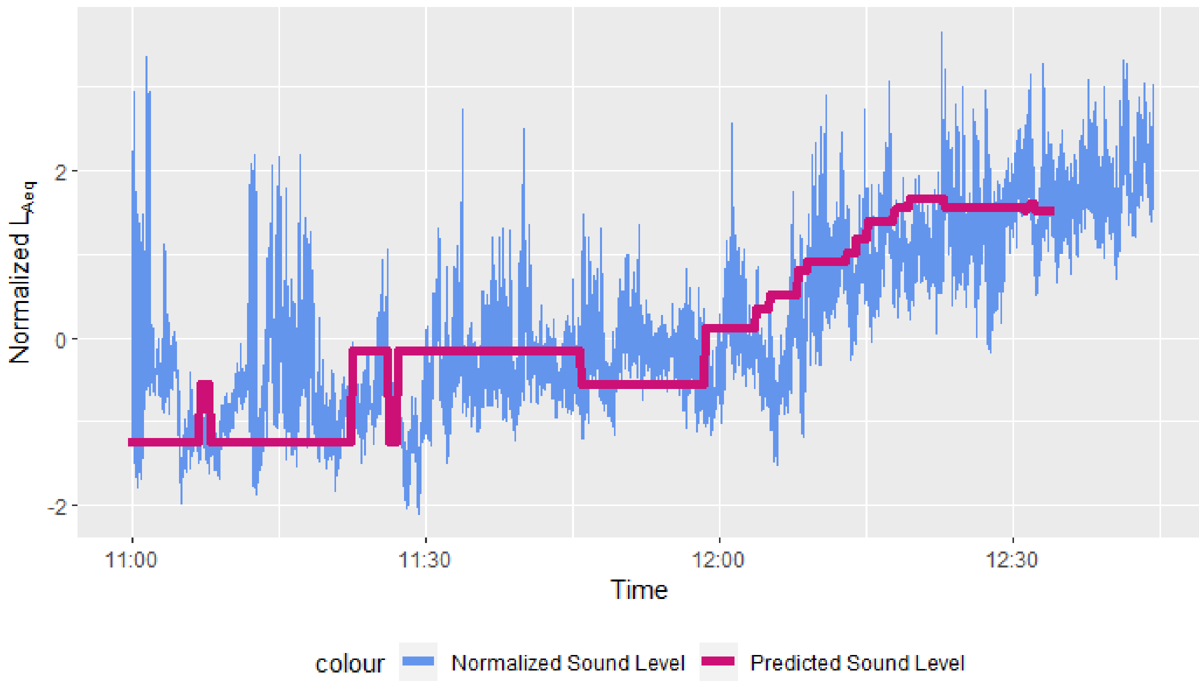

Figure A.26 The normalized sound level vs the normalized predicted levels in Restaurant 1

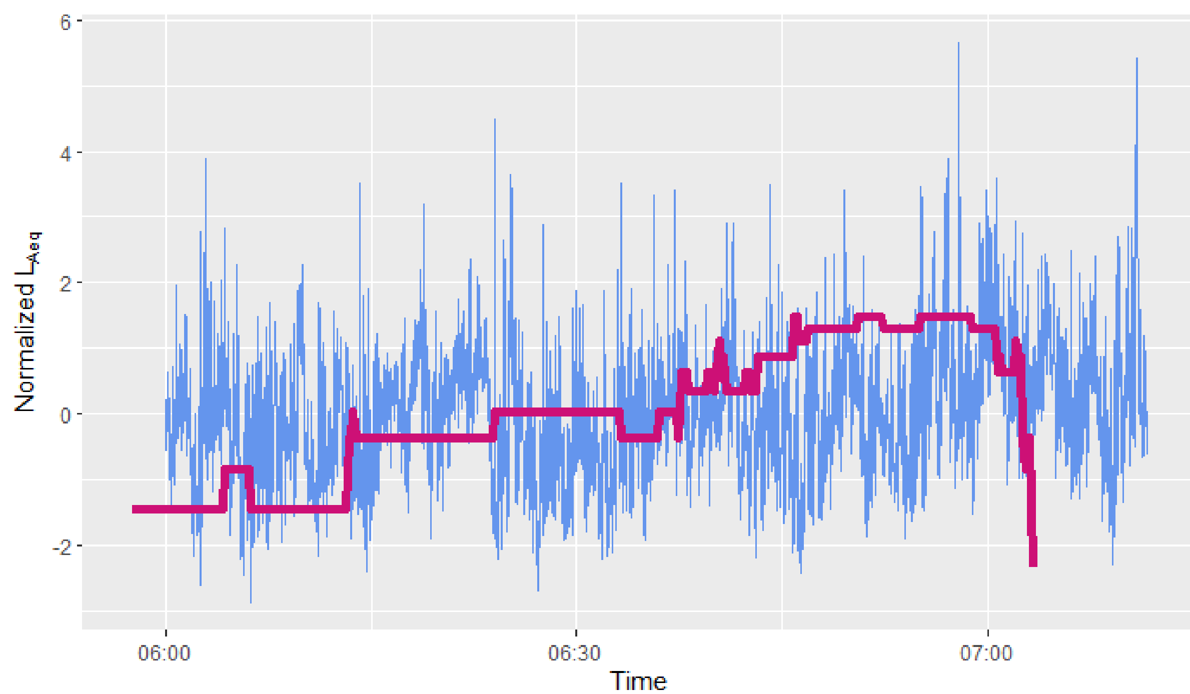

Figure A.27 The normalized sound level vs the normalized predicted levels in Restaurant 2

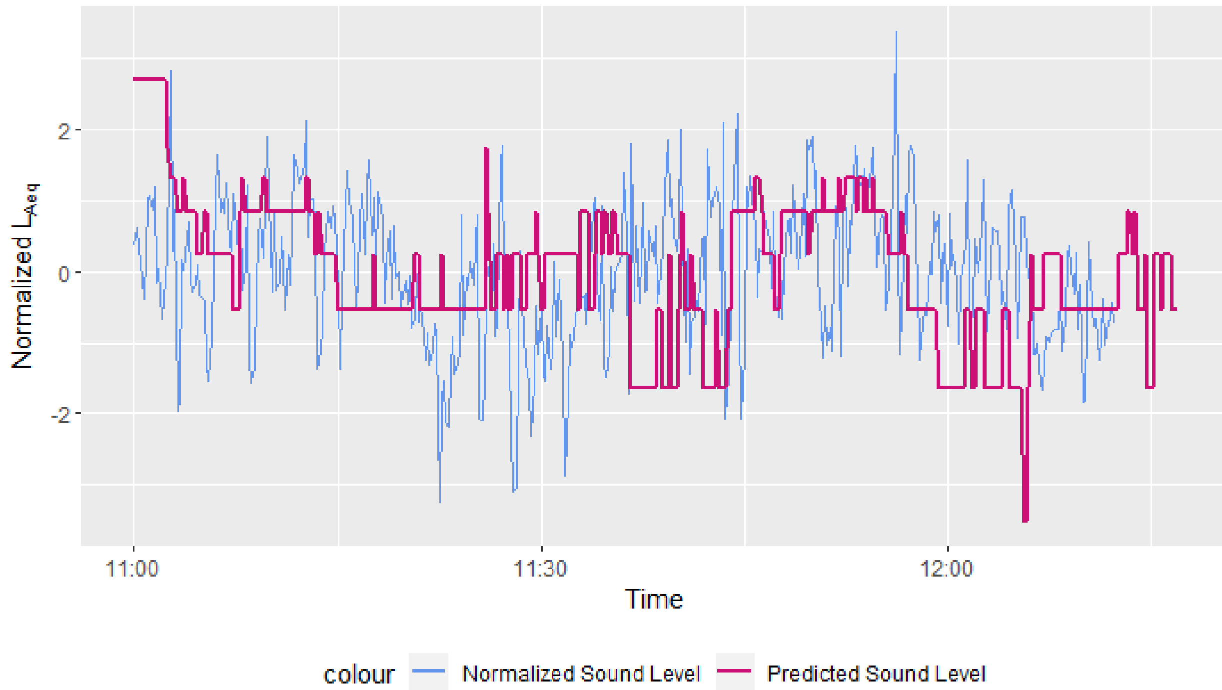

Figure A.28 The normalized sound level vs the normalized predicted levels in Restaurant 3

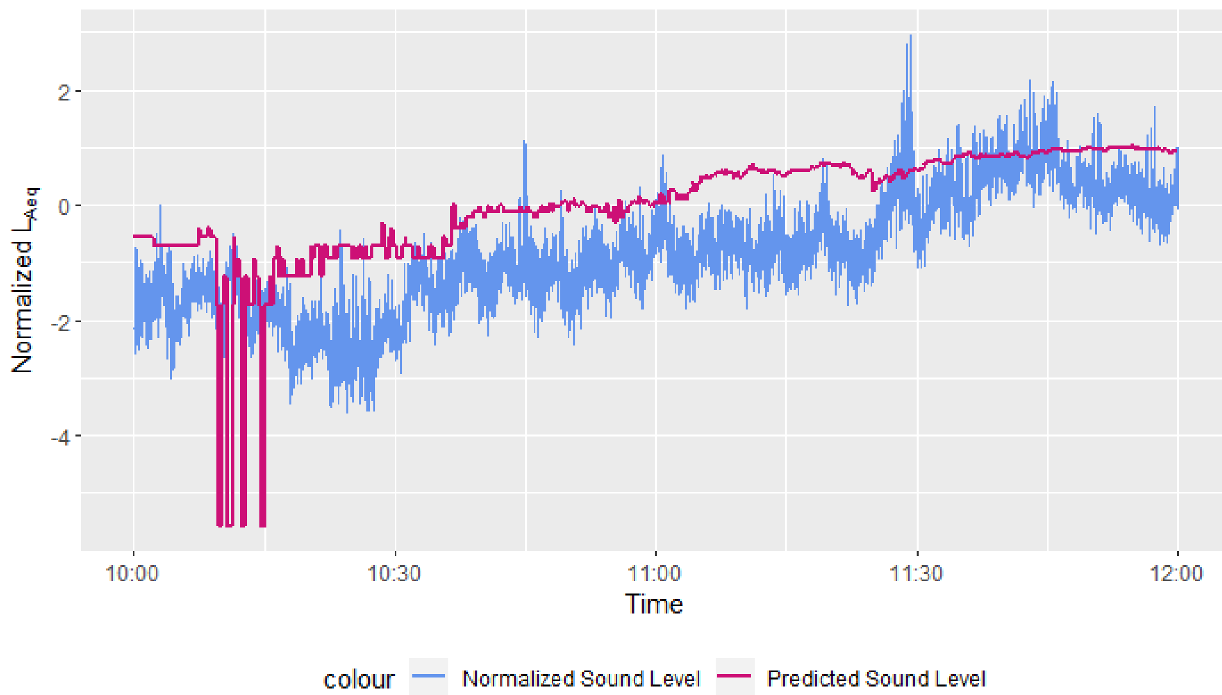

Figure A.29 The normalized sound level vs the normalized predicted levels in Restaurant 4

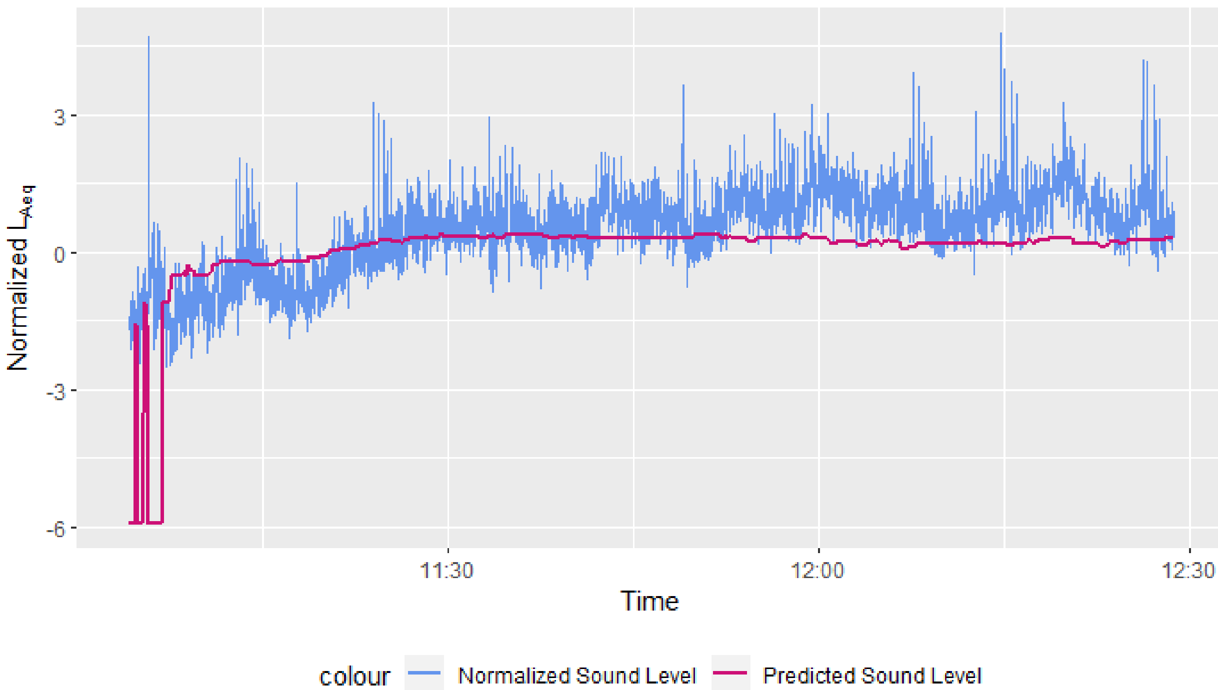

Figure A.30 The normalized sound level vs the normalized predicted levels in Restaurant 5