SIMULATED AND LABORATORY MODELS OF AIRCRAFT SOUND TRANSMISSION

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SIMULATED AND LABORATORY MODELS OF AIRCRAFT SOUND TRANSMISSION

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LIST OF SYMBOLS AND ABBREVIATIONS

A	Interior Sound Absorption (metric Sabins)
ANCA	Airport Noise and Capacity Act
ASTM	American Society for Testing and Materials
ATL	Hartsfield-Jackson International Airport
BOS	Logan International Airport
BTV	Burlington International Airport
DEN	Denver International Airport
DNL	Day-Night Average Sound Level
DOT	Department of Transportation
dB(A)	Decibel (A-weighted Decibel)
EWR	External Wall Rating
FAA	Federal Aviation Administration
FICAN	US Federal Interagency Committee on Aviation Noise
FICON	US Federal Interagency Committee on Noise
Hz	hertz
IAL	Integrated Acoustics Laboratory
IBANA	Insulating Buildings Against Aircraft Noise
ICP	IBANA-Calc Predicted
INM	Integrated Noise Model
ISO	International Standards Organization

L_1 (L_{ext})	Exterior Sound Level (dB)
L_2 (L_{in})	Interior Sound Level (dB)
LAX	Los Angeles International Airport
LM	Laboratory Measured
L_p	Sound Pressure Level (dB)
MaRC	Manufacturing Research Center
MIA	Miami International Airport
NEF	Noise Exposure Forecast
NLR	Noise Level Reduction
NR (OINR)	(Outdoor-Indoor) Noise Reduction (dB)
NRC-IRC	National Research Council (Canada) - Institute for Research in Construction
O.C.	On Center
OITC	Outdoor-Indoor Transmission Class
OSB	Oriented Strand Board
PHX	Phoenix Sky Harbor International Airport
RHWT	Raised-Heel Wood Truss
RSIP	Residential Sound Insulation Programs
RT (RT60)	Reverberation Time (required for sound to decay 60 dB)
RTA	Real-Time Analyzer
S	Total Surface Area of Partition or Specimen
SCR	Structural Clay Research
SLM	Sound Level Meter

SSA	Sound Spectrum Analyzer
STC	Sound Transmission Class
τ	Total Linear Transmission Coefficient
TL (OITL)	(Outdoor-Indoor) Transmission Loss (dB)

SUMMARY

With the increased modernization and expansion of civil aviation that started in the 20th century, aircraft noise has become a larger concern to society. Growing cities attracted more air traffic—more aircraft takeoffs, landings, and overflights. Measures have been taken to mitigate noise at the source, with design targeted to reduce noise generated from the airflow around the aircraft fuselage and from the mechanical means of propulsion, but noise pollution continues to be a concern in communities. While current aircraft noise guidelines are based upon outdoor sound levels, the annoyance and health impacts of aircraft noise pollution are more closely related to the indoor levels of occupied buildings. As such, it is imperative to quantify the sound transmission of typical constructions. This study aims to evaluate and offer further improvements of existing modeling software that simulates a wide range of construction types and configurations for US climate regions. The study has conducted a laboratory validation of predicted noise reduction and transmission loss models using standardized measurement practices. The variation seen between predicted models and laboratory measurements has been linked to testing conditions—allowed by current standards—that do not correspond to assumptions built into the modeling technology, such as the field incidence of exterior noise. The improved models will allow for increased flexibility in simulating the impacts of acoustic and energy retrofits. Overall, the project intends to improve the ability to predict acoustic performance for typical US construction types as well as for any possible design alterations for sound insulation.

CHAPTER 1

INTRODUCTION

1.1 Annoyance and Health Impact of Aircraft Noise

High levels of aircraft noise can interfere with daily indoor activities—working, having conversations, watching TV, listening to music, sleeping—and air traffic is generally perceived to be more annoying than other sources of transportation noise due to its sporadic and unique quality [1]. Passchier-Vermeer and Passchier define noise-induced annoyance as "resentment, displeasure, discomfort, dissatisfaction, or offense when noise interferes with one's thoughts, feelings, or actual activities" [2]. Annoyance is a subjective metric, difficult to quantify, and therefore difficult to regulate, but it has been increasing with further modernization [3] and continues to be an important area of study.

The most widely-accepted prediction metrics for annoyance were developed by the US Federal Interagency Committee on Noise (FICON), which determined that the 65 dB Day-Night Average Sound Level (this metric is also known as DNL and will be described further in the Section 1.2) would be the maximum threshold for acceptable outdoor aircraft noise [1]. As a result, a goal of most airport noise mitigation programs is to establish compatible land uses in areas at or above this threshold. The US Federal Aviation Administration (FAA) guides the actions of state and local government as both entities tend to hold zoning authority. Unfortunately, the dose-response curve used by FICON to predict community response with time-weighted average noise exposure has been proven to underestimate annoyance [4]. In fact, according to one estimate, most aircraft noise complaints are from areas outside the 65 dB DNL contour [5] surrounding airports—implying that aircraft noise-induced annoyance is a concern at lower thresholds. The US Federal Interagency Committee on Aviation Noise, or FICAN, has since succeeded FICON as the main body to better understand, predict and control the effects of aviation noise. Recently, researchers have endeavored to better understand human annoyance to aircraft noise, including potential modifications to the dose-response curves. Examples include an investigation into the relative effects of sound level and number-of-events as predictor variables in aircraft noise annoyance models [6] as well as a study which determined that absolute sound exposure levels fail to account for variance in dosage-response relationships to assess aircraft noise-induced sleep disturbance [7].

Other responses are possible in addition to annoyance. For example, correlations have been established between exposure to aircraft noise and hypertension in humans [8]. Aircraft noise has been proven to generate effects in both saliva cortisol levels (long-term) and blood pressure measurements conducted over a day (short-term) [9]. Noise at home can adversely affect children's cardiovascular health [10], and studies have shown that students attending schools near airports are more prone to long-term memory and reading impairment [11]. Aircraft noise continues to impact the health and levels of annoyance in communities, and accurate and reliable tools are needed to predict outdoor-to-indoor transmission of aircraft noise in order to estimate human response indoors.

1.2 Sound Transmission Metrics

Sound can be quantified by many metrics, but the most common unit of measurement is sound pressure level (L_P), measured in decibels (dB). L_P is calculated as a logarithmic value of the energy contained in sound relative to the minimum sound pressure that a human ear can detect. Complex sounds such as aircraft noise vary with their energy content across frequency, which is measured in hertz (Hz) and related to the human perception of pitch. Sound may be thought of as a composition of narrow frequency bands, with each band containing a range of frequencies. To facilitate comparison of measurements, frequency analysis bands have been agreed upon and standardized [12]. When detailed information about a sound signal is required, standard one-third octave bands (OBs) can be used. Filters such as A-weighting (dBA) can be applied across full or one-third OBs to approximate the human ear response [12].

A building envelope is essentially a sound filter that can attenuate any noise passing through it. Transmission loss (TL) and noise reduction (NR) are two metrics which describe this attenuation in decibels, with the distinction being that NR accounts for the effects of absorption present in the receiving space—TL and NR both vary across frequency. Outdoor-indoor transmission loss (OITL) and outdoor-indoor noise reduction (OINR) are terms used interchangeably with TL and NR. The American Society for Testing and Materials (ASTM) Standard E90 [13] is used to determine TL for individual partitions and façade elements, whereas ASTM Standard E966 [14] is targeted towards field measurements of TL and NR for building envelopes. When a single-number rating is of use one can calculate the noise level reduction (NLR)—the difference between the single-number log sum of the outdoor level and the single-number log sum of the indoor level.

It can be desirable to characterize the TL of façade elements or partitions with a single-number descriptor to facilitate comparison of the performance of different elements and partitions. Sound transmission class (STC), described by ASTM Standard E413 [15], is evaluated by a curve fitting technique which compares plotted TL data across one-third OBs against established STC contours. STC is weighted to rate the sound isolation of interior partitions at human speech frequencies, but is still widely used to evaluate the acoustic efficiency of exterior partitions such as doors, windows, and wall elements. Outdoor-indoor transmission class (OITC), described by ASTM E1332 [16] is a similar single-number rating that was developed specifically for transportation noise applications.

Day-Night Average Sound Level (DNL) is a single-number average of the A-weighted sound level of noise events occurring over a 24 hour period, while penalizing for events occurring between 10 pm and 7 am the following morning to reflect the greater invasiveness of nighttime noise [17]. DNL is used commonly to quantify environmental noise levels, and is used as the input factor in dose-response studies for its statistical correlation to levels of annoyance as nighttime tends to dominate aircraft noise related complaints [18].

1.3 Sound Insulation of Existing and New Constructions

Sound is transmitted into buildings through two primary paths: airborne sound energy transmits directly through the air (i.e. through penetrations such as open windows, leaks, or vents) and structure-borne sound energy transmits through the vibration of the building structure. It is also known that the overall building façade performance will be strongly influenced by the weakest façade element—gaps, vents, windows—and the element surface area. As such, the principal method to improve the sound insulation of a building is to eliminate direct air transmission paths by sealing and limiting the number and total surface area of gaps, leaks, or vents. The next step of an acoustical retrofit would then normally be to use windows and doors with higher sound insulation performance (higher STC ratings). However, recent research has shown that for poor performing wall constructions increasing window STC performance can have minimal impact [19]. The most substantial and expensive measures for acoustical retrofits might include the following: increasing the amount of fiberglass insulation, increasing the number of layers of gypsum board, mounting gypsum board on staggered or resilient studs, and adding attic space above rooms when there is none existing. Measures to improve sound insulation generally require a 5 dB improvement to be noticeable by building occupants, and yet at the higher end it is considered impractical to provide more than 40 dB of total NLR with typical residential constructions [1].

According to 2005 estimates, costs to acoustically retrofit existing constructions can range from ten to fifty thousand dollars [1], and governments have been subsidizing these efforts ever since the first airport community retrofit program in the 1960s at Los

Angeles International airport. After the Airport Noise and Capacity Act (ANCA) in 1990, billions of dollars have been spent by various levels of government on residential and educational sound insulation programs [20]. To avoid the higher costs of ex post facto measures for acoustical performance, more aircraft noise considerations are addressed in the design of new constructions. Noise sensitive rooms such as bedrooms or classrooms can be placed on the side of the building opposite from the main flight path. Upper stories and attic space can be incorporated to insulate rooms below. Heavier, more massive building elements can be used in the construction to increase sound insulation. And finally, it is now accepted that there is not always a direct correlation between thermal insulation—traditionally the primary concern of constructions—and acoustical insulation [1], and design should address both areas.

1.4 Existing Transmission Loss Resources

As described in previous sections, a wealth of information now exists on aircraft noise pollution including studies of its effect on annoyance and health, government standards and regulations regarding zoning, and practices to improve the acoustical insulation of buildings in airport communities. To properly evaluate sound insulation, a robust model to quantify sound transmission of typical constructions requires TL/NR performance for any building construction element measured across frequency. An ideal resource for models would include the following features: (i) TL/NR published across frequency, in contrast to the single-number ratings usually reported; (ii) detailed construction information for each construction element including the dimensions, number of layers, and mounting of all wall, roof, and window materials; (iii) data for both older and newer construction types; and (iv) data covering constructions typical for the variety of climate regions where one may find airport communities [19].

The most comprehensive database that addresses the features listed above is the IR-818 report published by the National Research Council Canada—Institute for Research in Construction (NRC-IRC) [21]. The IR-818 database of TL for exterior wall constructions is included in the IBANA-Calc software [22]. More than 50 other published TL/NR aircraft noise resources—textbooks, government reports and standards, data from industry affiliates—have been gathered and reviewed for this research [19, 23], but most lack several of the key features listed above.

1.5 Previous Research on Aircraft Sound Transmission

1.5.1 Sound Transmission by Typical Construction Type

Firesheets' thesis developed transmission loss models for typical residential constructions [19] and was an important reference point for its use of Insul and IBANA-Calc software, which will be described in further detail in Sections 2.1 and 2.2. As part of this work, typical construction types were identified [24] for the North American climate regions, shown in Figure 1.1, as determined by the Department of Energy (DOE) [25]. The construction profiles corresponding to the different climate regions were used to produce several representative predictions of OITL across frequency as well as NLR with Insul and IBANA-Calc.

Figure 1.1: DOE climate regions for North America (reproduced from [25])

Firesheets' study found that construction types are better grouped according to their outermost construction layer (such as brick, stucco, or vinyl siding), and not by the climate region the construction profile falls under [19]. The study also showed windows often dictate the composite whole-house NLR, as windows are often the poorest performing façade element in a structure, and that improving windows can significantly improve NLR performance. For example, in the case for a typical brick construction in Houston (in the Hot-Humid climate zone) shown in Table 1.1, gains of nearly 20 dB can be seen from increasing the performance of the window.

Table 1.1: Modeled NLR performance for window/wall combinations (adapted from [19])

Region *(Airport City)*	**Exterior Sheathing**	***Whole-House Noise Level Reduction (NLR) in dB(A)***		
		OITC 22 Window	OITC 31 Window	OITC 44 Window
Cold *(Chicago)*	Vinyl siding w/ rigid foam	26	26	26
Hot-Humid *(Houston)*	Fibercement siding w/ oriented strand board	25-35	36	36
Cold *(Concord)*	Wood siding w/ rigid foam & oriented strand board	25-35	37	37
Mixed-Humid *(Atlanta)*	Fibercement siding w/ oriented strand board	26-36	37	38
Hot-Dry *(Sacramento)*	Fibercement siding w/ oriented strand board	26-36	38	39
Hot-Dry *(Sacramento)*	Stucco w/ rigid foam	26-38	40	41
Mixed-Dry *(Albuquerque)*	Stucco w/ oriented strand board	25-38	40	41
Hot-Humid *(Houston)*	Brick w/ extruded polystyrene	26-39	39-42	43

However, when windows perform similarly to the wall (usually meaning that the wall is of poor acoustical performance), the study determined that the poor performing wall dictates the sound transmission. For example, in the case of the typical construction shown for Chicago (in the Cold climate zone) shown in Table 1.1, the poor performance of the vinyl siding exterior façade limits the gains that improved windows can offer.

1.5.2 Low Frequency Sound Transmission of Sonic Boom Signatures

Remillieux's dissertation on sonic boom transmission [26] also served as a reference for this research in that it also attempted to experimentally validate predictive acoustic models with test structures. However, that study's focus was on sonic boom aircraft noise. Commercial supersonic flight over land has been banned due to a lack of consensus agreement toward evidence which would prove that the disturbance is acceptable for human perception in buildings [26]. Previous investigations into sonic booms were limited to simple structures, did not account for coupled fluid-structure interaction, and did not address all aspects of transmission—such as exterior pressure loading, structure vibration, or interior acoustic response. The Remillieux study developed numerical finite element models and computer code to predict the vibroacoustic response of simplified building structures exposed to sonic booms at low frequencies. The experimental validation of the models included 3 test cases. The first case included a constructed single plaster-wood wall with excitation from a speaker generating sonic booms. The other two cases, depicted below in Figure 1.2(a)-(b), were entire enclosures consisting of plaster-wood walls, windows, and door openings. The single and double room test structures were exposed to sonic booms generated by explosive linear charges. The models were successfully validated to predict vibration and interior acoustic responses above 20 Hz within 5-10 dB [26]. The study also claimed that

2-D shell element models were sufficient to represent the dynamics of a wall assembly and were favorable computationally to complex 3-D geometries [26].

(a) (b)

Figure 1.2: (a) one and (b) two room test structures from sonic boom study (reproduced from [26])

The sonic boom study was a key resource in the development of this thesis research—it presented a unique approach of model validation using test structures and the experimental techniques used for low frequency measurement were taken into consideration for our study as well. This thesis research attempted to improve upon the limitations of the sonic boom study by constructing whole-house enclosures that better simulate typical residences. The Remillieux test structures lacked typical exterior façade layers or roofs, and glazing was used for window assemblies without any moving parts. Additionally, the Remillieux study focused on sonic boom signatures and corresponding low frequency (0 – 200 Hz) measurements and models, whereas this thesis focused on non-sonic boom signatures (315 Hz and above).

1.5.3 Variation in Field Measurements of NLR

A study of NLR variation [27] conducted around the Burlington International Airport (BTV) examined variations in field measurements using industry best-practices and ASTM Standard E966-10-type procedures [14]. NLR is used by the various residential sound insulation programs (RSIP) to determine indoor DNL and is measured by various testing procedures such as actual aircraft flyover as well as artificial noise sources. This BTV project, prepared by Landrum and Brown, attempted to systematically quantify the variation of NLR as a result of different testing methods (e.g. exterior microphone measurement method, noise source elevation) and parameters (angle of incidence and distance from noise source to façade) used in RSIP applications. The various testing methods that apply to this thesis research will be discussed further in Section 4.1.4.1. The BTV study determined that generally, the median NLR using external flush measurements is 0.6 dB higher than near average measurements and that the difference is more apparent when the artificial noise source is elevated [27]. Variation between interior sound level measurement methods proved to be inconclusive [27]. The median NLR difference from a reference 45 degrees horizontal angle of incidence was found to be 0.2 dB at 30 degrees and 0.0 dB at 60 degrees—but the authors stated that for the sample of rooms measured in the study, the NLR variation from changing the angle of incidence was not conclusive [27].

1.6 Hypothesis

Validation of current aircraft sound transmission modeling technologies will be discussed further in Sections 2.1.2 and 2.2.2, and has been limited to individual partitions and field measurements of whole-house constructions under sub-optimal testing conditions. It is hypothesized that further validation of modeling tools with existing data, while necessary, will likely be incomplete due to the lack of resources that address the features described in Section 1.4. As such, it is also hypothesized that a laboratory validation using test structures that are flexible to alterations—such as differing regional construction types and energy or acoustic retrofits—will allow for direct measurement of whole-house noise reduction and transmission loss across frequency. The results of such measurements, which can be considered as an expansion of an ideal TL database, could be used to validate model predictions of aircraft sound transmission.

CHAPTER 2

BACKGROUND INFORMATION – MODELING TECHNOLOGIES

2.1 Insul Overview

The commercial software package Insul, developed by Marshall Day Acoustics, is a sound insulation prediction program (version 7.0 was used in this study). Insul can generate TL across one-third OBs as well as STC and OITC ratings for composite wall, floor, or ceiling structures [28]. Insul was used by this study to create wall models for different construction configurations—the modeled TL could then be input into the IBANA-Calc software database (Section 2.2) as a custom wall element for the whole-house modeling.

2.1.1 Insul Features

Insul includes a built-in database of information such as surface mass, Young's modulus, critical frequency, and density for commonly-used construction materials. Custom elements can also be input if this information is known. The user can then build up a wall layer-by-layer while defining the following parameters: type and thickness of each panel layer, the number of layers of each type within a single panel, the stud size and spacing, the shape of the panel profile, the size and rating of cavity insulation, and stud constructions (e.g. staggered, wood/steel, etc.). Insul then uses classical transmission loss theory (i.e. mass law) to predict TL across frequency and single-number ratings for the user-defined wall. Insul includes modeling capabilities for floor/ceiling assemblies, but is limited to constant-depth joist configurations. Roof models in Insul are also limited to constant-depth joist configurations and to only predicting sound intensity level due to rainfall.

The software developers state that Insul offers “good prediction for noise that is incident from a range of different angles of incidence…and furthermore is a reasonable approximation for most building facades for any angle of incidence” [28]. The developers caution that predicted sound insulation for specific angles of incidence could be expected to have error at frequencies above 1 kHz, but that the frequency bands above this threshold “would not determine the overall loudness of the internal noise” [28].

2.1.2 Insul Validation

Ballagh [29] compared mass law theoretical models versus experimental measurements collected by the NRC-IRC [30, 31] for over 240 wall and floor types. Ballagh found that the models were within 3 dB at one-third OB center frequencies from 50 to 5,000 Hz, proving that the methodology that is used in the Insul software is sufficiently accurate for engineering purposes. The models were found, however, to generally slightly over-predict TL at low frequencies and under-predict TL otherwise.

2.2 IBANA-Calc Overview

IBANA-Calc is free software that was developed in 1998 by the NRC-IRC as part of the Insulating Buildings Against Noise from Aircraft (IBANA) project. The software was commissioned to be a convenient tool to model the sound insulation performance of various constructions and designs. IBANA-Calc was the primary software package for this research utilized to construct TL models of composite building façades.

2.2.1 IBANA-Calc Features

As described in Section 1.4, IBANA-Calc includes a large database of TL data across frequency for various building façade elements and also includes a database of source noise spectra—ranging from aircraft such as jets and helicopters to the standard OITC source defined in ASTM E1332 [16]. The relative levels of the source spectra chosen for a particular scenario are determined by the Noise Exposure Forecast (NEF) value, a single-number value which represents the average sound level at a building site surrounding an airport over a 24 hour period [22]. NEF contours are generated annually by the FAA Integrated Noise Model (INM), which calculates noise exposure values at various locations surrounding airports based on the modern aircraft fleet [32, 33]. It should be noted that the use of NEF as an input for IBANA-Calc implies that the software generates predictions assuming field incidence for the aircraft sound source—the source is assumed to be incident from all angles [22]. The default NEF value of 30 is used by IBANA-Calc.

After the user defines the relevant surface areas of all wall, window, door, and roof elements for a particular scenario, IBANA-Calc uses the TL database (which includes custom elements defined by the user) to calculate the overall sound insulation. The program generates the combined transmission loss for all construction components used, and depending on the source spectra and interior absorption (as a percentage of the defined floor area in metric Sabins) selected by the user, the program then generates indoor sound levels and therefore noise reduction across frequency.

The user can define the interior absorption with either (i) a slider in the software interface to assign a value from 50% to 150% of the room floor area or (ii) the following three preset definitions: “bedroom or meeting room” at 120% of floor area, “living room or office” at 100% of floor area, and “kitchen or work area” at 80% of floor area. The software also includes several correction factors (e.g. to account for sound source horizontal angle of view or ground reflections) that are based on limited data; the software developers caution against using the correction factors in models without further validation.

2.2.2 IBANA-Calc Validation

Homes and offices near the Toronto and Vancouver airports were included in a verification study [34] to compare IBANA-Calc model predictions to field measurements. Results showed that most models predicted NLR to within 1 to 3 dBA, but that variation was much larger—usually within +/- 6 dB but as high as +15 dB—when comparing the modeled and measured TL at one-third OB center frequencies. Several potential sources of error—such as the lack of high frequency energy in the aircraft noise test source and the relatively high level of background noise in buildings where measurements were conducted—were highlighted by the IBANA-Calc software developers, who emphasized the need for more field and laboratory data for residential and commercial constructions.

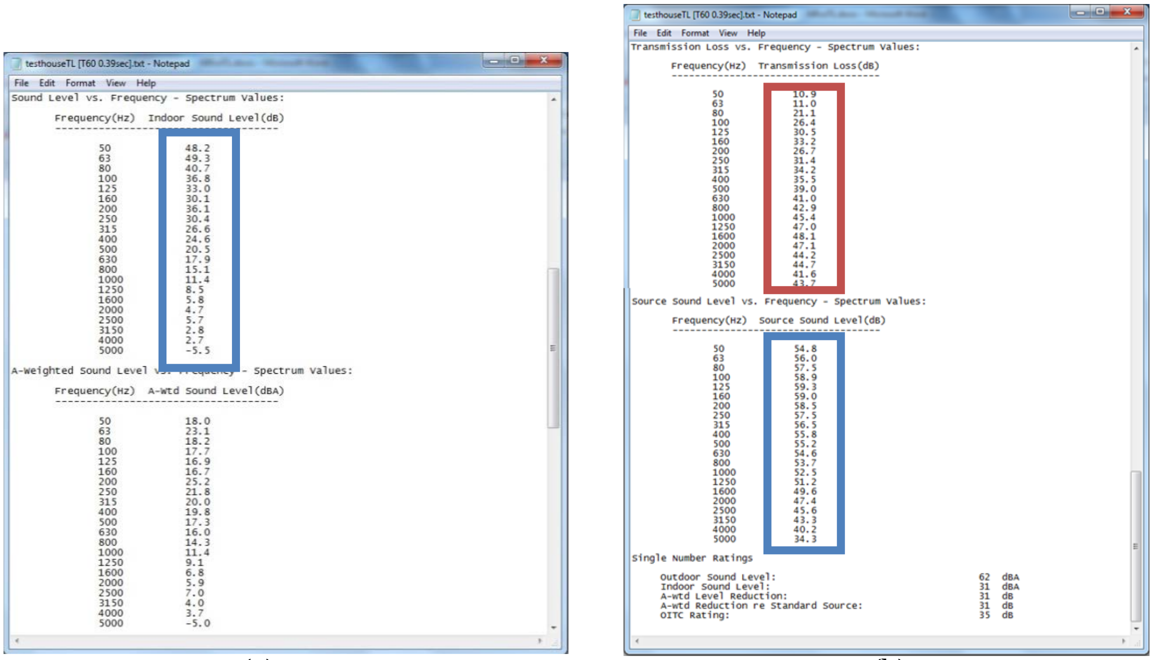
2.2.3 IBANA-Calc Calculation of TL and NR

This section is an explanation of the internal calculations made by the IBANA-Calc software to generate (1) TL and (2) NR predictions across one-third OB frequency. After setting parameters such as room area, interior absorption as a percentage of floor area, and the various façade elements of the room being modeled—wall, window, etc—the IBANA-Calc software generates results that can be "Print to File". The IBANA-Calc software calculates TL across frequency using

$$\boldsymbol{TL = L_1 - L_2 + 10\log\left(\frac{S}{A}\right)}, \text{dB} \tag{2.1}$$

Where L_1 is the outdoor incident sound level (dB) determined by the "Source" chosen for the scenario file, which have a NEF value associated with it, L_2 is the room average indoor received level (dB), S is the area of the partition (m^2), and A is the room sound absorption in metric Sabins (m^2)—reproduced from [22].

The screenshots below in Figure 2.1(a)-(b) display the information included in the "Scenario Calculation Results" output text file. The text file initially reports the user-defined parameters for the scenario, but this section of the output is not shown in Figure 2.1. The output continues to report "Sound Level" (L_2's), "A-weighted Sound Level", "Transmission Loss", "Source Sound Level" (L_1's), and averaged single number ratings. Reported values for "Sound Level" (L_2's) and "Source Sound Level" (L_1's) are shown within the blue boxes in Figure 2.1, whereas values reported for “Transmission Loss” are boxed in red.


testhouseTL [T60 0.39sec].txt - Notepad

File Edit Format View Help

Sound Level vs. Frequency - Spectrum Values:

Frequency(Hz)	Indoor Sound Level(dB)
50	48.2
63	49.3
80	40.7
100	36.8
125	33.0
160	30.1
200	36.1
250	30.4
315	26.6
400	24.6
500	20.5
630	17.9
800	15.1
1000	11.4
1250	8.5
1600	5.8
2000	4.7
2500	5.7
3150	2.8
4000	2.7
5000	-5.5

A-Weighted Sound Level vs. Frequency - Spectrum Values:

Frequency(Hz)	A-Wtd Sound Level(dBA)
50	18.0
63	23.1
80	18.2
100	17.7
125	16.9
160	16.7
200	25.2
250	21.8
315	20.0
400	19.8
500	17.3
630	16.0
800	14.3
1000	11.4
1250	9.1
1600	6.8
2000	5.9
2500	7.0
3150	4.0
4000	3.7
5000	-5.0

testhouseTL [T60 0.39sec].txt - Notepad

File Edit Format View Help

Transmission Loss vs. Frequency - Spectrum Values:

Frequency(Hz)	Transmission Loss(dB)
50	10.9
63	11.0
80	21.1
100	26.4
125	30.5
160	33.2
200	26.7
250	31.4
315	34.2
400	35.5
500	39.0
630	41.0
800	42.9
1000	45.4
1250	47.0
1600	48.1
2000	47.1
2500	44.2
3150	44.7
4000	41.6
5000	43.7

Source Sound Level vs. Frequency - Spectrum Values:

Frequency(Hz)	Source Sound Level(dB)
50	54.8
63	56.0
80	57.5
100	58.9
125	59.3
160	59.0
200	58.5
250	57.5
315	56.5
400	55.8
500	55.2
630	54.6
800	53.7
1000	52.5
1250	51.2
1600	49.6
2000	47.4
2500	45.6
3150	43.3
4000	40.2
5000	34.3

Single Number Ratings

Outdoor Sound Level:	62	dBA
Indoor Sound Level:	31	dBA
A-wtd Level Reduction:	31	dB
A-wtd Reduction re Standard Source:	31	dB
OITC Rating:	35	dB

(a) (b)

Figure 2.1: IBANA-Calc scenario output text file with reported sound levels (blue boxes) and TL (red box)

The flowchart in Figure 2.2 illustrates the process that this study has determined (as verified in Appendix G) the IBANA-Calc software uses in modeling TL and NR.

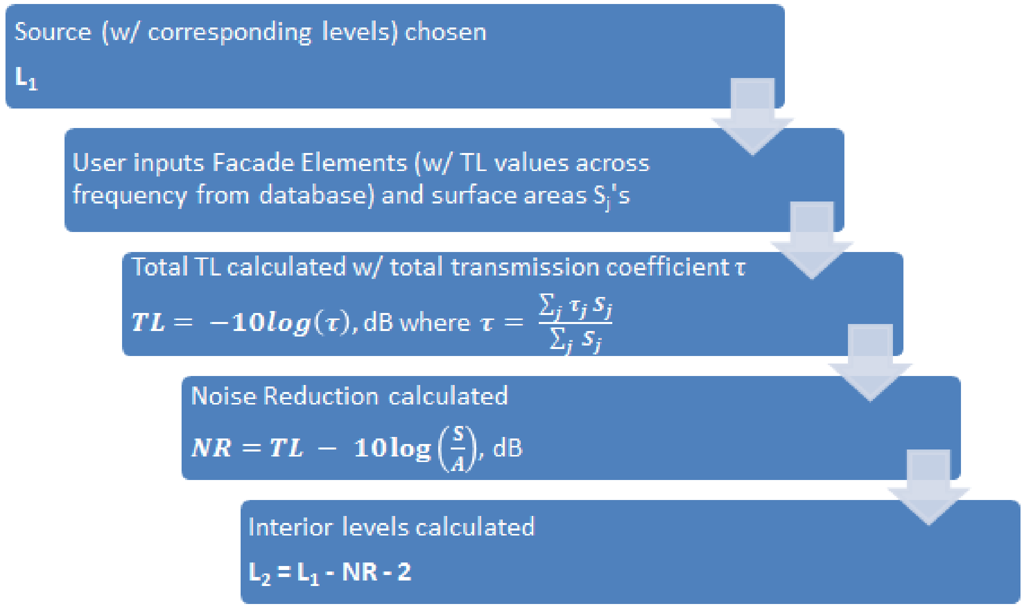


Figure 2.2: Process used by IBANA-Calc to predict TL and NR

CHAPTER 3

PILOT VALIDATION – COMPARING MODELS TO EXISTING DATA

3.1 Methodology

As discussed earlier, this project has compiled around 50 resources to build a database of TL values including the criteria given in Section 1.4, but the database is still incomplete for our purposes. A potential resource, a joint report by the US Department of Transportation (DOT) and FAA titled DOT-FAA-AEQ-77-9 "Study of Soundproofing Public Buildings Near Airports" [35] from 1977, did not address all of the ideal criteria for model validation. However, the DOT-FAA report, which offered an investigation of the sound attenuation of public buildings near airports and determined methods and costs for further soundproofing, did provide enough reported data for a limited validation of current sound transmission modeling technology. The DOT-FAA report used what was described as the External Wall Rating (EWR) method to calculate and measure NR for schools and hospitals in areas near major US airports. Six of the buildings—corresponding to six climate regions among the LAX, PHX, MIA, BOS, and ATL airports—described in this study were recreated in IBANA-Calc to validate and to further identify modeling limitations.

3.1.1 DOT Climate Regions

The US Department of Transportation (DOT) and Federal Aviation Administration (FAA) divided the country into six regions, A through F. Table 3.1 shows the geographic descriptions of each region. A map of these regions with the respective airports investigated by the DOT-FAA report is shown in Figure 3.1. Note the slight difference between these regions and those created by the US Department of Energy (DOE) as shown in Figure 1.1. The Sub-arctic/arctic and very cold regions were omitted from the DOT-FAA report due to the fact that they exist outside the continental US.

Table 3.1: Descriptions of DOT/FAA climate regions (adapted from [35])

Region	Geographic Description
A	Pacific Coastline (LAX)
B	Inland southern California, southern Nevada, and southwestern Arizona (PHX)
C	The gulf coast and south Atlantic coastline (MIA)
D	Eastern seaboard and inland to central Illinois (BOS)
E	Great Lakes (western) states and central south (ATL)
F	Central states (DEN)

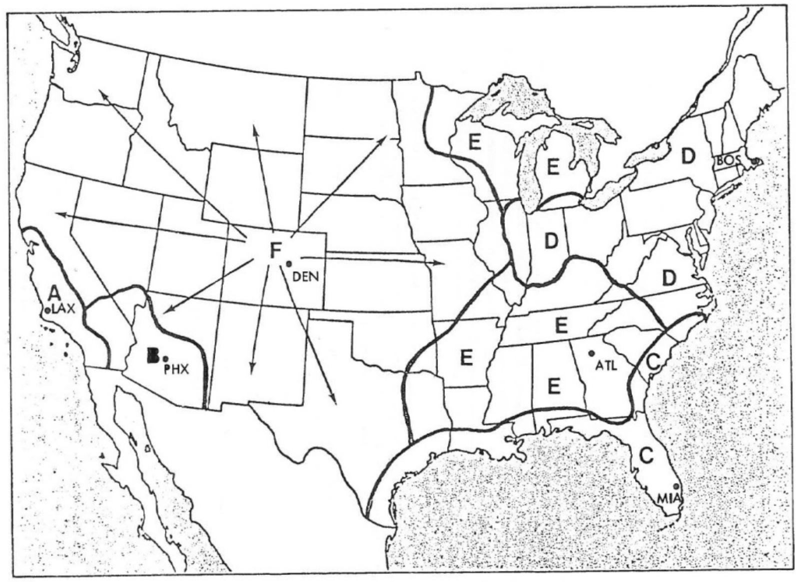


Figure 3.1: Map of DOT/FAA climate regions (reproduced from [35])

3.1.2 External Wall Rating

The external wall rating (EWR) is a single-number index that was originally created for use with buildings exposed to highway noise [35]. It can be used for aircraft noise, as it is in DOT-FAA-AEQ-77-9, with reduced accuracy [35]. The DOT-FAA report provided expressions for "NR", but the report was calculating single-number ratings from EWR values. As such, the following presentation of the external wall rating will use "NLR" instead, as it has been determined to be more appropriate to describe the single-number rating.

The DOT-FAA report related EWR to the NLR for a homogeneous structure by

$$\boldsymbol{NLR = EWR - 10\log\left(\frac{S}{A}\right) - 6 - C}, \text{dB} \tag{3.1}$$

Where *NLR* is the noise level reduction for the structure (dB), EWR is the external wall rating (dB) given by Equation 3.2. *S* is the transmitting surface area (m^2), *A* is the interior absorption value (m^2), and C is a constant which is a function of the source spectrum (equal to 5.8 dB for aircraft noise)-- reproduced from [35].

Equations (3.2) and (3.3), both also reproduced from [35], were used to calculate the EWR for a complex building consisting of multiple elements was calculated using

$$\boldsymbol{EWR_{composite}} = \mathbf{10\log_{10}}\left(\frac{\sum_i S_i}{\sum_i T'_i S_i}\right), \text{dB} \tag{3.2}$$

Where S_i is the surface area (m^2) of the i'th element and T'_i is the transmission coefficient of the i'th element, given by Equation (3.3)—both reproduced from [35].

$$\boldsymbol{T'_i} = \mathbf{10}^{-EWR_i/10} \tag{3.3}$$

Equations (3.2) and (3.3) were substituted into Equation (3.1) to yield

$$\boldsymbol{NLR} = -\mathbf{10\log}\left(\textstyle\sum_i S_i \mathbf{10}^{-EWR_i/10}\right) + \mathbf{10\log}\,\boldsymbol{A} - \mathbf{6} - \boldsymbol{C}, \text{dB} \tag{3.4}$$

The DOT-FAA report contained an Appendix D “Summary of Building Investigation” that detailed the construction of each particular school or hospital, as well as an Appendix H “Soundproofing Rehabilitation Worksheets” that contained any information that might have been left out of Appendix D. For example, if the number of windows for a classroom was not given in Appendix D of the DOT-FAA report, the school’s corresponding worksheet in Appendix H would display the total window area. Appendix B in the DOT-FAA report tabulated EWR values for various façade elements, and these values were substituted into Equation (3.4) to find the NLR of each building.

In an exercise to understand exactly how the DOT-FAA study was calculating NLR for each building, the results of calculating EWR and NLR with Equation (3.4) are shown in Table 3.2 and compared with the values given in Appendix E of the DOT-FAA report. There are minor discrepancies that can be seen from the calculation of NLR using the EWR method compared to the tabulated values given in Appendix E of the DOT-FAA report, and it is likely that the difference between the two values were related to the roofs. As the report did not contain detailed descriptions of the dimensions for each building's roof, we assumed the transmitting surface area of each room's roof to be the total floor area of the room. When comparing our values for $S_i * T'_i$ to the values given in Appendix E of the DOT-FAA report, it appears that the DOT study might have taken a different approach to assign dimensions to the roof's transmitting surface area.

Table 3.2: Calculation of NLR from EWR

Region	Building	NLR (dB)	NLR (dB)	ΔNLR (dB)
		Calculated	DOT-FAA Appendix E [33]	Calculated - Appendix E
A	Clyde Woodworth School	18.4	18	0.4
B	Arizona Children's Hospital	20.4	19	1.4
C	Jackson Memorial Hospital	27.3	27	0.3
D	Williams School	21.5	21	0.5
E	Woodward Academy	29.3	29	0.3
F	Clyde Miller School	20.1	18	2.1

3.1.3 IBANA-Calc Models

Six buildings—one from each region—were chosen from the report to be modeled in IBANA-Calc. Due to the limitations of both the information provided in the report and the limitations of the IBANA-Calc software, assumptions had to be made for each model. Each assumption and approximation is explained with the results in Section 3.2. For all IBANA-Calc models, a standard aircraft source was used and the absorption was set from measured *A* values (given for each building in Appendix E of the DOT-FAA report). As the constructions for most of the façade elements given in IBANA-Calc did not coincide with the constructions described in the DOT study, TL data across frequency from collected resources was entered manually into the software as custom façade elements.

3.2 Results – Pilot Validation

3.2.1 Region A – LAX

The Clyde Woodworth School, located 2.3 miles away from the Los Angeles International Airport (LAX) in Los Angeles, CA, was chosen to be modeled for region A. The classroom chosen by the study had a total floor area of 952 ft^2. The exterior walls consisted of 1” wood & stucco, while the interior walls were made of ½” gypsum board. The roof was composed of 1” wood, 6 Ply + Slag. The number of total windows was not given in the report, but the total area of the windows was given to be 240 ft^2.

The school was listed to be as within a NEF contour of 30 in one section of the report and as within a NEF contour of 37 in another section, so a standard aircraft source of NEF 37 was chosen in IBANA-Calc as a “worst-case” scenario. The exterior/interior walls were approximated to be the 2x4 wall studs, 24” o.c., with 5/8” gypsum board (side 1) and 5/8” gypsum board (side 2) element as given in our TL database. Likewise, the windows were assumed to be 1/4” single sheet glass and the roof/ceiling was approximated to be 1-1/8” layered plywood, ½” gypsum board. The wall height was assumed to be 10’. The room was calculated to have 66% floor area absorption from the reported *A* value. The wall of largest length was assumed to be the exterior wall.

The resulting IBANA-Calc scenario produced the single-number ratings in Table 3.3. Due to the limited availability of TL data for some of the façade elements used in the model, the model can only be considered reasonably accurate in the frequency range of 100-4000Hz.

Table 3.3: IBANA-Calc model for Clyde Woodworth School

Outdoor Sound Level	69 dBA
Indoor Sound Level	50 dBA
A-weighted Level Reduction (NLR)	19 dB

3.2.2 Region B – PHX

The Arizona Children's Hospital, located 3.1 miles away from Phoenix Sky Harbor International Airport (PHX) in Phoenix, AZ, was chosen to be modeled for region B. The hospital room chosen by the study had a total floor area of 191 ft^2. The exterior walls consisted of 4" brick concrete block cement grout, while the interior walls were made of 5/8" plaster. The roof was composed of 3" concrete slab. The room had two windows with a total window area of 43.84 ft^2.

The hospital was listed to be within a NEF contour of 30, so a standard aircraft source of NEF 30 was chosen in IBANA-Calc. The exterior/interior walls were approximated to be the hollow 6" concrete block element given in our TL database. Likewise, the windows were assumed to be 1/4" single sheet glass and the roof/ceiling was approximated to be 5" solid concrete slab. The wall height was assumed to be 10'. The room was calculated to have 65% floor area absorption from the reported *A* value. The wall of largest length was assumed to be the exterior wall.

The resulting IBANA-Calc scenario produced the single-number ratings in Table 3.4. Due to the limited availability of TL data from some of the façade elements used in the model, the model can only be considered reasonably accurate in the frequency range of 100-4000Hz.

Table 3.4: IBANA-Calc model for Arizona Children's Hospital

Outdoor Sound Level	62 dBA
Indoor Sound Level	44 dBA
A-weighted Level Reduction (NLR)	20 dB

3.2.3 Region C – MIA

The Jackson Memorial Hospital, in the community surrounding Miami International Airport (MIA) in Miami, FL, was chosen to be modeled for region C. The hospital room chosen by the study had a total floor area of 264 ft^2. The walls consisted of 8" concrete block, ½" plaster wire mesh, and 6" hollow block. The roof was composed of 6" concrete slab. The total window area for the room was 20 ft^2.

For the IBANA-Calc model, a standard aircraft source of NEF 30 was chosen for the noise source. The walls were assumed to be 8" concrete block with 1/2" plaster. The windows were assumed to be 1/4" single-glazed sheet glass. The roof/ceiling was assumed to be 4" concrete slab on 2" elastomeric isolators (2" gap), and 6" structural slab. It should be noted that our resource for this particular roof TL data included TL values that were greater than 100 dB, which is the maximum value for TL at any frequency in the IBANA-Calc software. The wall height was assumed to be 10'. The room was calculated to have 95% floor area absorption from the reported *A* value. The wall of largest length was assumed to be the exterior wall.

The resulting IBANA-Calc scenario produced the single-number ratings in Table 3.5. Due to the limited availability of TL data from some of the façade elements used in the model, the model can only be considered reasonably accurate in the frequency range of 100-4000Hz.

Table 3.5: IBANA-Calc model for Jackson Memorial Hospital

Outdoor Sound Level	62 dBA
Indoor Sound Level	43 dBA
A-weighted Level Reduction (NLR)	19 dB

3.2.4 Region D – BOS

The Williams School, built in 1909 and located 1.6 miles from Logan International Airport (BOS) in Boston, MA, was chosen to be modeled for region D. Though now demolished, it was located in the town of Chelsea, MA when the tests were originally conducted.

The classroom had a floor area of 892.44 ft^2. The exterior walls consisted of 16" brick with plaster and wood lath. The interior walls and ceiling were reported as 3/8" gypsum lath with 1/8" plaster. The roof had six-ply 3/4" wood planks with slag. There were four windows, each with an area of 34.67 ft^2.

For the IBANA-Calc model, a standard aircraft source of NEF 37 was chosen for the noise source. The exterior walls were assumed to be Structural Clay Research (SCR) brick with 1/2" gypsum/sand plaster. The interior walls were assumed to be 9" deep with 2 sets of 2x4 wood studs, with fiberglass insulation and 5/8" gypsum board. The windows were assumed to be 1/4" single sheet glass. The roof/ceiling was assumed to consist of 1/2" Oriented Strand Board (OSB), 1 1/2" perlins, 9 1/4" solid wood joists on 416" centers with fiberglass insulation, 1 of 1/2" gypsum board, and no ventilation. The wall height was assumed to be 10'. The room was assumed to have 100% floor area absorption. The wall of largest length was assumed to be the exterior wall.

The resulting IBANA-Calc scenario produced the single-number ratings in Table 3.6. Due to the limited availability of TL data from some of the façade elements used in the model, the model can only be considered reasonably accurate in the frequency range of 125-4000Hz.

Table 3.6: IBANA-Calc model for Williams School

Outdoor Sound Level	69 dBA
Indoor Sound Level	48 dBA
A-weighted Level Reduction (NLR)	21 dB

3.2.5 Region E – ATL

Woodward Academy, located 0.7 miles from the Hartsfield-Jackson International Airport (ATL) in Atlanta, GA, was chosen to be modeled for region E. The chosen room had a floor area of 736.47 ft^2. The exterior walls consisted of 8” brick with 4” concrete blocks. The interior walls and ceiling were 1/2” plaster. The roof was 6” concrete with ½” plaster ceiling. There were three windows totaling an area of 79.98 ft^2.

For the IBANA-Calc model, a standard aircraft source of NEF 35 was chosen for the noise source. The walls were assumed to be 9” brick and 6” dense concrete with 1/2” plaster. The windows were assumed to be 1/4” single sheet glass. The roof/ceiling was assumed to be 6” dense concrete. The wall height was assumed to be 10’. The room was assumed to have 100% floor area absorption. The wall of largest length was assumed to be the exterior wall.

The resulting IBANA-Calc scenario produced the single-number ratings in Table 3.7. Due to the limited availability of TL data from some of the façade elements used in the model, the model can only be considered reasonably accurate in the frequency range of 100-3150Hz.

Table 3.7: IBANA-Calc Model for Woodward Academy

Outdoor Sound Level	67 dBA
Indoor Sound Level	39 dBA
A-weighted Level Reduction (NLR)	28 dB

3.2.6 Region F – DEN

The Clyde Miller School, in the community surrounding the Denver International Airport (DEN) in Denver, CO, was chosen to be modeled for region F. The classroom chosen by the study had a total floor area of 600 ft^2. The walls consisted of 8” concrete, while the roof was composed of 1” wood sheathing with a plaster ceiling. The total window area for the room was 196 ft^2.

For the IBANA-Calc model, a standard aircraft source of NEF 29 was chosen for the noise source. The walls were assumed to be 8” concrete block with 1/2” plaster. The windows were assumed to be 1/4” single-glazed sheet glass. The roof/ceiling was assumed to be asphalt shingles, building paper, 7/16” OSB, and raised-heel wood trusses, with no vents installed. The wall height was assumed to be 10’. The room was calculated to have 67% floor area absorption from the reported *A* value. The wall of largest length was assumed to be the exterior wall.

The resulting IBANA-Calc scenario produced the single-number ratings in Table 3.8. Due to the limited availability of TL data from some of the façade elements used in the model, the model can only be considered reasonably accurate in the frequency range of 100-4000Hz.

Table 3.8: IBANA-Calc Model for Clyde Miller School

Outdoor Sound Level	61 dBA
Indoor Sound Level	42 dBA
A-weighted Level Reduction (NLR)	19 dB

3.3 Discussion

An shown in Table 3.9, there was good agreement overall between the previously published results and the predicted models from IBANA-Calc, but it is difficult to validate the models with confidence when working with older, nonresidential constructions that lack reported TL/NR data across frequency—as seen in DOT-FAA-AEQ-77-9. There was agreement of 1 dBA or less between the DOT published results and the IBANA-Calc predictions, with the exception of the Jackson Memorial Hospital room in Miami. There was some difficulty in interpreting the roof construction information provided in the DOT report for this hospital. This is believed to be the primary reason for the large 8 dB difference between the published and modeled single-number results.

Table 3.9: DOT-FAA-AEQ-77-9 measured values [35] and IBANA-Calc predicted

Region	Building	NLR (dB)	NLR (dB)	ΔNLR (dB)
		DOT-FAA Appendix E [33]	IBANA-Calc Predicted	|Measured - Predicted|
A	Clyde Woodworth School	18	19	1
B	Arizona Children's Hospital	19	18	1
C	Jackson Memorial Hospital	27	19	8
D	Williams School	21	21	0
E	Woodward Academy	29	28	1
F	Clyde Miller School	18	19	1

Another discovery of the pilot validation was the fact that caution must be used when reporting single-number ratings such as NLR (labeled “A-weighted Level Reduction” in the IBANA-Calc software). As described in the results, custom façade elements were input into the software without TL values in certain frequency ranges—usually below 100 Hz and above 4000 Hz. The modeling software currently does not correct single-number ratings such as NLR to be only averaged between the frequency range for which every façade element has entered TL values.

Although useful insights were provided by this pilot validation to highlight the ability of IBANA-Calc to predict single-number NLR, there were several limitations. Some assumptions had to be made with regard to construction information—the DOT report lacked residential constructions. And as the report was published in 1977, it lacked modern constructions. Residences were not examined in the report, and data for comparing across frequency was not available. A main takeaway is that IBANA-Calc appears to be doing well reproducing the single number ratings, but the limitations in our validation can be addressed with further laboratory studies.

CHAPTER 4

MAIN STUDY – COMPARING MODELS TO LABORATORY DATA

4.1 Methodology

As the pilot validation to compare models to existing transmission loss data had several limitations, the next area of focus was to compare predicted data from composite IBANA-Calc models to transmission loss data measured in a laboratory setting. In accordance with how the IBANA-Calc software calculates indoor sound levels, all laboratory measurements followed the guidelines established by ASTM Standard E966-10, “Standard Guide for Field Measurements of Airborne Sound Attenuation of Building Facades and Facade Elements” [14].

4.1.1 Georgia Tech Acoustic Facilities

The laboratory measurement of transmission loss required the construction of a pilot “test house” in a controlled environment. The test house was constructed in the Integrated Acoustics Laboratory (IAL) located in the Fuller E. Callaway Jr. Manufacturing Research Center (MaRC) on the Georgia Institute of Technology campus. The IAL includes the following qualified facilities: a reverberation chamber, a hemi-anechoic chamber, and a full anechoic chamber. Sound level meters, microphones, loudspeakers, signal generators, multi-channel data acquisition systems, and software packages are all available in the IAL to aid measurements.

The hemi-anechoic chamber (Figure 4.1) was chosen to accommodate laboratory measurements of the pilot test house. This type of acoustic chamber is isolated from exterior sources of noise and all surfaces except for the floor are covered with acoustically absorptive material. The acoustic absorption simulates a free-field environment with a single reflecting plane, and this allows the laboratory measurement to introduce the effect of different sound source angles of incidence relative to the test house. As stated earlier, the hemi-anechoic chamber is acoustically isolated from airborne as well as structure-borne sound energy, resulting in a very low standard background noise level inside the chamber. Preliminary measurements revealed ambient equivalent sound pressure levels of under 20 dBA for all one-third octave bend center frequencies above 100 Hz inside the hemi-anechoic chamber.

Figure 4.1: Hemi-anechoic chamber in MaRC

The hemi-anechoic chamber has dimensions of 23’4” by 28’8” by 16’9”. The acoustically absorptive wedges that cover the sides and ceiling of the chamber have a depth of 24” which make the effective dimensions of the chamber 19’4” by 24’8” by 14’9”. The test house was located in a corner of the chamber to allow for a maximum amount of room to change source positions for transmission loss measurements. Roughly 3’ of work space clearance was left in between the walls of the test house and chamber wedges.

4.1.2 Test House Construction

4.1.2.1 Choice of Construction Type

As discussed earlier in Section 1.5.1, the United States Department of Energy has divided North America into eight separate climate regions: subarctic/arctic, very cold, cold, marine, mixed-dry, mixed-humid, hot-dry, and hot-humid. The test house was constructed based on the recommended building profile described by the Building Science Corporation for Atlanta, Georgia—falling under the mixed-humid climate region.

The recommended building profiles for other climate regions shared many of the major components, especially with wall layers 2 through 6, of the Atlanta, GA design. This fact was taken into consideration when choosing the composition of the walls and roof (Table 4.1). This similarity would allow for measurements to be conducted using the mixed-humid construction, and then potentially allow for the simple swapping out of the outermost façade (e.g. replace fiber-cement with vinyl siding) for future testing iterations.

Table 4.1: Exterior wall and roof materials used in test house

Layer	Walls	Roof	
1	Fiber-cement siding (7/16")	Asphalt shingles	*Exterior*
2	House wrap	Roofing felt	↓
3	Oriented Strand Board (OSB; 7/16")	Oriented Strand Board (OSB; 7/16")	
4	2x4 wood framing @ 24" on center	Raised-heel wood truss framing	
5	3 ½" lay-in fiberglass cavity insul (R-13)	6 ¼" lay-in fiberglass cavity insul (R-19)	
6	½" gypsum board	½" gypsum board	*Interior*

Raised-heel wood trusses (RHWT) were selected for the roof framing due to the inclusion of RHWT roof-ceiling structures in the IBANA-Calc façade transmission loss database. As described in J.S. Bradley's IR-760 report "Insulating Buildings Against Aircraft Noise: A Review", there are very few studies that have reported sound transmission loss data of typical North American roof-ceiling structures [36]. All other roofs in the IBANA-Calc database are either wood joist/truss cathedral-style roofs or flat steel deck roofs, which are not typically seen in United States residential constructions. Although standard residential constructions would feature some combination of roof vents, the test house was designed without roof vents to avoid any potential flanking issues (i.e. the transmission of sound by paths other than directly through the test house structure) and to simplify the modeling. The test house design included an opening for a 3'x5' window. Three variations of acoustically-tested single hung vinyl windows, which will be discussed further in Section 4.1.4.2, were used in this opening. A door was not included to maximize the wall surface area and simplify modeling. The window was used as the primary means of entrance and egress.

4.1.2.2 Test House Geometry

The measurement standard ASTM E966-10 dictates a minimum receiving room volume of 25 m^3 (883 ft^3) to report for "frequencies of 125 Hz and higher" [14]. As such, the first proposed test house dimensions were chosen to meet this requirement. However, after meetings with collaborators at the Georgia Tech School of Building Construction (Dr. Daniel Castro-Lacouture, Dr. Javier Irizarry, and Rick Porter) the height of the test house was fixed to be 8' as is the norm for residential constructions. It was decided that as long as the effects of the test house volume were monitored by calculating the interior Schroeder frequency—below this frequency the room response is determined through modal analysis—it would be acceptable to select dimensions that were in line with typical construction practices.

ASTM E966-10 also directs that "the room length, width, and height should be all different with the largest dimension no greater than twice the shortest. The smallest room dimension must be at least [7'6"]" [14]. The test house single room was constructed to be 9' x 10' x 8' high, meeting the previous conditions and resulting in an interior volume of 720 ft^3 (20.38 m^3). The profile of the raised-heel wood truss roof structure resulted in a back wall that was about 3' higher than the front wall, but the "attic space" that this created was sealed from the test house interior by a tape and plastered gypsum board ceiling. Schematics of the test house design can be seen in Figure 4.2.

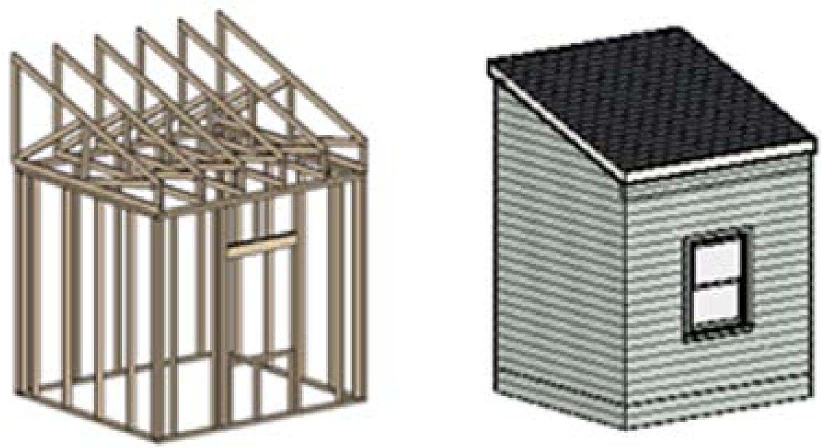


Figure 4.2: Test house design drawings

4.1.2.3 Test House Assembly

Dr. Javier Irizarry and students from the Georgia Tech School of Building Construction lab course BC2620 'Construction Tech II' led in the planning and full assembly of the test house. The model construction planning phase covered estimation of the quantity and cost as well as procurement and delivery of construction materials. The assembly of the test house included the following phases: (1) material pre-processing, (2) pre-assembly, and (3) final assembly in the hemi-anechoic chamber.

The construction process deviated from traditional practices to account for the constraints of working in the hemi-anechoic chamber. The reduced space of the chamber in addition to the requirement to limit the amount of debris—the acoustical properties of the absorptive material lining the walls and ceiling in the hemi-anechoic can be affected by the introduction of dust and debris—necessitated the separate three phases of the test house assembly.

(a) (b)

Figure 4.3: (a) Material pre-processing and (b) wall assembly in reverb chamber

Materials were pre-cut to final dimensions in the Advanced Wood Products Lab at Georgia Tech (Figure 4.3(a)), and then transported to the reverberation chamber adjacent to the hemi-anechoic chamber in the IAL for pre-assembly. As much of the construction as possible—including assembling the structural frames of the walls and roof, or nailing down the asphalt shingles and roof felt paper to the roof OSB sheathing—was completed as pre-assembly in the reverberation chamber (Figure 4.3(b)) to reduce construction dust in the hemi-anechoic chamber.

(a) (b)

Figure 4.4: (a) Installation of roof trusses and (b) finished exterior of test house

Major parts of the test house were then assembled in the hemi-anechoic chamber (Figure 4.4). Bolts were used in connections between adjacent wall panels. Again deviating from traditional construction practice, screws were used instead of nails in many applications (e.g. attaching fiber-cement siding as the exterior façade layer or securing interior gypsum board panels to the wooden framing) to allow for simple replacement of wall layers as well as a more deliberate final deconstruction. Joints between adjacent sheets of drywall in the test house interior were taped and plastered with all-purpose joint compound. Any other gaps found throughout the exterior and interior were filled with energy-efficient insulating foam sealant. Acoustically characterized insulating blankets, manufactured as Insul-Quilt, were evenly distributed and stapled to all walls and the ceiling in the test house interior (Figure 4.5) to simulate the amount of absorption present in a typical residence.

Figure 4.5: Insul-Quilt blankets stapled to test house interior to simulate absorption

4.1.2.4 Test House Absorption

The range of interior absorption that can be modeled by the IBANA-Calc software is from 50% to 150% of the room floor area. Given test house dimensions of 9’ x 10’ x 8’ high, the lowest allowable test house absorption in IBANA-Calc was 4.18 metric Sabins while the highest allowable test house absorption was 12.54 metric Sabins.

RT_{60}, or reverberation time, of the test house was calculated using

$$\boldsymbol{RT_{60}} = \frac{\mathbf{0.16}\boldsymbol{V}}{\boldsymbol{S}_{\text{total}}\ \bar{\propto}} = \frac{\mathbf{0.16}\boldsymbol{V}}{\boldsymbol{A}}, \text{sec} \tag{4.1}$$

Where V is the volume of the test house (m^3), S_{total} is the total surface area of the test house interior (m^2), α_{bar} is the average absorption coefficient of the test house, and A is the Sabine absorption area (m^2)—adapted from [37].

Assuming that the relevant RT_{60} used to calculate the following metric corresponds to the 1000 Hz band, the Schroeder frequency f_s was calculated as

$$\boldsymbol{f_s} = \mathbf{2000}\sqrt{\frac{\boldsymbol{RT_{60}}}{\boldsymbol{V}}}, \text{Hz} \tag{4.2}$$

Where RT_{60} is the reverberation time (sec) and V is the volume of the test house (m^3)—adapted from [37].

Table 4.2 below lists all relevant values corresponding to the low and high absorption conditions. If reverberation time measurements showed that the test house interior absorption fell extremely far outside the range of values, it would have still been possible to calculate modeled noise reduction independent of IBANA-Calc

Table 4.2: Range of possible values for modeling IBANA-Calc interior absorption

IBANA-Calc Absorption	Absorption	RT_{60}	Schroder Frequency
50% of floor area	4.18 m^2	0.78 sec	391 Hz
150% of floor area	12.54 m^2	0.26 sec	226 Hz

Given the total surface area of Insul-Quilt acoustical insulating blankets that were used to treat the test house interior, it was possible to predict the test house absorption using tabulated values (Table 4.3) for the Insul-Quilt as well as common construction materials.

Table 4.3: Sound absorption coefficients of interior surfaces (reproduced from [38])

	Insul Quilt	Drywall*	Plywood* (Floor)	Window*	Human Body*
	SA (m^2)				
	11.89	23.32	8.36	1.39	1.90
f (Hz)	**α**				
125	0.38	0.27	0.28	0.35	2.00
250	1.04	0.10	0.22	0.25	3.00
500	0.98	0.05	0.17	0.18	4.00
1000	0.87	0.04	0.09	0.12	5.00
2000	0.83	0.03	0.10	0.07	5.00
4000	0.80	0.03	0.11	0.04	4.00
		*taken from Mehta, *Architectural Acoustics - Appendix H*			

The average absorption coefficient of the test house α_{bar} could then be calculated as

$$\overline{\propto} = \frac{\sum_i (S_i \propto_i)}{S_{total}} \tag{4.3}$$

Where α_i and S_i are the absorption coefficient and surface area (m^2) of each interior treatment, and S_{total} (m^2) is the total surface area of the test house—adapted from [37].

Figure 4.6 below reports the calculated test house RT_{60} with and without the inclusion of the absorption of a human body—as it was determined early on that, with no electrical wiring or gaps to run electrical wiring through into the test house interior, a human operator would be present during measurements.

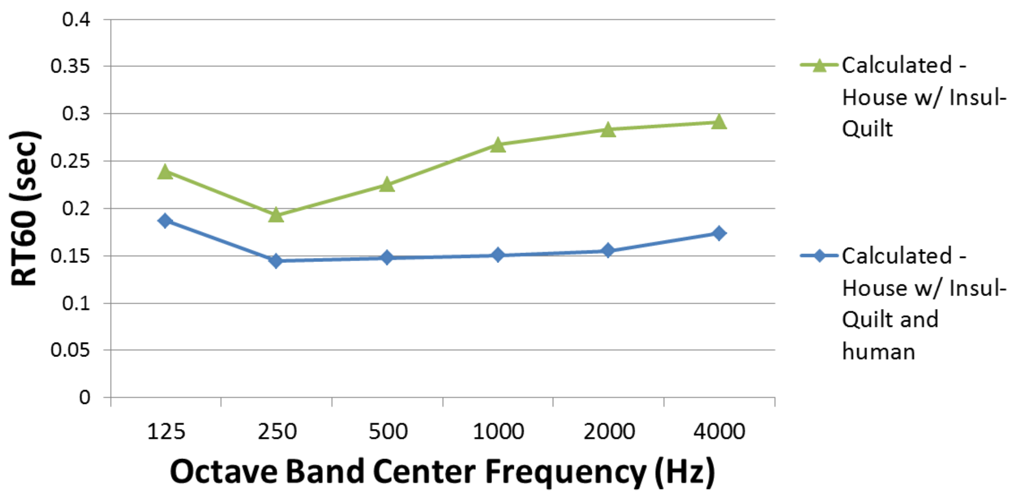


Figure 4.6: Calculated RT60 values for test house interior

4.1.3 Measurement Setup

4.1.3.1 Instrumentation

Table 4.4 is a summary of all equipment used for acoustic laboratory measurements.

Table 4.4: Instruments used in acoustic laboratory measurements

Instrument	Function
JBL EON 510 Self-Powered Loudspeaker	Sound Source
Peavey Impulse 12D Self-Powered Loudspeaker	
Superlux Pink Stick Signal Generator	
Behringer MicroPower PS400 Phantom Power Supply	
Larson Davis System 824 Sound Level Meter (SLM)	Sound Level Measurement
PCB Piezotronics 377A60 Condenser Microphone	
Larson Davis PRM 902 Preamplifier	
Larson Davis CAL200 Acoustic Calibrator	Calibration

The measurement standard ASTM E966-10 specifies the following guidelines for the choice of an artificial sound source:

> "A single loudspeaker enclosure is preferred… It must supply sufficient output in all measurement bands to achieve sound levels at least 5 dB and preferably 10 dB over the background level in the receiving room over the range from 80 to 4000 Hz". [14]

Figure 4.7 compares ambient levels in the test house to representative sound level measurements in the test house with the different loudspeakers generating pink noise at a 'standard' output level to verify the signal-to-noise specification given above. ASTM E966-10 also states that "the electrical signal to the loudspeaker shall consist of random noise over the test frequency range" [14]. As such, most transmission loss measurements were conducted using the Superlux Pink Stick Signal Generator to produce pink noise. The various positions of the sound source are discussed further in Section 4.1.4.1.

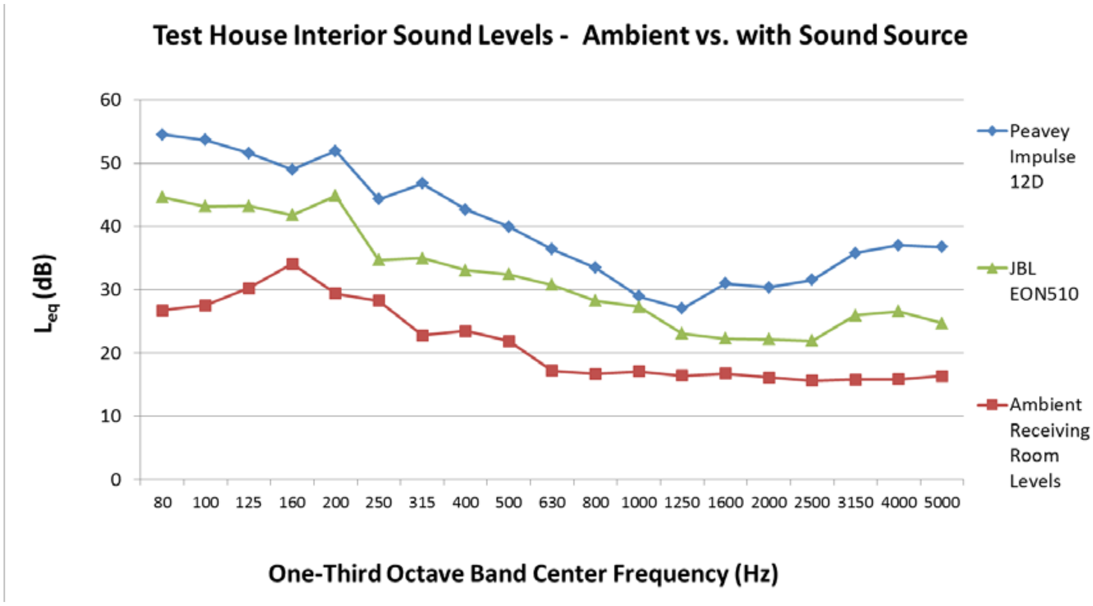


Figure 4.7: Loudspeaker levels and ambient levels measured in test house interior

Also in accordance with specifications given by ASTM E966-10, a Larson Davis System 824 sound level meter (SLM) was used for all sound level and RT60 measurements. The condenser microphones used in all measurements were calibrated with the Larson Davis CAL200 to verify a 114 dB level at 1 kHz before every set of measurements. All measurements used SLM ‘setups’ with user-defined preferences. All sound level measurements were conducted with the 824 virtual Sound Spectrum Analyzer (SSA) with a slow detector and flat weighting across one-third octave band center frequencies. Measurement interval histories were also logged for sound level measurements when needed (i.e. to sync up exterior and interior measurements that started and ended at different times). RT60 measurements used a built-in function on the

824 which is configured for the use of a steady-state noise source that is shut-off to initiate the sound decay measurement.

4.1.3.2 Exterior Sound Level Measurement

ASTM E966-10 specifies 6 different methods for outdoor-to-indoor sound level reduction measurements. This lab study investigated the use of two methods offered by the standard as they required only a loudspeaker as the outdoor signal source—and not a calibrated loudspeaker or line source of traffic noise as necessitated by the four other methods. The two measurements used were: (a) the near average outdoor measurement method and (b) the flush measurement method.

The near average outdoor measurement method (Figure 4.8) is described as follows:

> "To minimize wave interference effects, average five or more measurements at random distances from the specimen, at random positions across the specimen and at varying heights across the specimen. The random distances should be in the range of more than 1.2 m and less than 2.5 m from the specimen. The random positions and random heights should be within the left, right, upper, and lower limits of the specimen." [14]

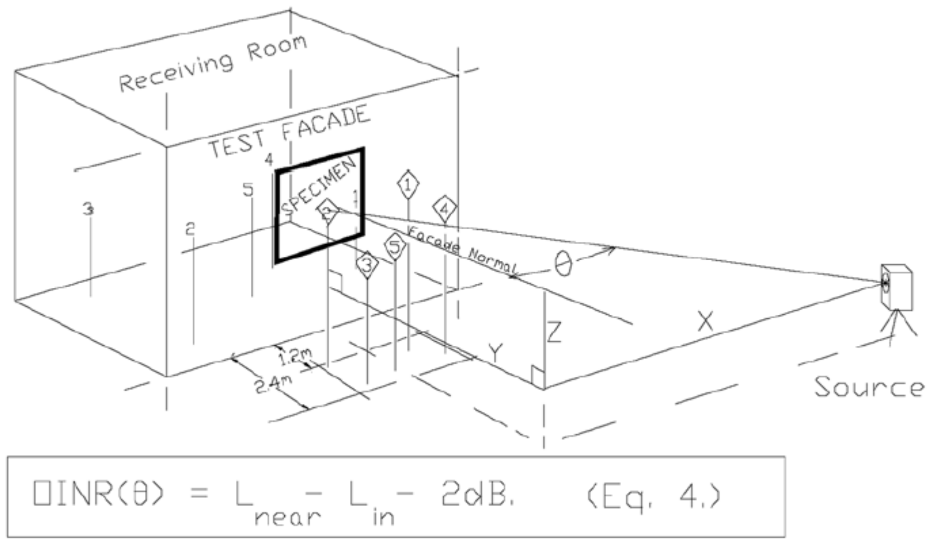
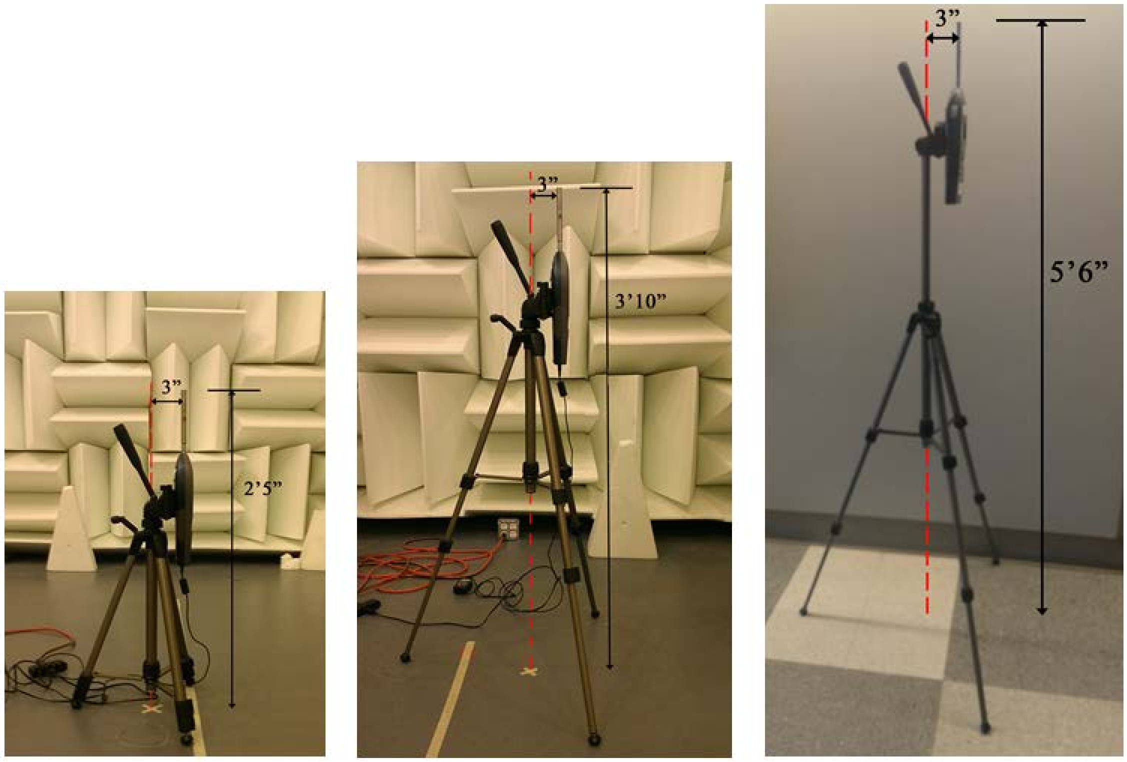


Figure 4.8: Diagram for near average measurements (reproduced from [14])

For near average measurements, six fixed positions were chosen at various distances between 3’11” (1.2 m) and 8’2” (2.5 m) from the front wall of the test house, and all positions were within the left and right limits of the front façade. Three heights for the microphone positions were determined by fixed low (2’5”), medium (3’10”), and high (5’6”) configurations (Figure 4.9(a)-(c)) of the SLM stands used in measurements. Accordingly, 6 out of the 18 possible microphone positions (Figure 4.10) were randomly chosen for each transmission loss measurement using the near average method. Detailed drawings for all measurements (including exterior microphone locations) can be found in Appendix F.



(a) (b) (c)

Figure 4.9: (a) Low, (b) medium, and (c) high configurations of SLM/microphone

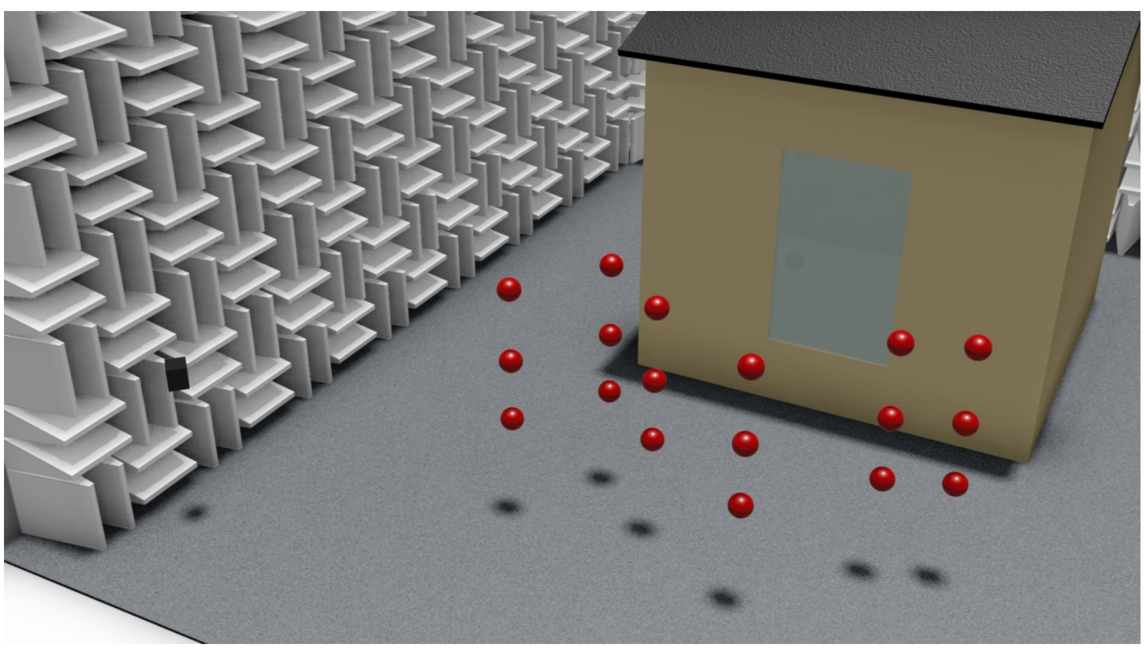


Figure 4.10: 18 exterior microphone positions used for near average measurements

The other exterior measurement technique, the flush measurement method (Figure 4.11), is described as follows:

> "This measurement method is feasible when the specimen is smooth and hard. Measure the sound pressure with a small condenser microphone…mounted very close to the specimen surface at the midpoint and at other positions on the surface of the specimen, but not so close that it is likely to touch the specimen surface or impede the airflow through the microphone grille… It is suggested that up to five measurements about the surface of the specimen be made and averaged."[14]

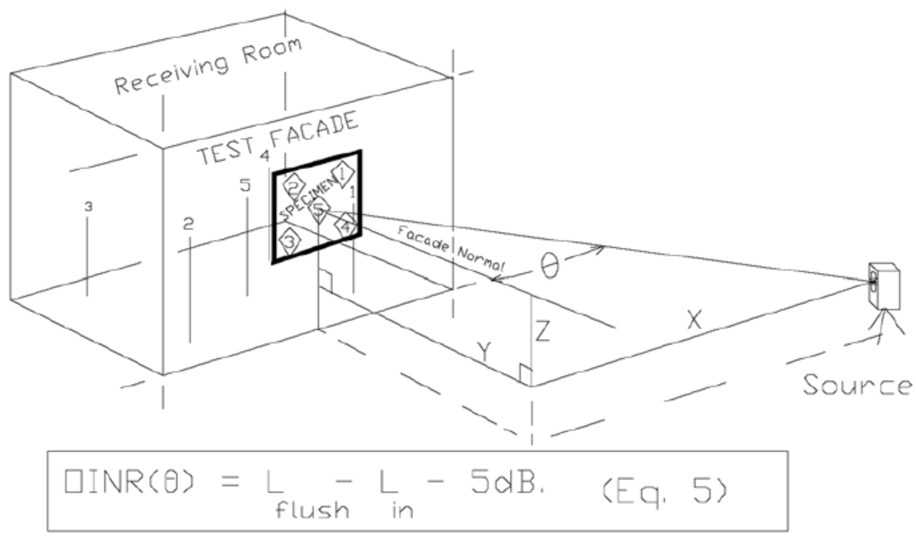


Figure 4.11: Diagram for flush measurements (reproduced from [14])

Extension LEMO audio cables were initially tested to allow for the mounting of the microphone/preamp assembly away from the SLM. However, it was difficult to implement and repeat this measurement configuration while also making sure that the microphone was not "so close that it is likely to touch the specimen", as stated previously. To allow for repeatability then, the microphone and SLM assemblies used for flush measurements were mounted on SLM stands and the microphone was placed as close as possible to the six microphone positions chosen (Figure 4.12). As such, the possible area for the six microphone positions chosen for flush measurements was limited by the minimum and maximum height of the SLM stands used in measurements. Further discussion of the two exterior sound level measurement methods can be found in Section 4.1.4.1.1. Detailed drawings of measurements and tabulated exterior microphone locations can be found in Appendix F.

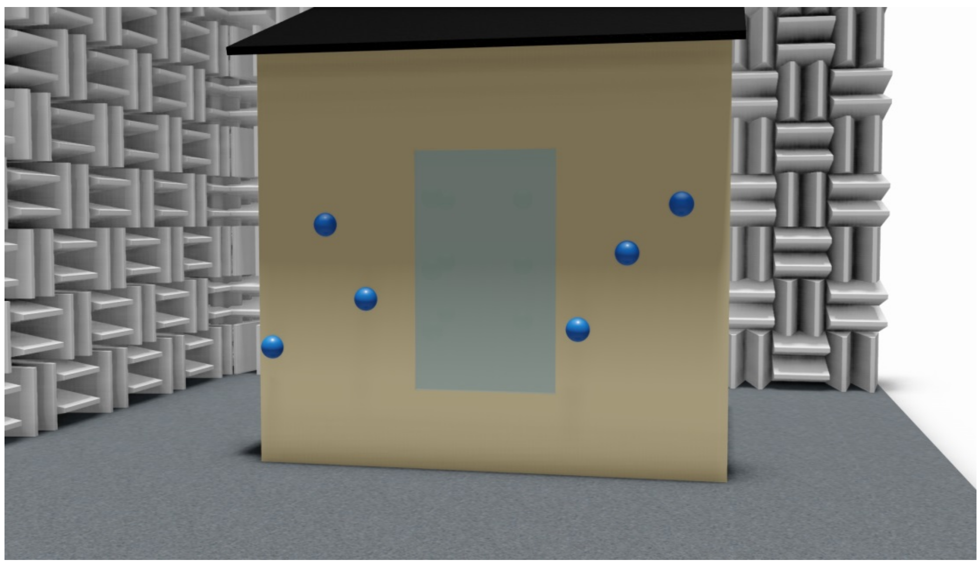


Figure 4.12: 6 façade microphone positions used for flush measurements

4.1.3.3 Interior Sound Level Measurement

ASTM E966-10 necessitated the following conditions for interior measurements of sound level:

> "Fixed microphone positions or a single moving microphone manually swept or moving continuously along a circular path may be used while satisfying the following conditions:

No microphone position shall be closer than 1m to the inside surface of the exterior wall or to any other boundary or extended surface, unless the room is too small to allow adequate microphone positions within this restriction in which case the microphones may be within 0.5 m of surfaces other than the specimen. For a fixed microphone, a minimum of three microphone positions is required, but up to six are recommended. The minimum separation of fixed microphone positions should be 1 m but may be less in small rooms if necessary to get adequate number of microphone positions."[14]

The smallest dimension of the test house is 8' (~2.4 m); if a microphone was placed in the dead center of the house it would still only be about 1.2 m away from reflecting surfaces. As a result, the size of the receiving room determined the use of the secondary restriction to place all interior measurement positions no closer than 0.5 m from reflecting surfaces (Figure 4.13). Given the small size of the test house room, the minimum separation between microphone positions was 0.6 m in order to get an adequate number of positions.

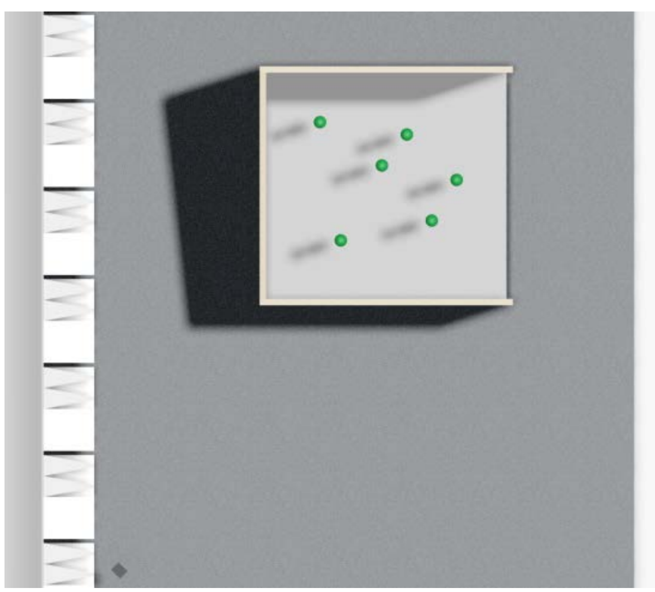


Figure 4.13: Interior microphone positions (Top Down View) no closer than 0.5 m from wall surfaces

As with the near average exterior measurement, 18 possible fixed microphone positions (Figure 4.14) were determined according to the stated guidelines—and 6 were randomly used for each transmission loss measurement. Except for the microphone positions chosen to conform to the restriction of being 1 m away from all reflecting surfaces, potential areas for nodal positions of the interior modes (e.g. the center or other geometric divisions of the test house) were avoided for microphone placement. Detailed drawings for measurements and tabulated interior microphone locations can be found in Appendix F.

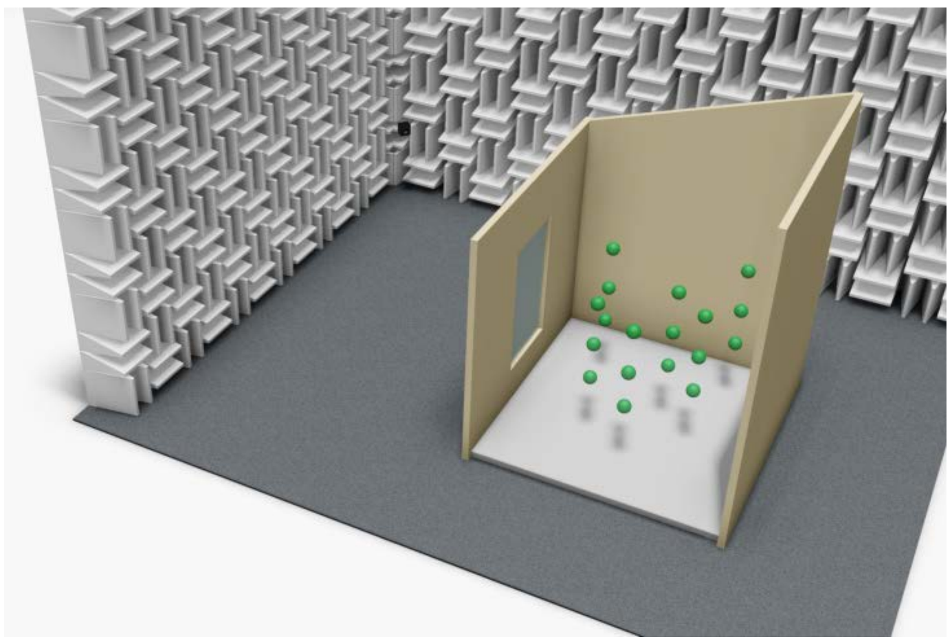


Figure 4.14: 18 interior microphone positions used for sound level measurements

4.1.3.4 Test House Interior Absorption Measurement

The test house was built without electrical wiring, so conducting RT60 measurements with the necessary equipment to characterize the interior absorption presented a unique challenge. SLM operation in the test house interior was feasible with the use of AA batteries to power the meter. However, the use of a sound source—including a loudspeaker, pink noise source, and phantom power supply—required a standard 120V AC outlet. No outlets would be accessible to the test house interior if reverb time measurements were to be made with the window closed and sealed. Initial attempts to circumvent this issue by using a starter pistol as an impulse noise source produced unrepeatable results. As such, a sealed 12 V battery was used with a power inverter to generate an AC source for the noise source setup (Figure 4.15).

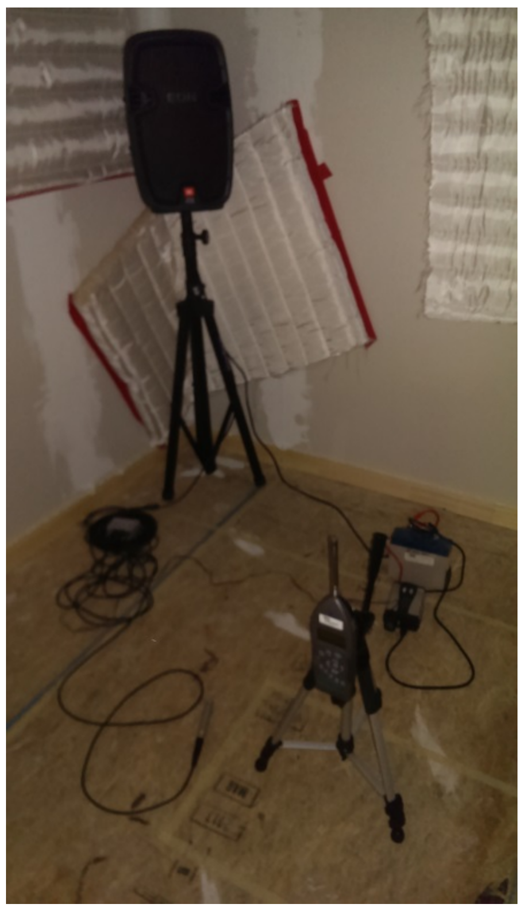


Figure 4.15: Equipment used for RT60 measurements of test house interior

Measurements were conducted with a SLM real-time analyzer (RTA) program intended to be used with a steady-state noise source. When the noise source is shut-off, the SLM would initiate the noise decay measurement. As with interior sound level measurements, random microphone positions and heights were used to avoid proximity to reflecting surfaces and to avoid potential areas for nodal positions of the interior modes. Detailed drawings for all measurements (including interior microphone locations) can be found in Appendix F.

It should be noted that all RT60 measurements required a human operator inside the test house. Accordingly, all interior sound level measurements were also conducted with a human SLM operator inside the test house so that the interior absorption—accounting for the added absorption of a human body—was properly represented.

4.1.3.5 Calculation of OINR and OITL

The SSA virtual instrument on the SLMs used for sound level measurements logged sound pressure level data across frequency (averaged over the entire measurement interval) as well as interval histories—averaged sound pressure level data across frequency divided by user-defined intervals (e.g. 1, 5, or 15 seconds). As human operators of the SLM were required for exterior and interior measurements, it was not possible to simultaneously start and stop measurements conducted in the test house exterior and interior. As such, in addition to calibration at 1 kHz, the internal clocks of SLMs were synced prior to each set of measurements. With the interval histories, only the data corresponding to the relevant time interval for a transmission loss measurement was extracted to use for the calculation of noise reduction and transmission loss.

For each transmission loss measurement, the 6 exterior and 6 interior positions were combined to calculate spatial averages of exterior and interior sound level across frequency. Noise reduction was then calculated in the following fashion described by ASTM E966-10 for the near average measurement method:

> "The presence of the façade approximately doubles the sound pressure near the façade (+3 dB), but in practice, this increase is found less; a 2 dB representation is used here…"[14]

$$\boldsymbol{NR_{near} = L_{near} - L_{in} - 2},\ \text{dB} \tag{4.4}$$

Where L_{near} is the spatial average of the near average exterior sound level measurement (dB) and L_{in} is the spatial average of the interior sound level measurement (dB)—adapted from [14].

Noise reduction measurements conducted using the flush measurement method were also evaluated in accordance with ASTM E966-10:

> "The presence of the façade approximately quadruples the sound pressure (+6 dB) on the specimen. But in practice, this increase is found to be about 5 dB... When the outdoor sound pressure level has been measured very close to the surface…"[14]

$$\boldsymbol{NR_{flush} = L_{flush} - L_{in} - 5},\ \text{dB} \tag{4.5}$$

Where L_{flush} is the spatial average of the flush exterior sound level measurement (dB) and L_{in} is the spatial average of the interior sound level measurement (dB)—adapted from [14].

Having already characterized the interior sound absorption from RT_{60} measurements, transmission loss could be evaluated from NR as

$$\boldsymbol{TL = NR + 10\log\left(\frac{S\cos(\theta)}{A}\right) + 6}, \text{ dB} \tag{4.6}$$

Where S is the area of the specimen being tested (m^2), θ is the horizontal angle of incidence (degrees), and A is the room sound absorption determined in metric Sabins (m^2)—reproduced from [14].

Compare Equation (4.6) used for measurements to the expression used by the IBANA-Calc software in Equation (2.1) ($\boldsymbol{TL = L_1 - L_2 + 10\log\left(\frac{S}{A}\right)}$) to calculate TL—the software assumes field incidence for the noise source. On the other hand, the standard allows for measurements that are dependent on horizontal angle of incidence. ASTM E966-10 uses a convention for horizontal angle of incidence (θ_1 in Fig. 5.16) that defines it as "the angle between a perpendicular line OY at the midpoint of the specimen and the line from that midpoint to the source" [14] as shown in Figure 4.8 and Figure 4.11.

Given the variety of microphone locations—18 exterior near average, 6 exterior façade mounted, and 18 interior positions—that can be used in a particular measurement, it would have been optimal to evaluate the repeatability of this particular methodology. Holding all the other conditions that will be described in detail in Section 4.1.4 constant, confidence intervals should have been established for a single choice of microphone locations to confirm repeatability. No such study was included in this thesis research, however, and will have to be addressed in future work.

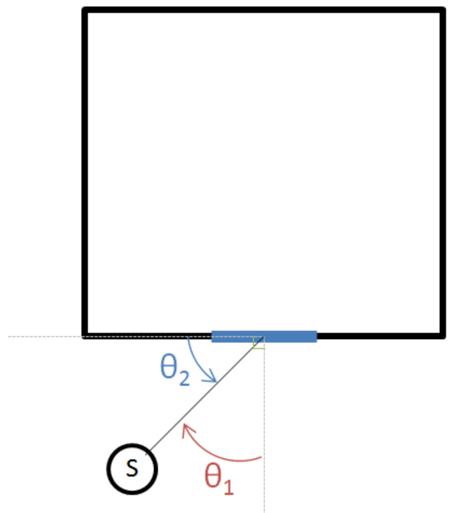


Figure 4.16: Change in convention of horizontal angle of incidence

Given the asymmetric placement of the test house in the hemi-anechoic chamber, source positions at equal angular offsets from normal incidence were not at equal distances away from the test house façade. As such, this lab study used an alternative horizontal angle of incidence (θ_2 in Figure 4.16) which required an adjustment in the calculation of TL. It is apparent from Figure 4.16 that $\theta_2 = 90° - \theta_1$, so with the use of the trigonometric identity that states $\sin(90° - \theta) = \cos(\theta)$, Equation (4.6) for transmission loss was updated to the following:

$$\mathbf{TL} = \boldsymbol{NR} + \mathbf{10}\log\left(\frac{\mathbf{S}\sin(\boldsymbol{\theta_2})}{\boldsymbol{A}}\right) + \mathbf{6}, \text{dB} \tag{4.7}$$

Where S is the area of the specimen being tested (m^2), θ_2 is the horizontal angle of incidence (degrees) and $\theta_2 = 90° - \theta_1$, and A is the room sound absorption determined in metric Sabins (m^2).

4.1.4 Test House Iterations

4.1.4.1 Measurement Iterations

The following measurement iterations were introduced into the laboratory study to investigate the various techniques used in field measurements by acousticians and consultants. These techniques are described by measurement standards and introduce more variance. IBANA-Calc includes “several optional corrections to the spectrum of the incident outdoor aircraft noise and for variations of transmission loss with the relative orientation of the aircraft and the façade” [22] that the lab measurement also set out to investigate.

4.1.4.1.1 Exterior Sound Level Measurement Method

Both the exterior near average and flush methods described by ASTM E966-10 are used in the field by acousticians conducting transmission loss or noise reduction measurements. The IBANA-Calc manual states the following:

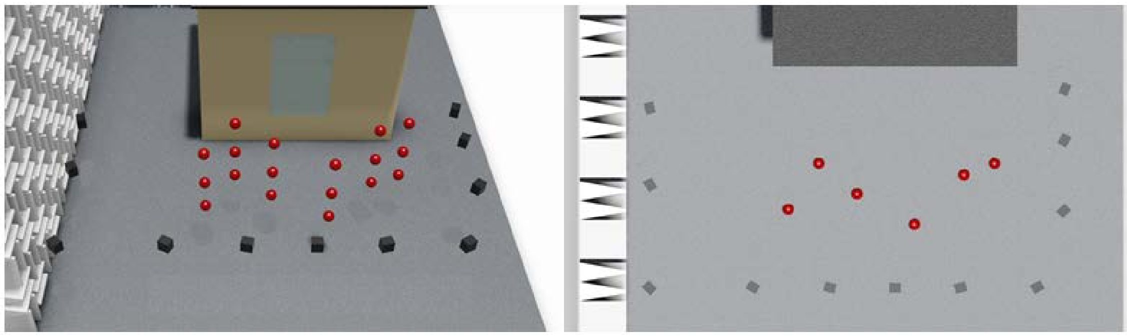
> “The ASTM and ISO measurement standards suggest that it is also acceptable to measure the incident sound with a microphone mounted on the exterior façade of the building and assume that this leads to a 6 dB increase in measured outdoor levels at all frequencies. However, the measurements in this project indicate that this assumption is not a very good approximation to what actually occurs and façade mounted microphones should not be used to obtain measurements of the incident aircraft noise.”[22]

Further investigation of the literature recovered a paper by J.S. Bradley, key developer of the IBANA-Calc software, which stated that “façade mounted” or flush microphones could produce errors of up to 12 dB and that “incident sound levels measured at the building façade are strongly influenced by ground reflections and diffraction effects that vary with the vertical angle of the aircraft" [39]. The IBANA-Calc software has been shown in Section 2.2 to use the near average correction of 2 dB in its calculation of noise reduction. As a result, most transmission loss measurements conducted for the lab study used the near average method to evaluate the exterior sound levels. However, both the near average and flush methods were used for measurements at "standard" conditions to further illuminate differences between these two measurement methods. The "standard" conditions consisted of using a JBL EON510 loudspeaker with pink noise input, 45° from the front façade, 3.4' source height, and closed window—to compare the two methods (near and flush) and to assess the correction factors (-2 dB and -5 dB, respectively) associated with calculating noise reduction.

4.1.4.1.2 Horizontal Incidence Angle of Sound Source

Given the constraints of the size of the hemi-anechoic chamber, the furthest distance the source was placed from the test house front façade was 14'8", at a 45° horizontal incidence angle—most testing was completed at this position. The ASTM standard states that when the objective is to minimize the number of source locations, an incident angle of 45° is preferred, and if the objective is to simulate a diffuse sound field, measurements should be made at 15° increments from 15° to 75° [14]. The objective of the lab measurement was not necessarily to simulate a diffuse sound field, but regardless transmission loss measurements were also conducted at various horizontal incidence angles around the house, from 15° to 165° in 15° increments (Figure 4.17 and Figure

4.18). Detailed drawings for all measurements (including loudspeaker locations) can be found in Appendix F.

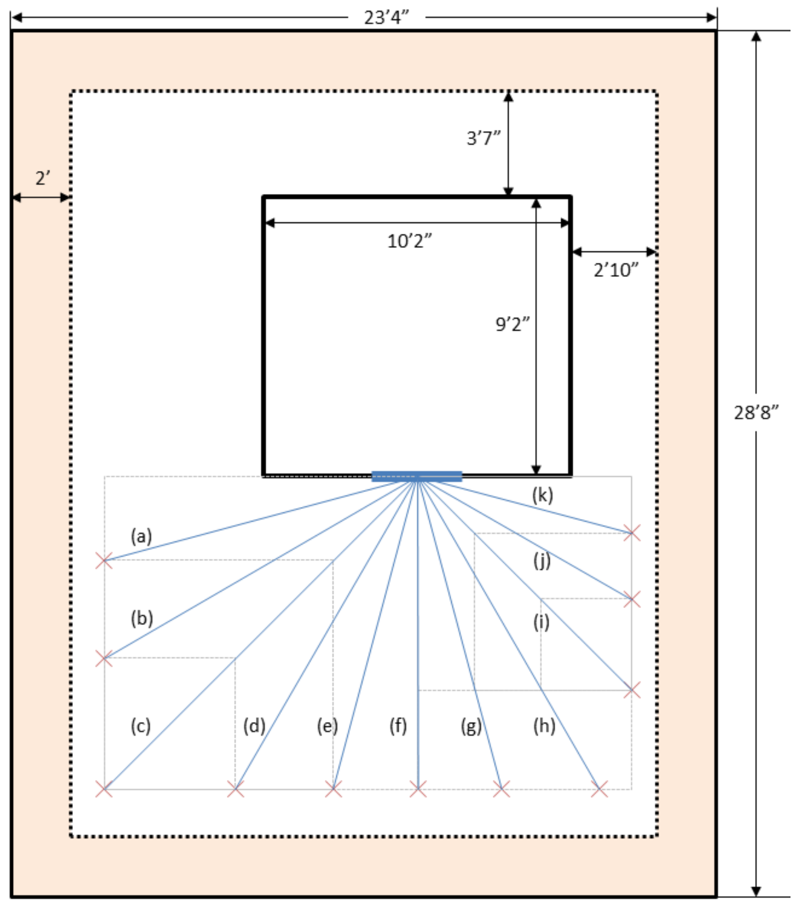


(a) (b)

Figure 4.17: (a) sound source (black boxes) locations with changing horizontal angle of incidence as well as near average microphone positions (red spheres) and (b) top view

Analysis of the literature has shown that the critical frequency, or lowest coincidence frequency, of a partition is determined by the mass and stiffness of the partition as well as the speed of sound (of the medium in which the partition is present) [37]. At a fixed frequency above this critical frequency, it has been shown that sound transmission through the partition can be controlled more by stiffness and damping control than mass control as the angle of incidence approaches grazing [37]. By our convention, grazing would be approaching an angle of incidence as small as 0° or as large as 180°. As this study used complex sound sources, we determined horizontal angles of incidence approaching grazing would still be reasonably valid in comparison to Insul wall models that assume the mass law.

The specifications for the JBL loudspeaker report a coverage pattern of 100° horizontally and 60° vertically. Figure 4.18 illustrates the the different horizontal angle iterations used in transmission loss measurements. E966-10 requires that the "source shall be far enough from the specimen so that the ratio of the distances from the source in the farthest and nearest parts of the test surface is no more than two" [14]. Although this requirement was apparently violated at angles less than 45° and greater than 120°, it was decided to measure transmission loss at all the following source positions while expecting greater variance in the results of the measurements.

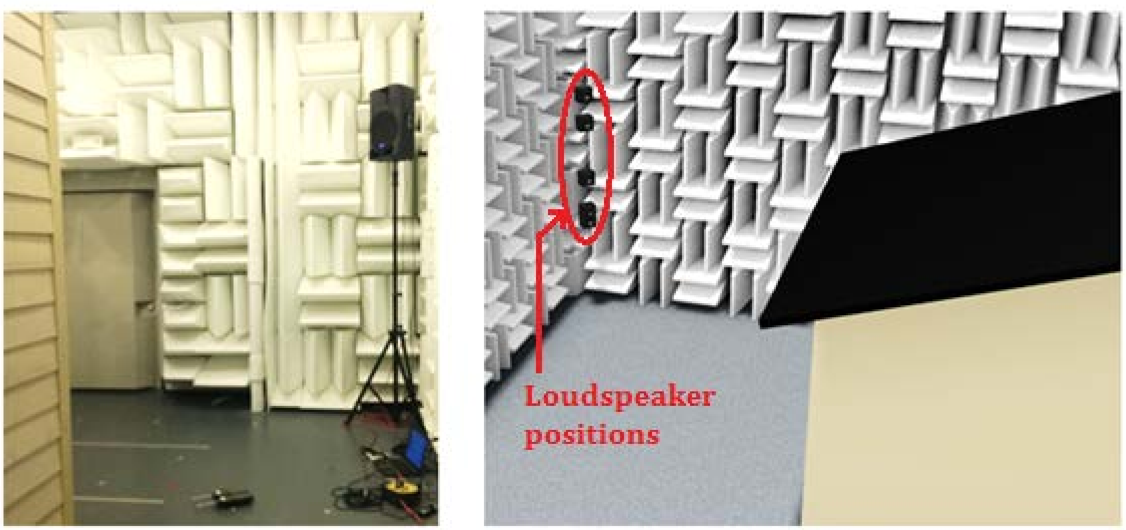


	(a)	(b)	(c)	(d)	(e)	(f)	(g)	(h)	(i)	(j)	(k)
Horizontal Incidence Angle	15°	30°	45°	60°	75°	90°	105°	120°	135°	150°	165°
Distance from source to center of test house front wall (ft)	10'8"	12'	14'8"	12'	10'8"	10'4"	10'8"	12'	10'	8'2"	7'4"

Figure 4.18: Horizontal incidence angle of sound source iterations

4.1.4.1.3 *Vertical Incidence Angle of Sound Source*

FAA Technical Directive Memorandum 0017 – "Study of Noise Level Reduction (NLR) Variation" [27] statistically compared the results of field measurements using an outdoor loudspeaker mounted on a tripod to field measurements using an outdoor loudspeaker mounted on a crane. It was decided to similarly introduce variation in the vertical incidence angle of sound source to the lab measurement. The maximum height of the loudspeaker source was limited by the mounting procedure used. Even with the use of the oversized speaker stand shown in Figure 4.19(a), placing the loudspeaker at heights greater than 8' appeared to be unstable and possibly unsafe.



(a) (b)

Figure 4.19: (a) Peavey loudspeaker on extension speaker stand and (b) different vertical positions of sound source (circled in red)

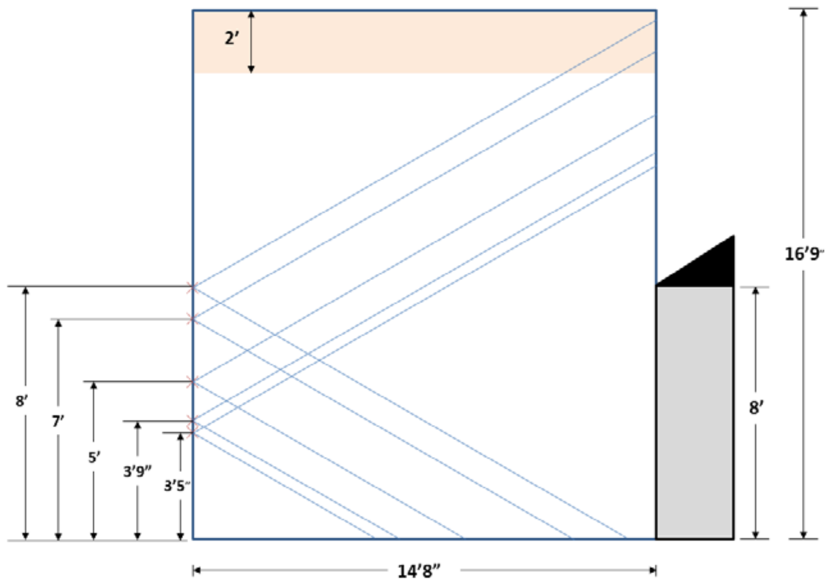
However, IBANA-Calc models were generated without including the software's correction to account for vertical angle of incidence. The IBANA-Calc validation study recommended users to "not use the vertical angle correction for vertical angles less than

60 degrees" [34]. The loudspeaker source at the highest position used in the study corresponded to a vertical angle of 15° incident relative to the plane coincident with half the height of the test house.

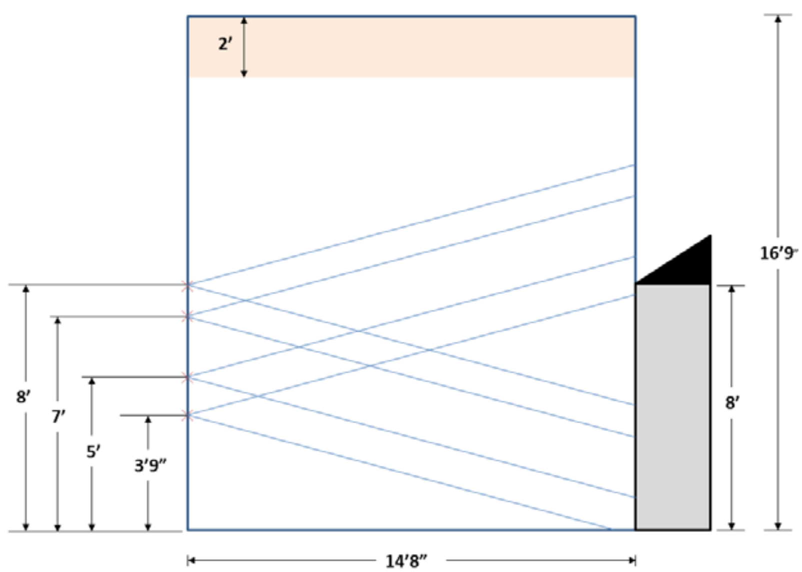
4.1.4.1.4 Sound Source

The JBL EON510 self-powered loudspeaker was used in 59 of 91 transmission loss measurements. Due to the speaker's reduced nominal coverage pattern, the Peavey Impulse 12D self-powered loudspeaker was used exclusively for the 32 measurements investigating the effects of vertical incidence angle of sound source. As stated before, the specifications for the JBL loudspeaker report a coverage pattern of 100° horizontally and 60° vertically, whereas the specifications for the Peavey report a coverage pattern of 100° horizontally and 30° vertically. As the maximum distance of the source from the front façade of the test house was limited by the size of the hemi-anechoic chamber, it was assumed that the smallest nominal vertical coverage pattern would better approximate the incident plane waves of distant aircraft sound sources. Figure 4.20(a) illustrates the coverage pattern of the JBL EON510 if it were used for the different vertical angle iterations, and Figure 4.20(b) illustrates the coverage pattern of the Peavey Impulse 12D as it was used for the different vertical angle iterations. Given the limit on the maximum allowable distance from the sound source to the test house, it was decided that the JBL EON510 would have likely not generated much variance in the test house exposure to the sound source for vertical incidence angle testing.

It was not possible in this study to pivot the loudspeaker at various vertical heights to direct its main axis towards, for example, the plane coinciding with half the height of the test house to create a more accurate vertical angle of incidence. However, the following vertical angles of incidence (as shown in Figure 4.20) were evaluated as if it were possible to pivot the loudspeaker: 1° at 3’9”, 4° at 5’, 11.5° at 7’, and 15° at 8’.



(a)



(b)

Figure 4.20: Vertical coverage pattern for (a) JBL EON510 and (b) Peavey Impulse 12D

4.1.4.1.5 Window Condition

Measurements were conducted to investigate the effect of leaving the window closed versus half-open or fully open (Figure 4.21), as this condition can be relevant to acoustical consultants conducting field transmission loss measurements and provided an opportunity for a straight-forward, no-cost source of variance in the measurements.

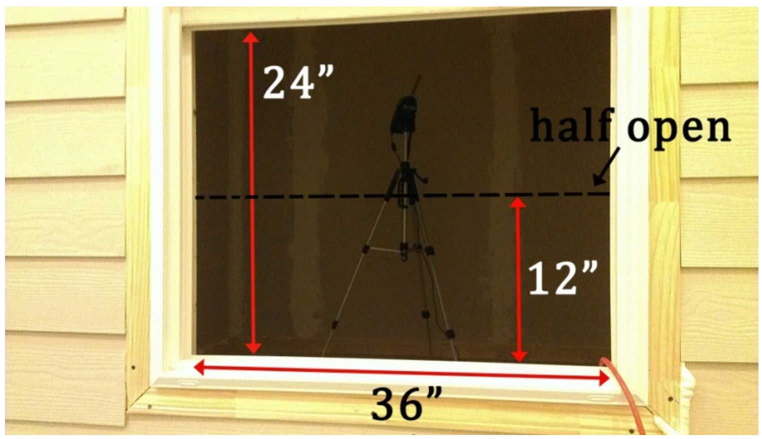


Figure 4.21: Dimensions of window opening for half-open and fully open configurations

The various window conditions were modeled in separate IBANA-Calc scenarios as an ‘Opening’ (Figure 4.22).

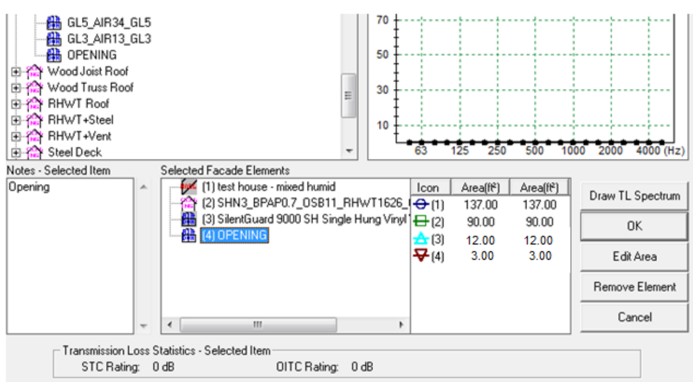


Figure 4.22: ‘Opening’ input as façade element in IBANA-Calc software

4.1.4.1.6 Sound Source Signal Type

Both pink noise and a recording of a 737 jet flyby were used as the sound source signal at the different vertical incidence angles. The 20 second recording is a .wav file embedded in the IBANA-Calc software to simulate the aircraft flyby as it would sound outdoors and indoors for a scenario. The aircraft signature would be filtered according to the user-defined NEF value for the noise source and the transmission loss/noise reduction values calculated for the user-defined construction.

4.1.4.2 Construction Iterations

The following construction iterations were introduced into the laboratory measurement study to help further develop a comprehensive database of transmission loss performance across frequency. RT60 measurements to characterize the interior sound absorption were conducted for the various construction iterations.

4.1.4.2.1 Windows with Varying Acoustical Performance

Windows are often the poorest performing façade element in typical residential constructions. As concluded by Firesheets, the performance of the window relative to the other façade elements can dictate the whole-house acoustical performance, except in cases of very poor performing wall or roof constructions [19]. Three 3' x 5' vinyl, single-hung Atrium Silent Guard® windows with varying acoustical performance were used for the lab measurement because the manufacturer was able to supply acoustical testing data reporting transmission loss across frequency for each window. Table 4.5 below provides a summary of the windows used with single-number ratings, and transmission loss data across frequency can be seen as they were input in IBANA-Calc models in Appendix B. It should be noted that the testing data provided by the manufacturer reported for windows of slightly different sizes than that was used in the test house construction—testing data for the 7100 series reported results for a 4’ x 6’ window and the 9000 series reported results for 4’ x 5’ windows.

Table 4.5: Windows used in test house construction

Window	STC	Description
SilentGuard 9000 SH	25	3/32" glazing - 9/16" gap/space - 3/32" glazing
SilentGuard 9000 SH	31	1/8" glazing - 13/16" gap/space - 1/8" glazing
SilentGuard 7100 SH	41	2 x 1/8" glazing - 11/16" gap/space - 1/8" glazing

4.1.4.2.2 Layers of Interior Gypsum Board

Adding a layer of gypsum board can increase sound insulation, especially at lower frequencies due to the increased heaviness and damping of the wall layer [40]. Table 4.6 highlights the updated construction configuration with a second layer of gypsum board. The extra layer of gypsum board was attached to the test house interior at the same joints/studs as the first layer—longer screws were staggered along the joints to avoid the attachment points of the original gypsum board layer.

Table 4.6: Structure composition with (a) single and (b) double layer of gypsum board

Layer	Walls	Roof	
1	Fiber-cement siding (7/16")	Asphalt shingles	*Exterior*
2	House wrap	Roofing felt	↓
3	Oriented Strand Board (OSB; 7/16")	Oriented Strand Board (OSB; 7/16")	
4	2x4 wood framing @ 24" on center	Raised-heel wood truss framing	
5	3 ½" lay-in fiberglass cavity insul (R-	6 ¼" lay-in fiberglass cavity insul (R-19)	
6	½" gypsum board	½" gypsum board	*Interior*

(a)

Layer	Walls	Roof	
1	Fiber-cement siding (7/16")	Asphalt shingles	*Exterior*
2	House wrap	Roofing felt	↓
3	Oriented Strand Board (OSB; 7/16")	Oriented Strand Board (OSB; 7/16")	
4	2x4 wood framing @ 24" on center	Raised-heel wood truss framing	
5	3 ½" lay-in fiberglass cavity insul (R-	6 ¼" lay-in fiberglass cavity insul (R-19)	
6	½" gypsum board	½" gypsum board	
7	½" gypsum board	½" gypsum board	*Interior*

(b)

4.1.4.3 <u>Summary of Testing Iterations</u>

Table 4.7 below displays the conditions used for the total laboratory sound insulation measurements of the constructed test house. The measurements numbered as 3, 6, and 9 are the only measured iterations that included the same set of all conditions.

Table 4.7: Summary of testing iterations used for lab study measurements

	Instrumentation		Sound Source		Exterior Level Msmt						
#	JBL EON 510	Peavey Impulse 12D	Pink Noise	737 recording	Near average	Flush	**Window STC**	**Window condition**	**Horizontal Incidence Angle (deg)**	**Vertical Height of Source (ft)**	**Layers of Interior Gypboard**
1	X		X			X	31	closed	45	3.4	1
2	X			X	X		31	closed	45	3.4	1
3	X		X		X		31	closed	45	3.4	1
4	X		X		X		31	closed	15	3.4	1
5	X		X		X		31	closed	30	3.4	1
6	X		X		X		31	closed	45	3.4	1
7	X		X		X		31	half	45	3.4	1
8	X		X		X		31	open	45	3.4	1
9	X		X		X		31	closed	45	3.4	1
10	X		X		X		31	closed	60	3.4	1
11	X		X		X		31	closed	75	3.4	1
12	X		X		X		31	closed	90	3.4	1
13	X		X		X		31	closed	105	3.4	1
14	X		X		X		31	closed	120	3.4	1
15	X		X		X		31	closed	135	3.4	1
16	X		X		X		31	closed	150	3.4	1
17	X		X		X		31	closed	165	3.4	1
18		X		X	X		31	closed	45	3.75	1
19		X	X		X		31	closed	45	3.75	1
20		X		X	X		31	closed	45	5	1
21		X	X		X		31	closed	45	5	1
22		X		X	X		31	closed	45	7	1
23		X	X		X		31	closed	45	7	1
24		X		X	X		31	closed	45	8	1
25		X	X		X		31	closed	45	8	1
26	X		X			X	25	closed	45	3.4	1
27	X		X		X		25	closed	45	3.4	1
28	X		X		X		25	half	45	3.4	1
29	X		X		X		25	open	45	3.4	1
30	X		X		X		25	closed	15	3.4	1

Table 4.7 (cont.): Summary of testing iterations used for lab study measurements

#	Instrumentation: JBL EON 510	Instrumentation: Peavey Impulse 12D	Sound Source: Pink Noise	Sound Source: 737 recording	Exterior Level Msmt: Near average	Exterior Level Msmt: Flush	**Window STC**	**Window condition**	**Horizontal Incidence Angle (deg)**	**Vertical Height of Source (ft)**	**Layers of Interior Gypboard**
31	X		X		X		25	closed	30	3.4	1
32	X		X		X		25	closed	60	3.4	1
33	X		X		X		25	closed	75	3.4	1
34	X		X		X		25	closed	90	3.4	1
35	X		X		X		25	closed	105	3.4	1
36	X		X		X		25	closed	120	3.4	1
37	X		X		X		25	closed	135	3.4	1
38	X		X		X		25	closed	150	3.4	1
39	X		X		X		25	closed	165	3.4	1
40		X		X	X		25	closed	45	3.75	1
41		X	X		X		25	closed	45	3.75	1
42		X		X	X		25	closed	45	5	1
43		X	X		X		25	closed	45	5	1
44		X		X	X		25	closed	45	7	1
45		X	X		X		25	closed	45	7	1
46		X		X	X		25	closed	45	8	1
47		X	X		X		25	closed	45	8	1
48	X		X			X	41	closed	45	3.4	1
49	X		X		X		41	closed	45	3.4	1
50	X		X		X		41	half	45	3.4	1
51	X		X		X		41	open	45	3.4	1
52	X		X		X		41	closed	15	3.4	1
53	X		X		X		41	closed	30	3.4	1
54	X		X		X		41	closed	60	3.4	1
55	X		X		X		41	closed	75	3.4	1
56	X		X		X		41	closed	90	3.4	1
57	X		X		X		41	closed	105	3.4	1
58	X		X		X		41	closed	120	3.4	1
59	X		X		X		41	closed	135	3.4	1
60	X		X		X		41	closed	150	3.4	1

Table 4.7 (cont.): Summary of testing iterations used for lab study measurements

#	Instrumentation		Sound Source		Exterior Level Msmt						
#	JBL EON 510	Peavey Impulse 12D	Pink Noise	737 recording	Near average	Flush	**Window STC**	**Window condition**	**Horizontal Incidence Angle (deg)**	**Vertical Height of Source (ft)**	**Layers of Interior Gypboard**
61	X		X		X		41	closed	165	3.4	1
62		X		X	X		41	closed	45	3.75	1
63		X	X		X		41	closed	45	3.75	1
64		X		X	X		41	closed	45	5	1
65		X	X		X		41	closed	45	5	1
66		X		X	X		41	closed	45	7	1
67		X	X		X		41	closed	45	7	1
68		X		X	X		41	closed	45	8	1
69		X	X		X		41	closed	45	8	1
70		X	X		X		41	closed	45	3.75	2
71		X		X	X		41	closed	45	3.75	2
72		X	X		X		41	closed	45	5	2
73		X		X	X		41	closed	45	5	2
74		X	X		X		41	closed	45	7	2
75		X		X	X		41	closed	45	7	2
76		X	X		X		41	closed	45	8	2
77		X		X	X		41	closed	45	8	2
78	X		X			X	41	closed	45	3.4	2
79	X		X		X		41	closed	45	3.4	2
80	X		X		X		41	half	45	3.4	2
81	X		X		X		41	open	45	3.4	2
82	X		X		X		41	closed	15	3.4	2
83	X		X		X		41	closed	30	3.4	2
84	X		X		X		41	closed	60	3.4	2
85	X		X		X		41	closed	75	3.4	2
86	X		X		X		41	closed	90	3.4	2
87	X		X		X		41	closed	105	3.4	2
88	X		X		X		41	closed	120	3.4	2
89	X		X		X		41	closed	135	3.4	2
90	X		X		X		41	closed	150	3.4	2
91	X		X		X		41	closed	165	3.4	2

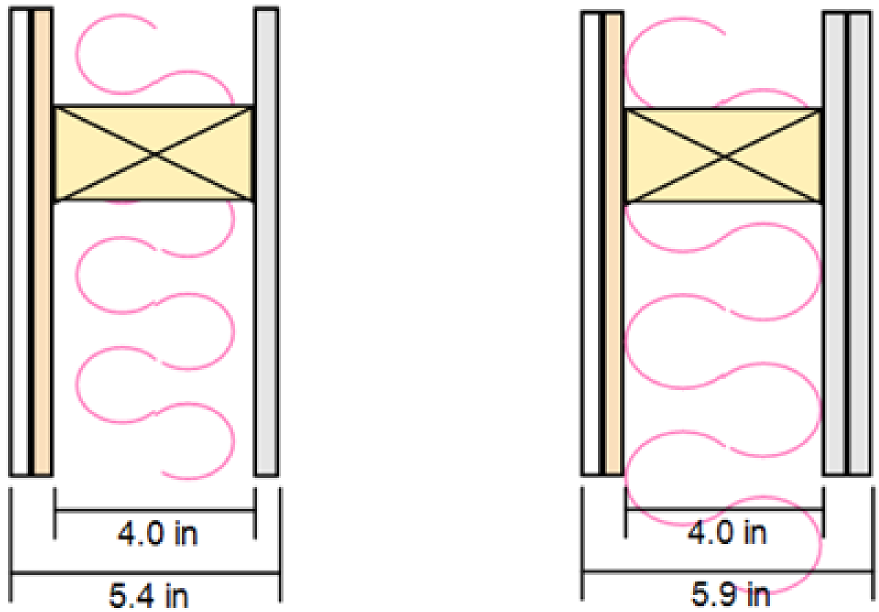
4.1.5 Predicted Models of Test House

4.1.5.1 Insul Wall Models

Refer to Section 2.1 for an overview of the Insul modeling software. Insul was used to model the transmission loss of the test house wall structure. Table 4.8 shows relevant material properties used by Insul to model the wall structure, which was modelled layer by layer using the same parameters shown in Table 4.6 in Section 4.1.4.2. The construction configuration including a single layer of gypsum board (Figure 4.23(a)) resulted in an STC rating of 46 and an OITC rating of 36; the configuration including two layers of gypsum board (Figure 4.23(b)) resulted in a STC rating of 48 and an OITC rating of 42. Transmission loss data across frequency for both configurations is provided in Appendix A. The layer of Tyvek® house wrap that was included in between the fiber-cement siding and the OSB sheathing was not modeled in Insul due to its negligible mass.

Table 4.8: Material properties used for wall structure model in Insul

Material	Surface Mass (lb/ft^2)	Young's Modulus (10^6 psi)	Critical Frequency (Hz)	Spacing (in)	Density (lb/ft^3)	Thickness (in)
Fiber-cement	3.55	1.06	2700	-	97	-
Oriented Strand Board	1.28	0.553	2242	-	35	-
Timber Stud	-	-	-	22	-	-
Fiberglass insulation	-	-	-	-	0.6	4
Gypsum plasterboard	1.79	0.292	2992	-	43	-



(a) (b)

Figure 4.23: (a) Single and (b) double layer gypsum board Insul wall models

4.1.5.2 IBANA-Calc Composite Models

Refer to Section 3.2 for an overview of the IBANA-Calc modeling software. The wall transmission loss data produced by Insul and the transmission loss data provided by the window manufacturer of the three windows used in the test house were input as custom wall and window façade elements into the IBANA-Calc TL database. As stated in Section 5.1.2.1, the general lack of transmission loss data for roof/ceiling structures prompted the use of a RHWT roof already included in the IBANA-Calc TL database. The resulting composite models in IBANA-Calc were produced using iterations of the following façade elements that corresponded to the actual configurations of the test house:

- Walls (2 total) – 137 ft^2 total, accounting for two walls of the test house

- Single layer of gypsum board
  - Fiber-cement: 7/16", OSB: 7/16", 2x4 wood studs, 24" O.C., fiberglass insulation: 3.5", gyp board: 1/2"
- Double layer of gypsum board
  - Fiber-cement: 7/16", OSB: 7/16", 2x4 wood studs, 24" O.C., fiberglass insulation: 3.5", gyp board: 1/2", gyp board: 1/2"

- Windows (3 total) – 15 ft^2 total
  - Atrium SilentGuard® 9000 SH (STC 25)
    - 15 ft^2 for closed, 12 ft^2 for half-open, 9 ft^2 for fully-open
  - Atrium SilentGuard® 9000 SH (STC 31)
    - 15 ft^2 for closed, 12 ft^2 for half-open, 9 ft^2 for fully-open
  - Atrium SilentGuard® 7100 SH (STC 41)
    - 15 ft^2 for closed, 12 ft^2 for half-open, 9 ft^2 for fully-open
  - Opening
    - 3 ft^2 for half-open, 6 ft^2 for fully-open
- Roof - 90 ft^2 total
  - Raised-heel wood truss (RHWT) roof
    - Asphalt shingles, building paper, 0.433 in OSB, RHWT with R-20 fiberglass cavity insulation, 0.512 in gypsum board, no vents installed

Transmission loss data across frequency for all façade elements and composite IBANA-Calc models used in this study is provided in Appendix B.

4.2 Results – Lab Validation

4.2.1 RT60 Measurements

Interior absorption measurements were conducted for the test house as described in Section 4.1.3.4. RT_{60} values across frequency—calculated spatial averages of 10 decay measurements—are tabulated in Appendix C with values most relevant to this study highlighted in blue. Figure C.1-Figure C.4 in Appendix C plot the RT60 values with a logarithmic interpolation fit line.

Figure 4.24 below compares the average of all RT60 measurements at full octave band center frequencies to the calculated values previously shown in Figure 4.6. It is apparent that the absorption matches prediction above 250 Hz. Initial analysis of the test house interior absorption revealed a Schroeder frequency around 200-250 Hz, depending on the construction iteration, which explains the large deviation between measured and calculated reverberation times in the low frequencies of Figure 4.24. Therefore, this study narrowed the focus of the software validation to one-third octave band center frequencies above 250 Hz—that is, from 315 Hz to 5000 Hz.

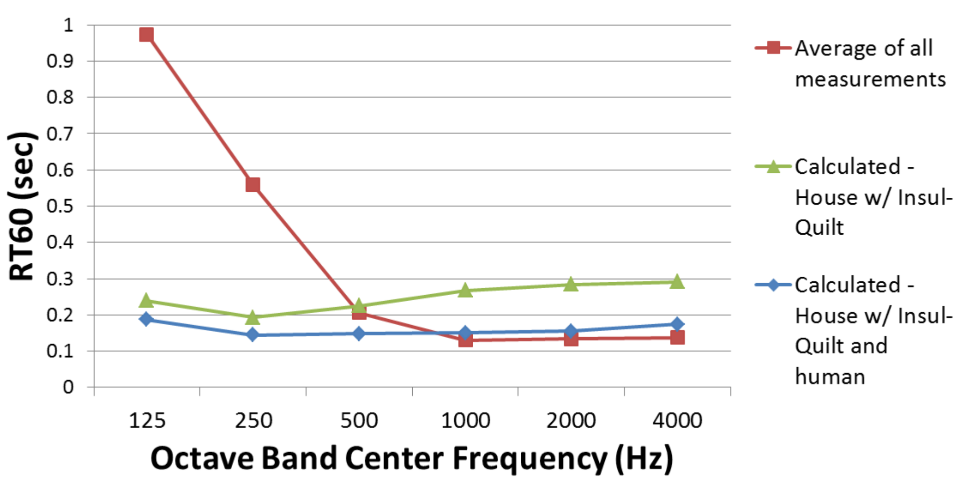


Figure 4.24: Measured and calculated RT60 values for test house interior

4.2.2 Overall Noise Reduction and Transmission Loss Results

4.2.2.1 IBANA-Calc Models

Calculated absorption values were used to set the test house absorption in the composite IBANA-Calc models for each construction iteration—as a result most models used the maximum "150% floor area" for the scenario absorption. Preliminary RT_{60} measurements of the construction configuration with the STC 41 window and a single layer of gypsum board appeared to reveal a reverberation time at 1000 Hz that would correspond to an absorption of "130% floor area" to be used in IBANA-Calc models (for only that configuration). Further review of the reverberation time measurements exposed outliers which skewed the spatial RT_{60} averages, however, and as shown in Figure C.1-Figure C.4 the corrected RT_{60} values at 1000 Hz corresponded to an interior absorption greater than the maximum "150% floor area" used for all other construction iterations. It should be noted that setting an absorption of "130% floor area" for IBANA-Calc models which included the STC 41 window and a single layer of gypsum board resulted in NR values across frequency that were 0.6-0.7 dB lower than if "150% floor area" had been used. TL values were unchanged by the representation in absorption.

Figure 4.25 through Figure 4.28 show the composite TL performance predicted by IBANA-Calc, as well as the TL performance of each façade element used in the model for the particular construction iteration. IBANA-Calc models were generated without any of the corrections described in Section 2.2.1. As stated before, transmission loss data across frequency for all façade elements and composite IBANA-Calc models used in this study is provided in Appendix B.

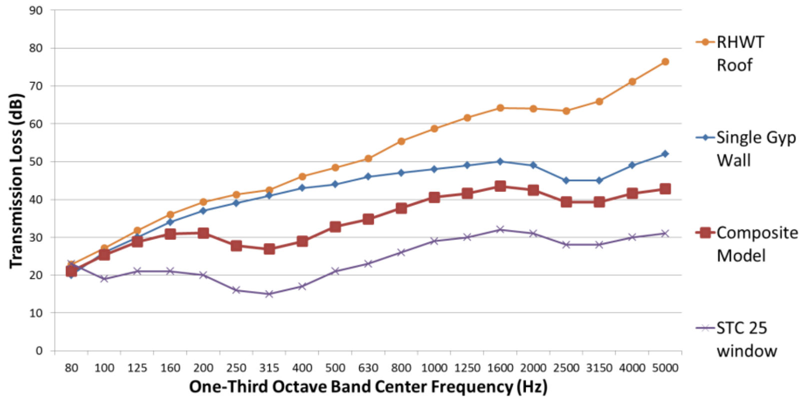


Figure 4.25: Predicted composite TL performance for STC 25 window and single gypsum board

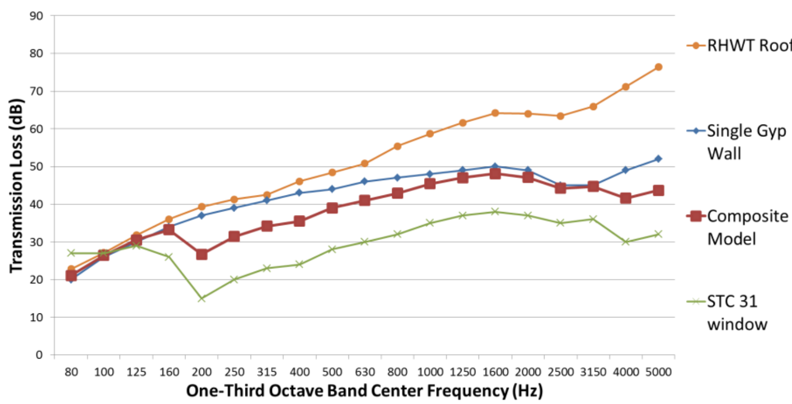


Figure 4.26: Predicted composite TL performance for STC 31 window and single gypsum board

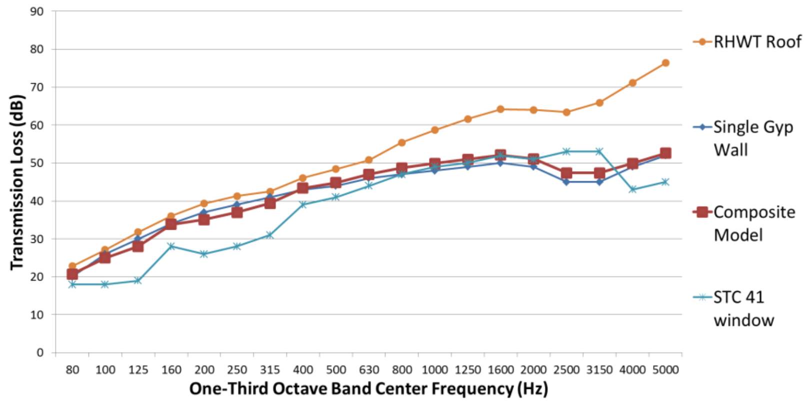


Figure 4.27: Predicted composite TL performance for STC 41 window and single gypsum board

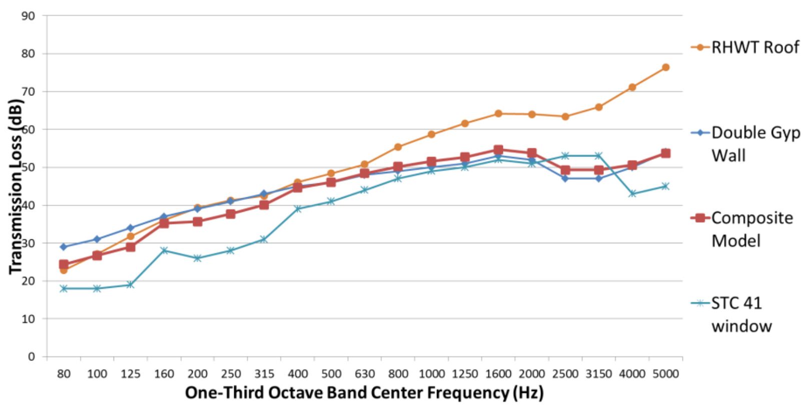


Figure 4.28: Predicted composite TL performance for STC 41 window and double gypsum board

The IBANA-Calc models generated in this study reveal similar conclusions to Firesheets' thesis [19] (discussed in Section 1.5.1). The composite model for TL appears to shadow the performance of the weakest performing element for the STC 25 and 31 configurations. And yet when the window and wall perform similarly, as shown for the STC 41 configurations, additional noise attenuation measures such as the extra layer of gypsum board do not appear to increase the composite TL performance by much. It is also interesting to note the drop in TL at the 2500 Hz and 3150 Hz frequency bands that can be seen for the composite models corresponding to the STC 25 (Figure 4.25) and STC 41 (Figure 4.27-Figure 4.28) windows. The dip is less pronounced at these frequency bands for the predicted TL of the STC 31 window whole house model, which appears to follow the shape of the window TL curve above 2500 Hz. All other models (with the STC 25 and 41 windows) appear to follow the shape of the wall TL curve.

4.2.2.2 Measured NR and TL

NR and TL measured across frequency are tabulated for all test iterations in Appendices D and E. The values for NR and TL across frequency, averaged across all construction and measurement iterations included in this study, are plotted across frequency in Figure 4.29 and Figure 4.30. It can be seen that both NR and TL varied across frequency, and that the general trend was an increase in NR and TL from 50-5000 Hz. Minimum NR ranged from 8-17 dB, mean NR ranged from 28-42 dB, and maximum NR ranged from 37-53 dB across frequency. Minimum TL ranged from 15-24 dB, mean TL ranged from 39-48 dB, and maximum TL ranged from 51-61 dB across frequency.

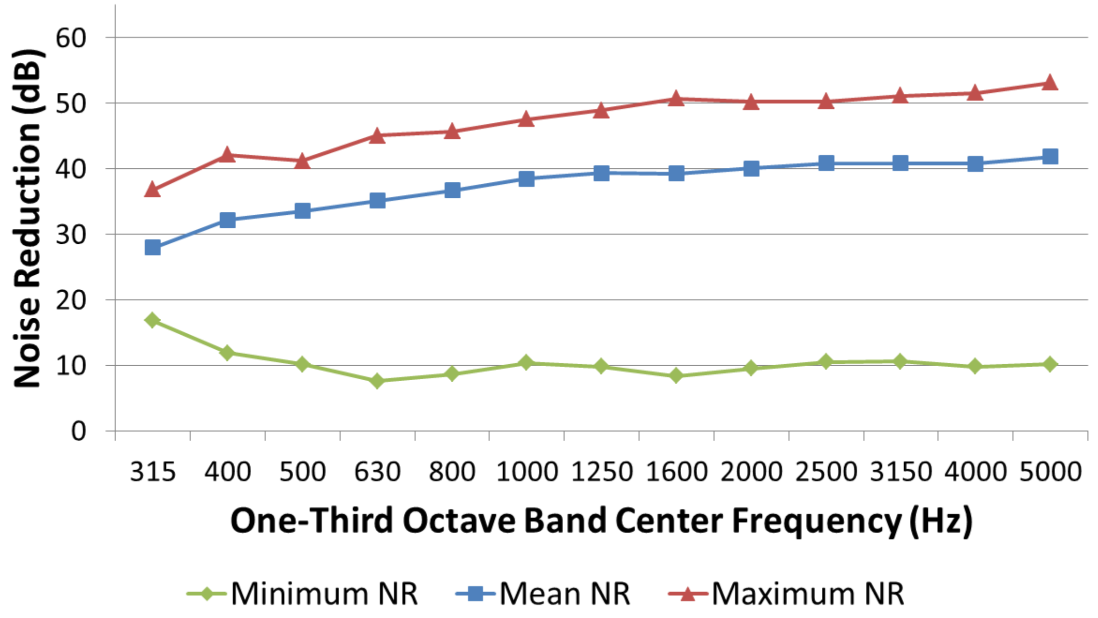


Figure 4.29: Minimum, mean, and maximum NR across all iterations

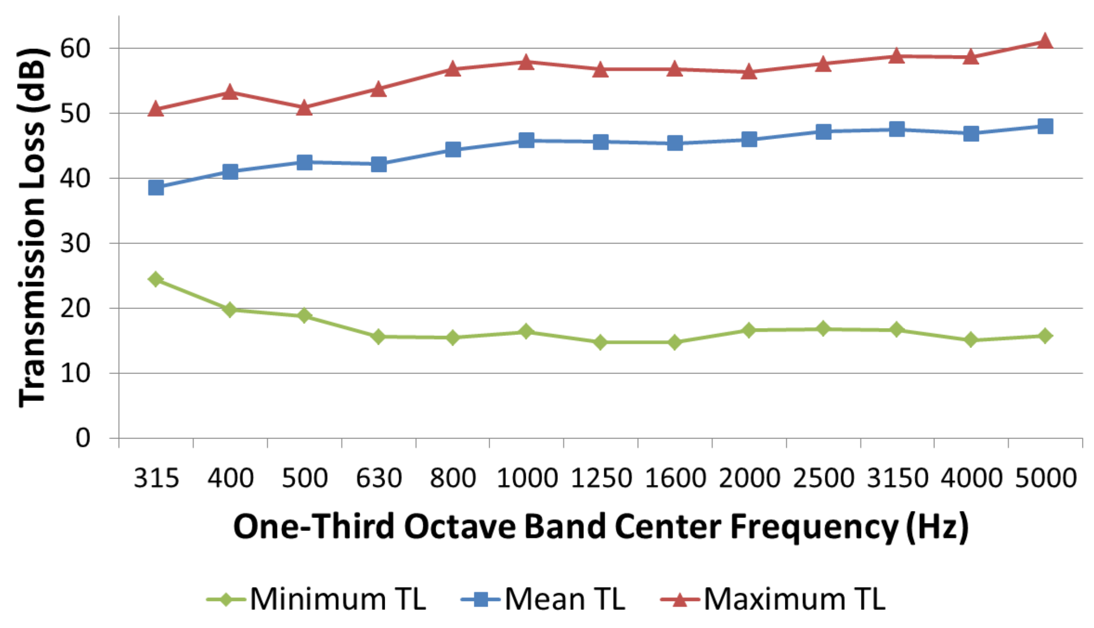


Figure 4.30: Minimum, mean, and maximum TL across all iterations

4.2.3 Statistical Comparison

It can be challenging to extract trends from visual comparisons across dozens of graphs, as shown in the next section. For a statistical comparison, certain parameters were held constant to isolate the variation caused by other conditions. The differences between measured and predicted values for NR and TL (at each one-third OB center frequency) with each iteration were evaluated by Equations (4.8)-(4.11). The differences were averaged across the desired frequency range according to Equations (4.12)-(4.15). The mean differences for corresponding iterations were then averaged again across desired variable conditions to produce the values shown in Table 4.9 and Table 4.10.

$$\Delta NR_i = (NR_{measured} - NR_{predicted})_i \tag{4.8}$$

$$\Delta TL_i = (TL_{measured} - TL_{predicted})_i \tag{4.9}$$

$$|\Delta NR|_{\boldsymbol{i}} = \left|NR_{measured} - NR_{predicted}\right|_i \tag{4.10}$$

$$|\Delta TL|_i = \left|TL_{measured} - TL_{predicted}\right|_i \tag{4.11}$$

$$\Delta \boldsymbol{NR} = \frac{1}{n}\sum_i \Delta NR_{\boldsymbol{i}} \tag{4.12}$$

$$\Delta \boldsymbol{TL} = \frac{1}{n}\sum_i \Delta TL_{\boldsymbol{i}} \tag{4.13}$$

$$|\Delta \boldsymbol{NR}| = \frac{1}{n}\sum_i |\Delta NR|_{\boldsymbol{i}} \tag{4.14}$$

$$|\Delta \boldsymbol{TL}| = \frac{1}{n}\sum_{i} |\Delta TL|_{\boldsymbol{i}} \tag{4.15}$$

$$|\Delta \boldsymbol{NLR}| = \left|NLR_{measured} - NLR_{predicted}\right| \tag{4.16}$$

Where i corresponds to each one-third octave band and n corresponds to the number of one-third octave bands chosen to average across (13 one-third octave bands between 315 – 5000 Hz, the focus of this study).

ΔNR and **ΔTL** were useful to evaluate whether the models were under- or over-predicting sound attenuation, whereas **|ΔNR|** and **|ΔTL|** as measures of absolute difference were most valuable to this research in comparing the overall performance of the models. Given that aircraft sources used in IBANA-Calc scenarios are adjusted by NEF values that can be considered as energy averages of exterior sound levels, **ΔNR** and **ΔTL** might be considered to be better measures of the net change in acoustic energy represented by NR and TL. **ΔNR**, **|ΔNR|**, **ΔTL** and **|ΔTL|** as shown in Table 4.9 and Table 4.10 were taken as averages between 315 – 5000 Hz, as this frequency range was the focus of this study. **ΔNR**, **|ΔNR|**, **ΔTL** and **|ΔTL|** were developed to better rate the performance of models across frequency. NLR was evaluated (as described in Section 1.2) to be the difference between the single-number energy (or logarithmic) average of the outdoor level and the single-number energy (or logarithmic) average of the indoor level. As such, NLR was evaluated from single-number outdoor/indoor sound levels averaged across the full frequency range of the model predictions and measurements—50 Hz to 5,000 Hz.

The colored columns in Table 4.9 and Table 4.10 are highlighted in a gradient to contrast the smallest differences in magnitude from measured to predicted (green for "better" modeling performance) against the largest differences in magnitude from measured to predicted (red for "worse" modeling performance). Generally, green corresponded to differences less than 3 dB, yellow/orange corresponded to differences between 3-5 dB, and red corresponded to differences greater than 5 dB for NR and TL. For NLR, green generally corresponded to differences less than 3 dB, yellow/orange generally corresponded to differences between 3-7 dB, and red generally corresponded to differences greater than 7 dB.

The following results, however, should be reviewed with caution. Once again, this research has not conducted a study of the repeatability of any single measurement location. Accordingly, it is difficult to establish to what degree the difference in NR and TL between measurements and predictions is independent of the variation introduced by using different possible microphone locations used in a measurement. Also, the results must be viewed within the context that the modeling technology assumes field incidence, while the measurements conducted according to the current standard do not. All TL measurements in this laboratory validation have been calculated with a correction factor to account for horizontal angle of incidence, and this difference between measured and predicted values is expected to cause variation.

Table 4.9: Statistical metrics for NR comparison

				Averaged Values					
				315-5000 Hz		315-5000 Hz	50-5000 Hz		
Constant Conditions	**Combined Variable Conditions**	**Category**	**Iteration**	**|ΔNR|**	**Std Dev |ΔNR|**	**ΔNR**	**|ΔNLR|**	**Std Dev |ΔNLR|**	**Row #**
pink noise, ~3.5 ft high, 45 deg, near avg, window closed	Window STC, layers of gypboard	**Loudspeaker**	JBL	**2.76**	1.24	-2.2	**4.96**	1.73	1
			Peavey	**3.55**	1.75	-1.6	**6.05**	0.70	2
Peavey, 45 deg, near avg, window closed	Window STC, layers of gypboard, vertical height of source	**Sound Source**	Pink Noise	**3.80**	2.10	-1.9	**4.64**	1.89	3
			737 jet	**3.56**	1.63	-2.2	**2.21**	1.43	4
JBL, pink noise, 3.4 ft high, near avg, window closed	Window STC, layers of gypboard	**Horizontal Incidence Angle**	15	**7.30**	2.83	-7.1	**1.55**	0.78	5
			30	**4.98**	1.94	-4.4	**2.51**	1.40	6
			45	**3.33**	1.12	-2.9	**4.28**	1.75	7
			60	**2.74**	1.36	-0.1	**6.91**	1.74	8
			75	**3.11**	1.13	-0.8	**5.91**	1.46	9
			90	**3.35**	1.47	-0.2	**6.62**	2.15	10
			105	**3.17**	0.83	-1.2	**5.56**	1.61	11
			120	**4.00**	1.46	-1.2	**5.61**	2.91	12
			135	**3.15**	1.22	-0.9	**5.93**	2.95	13
			150	**4.14**	1.67	-3.1	**3.06**	1.82	14
			165	**6.58**	2.95	-6.3	**2.06**	1.74	15
Peavey, 45 deg, near avg, window closed	Pink noise/jet, Window STC, layers of gypboard	**Vertical Height of Source**	3.75	**3.50**	1.75	-1.8	**3.98**	2.23	16
			5	**3.68**	1.83	-1.8	**3.73**	2.02	17
			7	**3.74**	2.13	-2.1	**3.23**	2.04	18
			8	**3.80**	2.06	-2.3	**2.77**	2.13	19
JBL, pink noise, 3.4 ft high, 45 deg, window closed	Window STC, layers of gypboard	**Exterior Level Msmt**	near avg	**2.55**	0.91	-1.8	**5.37**	1.45	20
			flush	**2.48**	0.75	-1.3	**9.07**	1.82	21
JBL, pink noise, 3.4 ft high, 45 deg, window closed, 1 layer of gypboard	Window STC, near avg/flush	**Window STC rating**	25	**2.41**	0.25	-1.0	**5.06**	2.29	22
			31	**2.38**	1.55	-1.5	**6.40**	3.41	23
			41	**2.48**	0.23	-1.7	**8.30**	2.87	24
JBL, pink noise, 3.4 ft high, 45 deg, near avg	Near avg/flush	**Window condition**	closed	**3.33**	1.12	-2.9	**4.28**	1.75	25
			half open	**2.63**	0.45	0.8	**1.90**	2.09	26
			open	**2.77**	0.96	-0.4	**2.31**	1.23	27
45 deg, near avg, window closed, STC 41	JBL/Peavey, Pink noise/jet, Window STC, vertical height of source	**Layers of gypboard**	single layer	**2.82**	0.28	-1.4	**4.35**	3.23	28
			double layer	**6.09**	1.48	-6.0	**4.18**	2.65	29

NR	< 3 dB	3-5 dB	> 5 dB

NLR	< 3 dB	3-7 dB	> 7 dB

Table 4.10: Statistical metrics for TL comparison

				Averaged Values					
				315-5000 Hz		315-5000 Hz	50-5000 Hz		
Constant Conditions	Combined Variable Conditions	Category	Iteration	|ΔTL|	Std Dev |ΔTL|	ΔTL	|ΔNLR|	Std Dev |ΔNLR|	Row #
pink noise, ~3.5 ft high, 45 deg, near avg, window closed	Window STC, layers of gypboard	**Loudspeaker**	JBL	**3.39**	1.19	2.8	**4.96**	1.73	1
			Peavey	**4.72**	1.39	3.3	**6.05**	0.70	2
Peavey, 45 deg, near avg, window closed	Window STC, layers of gypboard, vertical height of source	**Sound Source**	Pink Noise	**4.65**	1.30	3.0	**4.64**	1.89	3
			737 jet	**4.09**	1.15	2.7	**2.21**	1.43	4
JBL, pink noise, 3.4 ft high, near avg, window closed	Window STC, layers of gypboard	**Horizontal Incidence Angle**	15	**6.74**	2.69	-6.5	**1.55**	0.78	5
			30	**2.98**	0.53	-1.1	**2.51**	1.40	6
			45	**2.76**	0.68	1.9	**4.28**	1.75	7
			60	**5.95**	2.66	5.7	**6.91**	1.74	8
			75	**5.75**	2.83	5.5	**5.91**	1.46	9
			90	**6.46**	3.14	6.2	**6.62**	2.15	10
			105	**5.18**	2.51	5.0	**5.56**	1.61	11
			120	**5.45**	2.75	4.5	**5.61**	2.91	12
			135	**4.52**	2.53	3.9	**5.93**	2.95	13
			150	**3.39**	0.18	0.2	**3.06**	1.82	14
			165	**6.15**	2.85	-5.8	**2.06**	1.74	15
Peavey, 45 deg, near avg, window closed	Pink noise/jet, Window STC, layers of gypboard	**Vertical Height of Source**	3.75	**4.46**	1.29	3.0	**3.98**	2.23	16
			5	**4.68**	1.15	3.0	**3.73**	2.02	17
			7	**4.28**	1.37	2.7	**3.23**	2.04	18
			8	**4.06**	1.30	2.5	**2.77**	2.13	19
JBL, pink noise, 3.4 ft high, 45 deg, window closed	Window STC, layers of gypboard	**Exterior Level Msmt**	near avg	**3.62**	1.19	3.1	**5.37**	1.45	20
			flush	**3.87**	1.36	3.5	**9.07**	1.82	21
JBL, pink noise, 3.4 ft high, 45 deg, window closed, 1 layer of gypboard	Window STC, near avg/flush	**Window STC rating**	25	**3.43**	0.39	3.3	**5.06**	2.29	22
			31	**4.22**	1.71	3.9	**6.40**	3.41	23
			41	**3.60**	0.27	3.4	**8.30**	2.87	24
JBL, pink noise, 3.4 ft high, 45 deg, near avg	Near avg/flush	**Window condition**	closed	**2.76**	0.68	1.9	**4.28**	1.75	25
			half open	**5.65**	2.21	5.6	**1.90**	2.09	26
			open	**4.71**	2.35	4.5	**2.31**	1.23	27
45 deg, near avg, window closed, STC 41	JBL/Peavey, Pink noise/jet, Window STC, vertical height of source	**Layers of gypboard**	single layer	**4.17**	0.60	3.7	**4.35**	3.23	28
			double layer	**3.07**	0.50	-1.5	**4.18**	2.65	29

TL	< 3 dB	3-5 dB	> 5 dB

NLR	< 3 dB	3-7 dB	> 7 dB

While bearing in mind the concerns explained in the paragraph preceding Table 4.9, it appears that the IBANA-Calc models performed well for engineering purposes. **|ΔNR|** and **|ΔTL|** were generally less than ~3-4 dB in predicting both NR and TL across iterations covering the difference in the loudspeaker sound source (rows 1-2 in Table 4.9 and Table 4.10), sound source signal type (rows 3-4), vertical incidence angle of the source (rows 16-19), exterior measurement method (rows 20-21) and acoustical performance of the window (rows 22-24). The lack of variation across these particular measurement and construction iterations appears to suggest that using the various loudspeaker sound sources, sound source signal types, vertical incidence angles, exterior measurement methods and windows did not affect the resulting measurements. Given the variation of **|ΔNR|** and **|ΔTL|** evident in rows 5 through 15 of Table 4.9 and Table 4.10, it is also apparent that horizontal angle of incidence (as expected) is a key source in the difference from measured to predicted sound attenuation performance.

Considering that introducing an 'Opening' in IBANA-Calc as a façade element simply applies a flat TL contour of 0 dB across frequency, it does appear that the models accounting for an opening (rows 25-27 in Table 4.9 and Table 4.10) predicted NR well and TL with less accuracy for the configurations that included a half- or fully-open window. It is also apparent that there is a conflicting relationship between the performance of single-number ratings and the NR or TL performance across frequency from measured to predicted. As shown in Table 4.9 and Table 4.10, groups of iterations that showed the "worst" performance in predicting NR and TL were often the iterations that showed the "best" performance in predicting NLR (such as the 15° and 165° horizontal angle iterations, rows 5 and 15 respectively) and vice versa.

4.2.4 Noise Reduction and Transmission Loss Comparison

4.2.4.1 External Measurement Method

The comparisons from Figure 4.31 to Figure 4.34 held the following conditions constant: JBL loudspeaker at 3.4’ and at θ=45°, pink noise signal, and window closed. The acronyms “LM” and “ICP” correspond to “Laboratory Measured” and “IBANA-Calc Predicted”, respectively.

It appears that NR (Figure 4.31(a)-Figure 4.34(a)) is over-predicted below ~1250-1600 Hz and under-predicted at a dip covering the 2500 Hz and 3150 Hz frequency bands for the following comparisons of external measurement method. Looking over to TL (Figure 4.31(b)-Figure 4.34(b)) for each comparison, it appears that the overall shape and features of the predicted curve stays the same moving between NR and TL. The TL prediction curves across frequency appear to be the NR curves translated uniformly to higher values, and yet still appear to under-predict TL except for the STC 41 window and double gypsum board layer construction iteration.

Flush measurements appeared to have resulted in slightly higher NR and TL values across frequency (more clearly seen in Figure 4.31 and Figure 4.33) than near average measurements, which is unexpected by the convention given to evaluate the two in Equations (4.4) and (4.5). The difference between the two measurements methods, however, appears to be less than significant.

|ΔNR| between flush measurements and predictions tended to be lowest (corresponding to better performance) with frequency bands above 1250 Hz and highest (corresponding to worse performance) at 315 Hz. |ΔNR| between near average

measurements and predictions tended to be lowest with frequency bands above 2000 Hz and once again highest at 315 Hz.

|ΔTL| between flush measurements and predictions tended to be lowest with frequency bands between 630-2000 Hz and highest both below 630 Hz and above 2000 Hz. |ΔTL| between near average measurements and predictions tended to be lowest with frequency bands between 800-2000 Hz and, once again, highest both below 630 Hz and above 2000 Hz.

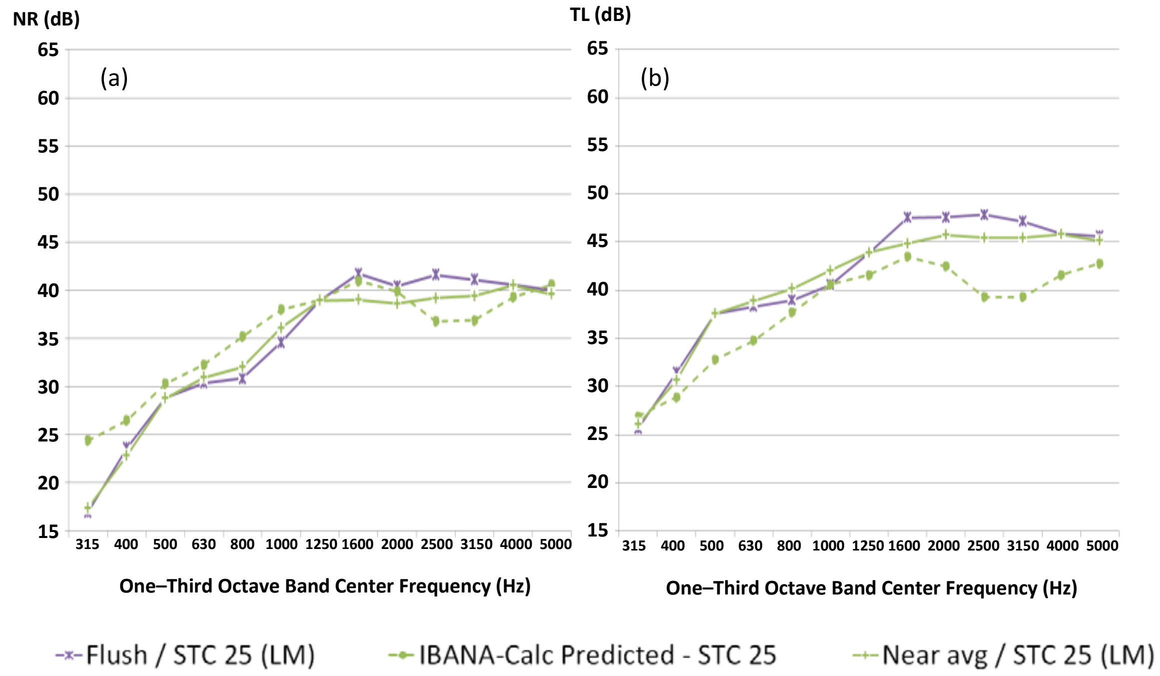


Figure 4.31: (a) NR and (b) TL comparison of external measurement methods with STC 25 window (Iterations #26 & 27 from Table 4.7)

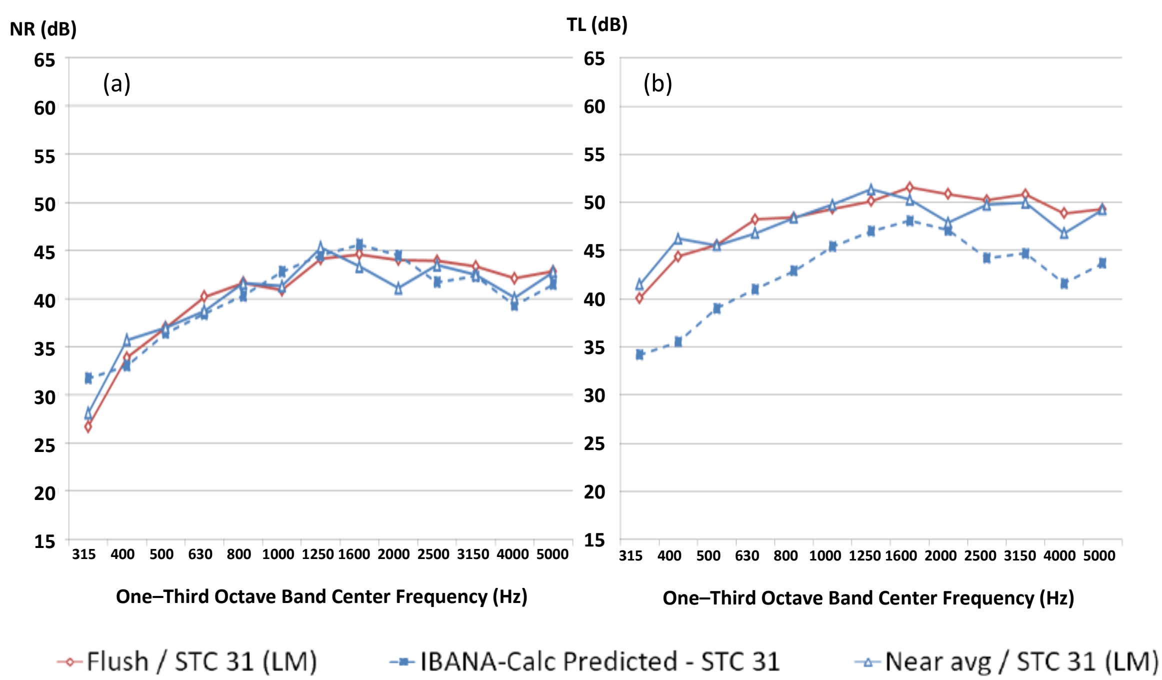


Figure 4.32: (a) NR and (b) TL comparison of external measurement methods with STC 31 window (Iterations #1 & 3 from Table 4.7)

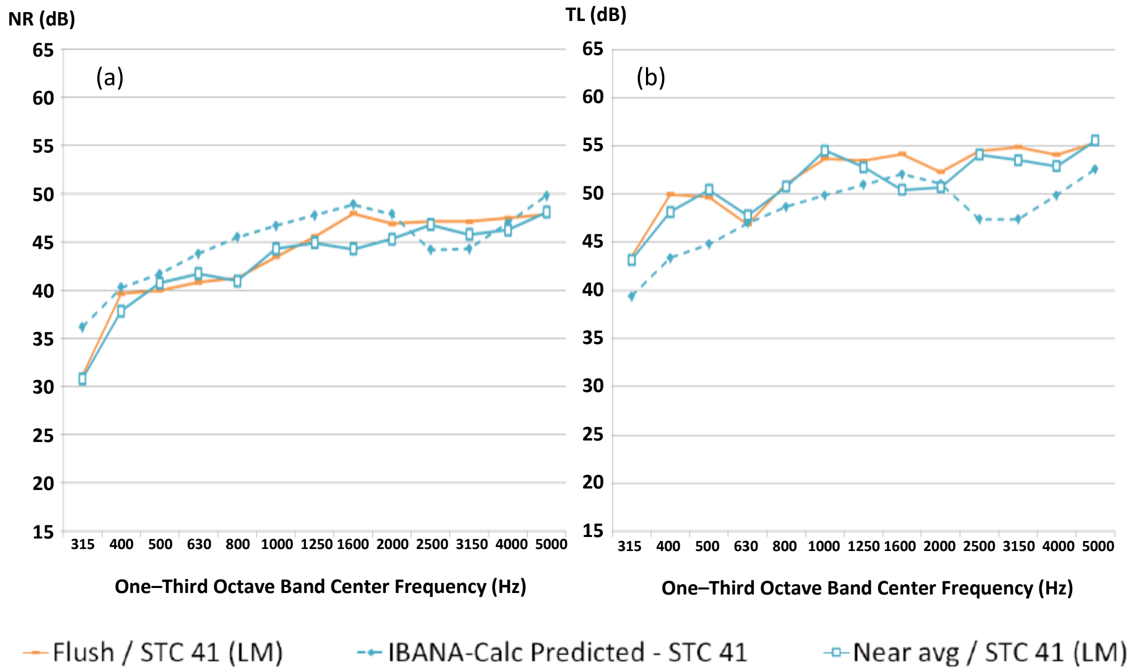


Figure 4.33: (a) NR and (b) TL comparison of external measurement methods with STC 41 window (Iterations #48 & 49 from Table 4.7)

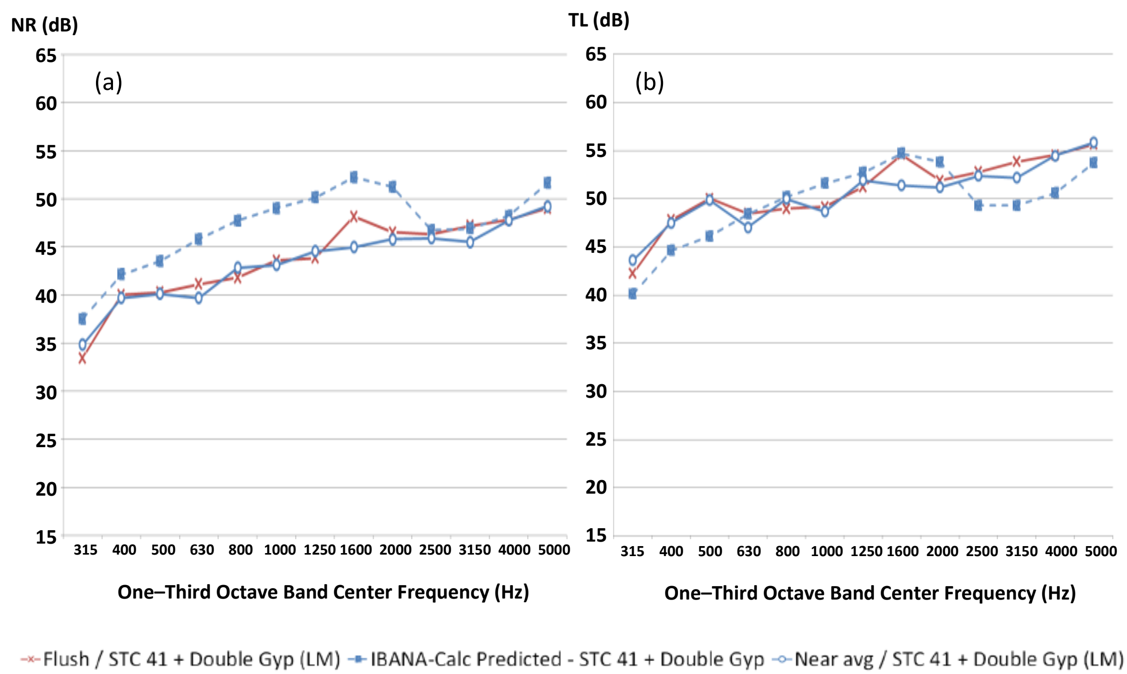


Figure 4.34: (a) NR and (b) TL comparison of external measurement methods with STC 41 window + double gyp (Iterations 78 # 79 from Table 4.7)

4.2.4.2 Horizontal Incidence Angle of Sound Source

The comparisons from Figure 4.35 to Figure 4.38 held the following conditions constant: JBL loudspeaker at 3.4’, pink noise signal, near average measurement, window closed, and single layer of gypsum board. The acronyms “LM” and “ICP” correspond to “Laboratory Measured” and “IBANA-Calc Predicted”, respectively.

For this comparison of the different source horizontal angles of incidence (Figure 4.35-Figure 4.38), it is difficult to ascertain broad generalizations regarding the over- or under-prediction of NR and TL. However, it is apparent that angles of incidence approaching grazing (i.e. 15°/165°) tend to have both NR and TL significantly over-predicted. It is also apparent that angles approaching normal incidence (i.e. 90°) have TL significantly under-predicted.

Otherwise, measurements of NR appear to follow expectations. As angles of incidence approach grazing, large differences ($|\Delta NR|$ ~10 dB) between measured and predicted are seen especially at the middle frequency bands from 800-2000 Hz. Also, as angles of incidence approach 45° from normal (i.e. 45°/135°), smaller differences ($|\Delta NR|$ never exceeding 4 dB) are seen across the entire frequency range.

TL comparisons reveal another finding. Once again, as angles of incidence approach grazing, large differences ($|\Delta TL|$ ~10 dB) between measured and predicted are seen especially at the middle frequency bands from 800-2000 Hz. With TL, however, large differences ($|\Delta TL|$ ~7-8 dB) between measured and predicted are seen with angles approaching normal incidence–likely due to the sound source being normally incident with the window assembly in the center of the test house front wall. This time, the variation is seen especially at frequency bands lower than 800 Hz and higher than 2000

Hz. Similarly to NR, the best average TL performance appears to be with iterations at 45°.

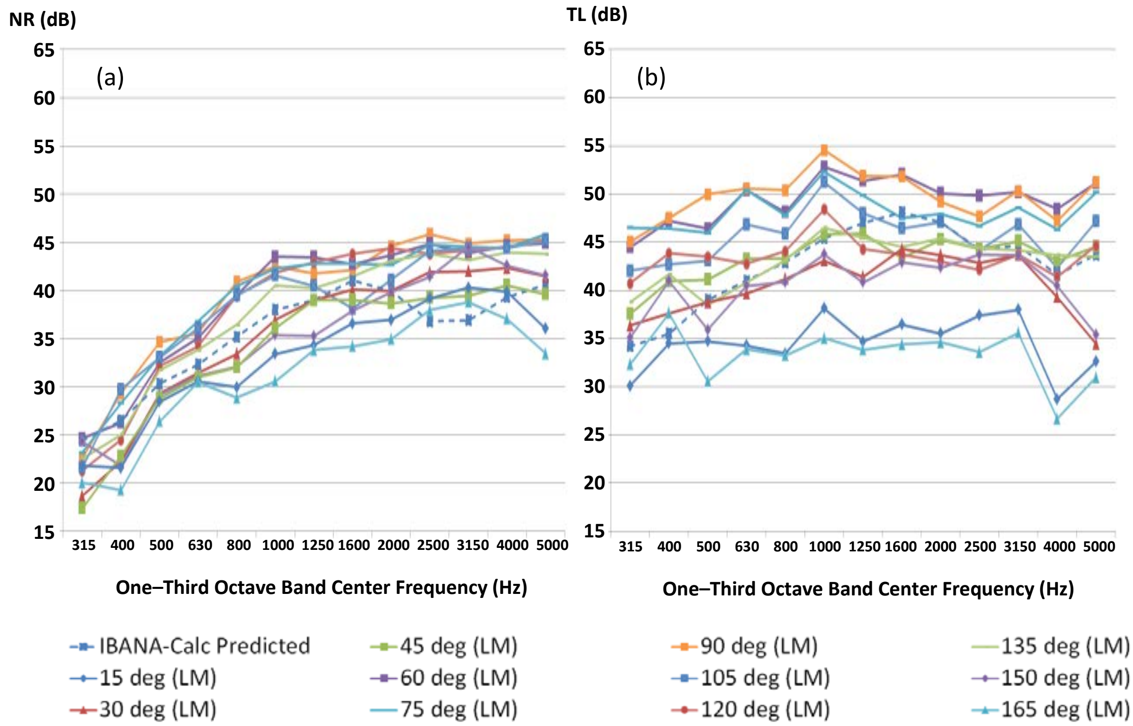


Figure 4.35: (a) NR and (b) TL comparison of horizontal incidence angle with STC 25 window (Iterations #27 & 30-39 from Table 4.7)

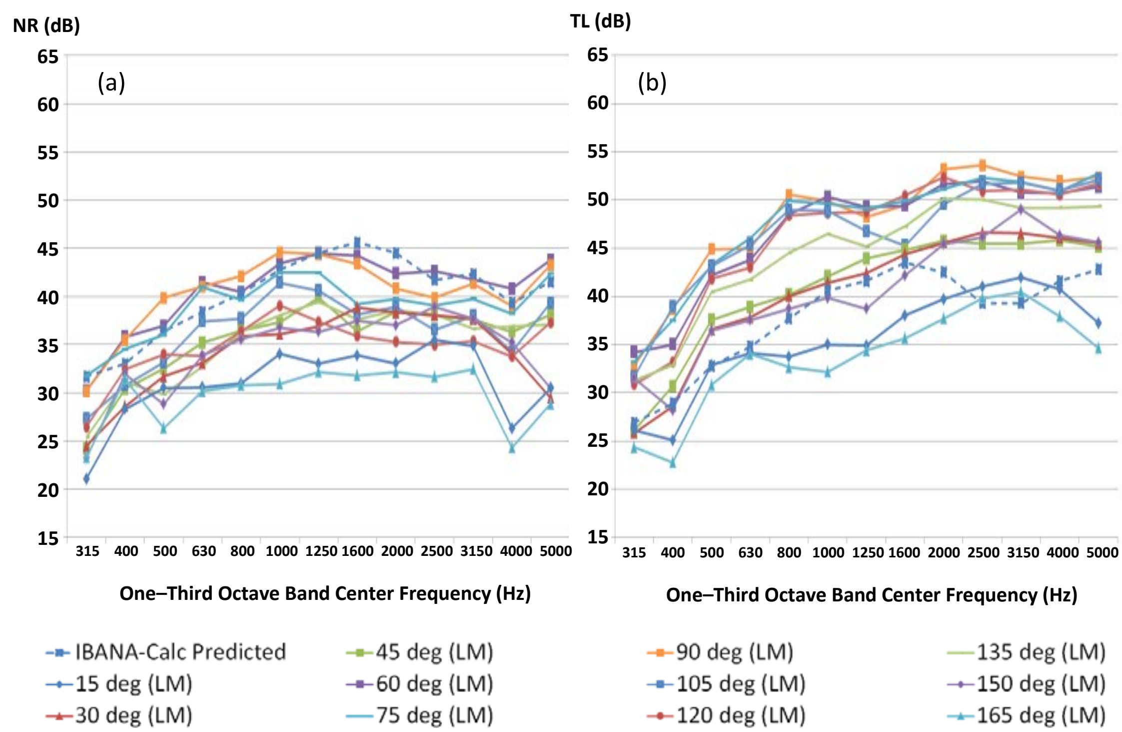


Figure 4.36: (a) NR and (b) TL comparison of horizontal incidence angle with STC 31 window (Iterations #4-6, 10-17 from Table 4.7)

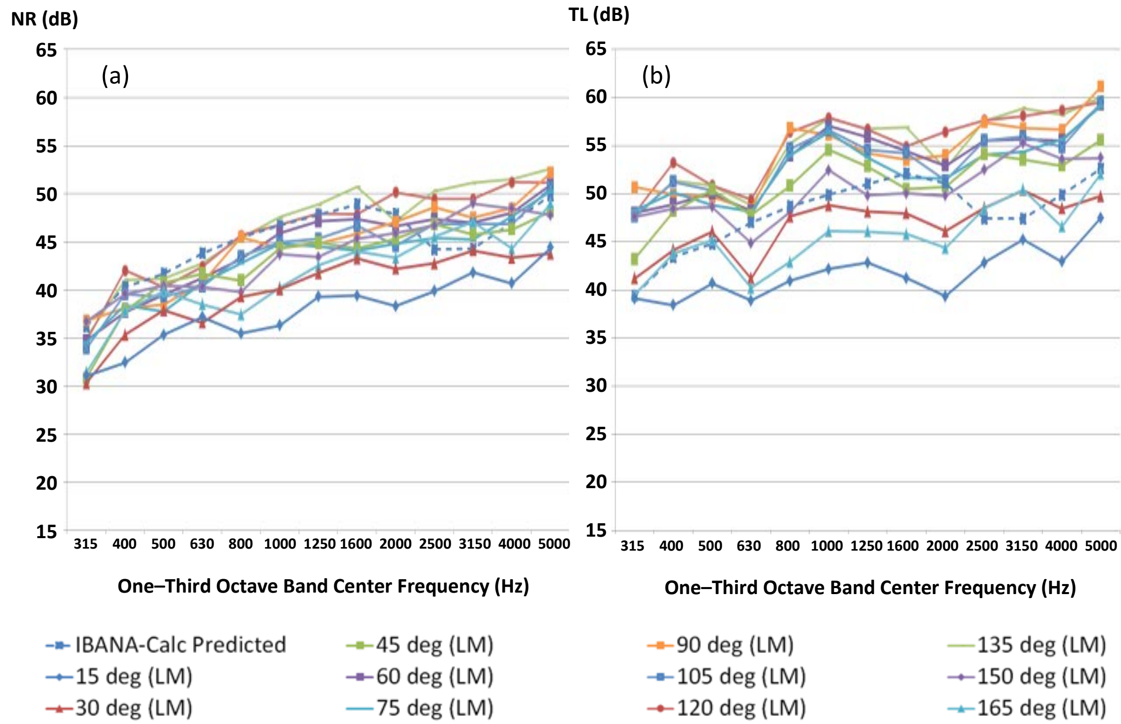


Figure 4.37: (a) NR and (b) TL comparison of horizontal incidence angle with STC 41 window (Iterations #49 & 52-61 from Table 4.7)

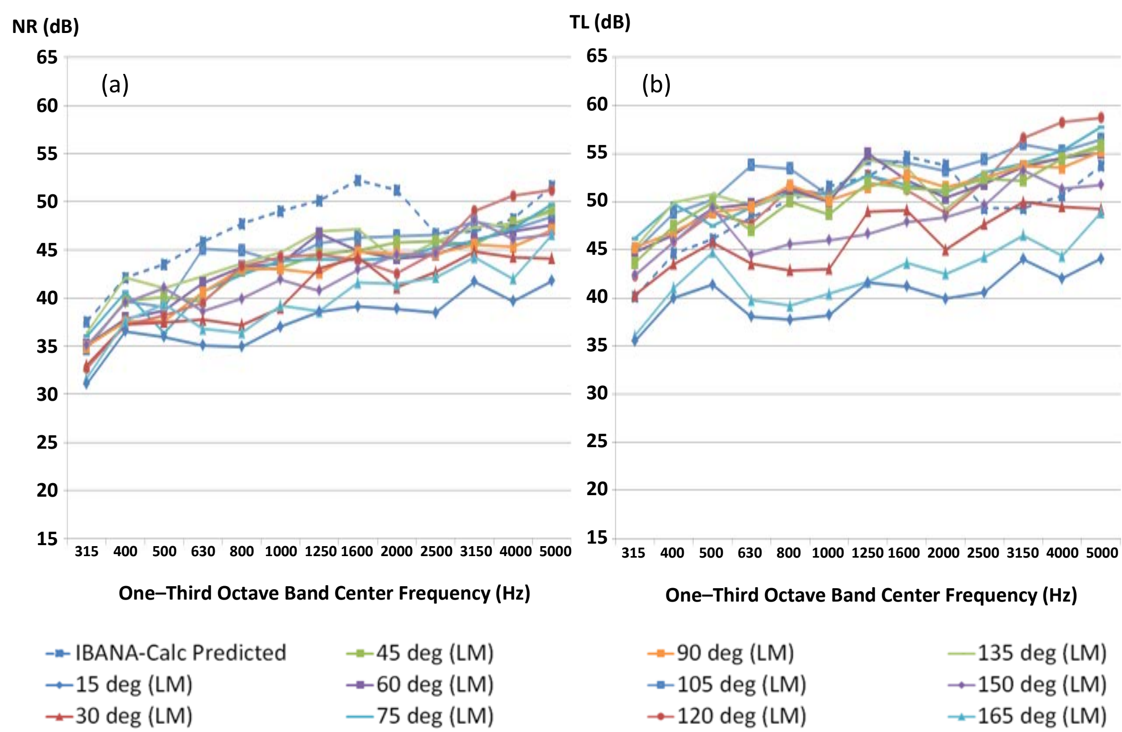


Figure 4.38: (a) NR and (b) TL comparison of horizontal incidence angle with STC 41 window + double gyp (Iterations #79 & 82-91 from Table 4.7)

4.2.4.3 Vertical Incidence Angle of Sound Source and Signal Type

The comparisons from Figure 4.39 to Figure 4.46 held the following conditions constant: Peavey loudspeaker at θ=45°, near average measurement, and window closed. The acronyms "LM" and "ICP" correspond to "Laboratory Measured" and "IBANA-Calc Predicted", respectively. Comparisons for measurements conducted with the pink noise and jet recording measurements are shown separately, as it was unknown how the two different sound source types might have an effect on measurements.

Once again, it appears that NR (Figure 4.39(a)-Figure 4.46(a)) is generally over-predicted for the following comparisons of both the vertical incidence angle and the signal type of the sound source used in testing—only the iterations with the STC 25 window do not appear to follow this trend. And as before, the TL (Figure 4.39(b)-Figure 4.46(b)) prediction curves across frequency appear to be the NR curves translated uniformly to higher values, and again appear to under-predict TL except for the STC 41 window and double gypsum board layer construction iteration.

Otherwise, there are interesting takeaways from the comparisons illustrated in Figure 4.39 to Figure 4.46. Neither the vertical angle of incidence nor the source signal type appears to have resulted in much variation across measurements, and as a result neither of the two conditions appears to have caused variation in the performance of models predictions.

$|\Delta NR|$ for all vertical incidence angles tended to be lowest (corresponding to better performance) with frequency bands above 1600 Hz, lower with frequency bands below 630 Hz, and highest (corresponding to worse performance) with frequency bands between 1250-1600 Hz.

|ΔTL| for all vertical incidence angles tended to be lowest (corresponding to better performance) with frequency bands between 500-2000 Hz, and highest (corresponding to worse performance) with frequency bands between 2500-4000 Hz.

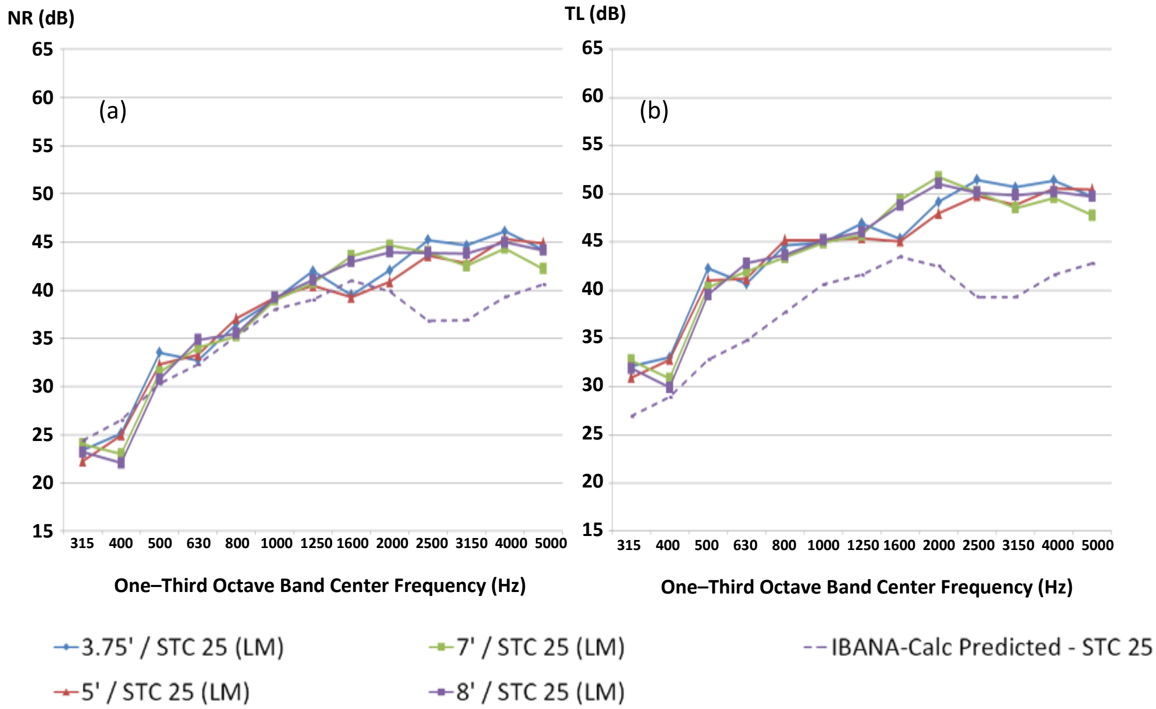


Figure 4.39: (a) NR and (b) TL comparison of vertical incidence angle with STC 25 window + pink noise (Iterations #41, 43, 45 & 47 from Table 4.7)

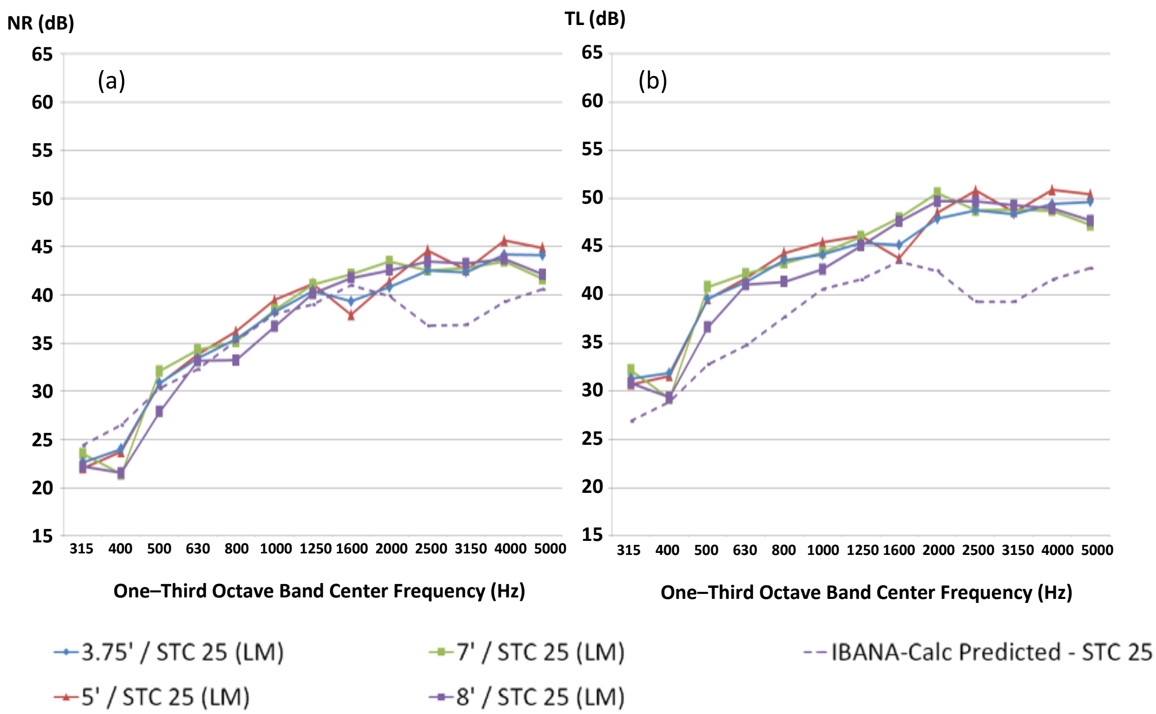


Figure 4.40: (a) NR and (b) TL comparison of vertical incidence angle with STC 25 window + jet source (Iterations #40, 42, 44 & 46 from Table 4.7)

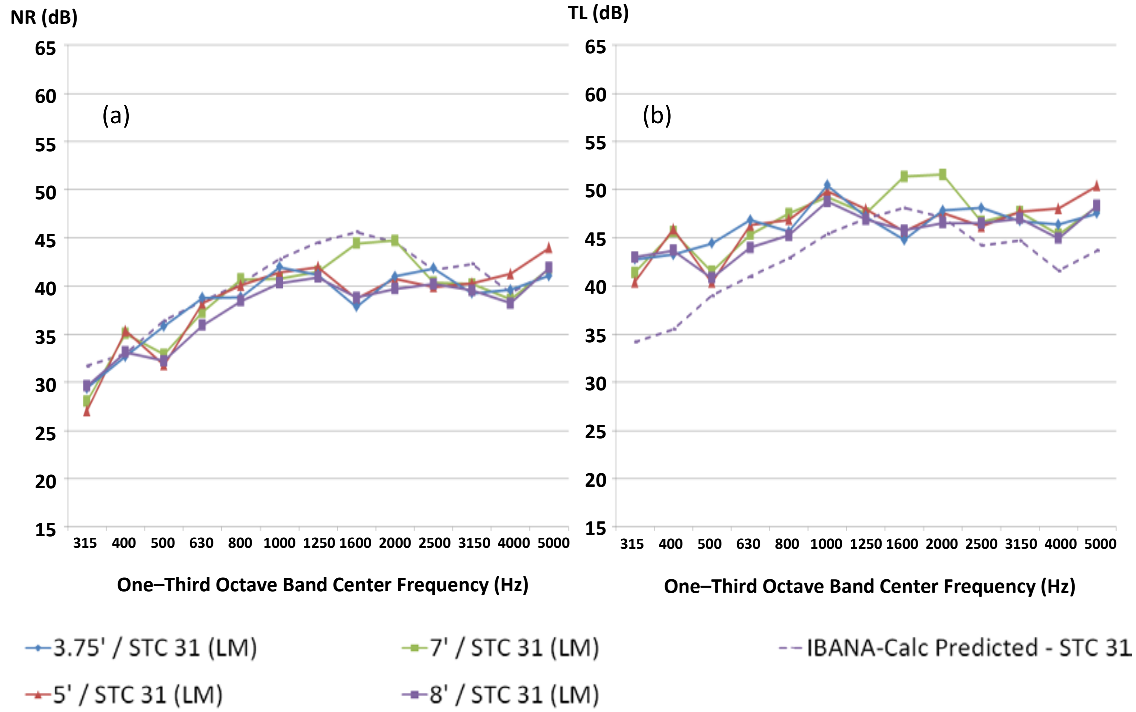


Figure 4.41: (a) NR and (b) TL comparison of vertical incidence angle with STC 31 window + pink noise (Iterations #19, 21, 23 & 25 from Table 4.7)

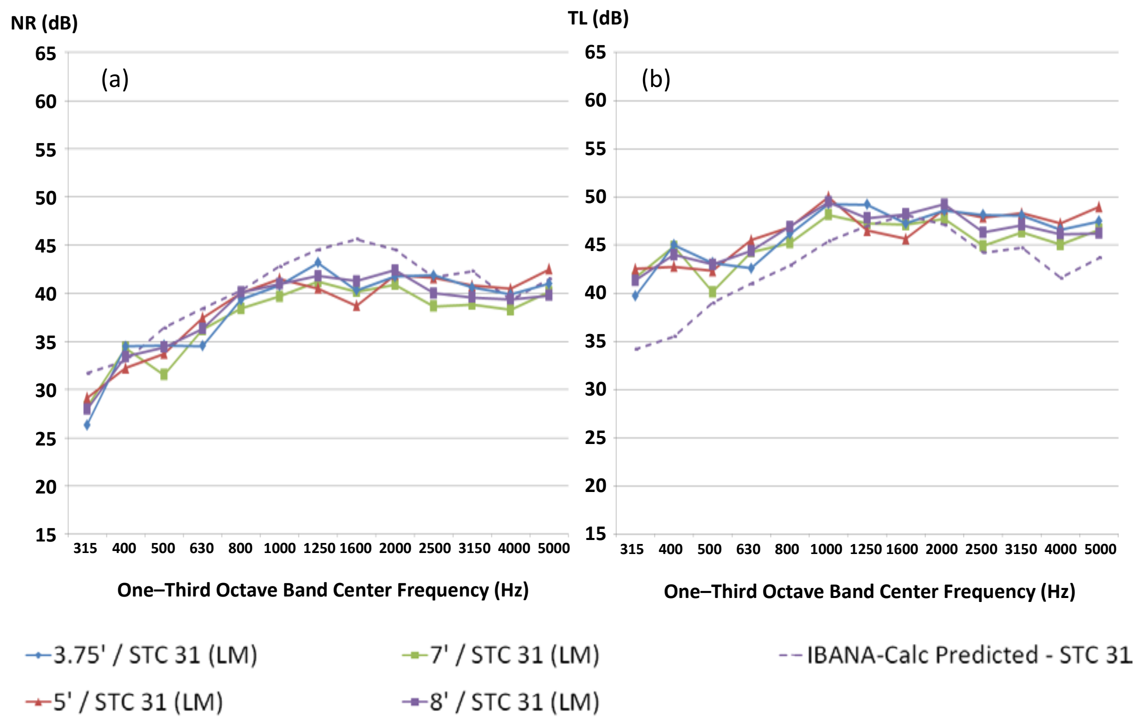


Figure 4.42: (a) NR and (b) TL comparison of vertical incidence angle with STC 31 window + jet source (Iterations #18, 20, 22 & 24 from Table 4.7)

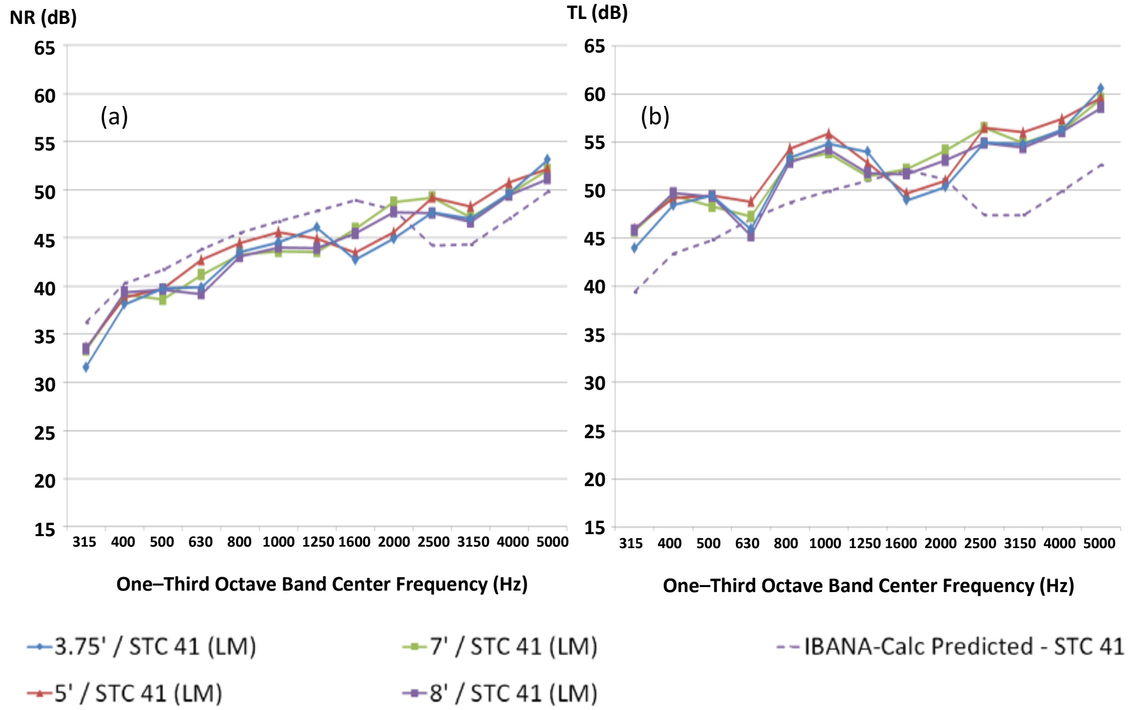


Figure 4.43: (a) NR and (b) TL comparison of vertical incidence angle with STC 41 window + pink noise (Iterations #63, 65, 67, & 69 from Table 4.7)

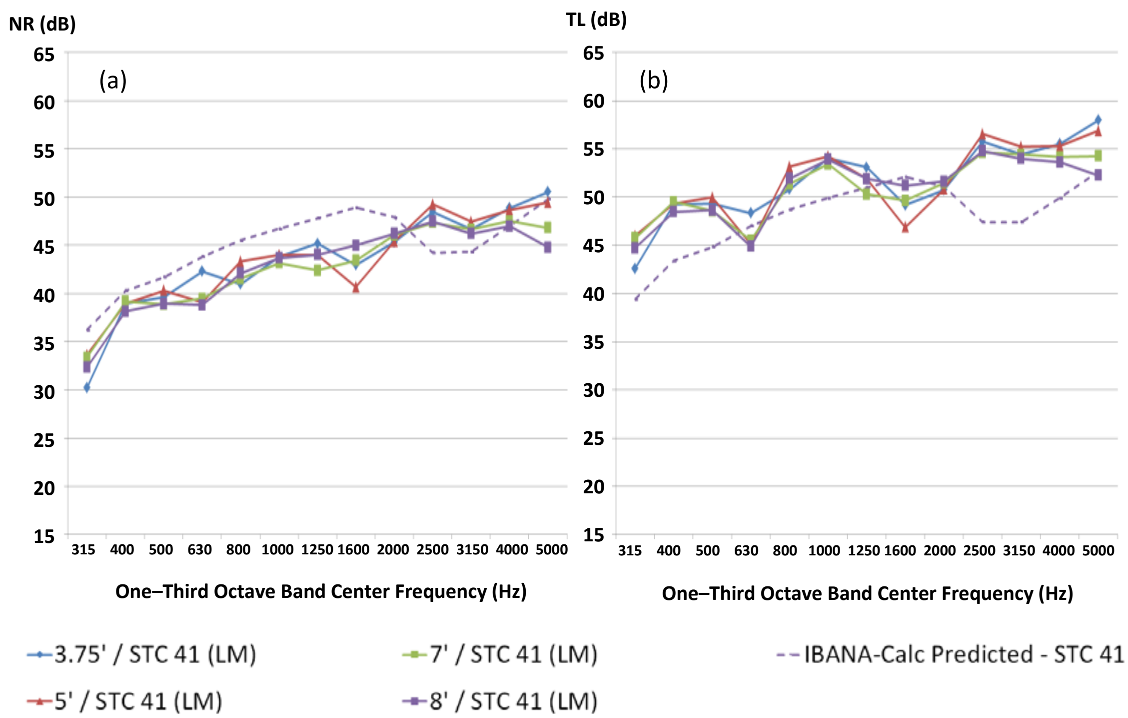


Figure 4.44: (a) NR and (b) TL comparison of vertical incidence angle with STC 41 window + jet source (Iterations #62, 64, 66, & 68 from Table 4.7)

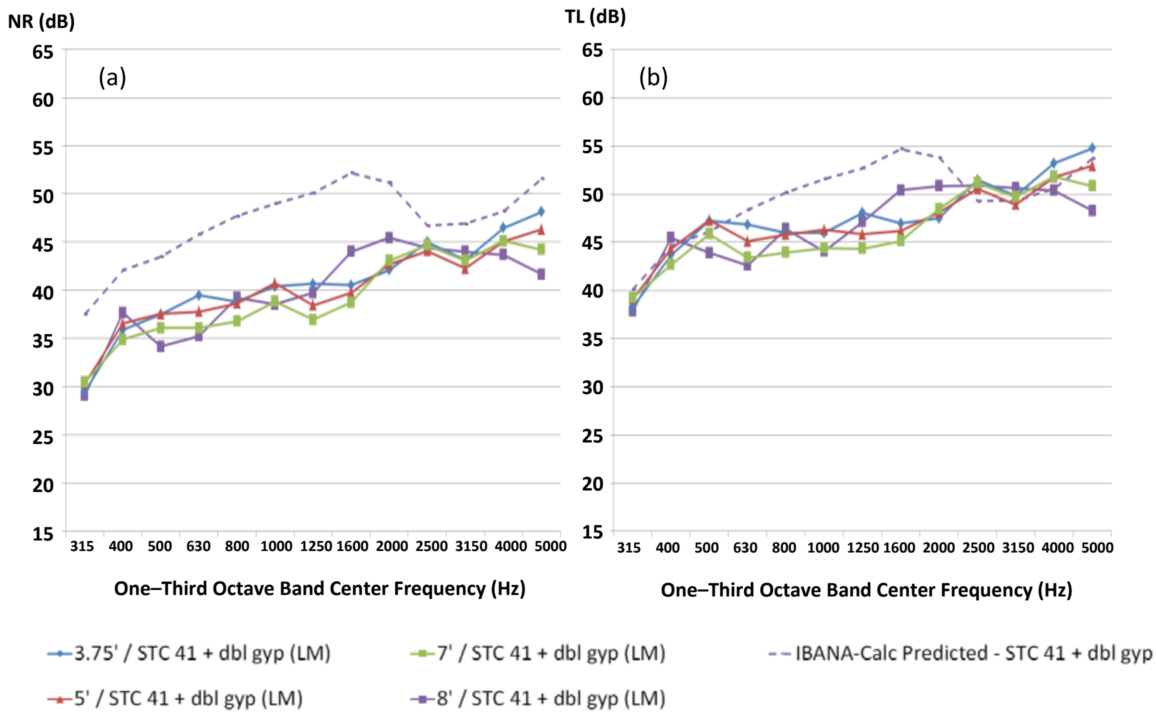


Figure 4.45: (a) NR and (b) TL comparison of vertical incidence angle with STC 41 window and double gyp + pink (Iterations #70, 72, 74 & 76 from Table 4.7)

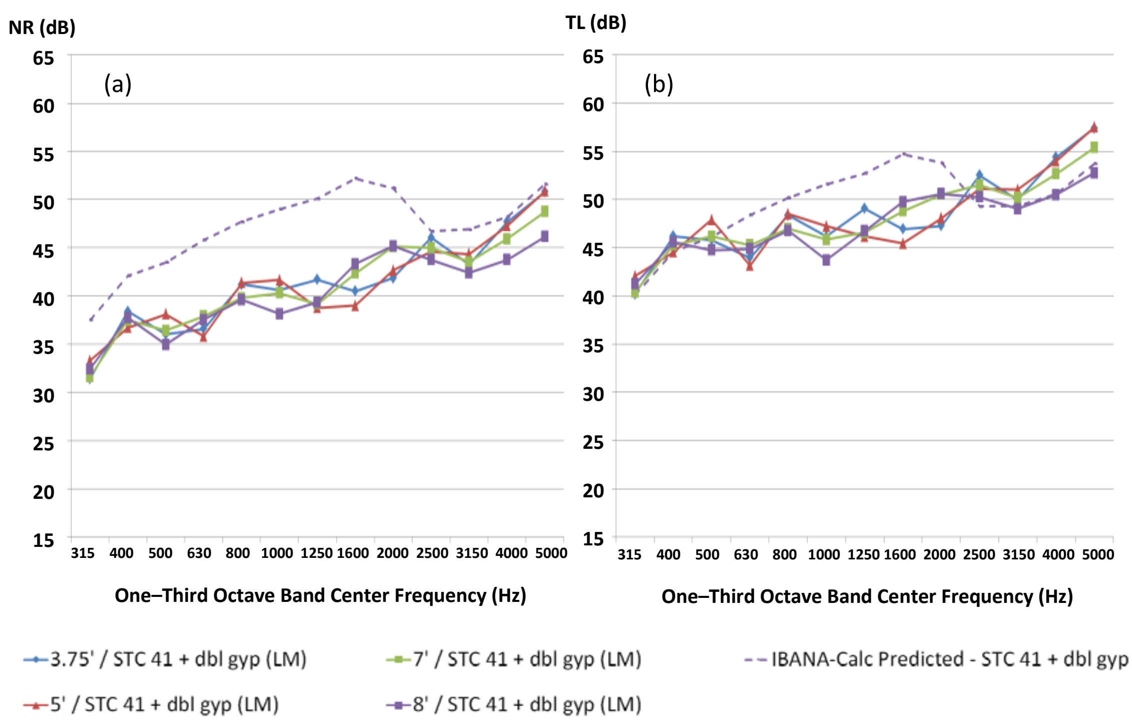


Figure 4.46: (a) NR and (b) TL comparison of vertical incidence angle with STC 41 window and double gyp + jet (Iterations #71, 73, 75 & 77 from Table 4.7)

4.2.4.4 Sound Source

The comparisons from Figure 4.47 to Figure 4.50 held the following conditions constant: sound source at ~3.5' and at θ=45°, pink noise signal, near average measurement, and window closed. The acronyms "LM" and "ICP" correspond to "Laboratory Measured" and "IBANA-Calc Predicted", respectively.

Once again, it appears that NR (Figure 4.47(a)-Figure 4.50(a)) is generally over-predicted for the following comparisons of the loudspeaker sound source used in testing. And as before, the TL prediction curves across frequency (Figure 4.47(b)-Figure 4.50(b)) appear to be the NR curves translated uniformly to higher values, and again appear to under-predict TL except for the STC 41 window and double gypsum board layer construction iteration.

Neither the JBL EON 510 nor the Peavey Impulse 12D loudspeakers appear to have resulted in significantly higher or lower NR and TL across frequency. Measurements conducted with the JBL EON 510 loudspeaker appear to have slightly better matched predictions for both NR and TL, however.

|ΔNR| between measurements using the JBL and predictions tended to be lowest (corresponding to better performance) with frequency bands between 400-500 Hz and above 2000 Hz, and tended to be highest (corresponding to worse performance) at 1600 Hz. |ΔNR| between measurements using the Peavey and predictions tended to be lowest with frequency bands between 400-500 Hz and above 3150 Hz, and tended to be once again highest at 1600 Hz.

|ΔTL| between measurements using the JBL and predictions tended to be lowest at frequency bands between 630-2000 Hz and highest below 630 Hz. |ΔTL| between

measurements using the Peavey and predictions tended to be lowest at frequency bands between 1250-2000 Hz and highest above 2500 Hz.

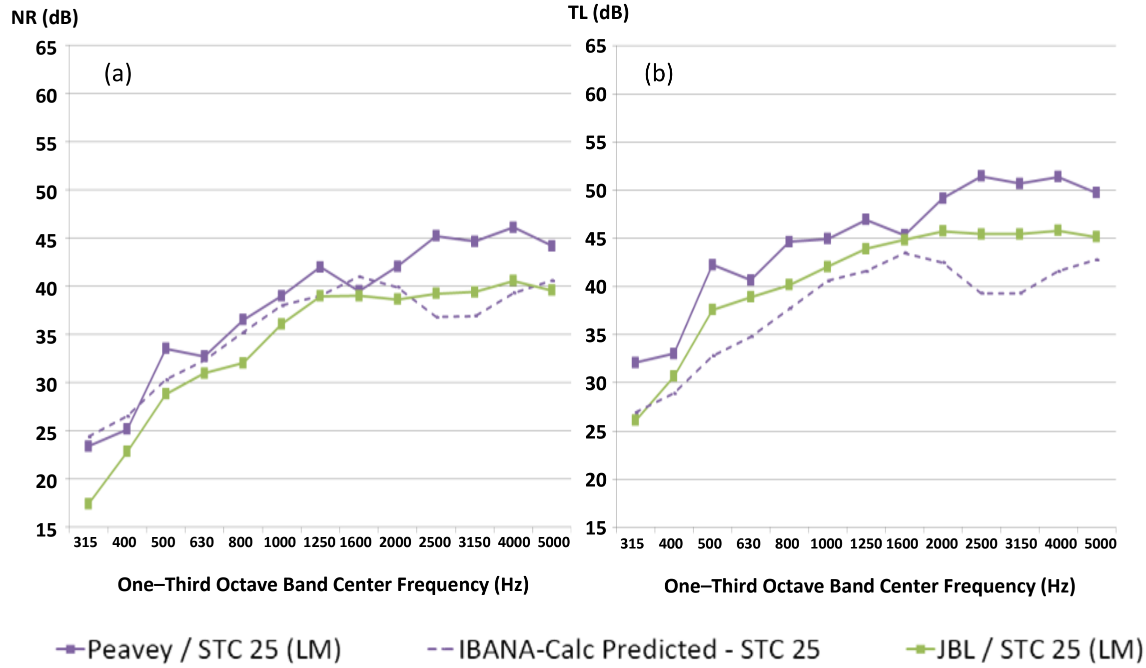


Figure 4.47: (a) NR and (b) TL comparison of sound source with STC 25 window (Iterations #27 & 41 from Table 4.7)

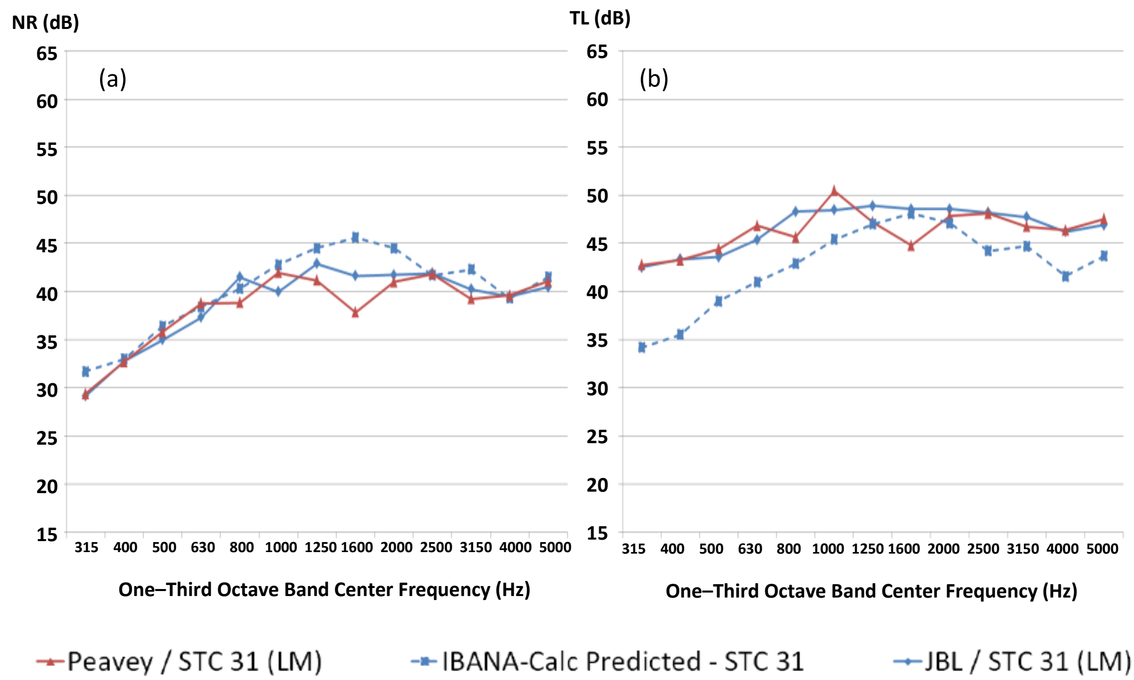


Figure 4.48: (a) NR and (b) TL comparison of sound source with STC 31 window (Iterations #9 & 19 from Table 4.7)

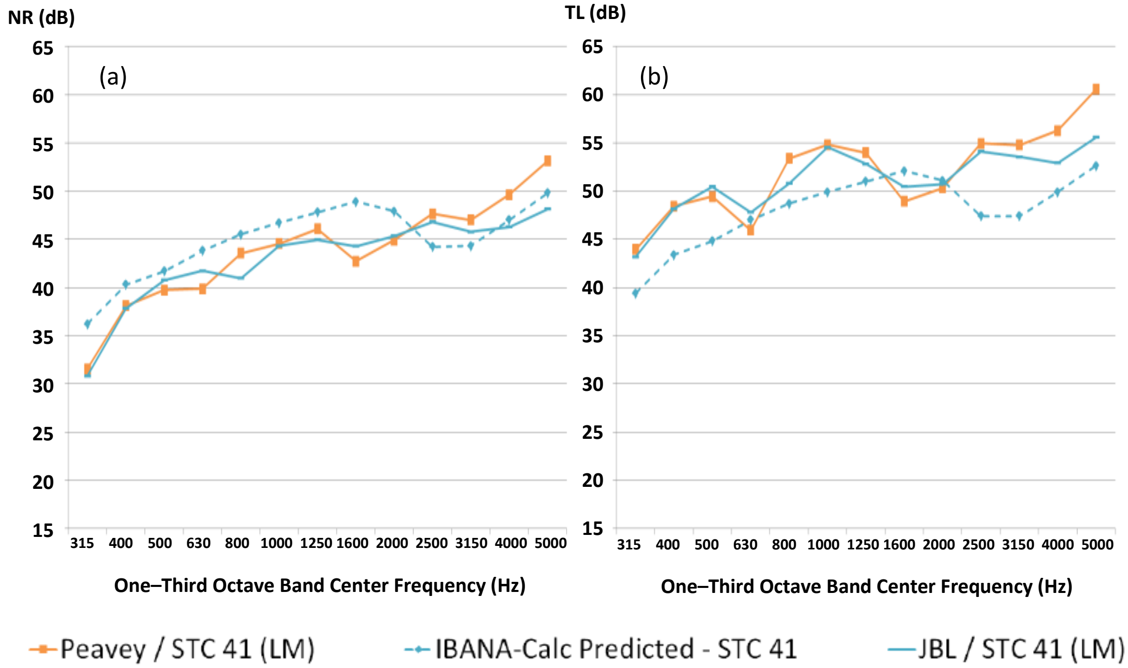


Figure 4.49: (a) NR and (b) TL comparison of sound source with STC 41 window (Iterations #49 & 63 from Table 4.7)

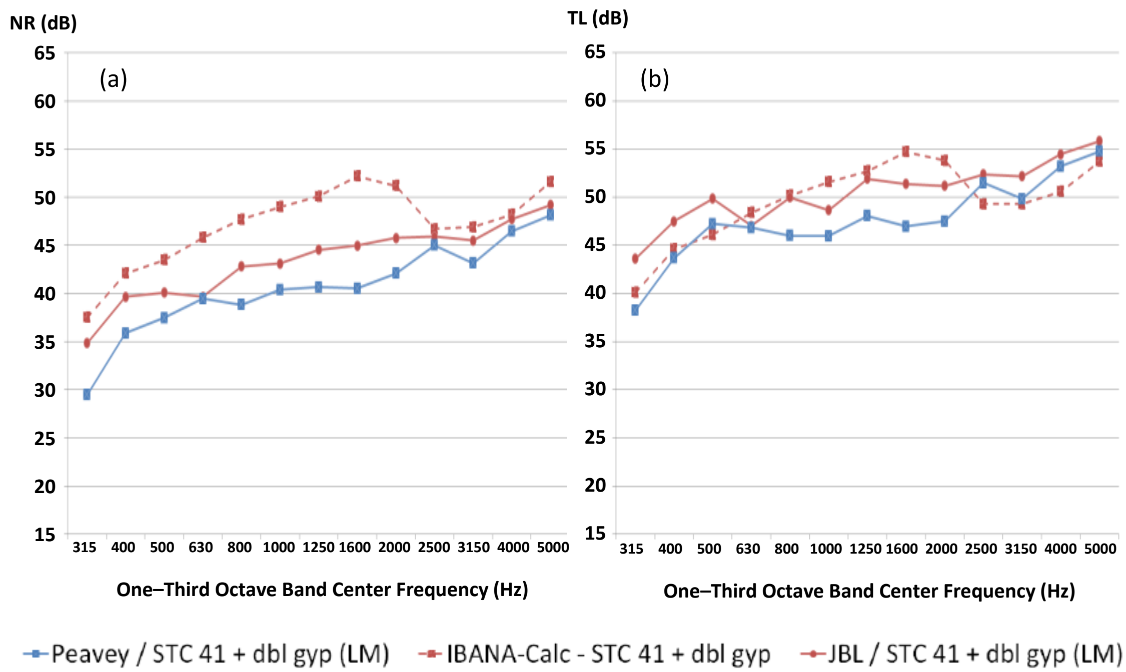


Figure 4.50: (a) NR and (b) TL comparison of sound source with STC 41 window + double gyp (Iterations #70 & 79 from Table 4.7)

4.2.4.5 Window Condition

The comparisons from Figure 4.51 to Figure 4.54 held the following conditions constant: JBL loudspeaker at 3.4' and at θ=45°, pink noise signal, and near average measurement. The acronyms "LM" and "ICP" correspond to "Laboratory Measured" and "IBANA-Calc Predicted", respectively.

The graphical comparison of iterations covering the various window conditions reveals strongly intuitive results for NR and TL. NR and TL are higher for iterations in which the window was closed during testing at nearly every frequency band than for iterations in which the window was half-open or fully open—as expected. Also, NR and TL are higher for iterations in which the window was half-open during testing at nearly every frequency band than for iterations in which the window was fully open—also expected.

Once again, it appears that NR (Figure 4.51(a)-Figure 4.54(a)) is generally over-predicted for the following comparisons of the window condition used in testing. As before, the TL prediction curves across frequency (Figure 4.51(b)-Figure 4.54(b)) appear to be the NR curves translated uniformly to higher values, and appear to under-predict TL except for half of the construction iterations. $|\Delta NR|$ between measurements with the window closed tended to be lowest (corresponding to better performance) with frequency bands between 400-500 Hz and above 2000 Hz, and tended to be highest (corresponding to worse performance) at 315 Hz and 1600 Hz. $|\Delta NR|$ between measurements with the window half-open tended to be lowest with frequency bands between 500-5000 Hz and tended to be highest below 500 Hz. $|\Delta NR|$ between measurements with the window fully open tended to be lowest with frequency bands between 500-5000 Hz and tended highest at 315 Hz.

|ΔTL| between measurements with the window closed tended to be lowest at frequency bands between 630-2000 Hz and above 3150 Hz, and tended to be highest at frequency bands between 315-400 Hz and 2500-3150 Hz. |ΔTL| between measurements with the window half-open tended to be lowest at 800 Hz and between the 1600-2000 Hz frequency bands, and reaching differences between measured and predicted greater than 10 dB below 630 Hz. |ΔTL| between measurements with the window fully open tended to be lowest at 630 Hz and between the 1250-2000 Hz frequency bands, and reaching differences between measured and predicted greater than 10 dB below 500 Hz.

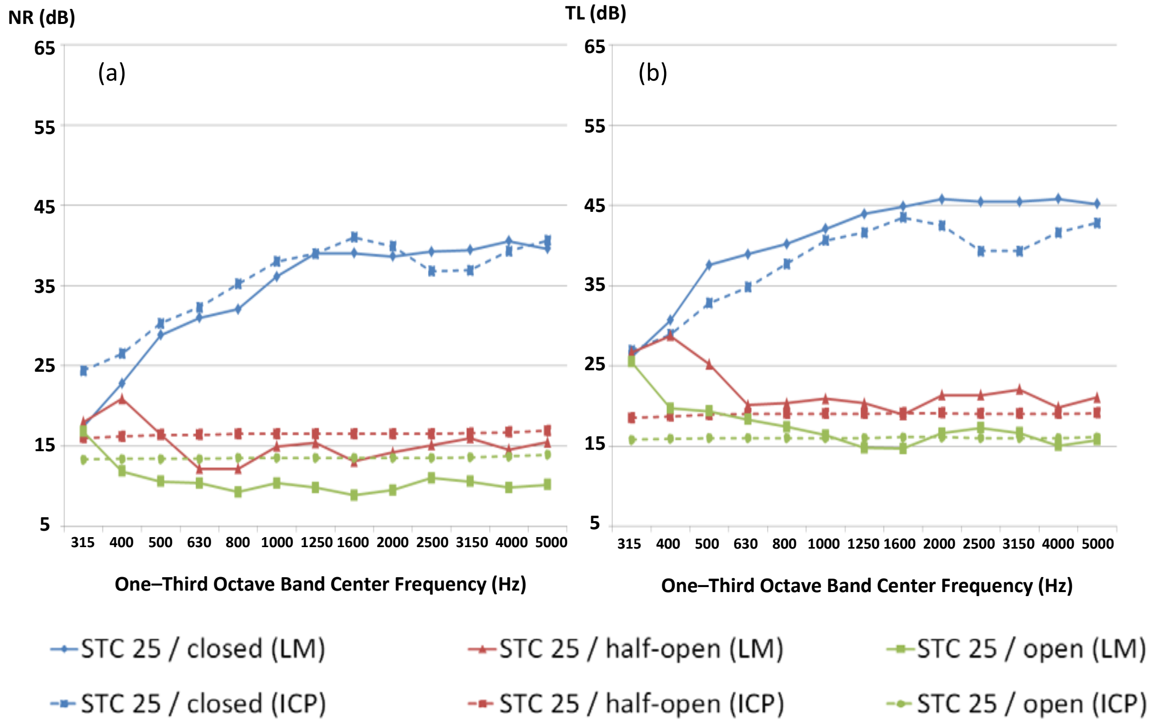


Figure 4.51: (a) NR and (b) TL comparison of window condition with STC 25 window (Iterations #27-29 from Table 4.7)

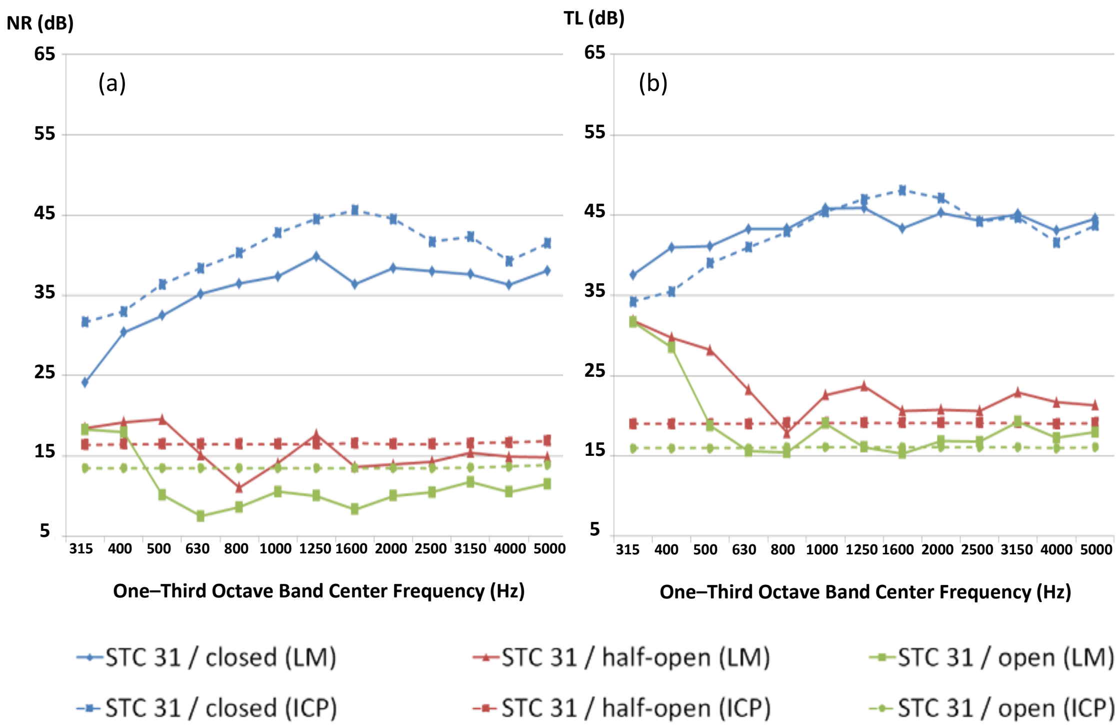


Figure 4.52: (a) NR and (b) TL comparison of window condition with STC 31 window (Iterations #6-8 from Table 4.7)

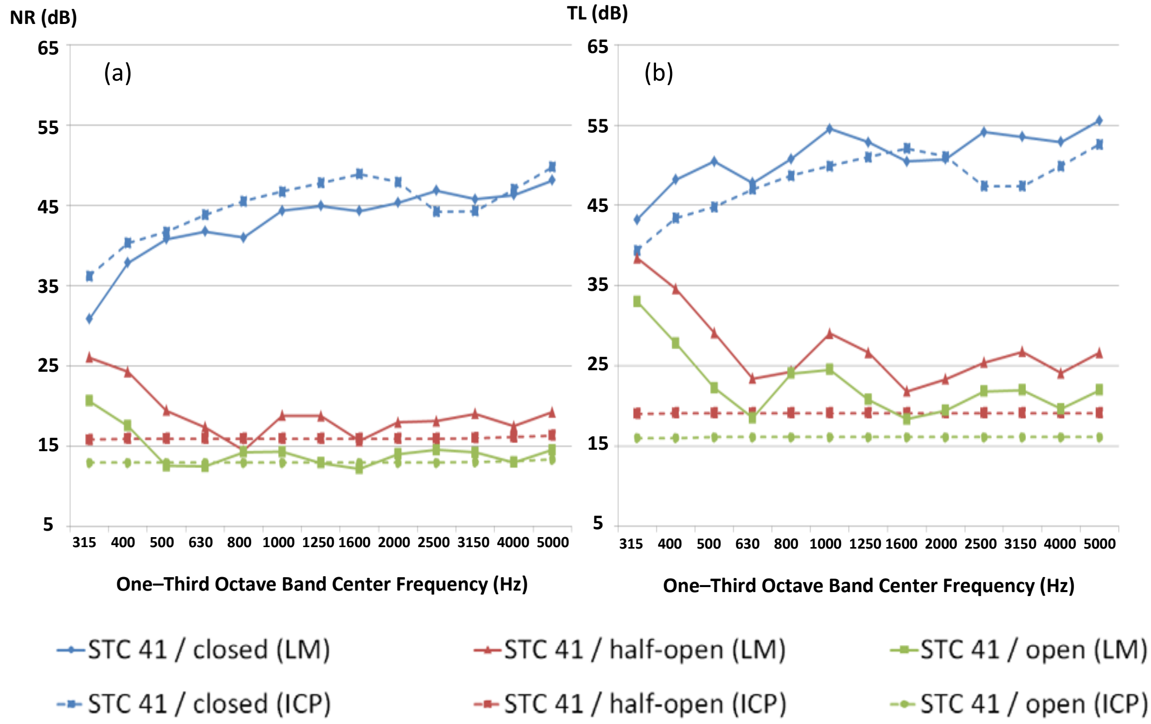


Figure 4.53: (a) NR and (b) TL comparison of window condition with STC 41 window (Iterations #49-51 from Table 4.7)

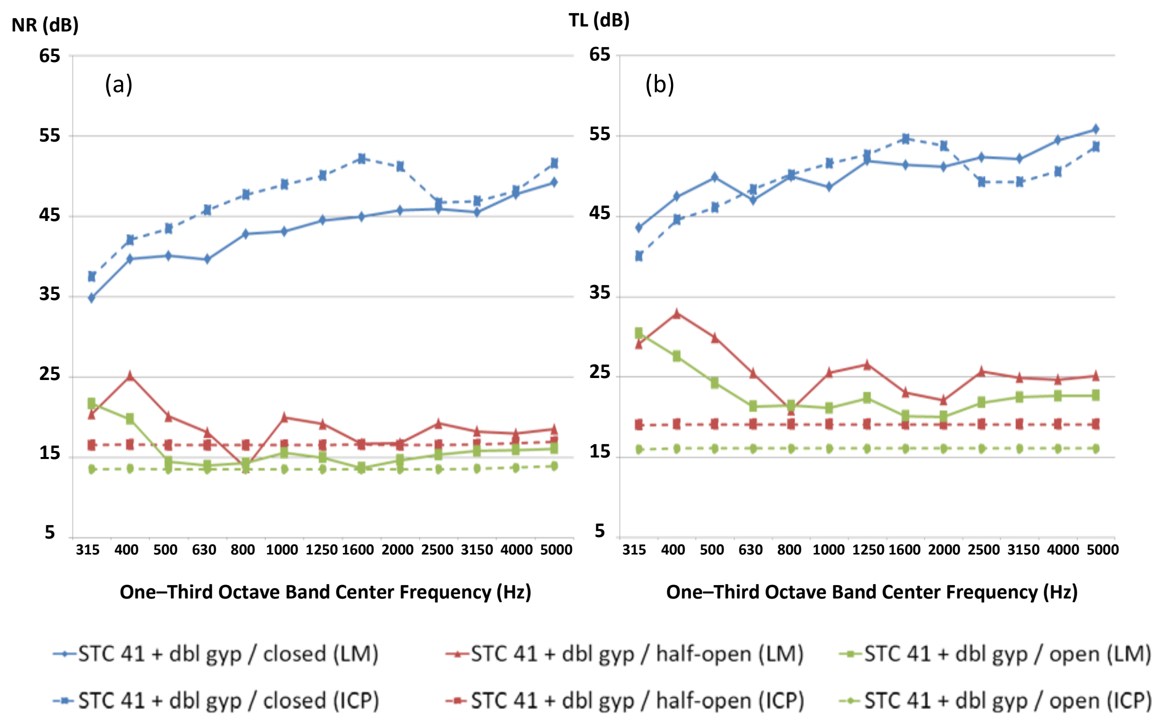


Figure 4.54: (a) NR and (b) TL comparison of window condition with STC 41 window + double gypsum board (Iterations #79-81 from Table 4.7)

4.2.4.6 Windows with Varying Acoustical Performance

The comparisons in Figure 4.55 and Figure 4.56 held the following conditions constant: JBL loudspeaker at 3.4’ and at θ=45°, pink noise signal, window closed, and single layer of gypsum board. The acronyms “LM” and “ICP” correspond to “Laboratory Measured” and “IBANA-Calc Predicted”, respectively. Comparisons for measurements conducted with near average and flush methods are shown separately, as it was expected that the two different methods might have an effect on measurements.

Once again, it appears that NR (Figure 4.55(a)-Figure 4.56(a)) is generally over-predicted for the following comparisons of the different acoustically-rated windows used in testing. As before, the TL prediction curves across frequency (Figure 4.55(b)-Figure 4.56(b)) appear to be the NR curves translated uniformly to higher values, and appear to under-predict TL for all construction iterations shown.

Measurements conducted with various windows appear to have followed expectations—NR and TL were evaluated to be highest for the STC 41 window and lowest for the STC 25 window. No window type stood out as matching NR or TL predictions better compared to the others. And as seen in Section 4.2.4.1, flush measurements appear to have resulted in slightly higher NR and TL values across frequency than near average measurements. The difference between the two measurement methods, however, once again appears to be less than significant.

|ΔNR| between measurements with the STC 25 window tended to be lowest (corresponding to better performance) with frequency bands between 400-2000 Hz and above 3150 Hz, and tended to be highest (corresponding to worse performance) below 400 Hz. |ΔNR| between measurements with the STC 31 window tended to be lowest with

frequency bands between 400-1250 Hz and above 2000 Hz, and tended to be highest below 400 Hz. |ΔNR| between measurements with the STC 41 window tended to be lowest with frequency bands between 400-630 Hz and 1000-5000 Hz, and tended to be highest below 400 Hz.

|ΔTL| between measurements with the STC 25 window tended to be lowest with frequency bands between 315-400 Hz and 800-1600 Hz, and tended to be highest between 2000-4000 Hz. |ΔTL| between measurements with the STC 31 window tended to be lowest with frequency bands between 1000-1600 Hz, and tended to be highest below 800 Hz. |ΔTL| between measurements with the STC 41 window tended to be lowest with frequency bands between 630-800 Hz and 1250-2000 Hz, and tended to be highest between 2500-3150 Hz.

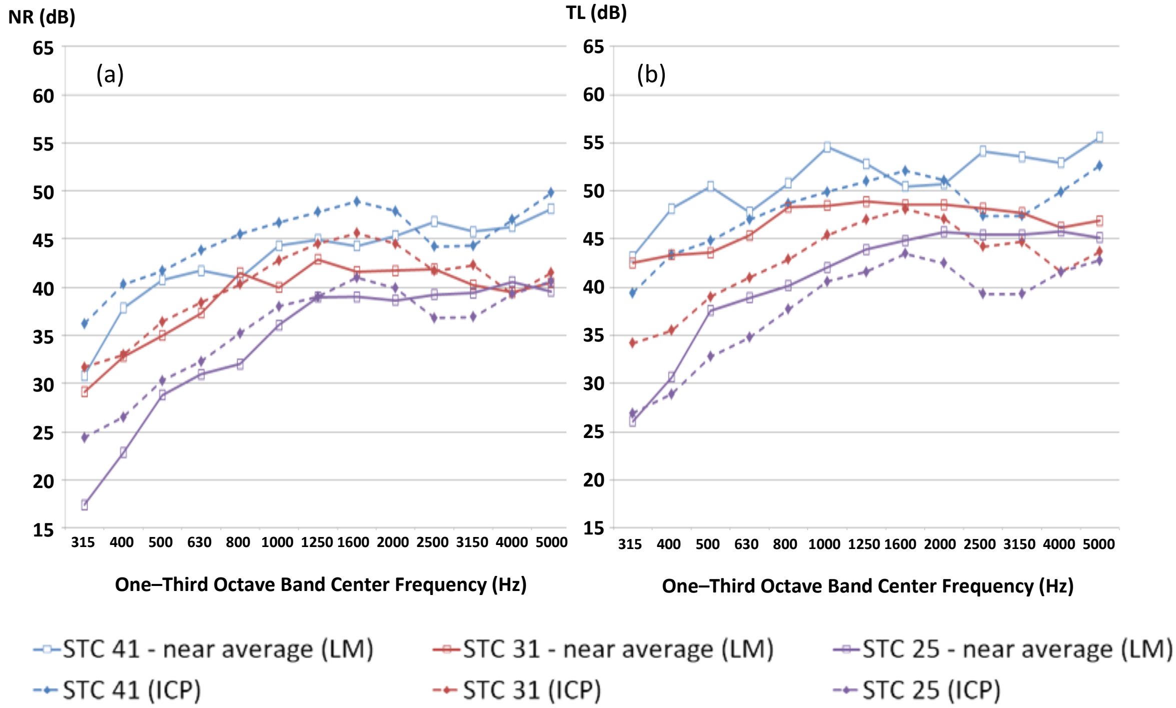


Figure 4.55: (a) NR and (b) TL comparison of near average measurements for different window STC ratings (Iterations #9, 27 & 49 from Table 4.7)

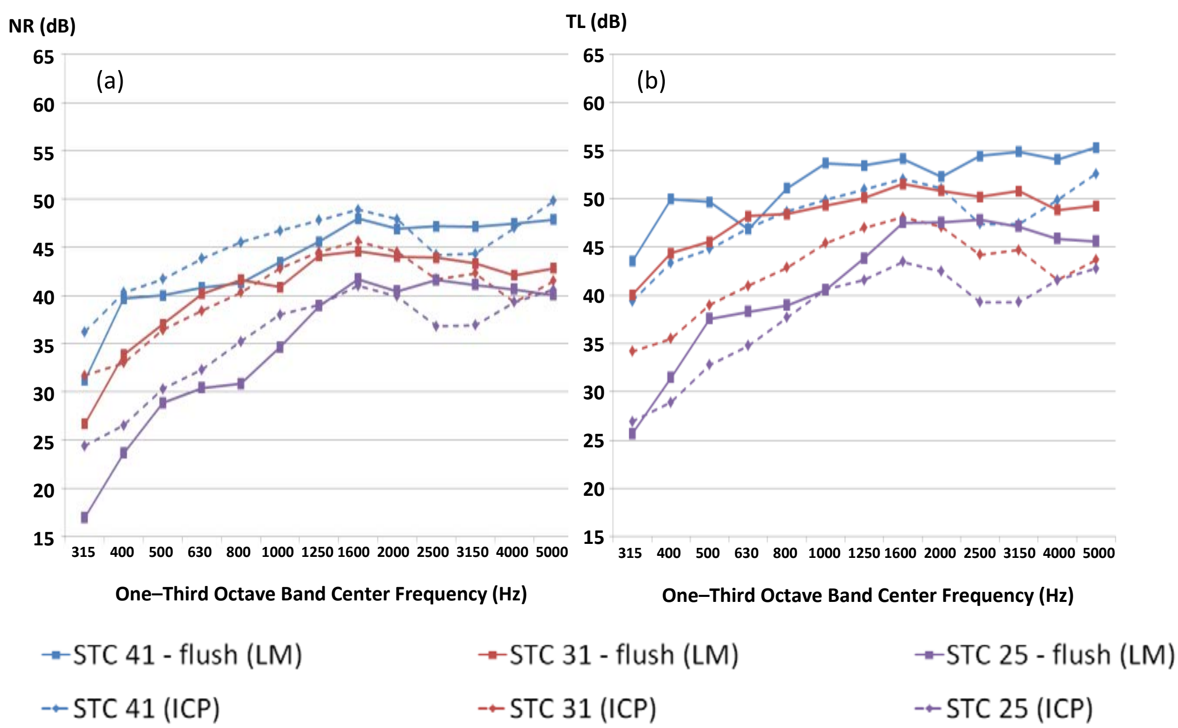


Figure 4.56: (a) NR and (b) TL comparison of flush measurements for different window STC ratings (Iterations #1, 26 & 48 from Table 4.7)

4.2.4.7 Layers of Interior Gypsum Board

The comparisons in Figure 4.57 and Figure 4.58 held the following conditions constant: source at θ=45°, STC 41 window, and window closed. Curves representing laboratory measurement for the following comparisons were averaged across iterations with different sound source signals and different vertical angles of incidence, as these conditions were not expected to introduce variation to the results across frequency.

Once again, it appears that NR (Figure 4.57(a)-Figure 4.58(a)) is generally over-predicted for the following comparisons of the number of layers of interior gypsum board installed in the test house during testing. As before, the TL prediction curves across frequency (Figure 4.57(b)-Figure 4.58(b)) appear to be the NR curves translated uniformly to higher values, and appear to once again under-predict TL for the single gypsum board layer configuration.

Measurements conducted with the double layer of gypsum board do not appear to have followed expectations—NR and TL were measured to be higher on average for the construction iterations with only the single layer of gypsum board. This is a highly non-intuitive result that will be discussed further in Section 4.3.1. The averaged iterations appear to show that model predictions for NR of the single layer of gypsum board construction clearly outperformed model predictions for NR of the double layer of gypsum board. The difference in performance compared to model predictions is less pronounced for TL.

$|\Delta NR|$ between measurements with the single layer of gypsum board tended to be lowest (corresponding to better performance) with frequency bands between 400-500 Hz and above 2500 Hz, and tended to be highest (corresponding to worse performance) at

1600 Hz. |ΔNR| between measurements with the double layer of gypsum board tended to be lowest with frequency bands between 2500-4000 Hz, and tended to be highest with frequency bands between 500-2000 Hz.

|ΔTL| between measurements with the single layer of gypsum board tended to be lowest with frequency bands between 630-800 Hz and 1250-2000 Hz, and tended to be highest with frequency bands below 630 Hz and above 2000 Hz. |ΔTL| between measurements with the double layer of gypsum board tended to be lowest with frequency bands between 315-500 Hz and 2500-3150 Hz, and tended to be highest with frequency bands between 1000-2000 Hz.

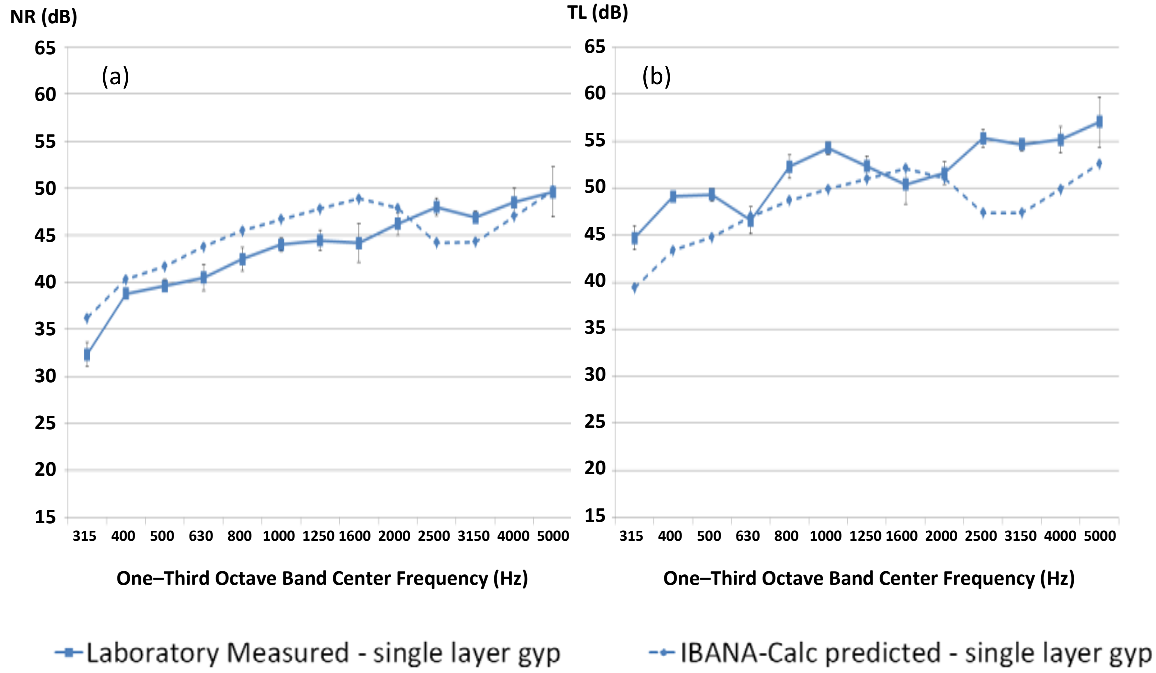


Figure 4.57: (a) NR and (b) TL comparison of single gypsum board layer configuration (Average and standard deviation of iterations #48-49 & 62-69 from Table 4.7)

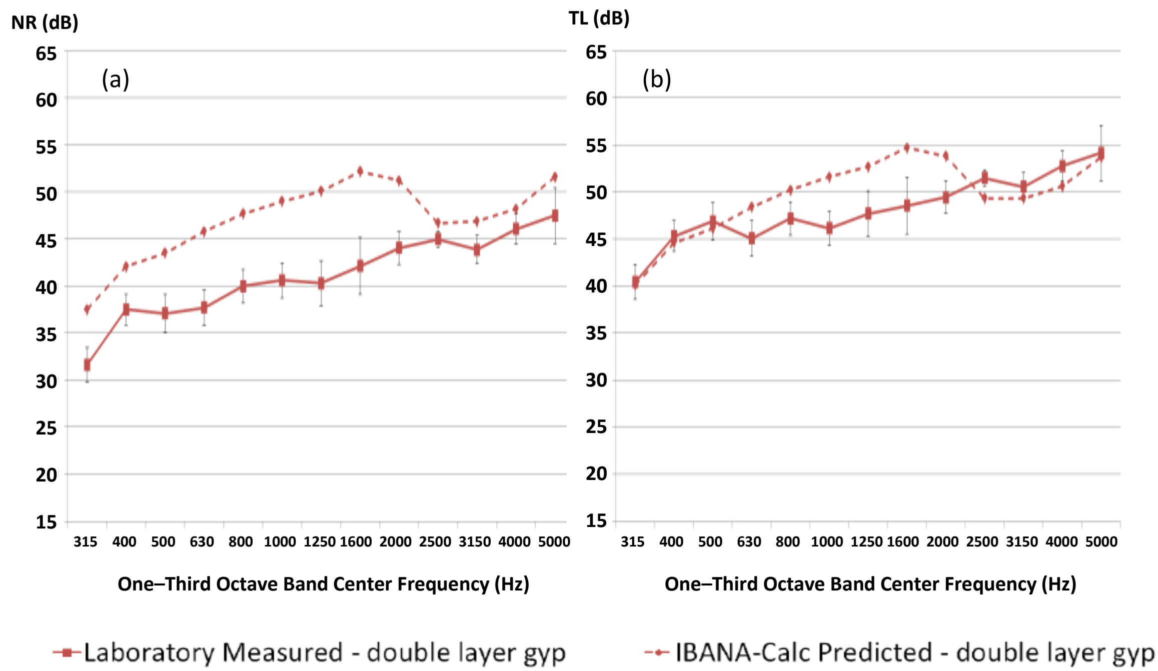


Figure 4.58: (a) NR and (b) TL comparison of double gypsum board layer configuration (Average and standard deviation of iterations #70-79 from Table 4.7)

4.2.5 Pressure Correction for External Level Measurements

This study was also interested in validating the sound pressure level corrections included by the measurement standard [14] for the calculation of NR, as shown in Equations (4.4)-(4.5). Without the use of a reference free-field microphone in our measurement setup, it would be difficult to investigate the accuracy of using the pressure doubling (2 dB) correction for near average measurements and the pressure quadrupling (5 dB) correction for flush mounted measurements. It was possible, however, to extract cases from the raw measurement data to investigate the relative difference between near average and flush measurements. Table 4.11 below displays the absolute difference between raw flush and near average sound level measurements, averaged across frequency. As the average difference across frequency between raw flush and near average sound levels ranged from ~2-3 dB, the pressure doubling between exterior sound level measurement methods appears to be confirmed. As illustrated on Table 4.7, the STC 25 measurements specifically corresponded to iterations #26 & 27; the STC 31 measurements specifically corresponded to iterations #1 & 9; the STC 41 measurements specifically corresponded to iterations #48 & 49; the STC 41 and double gypsum board measurements specifically corresponded to iterations #78 & 79.

Table 4.11: NR pressure analysis

Window type	L_{flush} - L_{near} (dB)
STC 25	1.84
STC 31	2.37
STC 41	2.44
STC 41 + dbl gyp	2.18

4.3 Discussion

4.3.1 Overall Performance

It is important to restate that this research has not conducted a study or established confidence intervals to evaluate the repeatability of any single measurement location that was used in the laboratory validation. It is undetermined whether the difference in NR and TL between measurements and predictions is independent of the variation introduced by using different possible microphone locations in a measurement. With all this in consideration, however, the IBANA-Calc models seem to have overall predicted NR with greater accuracy than TL. As seen in most of the comparisons shown on Table 4.9 and Table 4.10, **|ΔNR|** was a lower value than **|ΔTL|** for 57 out of the 91 (63%) measurements conducted. It is also interesting to note that **ΔNR** was typically a negative value, as seen in 68 out of the 91 (75%) measurements conducted. **ΔTL** was typically positive, except for the most extreme cases (extreme incidence angle of incidence, window half-open, etc.), as seen in 70 out of the 91 (77%) measurements conducted. Given our convention in calculating **ΔNR** and **ΔTL**, this can be interpreted as the IBANA-Calc models typically over-predicting NR and under-predicting TL.

The over-prediction of NR by the models is expected, given the fact that IBANA-Calc assumes field incidence in its model predictions. The expression used by IBANA-Calc to calculate TL is shown again in Equation (4.17), and can be compared to the expression used by this research to evaluate measured TL shown as Equation (4.18).

$$\boldsymbol{TL = NR + 10\log\left(\frac{S}{A}\right)}, \text{ dB} \tag{4.17}$$

$$\boldsymbol{TL} = \boldsymbol{NR} + \mathbf{10}\,\mathbf{log}\left(\frac{\boldsymbol{S}}{\boldsymbol{A}}\right) + \mathbf{10}\,\mathbf{log}(\mathbf{sin}(\boldsymbol{\theta_2})) + \mathbf{6}, \text{ dB} \quad (4.18)$$

It might appear that IBANA-Calc simply assumes a reference angle of incidence of 14.5° or 165.5° by our convention (or 75.5° relative to normal incidence by the convention of ASTM E966) for the 10*log(sin(θ)) and the +6 dB terms to cancel out, but it appears that the software uses Equation (4.17) with an alternative reasoning. The IBANA-Calc software user manual refers to both Equations (4.17) and (4.18), stating that (4.17) is a reduction of (4.18) for indoor transmission loss between rooms, when sound is virtually incident from all angles [22]. The user manual also states that integrating incident sound levels over complete aircraft fly-bys also averages over a range of angle of incidence, and that although intermediate equations between the two have been suggested that "the comparisons obtained in this project suggest that equation [(4.17)] is most appropriate and used in the calculations in the IBANA-Calc software" [22]. Given the method that this study has determined that IBANA-Calc uses to model aircraft sound transmission, shown again in Figure 4.59, it appears that NR would be over-predicted compared to horizontal incidence angle-dependent measurements. The software does not subtract the extra terms (10*log(sin(θ)) + 6 dB) of Equation (4.18) from predicted TL to evaluate NR.

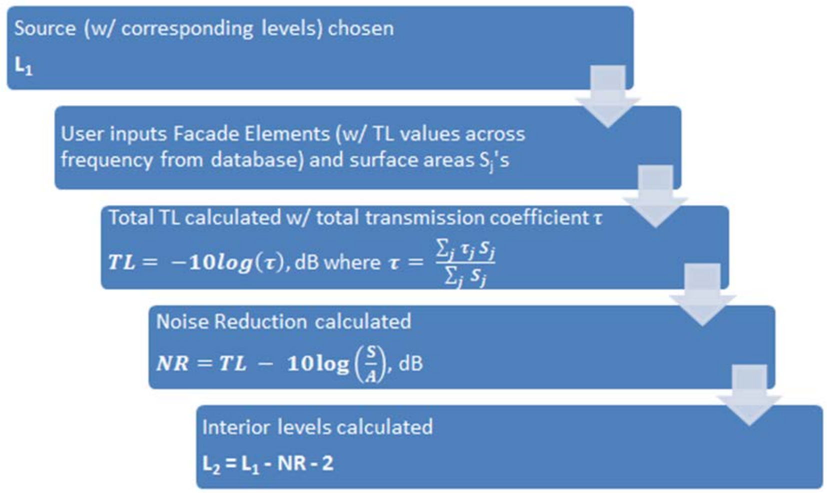


Figure 4.59: Process used by IBANA-Calc to predict TL and NR (identical to Figure 2.2)

Even with the expected variation from testing conditions such as horizontal incidence angle and the unknown variation from using different microphone locations, it appears that the IBANA-Calc models performed well for engineering purposes, with **|ΔNR|** and **|ΔTL|** generally less than ~3-4 dB. Comparisons of exterior measurement method (this will be addressed further in Section 4.3.2), and acoustical performance of the window all revealed **|ΔNR|** no greater than 2.6 dB (Table 4.9). Comparisons of the loudspeaker sound source, sound source signal, and vertical incidence angle of the source all revealed **|ΔNR|** no greater than 3.8 dB (Table 4.9). It has been established that the differences between measured and predicted are greater with TL than NR (**|ΔNR|** < **|ΔTL|**). And yet, Table 4.10 also shows that for the various conditions listed above—exterior measurement method, acoustical performance of the window, loudspeaker sound source, sound source signal, and vertical incidence angle of the source—**|ΔTL|** never exceeds 4.7 dB**.** The lack of variation across these particular measurement and construction iterations appears to suggest that using the various loudspeaker sound sources, sound source signal types, vertical incidence angles, exterior measurement methods and windows did not significantly affect the resulting measurements. Given the variation evident from Figure 4.35 to Figure 4.38 as well as from Table 4.9 and Table 4.10, it is also apparent that horizontal angle of incidence is a key source in the difference from measured to predicted sound attenuation performance—this will be elaborated further in Section 4.3.3.

Considering that introducing an 'Opening' in IBANA-Calc as a façade element simply applies a flat TL contour of 0 dB across frequency, it does appear the software performed well. Models accounting for an opening predicted NR within 3.3 dB and TL within 5.7 dB for the configurations that included a half- or fully-open window. Still, future modeling software should probably use a more nuanced approach to model openings, especially at lower frequencies. Very large differences in NR and TL can be seen at frequency bands below 800 Hz from Figure 4.51 to Figure 4.54.

Predictions for NR were also prominently over-predicted for the configuration including a double layer of gypsum board (11 of 22, or 50%, of the iterations showed **ΔNR** which corresponded to over-prediction greater than 5 dB), which might point toward limitations of the application of transmission loss theory as applied by the Insul modeling software. It is inexplicable, however, that NR and TL were measured to be higher in iterations with the STC 41 window and a single layer of gypsum board than NR and TL in iterations with the STC 41 window and a double layer of gypsum board.

It is possible that there were issues with sealing or the window assembly itself after the second layer of gypsum board (the final construction iteration carried out) was installed. TL measured for the single gypsum board configuration, shown in Figure

4.57(b), can be seen to be 8 dB higher at 1000 Hz than TL measured for the double gypsum board configuration, shown in Figure 4.58(b). A simple TL calculation, similar to what the IBANA-Calc software evaluates, revealed that an opening or combination of smaller openings (with TL = 0 dB across frequency) would only need a total area of 1.4 sq. in. to result in a drop of 8 dB at 1000 Hz from the expected TL performance of the double gypsum board configuration. It is also possible that the mounting of the second layer of gypsum board, described in Section 4.1.4.2.2, could have affected the radiation efficiency of the composite façade and reduced the TL performance. The attachment of the second layer of gypsum board, with screws staggered along the joints to avoid the attachment points of the original gypsum board layer, likely increased stiffness and quadrupled the density of the pinning points in the structure.

It is apparent that there is a conflicting relationship between the performance of single-number ratings and the NR or TL performance across frequency from measured to predicted. As shown in Table 4.9 and Table 4.10, groups of iterations that showed the "worst" performance in predicting NR and TL were often the iterations that showed the "best" performance in predicting NLR (such as the 15° and 165° horizontal angle iterations). It is likely that the discrepancy might be explained by the range of values used to evaluate the different metrics. **|ΔNR|** and **|ΔTL|** as shown in Table 4.9 and Table 4.10 were taken as averages between 315 – 5000 Hz, as this frequency range was the focus of this study. NLR was evaluated to be the difference between the single-number logarithmic sum of the outdoor level and the single-number logarithmic sum of the indoor level. As such, NLR was evaluated from single-number outdoor/indoor sound levels that were summed across the full frequency range of the model predictions and measurements—50 Hz to 5,000 Hz. Interior sound levels measured below 315 Hz, corresponding roughly to the lower limit that the room response can be determined through frequency analysis, may have been unreliable and inconsistent. This should once again establish the importance of analysis that is conducted and reported across frequency, as human response to sound is more sensitive to specific frequency bands. While statistical metrics such as **|ΔNR|** and **|ΔTL|** calculated the arithmetic mean of differences between measured and predicted across frequency, ΔNLR values were relatively muted by the exterior and interior acoustic environments described by logarithmically summed single-number ratings.

Finally, it appears that the existing aircraft sound transmission software does not have the capabilities to adequately model interior room absorption as it would exist in buildings. Given the method to define interior absorption used in IBANA-Calc, as shown in Section 2.2.1, the user is essentially applying a “flat” absorption to the interior space across frequency. When the user assigns absorption to the modeled scenario (from 50% to 150% of the room floor area), a single absorption value is assumed to correspond to all frequency bands. This explains why the overall shape of IBANA-Calc prediction curves did not change from NR to TL, as shown from Figure 4.31 to Figure 4.58. The curves across frequency appear to have been translated by 10*log10(S/A), as shown in Equation (4.17) with A constant across frequency. Measured NR and TL curves, however, vary in shape across frequency. Absorption values across frequency specific to the construction iteration being measured were applied to TL calculations (as given in Section 4.1.3.5). Future updates to the modeling technology should likely address this limitation.

4.3.2 External Measurement Method

While it should be emphasized that comparisons of the external measurement method were taken from a limited sample size, there are some interesting takeaways from the measurement iterations that used the near average of the flush method. First, the results shown in Section 4.2.5 appear to confirm a pressure doubling going when from near average to flush measurements. Next, it has been shown in Section 2.2.3 that the IBANA-Calc software uses the near average correction factor to calculate NR (and accordingly, indoor sound level). As a reminder, the following equations to evaluate NR include the expression used for near average measurement, Equation (4.19), and the expression used for flush measurements, Equation (4.20).

$$\boldsymbol{NR_{near} = L_{ext} - L_{in} - 2}, \text{ dB} \tag{4.19}$$

$$\boldsymbol{NR_{flush} = L_{ext} - L_{in} - 5}, \text{ dB} \tag{4.20}$$

Reviewing the two expressions, one might expect that **|ΔNR|** would equal 0 for near average measurements and **|ΔNR|** would equal 3 for flush measurements—as shown in Equations (4.21)-(4.22)—if the difference between measured and predicted levels were equal.

$$\begin{aligned} |\Delta NR|_{near} &= \left|NR_{measured} - NR_{predicted}\right|_{near} \\ &= \left|(L_{ext} - L_{in} - 2)_{measured} - (L_{ext} - L_{in} - 2)_{predicted}\right| \\ &= 0 \end{aligned} \tag{4.21}$$

$$|\Delta NR|_{flush} = \left|NR_{measured} - NR_{predicted}\right|_{flush} \tag{4.22}$$
$$= \left|(L_{ext} - L_{in} - 5)_{measured} - (L_{ext} - L_{in} - 2)_{predicted}\right|$$
$$= 3$$

On the surface, the reported values of **|ΔNR|** = 2.55 for near average and **|ΔNR|** = 2.48 for flush measurements on Table 4.9 appear to point to a congruence between the two exterior level measurement methods. Given the expressions of Equations (4.21)-(4.22), however, it seems that the limited sample size of flush measurements reveal better matching between measured and predicted values. This is especially interesting considering the statement from a J.S. Bradley paper (previously shown in Section 4.1.4.1.1) that "façade mounted" or flush microphones could produce errors of up to 12 dB and that "incident sound levels measured at the building façade are strongly influenced by ground reflections and diffraction effects that vary with the vertical angle of the aircraft" [12]. It is clear that these laboratory measurements never elevated the sound source to comparable vertical angles to aircraft. The results of this laboratory validation seem to fall more in line with the results of the BTV study introduced in Section 1.5.3, which found that median NLR using flush measurements were on average 0.6 dB higher than near average measurements [27], suggesting an insignificant difference between methods that also appear to disagree with Bradley's findings. Further investigation is needed in the appropriate use of the two measurement methods.

4.3.3 Horizontal Angle of Incidence

As previously stated, it was expected that horizontal angle of incidence would be a key source in the difference from measured to predicted sound attenuation performance. The authors of the NLR study (reviewed in Section 1.5.3) stated that, while the variation attributed to changing horizontal angle of incidence was inconclusive given the sample of rooms measured in the project, that the median NLR difference from a reference 45° incidence was only 0.2 dB at 30° and 0.0 dB at 60° [27]. The differences in the findings of this laboratory validation and the NLR study conducted around the BTV airport can likely be attributed to the focus of the two analyses—metrics across frequency versus single-number ratings such as NLR. Also, it doesn't appear that the BTV study conducted measurements at other angles of horizontal incidence. The feature to correct scenarios for the horizontal angle of incidence of the sound source is not implemented by the IBANA-Calc software due to a "lack of supporting evidence" [22] that it would be relevant to its field incident model predictions. An analysis of the metrics **ΔTL** and **ΔNR** confirmed the expected variation between measurements and predictions.

$$\Delta NR = NR_{measured} - NR_{predicted} \tag{4.23}$$

$$\begin{aligned}\Delta TL &= TL_{measured} - TL_{predicted} \\ &= \left[NR_{measured} + 10\log\left(\frac{S}{A}\right) + 10\log(\sin(\theta_2)) + 6\right] - \\ &\qquad \left[NR_{predicted} + 10\log\left(\frac{S}{A}\right)\right]\end{aligned} \tag{4.24}$$

$$\Delta TL - \Delta NR = \left[NR_{measured} + 10\log\left(\frac{S}{A}\right) + 10\log(\sin(\theta_2)) + 6\right] - \left[NR_{predicted} + 10\log\left(\frac{S}{A}\right)\right] - \left[NR_{measured} - NR_{predicted}\right] = 10\log(\sin(\theta_2)) + 6 \tag{4.25}$$

Following the logic of Equations (4.23)-(4.25), **ΔTL-ΔNR** could be expected equal to the horizontal angle correction factor of 10*log(sin(θ)) + 6. With **ΔTL-ΔNR** calculated across 315 to 5000 Hz, this equality was verified to be within 1 dB for all comparisons as shown in Table 4.12. This finding confirmed the expected variation between measurements and predictions, and also seems to suggest that the horizontal angle of incidence correction factor (if relevant to the modeling) could be implemented by any future NR and TL modeling tools. Going back to Figure 4.59, it appears that implementing a horizontal angle of incidence correction factor would decrease predicted NR across frequency and likely increase the performance of NR model predictions—this study has shown IBANA-Calc to generally over-predict NR compared to measurements. Given the IBANA-Calc's software methodology described in Figure 4.59, however, it seems that a horizontal angle of incidence correction factor would not affect the performance of TL model predictions.

Table 4.12: Comparison of ΔTL-ΔNR to horizontal angle of incidence correction factor

Msmt #	ΔTL-ΔNR	Horiz Angle Corr	Diff	Msmt #	ΔTL-ΔNR	Horiz Angle Corr	Diff	Msmt #	ΔTL-ΔNR	Horiz Angle Corr	Diff
1	5.41	4.49	**0.91**	31	2.82	2.99	**0.17**	61	0.76	0.13	**0.63**
2	5.41	4.49	**0.91**	32	5.20	5.38	**0.17**	62	5.12	4.49	**0.63**
3	5.41	4.49	**0.91**	33	5.68	5.85	**0.17**	63	5.12	4.49	**0.63**
4	1.04	0.13	**0.91**	34	5.83	6.00	**0.17**	64	5.12	4.49	**0.63**
5	3.90	2.99	**0.91**	35	5.68	5.85	**0.17**	65	5.12	4.49	**0.63**
6	5.41	4.49	**0.91**	36	5.20	5.38	**0.17**	66	5.12	4.49	**0.63**
7	5.39	4.49	**0.90**	37	4.32	4.49	**0.17**	67	5.12	4.49	**0.63**
8	5.39	4.49	**0.90**	38	2.82	2.99	**0.17**	68	5.12	4.49	**0.63**
9	5.41	4.49	**0.91**	39	-0.04	0.13	**0.17**	69	5.12	4.49	**0.63**
10	6.29	5.38	**0.91**	40	4.32	4.49	**0.17**	70	4.59	4.49	**0.09**
11	6.76	5.85	**0.91**	41	4.32	4.49	**0.17**	71	4.59	4.49	**0.09**
12	6.91	6.00	**0.91**	42	4.32	4.49	**0.17**	72	4.59	4.49	**0.09**
13	6.76	5.85	**0.91**	43	4.32	4.49	**0.17**	73	4.59	4.49	**0.09**
14	6.29	5.38	**0.91**	44	4.32	4.49	**0.17**	74	4.59	4.49	**0.09**
15	5.41	4.49	**0.91**	45	4.32	4.49	**0.17**	75	4.59	4.49	**0.09**
16	3.90	2.99	**0.91**	46	4.32	4.49	**0.17**	76	4.59	4.49	**0.09**
17	1.04	0.13	**0.91**	47	4.32	4.49	**0.17**	77	4.59	4.49	**0.09**
18	5.41	4.49	**0.91**	48	5.12	4.49	**0.63**	78	4.59	4.49	**0.09**
19	5.41	4.49	**0.91**	49	5.12	4.49	**0.63**	79	4.59	4.49	**0.09**
20	5.41	4.49	**0.91**	50	5.10	4.49	**0.60**	80	4.58	4.49	**0.08**
21	5.41	4.49	**0.91**	51	5.12	4.49	**0.62**	81	4.56	4.49	**0.07**
22	5.41	4.49	**0.91**	52	0.76	0.13	**0.63**	82	0.22	0.13	**0.09**
23	5.41	4.49	**0.91**	53	3.62	2.99	**0.63**	83	3.08	2.99	**0.09**
24	5.41	4.49	**0.91**	54	6.00	5.38	**0.63**	84	5.47	5.38	**0.09**
25	5.41	4.49	**0.91**	55	6.48	5.85	**0.63**	85	5.94	5.85	**0.09**
26	4.32	4.49	**0.17**	56	6.63	6.00	**0.63**	86	6.09	6.00	**0.09**
27	4.32	4.49	**0.17**	57	6.48	5.85	**0.63**	87	5.94	5.85	**0.09**
28	4.31	4.49	**0.18**	58	6.00	5.38	**0.63**	88	5.47	5.38	**0.09**
29	4.31	4.49	**0.19**	59	5.12	4.49	**0.63**	89	4.59	4.49	**0.09**
30	-0.04	0.13	**0.17**	60	3.62	2.99	**0.63**	90	3.08	2.99	**0.09**
								91	0.22	0.13	**0.09**

where **ΔTL-ΔNR** has been taken from 315-5000 Hz

While it was of interest to also evaluate the vertical angle of incidence correction factor included in the IBANA-Calc software, a review of Firesheet's thesis revealed the following limitation of the software: to apply any correction other than Air Absorption, “it is necessary to model the exposed walls and roof separately and apply the correction factors to the appropriate surface (due to differences in the angles of incidence)…as the primary concern of this research is on the TL of the building envelope, these correction factors have limited usefulness” [19].

4.4 Future Research

The most immediate area of development for this study would be to conduct more test structure measurements, with more construction iterations to reflect various building profiles and energy retrofits, to further build up a comprehensive TL database even further. An area of focus would specifically be to collect TL data across frequency for various roof types and floor/ceiling structures, as this has often given acoustic consultants issues in modeling. Although standard residential constructions would feature doorways and some combination of roof vents, the test house was designed without roof vents to avoid any potential flanking issues and to simplify the modeling. Future testing should attempt to continue to evaluate standard construction elements such as doors and roof vents that would be found in most buildings in airport communities. Once again, the ideal resource for further modeling would include the following features: (i) TL/NR published across frequency, in contrast to the single-number ratings usually reported; (ii) detailed construction information for each construction element including the dimensions, number of layers, and mounting of all wall, roof, and window materials; (iii) data for both older and newer construction types; and (iv) data covering constructions typical for the variety of climate regions found in North America.

As described in Section 4.1.3.5, the next phase of the research will have to evaluate the repeatability of the current methodology. For example, the ASTM standard used to develop this laboratory validation called for "five or more measurements at random distances from the specimen, at random positions across the specimen and at varying heights across the specimen" [14] for exterior near average measurements, and similar random microphone placements for flush mounted and interior sound level measurements. Holding all other conditions constant, confidence intervals should be established to confirm the repeatability of a single choice of microphone locations. No such study was included in this thesis research, but future research will need to confirm that the variation from measured to predicted is independent of the testing repeatability before making any strong conclusions regarding the performance of the predicted models. It might also be of use to extend the current standards to allow for more direct comparison of measured sound insulation, which can be very dependent on horizontal angle of incidence, to predicted sound insulation, which assumes field incidence. It would be valuable to develop a back-calculation method that would allow acousticians to "translate" a TL or NR measurement at a single angle of incidence to field incidence—across multiple angles of incidence.

Another area of improvement that could be applied to future test structure measurements would be to use an exterior free-field microphone and an interior sweep to measure exterior and interior sound levels. The use of instrumentation in this manner could increase measurement repeatability, allowing for more measurements covering more construction and testing iterations. Also, the laboratory validation in this study could have been improved by symmetric testing for source horizontal angle of incidence iterations. Given the asymmetric placement of the test house in the hemi-anechoic chamber, source positions at equal angular offsets from normal incidence were not at equal distances away from the test house façade. As such, this lab study used an alternative convention for horizontal angle of incidence (θ_2 in Figure 4.16). If the testing allowed for the angular convention offered by the measurement standard, iterations for corresponding source positions at equal angular offsets from normal incidence would be at equal distances and these iterations could be combined. For example, iterations for 15° or 165° (by this study's convention) would be both considered as 75° (by the ASTM E966-10 convention). This simplification would allow for stronger statistical validation of a method to convert a TL or NR measurement at a single angle of incidence to field incidence.

Updates to the modeling technologies should ideally address the issues described in previous sections. Absorption varies across frequency in real buildings, and future modeling software should include the ability for the user to input custom absorption profiles for the receiving room. Additionally, custom façade elements can currently be input into the modeling software without TL values in certain frequency ranges. If the façade elements making up a composite model do not have complete overlap in the frequency bands for which TL values are reported, the models should report single-number values corrected to include the narrowest frequency range for which every façade element has entered TL values.

Collaborators at Pennsylvania State University have been involved with this study to develop and validate a finite element model for low frequency transmission [41]. Low frequency tends to penetrate walls easily due to the thickness of most building walls and the quarter wavelength of low frequency sound waves. The vibration and resonance of the building structure, as well as possible fluid and structure interaction, affect TL so it was deemed appropriate to apply finite element analysis. Low frequency measurements were conducted in the test structure using façade-mounted accelerometers and both acoustic and mechanical shaker noise sources. Preliminary results from the validation have been presented [41] and will be compared to measurements and IBANA-Calc predictions from this study. In relation to this collaborative study it will also be of interest to investigate how low frequency content is used to evaluate NEF, which is the input setting for the resulting levels of a sound source modeled in IBANA-CAlc.

Improved models will be relevant to human response testing, as accurate NR and TL filters could be used in studies of annoyance, sleep disturbance, learning outcomes, among many other applications. The models may be adapted for varying inputs, such as multiple sources or retrofit impacts. And finally, it is clear that the difference between the prediction and lab measurement needs further investigation. Such effort may help to inform considerations to any future updates of the measurement standards as well as the modeling enhancement.

APPENDIX A

INSUL WALL MODELS

Sound Insulation Prediction (v7.0.6)

Program copyright Marshall Day Acoustics 2012

- Key No. 2305

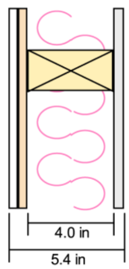
Margin of error is generally within STC +/- 3 dB

Job Name:

Job No.: Page No.: Notes:

Date: 2 Aug 13 Initials:Ryherd

File Name: testhousew all.ixl



STC 46

OITC 36

System description

Panel 1 Outer layer: 1 x 0.44 in Fibre Cement- (m=3.55 lb/ft2, fc=2700 Hz, Damping=0.01) Profile
Panel 1 Inner layer: 1 x 0.44 in OSB (Oriented Strand Board) (m=1.28 lb/ft2, fc=2242 Hz,Damping=0.03)

Cavity: Timber stud @ 22 in , Infill 3" fiberglass (0.6 lb/ft3) Thickness 4 in
Panel 2 Inner layer: 1 x 0.50 in Gypsum plasterboard- (m=1.79 lb/ft2, fc=2992 Hz, Damping=0.01) Profile

Mass-air-mass resonant frequency =63 Hz

frequency (Hz)	TL(dB)	TL(dB)
50	17	
63	16	18
80	20	
100	26	
125	30	29
160	34	
200	37	
250	39	38
315	41	
400	43	
500	44	44
630	46	
800	47	
1000	48	48
1250	49	
1600	50	
2000	49	47
2500	45	
3150	45	
4000	49	48
5000	52	

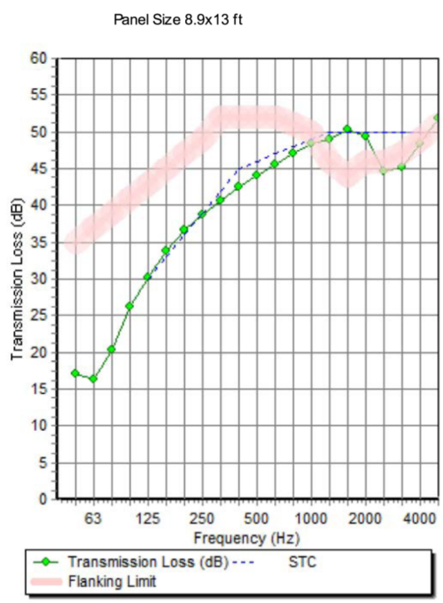


Figure A.1: Single-layer gypsum board Insul wall model

Sound Insulation Prediction (v7.0.6)

- Key No. 2305

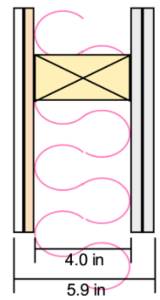
Margin of error is generally within STC +/- 3 dB

Job Name:

Job No.: Page No.: Notes:

Date: 24 Feb 14 Initials:Ryherd

File Name: testhousew all_dblegyp.ixl



STC 48

OITC 42

System description

Panel 1 Outer layer: 1 x 0.44 in Fibre Cement- (m=3.57 lb/ft2, fc=2684 Hz, Damping=0.01) Profile
Panel 1 Inner layer: 1 x 0.44 in OSB (Oriented Strand Board) (m=1.29 lb/ft2, fc=2229 Hz,Damping=0.03)

Cavity: Timber stud @ 22 in , Infill 3" fiberglass (0.6 lb/ft3) Thickness 4 in
Panel 2 Inner layer: 2 x 0.50 in Gypsum plasterboard- (m=3.59 lb/ft2, fc=2992 Hz, Damping=0.01) Profile

Mass-air-mass resonant frequency =50 Hz

frequency (Hz)	TL(dB)	TL(dB)
50	16	
63	25	20
80	29	
100	31	
125	34	33
160	37	
200	39	
250	41	41
315	43	
400	45	
500	46	46
630	48	
800	49	
1000	50	50
1250	51	
1600	53	
2000	52	50
2500	47	
3150	47	
4000	50	50
5000	54	

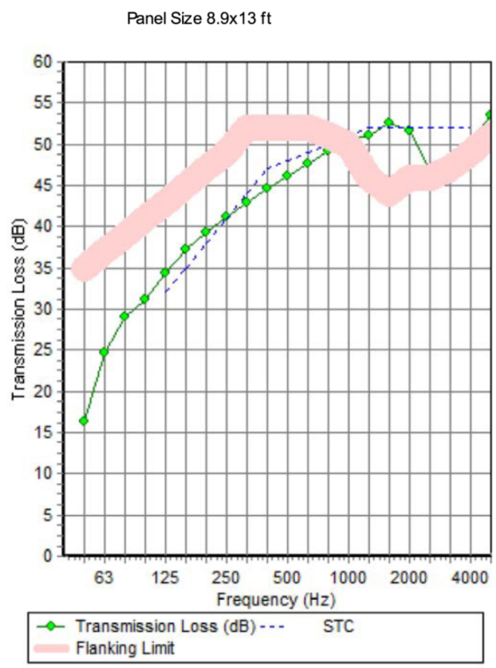


Figure A.2: Double-layer gypsum board Insul wall model

APPENDIX B

IBANA-CALC ROOM MODELS

IBANA-Calc Composite Model with STC 25 window

```
         Aircraft Noise Sound Insulation Scenario Calculation Results


Project:
ProjectID:
Date:10/27/2013
Outdoor level:    NEF 30  or Leq24 62  or Ldn 63 dBA

Source Spectrum details:

     100% Standard Aircraft
                                   Corrections:


Receiving room:

     Floor Area:    90 ft²
     Absorbtion:    150% of floor area

Construction Description:

Element 1:  test house - mixed humid

     Construction Type:    Custom Wall
     Area:    137.00 ft²
     Test ID:
     Test Date:  8/26/2013

     fibercement: 7/16", OSB: 7/16", 2x4 wood studs, 24" O.C.
fibergalss insula
tion: 3.5", gyp board: 1/2"

Element 2:  SHN3_BPAP0.7_OSB11_RHWT1626_GFB152_G13

     Construction Type:    RHWT Roof
     Area:    90.00 ft²
     Test ID:    TLF-98-097a
     Test Date:  11/19/1998

     Asphalt shingles, building paper, 11 mm OSB, raised heel wood trusses with
glass fibre cavity insulation, 1 of 13 mm gypsum board, no vents installed.

Element 3:  SilentGuard 9000 SH Single Hung Vinyl Window [STC 25]

     Construction Type:    Custom Window
     Area:    15.00 ft² / 12.00 ft² (half-open) / 9.00 ft² (fully open)
     Test ID:
     Test Date:  10/21/2013

     48" W x 60" H
3/32" (2.2 mm) glazing - 9/16" (14.5 mm) gap/space - 3/32" (
2.2 mm) glazing

Element 4:  OPENING

     Construction Type:    Window
     Area:    3.00 ft² (half-open) / 6.00 ft² (fully open)
     Test ID:
     Test Date:  12:00:00 AM

     Opening
```

Table B.1: IBANA-Calc composite model with STC 25 window

				Composite Model				Indoor Sound Level		
	Wall	RHWT roof	Window	Window Closed	Window Half-Open	Window Open	Source Sound Level	Window Closed	Window Half-Open	Window Open
f (Hz)	**TL (dB)**						**L_{ext}(dB)**	**L_{in}(dB)**		
50	17	16.4	-	**10.9**	10.9	10.9	54.8	46.5	46.5	46.5
63	16	21.7	-	**11**	11	11	56	47.5	47.5	47.5
80	20	22.8	23	**21**	16.9	14.9	57.5	39.1	43.1	45.2
100	26	27.1	19	**25.3**	18.2	15.6	58.9	36.1	43.3	45.8
125	30	31.8	21	**28.8**	18.7	15.9	59.3	32.9	43.1	45.9
160	34	36	21	**30.9**	18.8	16	59	30.6	42.7	45.6
200	37	39.3	20	**31.1**	18.8	16	58.5	30	42.2	45.1
250	39	41.3	16	**27.8**	18.6	15.9	57.5	32.2	41.4	44.2
315	41	42.5	15	**26.9**	18.5	15.8	56.5	32.1	40.5	43.2
400	43	46.1	17	**28.9**	18.7	15.9	55.8	29.3	39.6	42.4
500	44	48.4	21	**32.8**	18.9	16	55.2	24.9	38.8	41.8
630	46	50.8	23	**34.8**	19	16	54.6	22.3	38.2	41.2
800	47	55.4	26	**37.7**	19	16	53.7	18.5	37.2	40.2
1000	48	58.7	29	**40.6**	19	16	52.5	14.5	36	39
1250	49	61.6	30	**41.6**	19	16	51.2	12.2	34.7	37.7
1600	50	64.2	32	**43.5**	19.1	16.1	49.6	8.6	33.1	36.1
2000	49	64	31	**42.5**	19.1	16.1	47.4	7.5	30.9	33.9
2500	45	63.4	28	**39.3**	19	16	45.6	8.8	29.1	32.1
3150	45	65.9	28	**39.3**	19	16	43.3	6.4	26.7	29.7
4000	49	71.2	30	**41.6**	19	16	40.2	0.9	23.5	26.5
5000	52	76.4	31	**42.8**	19.1	16.1	34.3	-6.3	17.4	20.4
STC	46	52	25							
OITC	36.4	39	22	32	19	16				
				Outdoor Sound Level		dBA	62			
				Indoor Sound Level				32	46	49
				A-wtd Level Reduction				30	16	13
			Corrected	Indoor Sound Level				31.9	45.6	48.5
				A-wtd Level Reduction				30.1	16.4	13.4

IBANA-Calc Composite Model with STC 31 window

```
        Aircraft Noise Sound Insulation Scenario Calculation Results

Project:
ProjectID:
Date:10/27/2013
Outdoor level:    NEF 30  or Leq24 62  or Ldn 63 dBA

Source Spectrum details:

     100% Standard Aircraft
Corrections:


Receiving room:

     Floor Area:    90 ft²
     Absorbtion:    150% of floor area

Construction Description:

Element 1:  test house - mixed humid

     Construction Type:    Custom Wall
     Area:    137.00 ft²
     Test ID:
     Test Date:  8/26/2013

     fibercement: 7/16", OSB: 7/16", 2x4 wood studs, 24" O.C.
fibergalss insula
tion: 3.5", gyp board: 1/2"

Element 2:  SilentGuard 9000 SH Single Hung Vinyl Window [STC 31]

     Construction Type:    Custom Window
     Area:    15.00 ft² / 12.00 ft² (half-open) / 9.00 ft² (fully open)
     Test ID:
     Test Date:  8/26/2013

     48" W x 60" H
1/8" (3.2 mm) glazing - 13/16" (20.6 mm) gap/space - 1/8" (3
.2 mm) glazing

Element 3:  SHN3_BPAP0.7_OSB11_RHWT1626_GFB152_G13

     Construction Type:    RHWT Roof
     Area:    90.00 ft²
     Test ID:    TLF-98-097a
     Test Date:  11/19/1998

     Asphalt shingles, building paper, 11 mm OSB, raised heel wood trusses with
glass fibre cavity insulation, 1 of 13 mm gypsum board, no vents installed.

Element 4:  OPENING

     Construction Type:    Window
     Area:    3.00 ft² (half-open) / 6.00 ft² (fully open)
     Test ID:
     Test Date:  12:00:00 AM

     Opening
```

Table B.2: IBANA-Calc composite model with STC 31 window

				Composite Model			Source Sound Level	Indoor Sound Level		
	Wall	RHWT roof	Window	Window Closed	Window Half-Open	Window Open		Window Closed	Window Half-Open	Window Open
f (Hz)	TL (dB)						L_{ext}(dB)	L_{in}(dB)		
50	17	16.4	-	**10.9**	10.9	10.9	54.8	46.5	46.5	46.5
63	16	21.7	-	**11**	11	11	56	47.5	47.5	47.5
80	20	22.8	27	**21.1**	17	14.9	57.5	39	43.1	45.2
100	26	27.1	27	**26.4**	18.3	15.7	58.9	35	43.1	45.8
125	30	31.8	29	**30.5**	18.8	15.9	59.3	31.3	43	45.9
160	34	36	26	**33.2**	18.9	16	59	28.3	42.6	45.6
200	37	39.3	15	**26.7**	18.5	15.8	58.5	34.3	42.6	45.2
250	39	41.3	20	**31.4**	18.9	16	57.5	28.6	41.2	44.1
315	41	42.5	23	**34.2**	19	16	56.5	24.8	40.1	43
400	43	46.1	24	**35.5**	19	16	55.8	22.8	39.3	42.3
500	44	48.4	28	**39**	19	16	55.2	18.8	38.7	41.7
630	46	50.8	30	**41**	19	16	54.6	16.2	38.1	41.1
800	47	55.4	32	**42.9**	19.1	16.1	53.7	13.4	37.2	40.2
1000	48	58.7	35	**45.4**	19.1	16.1	52.5	9.7	36	39
1250	49	61.6	37	**47**	19.1	16.1	51.2	6.7	34.7	37.7
1600	50	64.2	38	**48.1**	19.1	16.1	49.6	4	33	36.1
2000	49	64	37	**47.1**	19.1	16.1	47.4	2.9	30.9	33.9
2500	45	63.4	35	**44.2**	19.1	16.1	45.6	3.9	29.1	32.1
3150	45	65.9	36	**44.7**	19.1	16.1	43.3	1	26.7	29.7
4000	49	71.2	30	**41.6**	19	16	40.2	0.9	23.5	26.5
5000	52	76.4	32	**43.7**	19.1	16.1	34.3	-7.2	17.4	20.4
STC	46	52	31							
OITC	36.4	39	26	35	19	16				
				Outdoor Sound Level		dBA	62			
				Indoor Sound Level		dBA		29	46	49
				A-wtd Level Reduction		dBA		33	16	13
			Corrected	Indoor Sound Level		dBA		28.5	45.5	48.5
			Corrected	A-wtd Level Reduction		dBA		33.5	16.5	13.5

IBANA-Calc Composite Model with STC 41 window

```
     Aircraft Noise Sound Insulation Scenario Calculation Results


Project:
ProjectID:
Date:10/27/2013
Outdoor level:    NEF 30  or Leq24 62  or Ldn 63 dBA

Source Spectrum details:

     100% Standard Aircraft
Corrections:


Receiving room:

     Floor Area:    90 ft²
     Absorbtion:    130% of floor area

Construction Description:

Element 1:  test house - mixed humid

     Construction Type:    Custom Wall
     Area:    137.00 ft²
     Test ID:
     Test Date:  8/26/2013

     fibercement: 7/16", OSB: 7/16", 2x4 wood studs, 24" O.C.
fibergalss insula
tion: 3.5", gyp board: 1/2"

Element 2:  SHN3_BPAP0.7_OSB11_RHWT1626_GFB152_G13

     Construction Type:    RHWT Roof
     Area:    90.00 ft²
     Test ID:    TLF-98-097a
     Test Date:  11/19/1998

     Asphalt shingles, building paper, 11 mm OSB, raised heel wood trusses with
glass fibre cavity insulation, 1 of 13 mm gypsum board, no vents installed.

Element 3:  SilentGuard 7100 Double Glazed Vinyl Window [STC 41]

     Construction Type:    Custom Window
     Area:    15.00 ft²/ 12.00 ft² (half-open) / 9.00 ft² (fully open)
     Test ID:
     Test Date:  10/21/2013

     48" W x 60" H
1/8" (3.2 mm) glazing - 11/16" (18 mm) gap/space - 1/8" (3.2
 mm) glazing

Element 4:  OPENING

     Construction Type:    Window
     Area:    3.00 ft² (half-open) / 6.00 ft² (fully open)
     Test ID:
     Test Date:  12:00:00 AM

     Opening
```

Table B.3: IBANA-Calc composite model with STC 41 window

				Composite Model				Indoor Sound Level		
	Wall	RHWT roof	Window	Window Closed	Window Half-Open	Window Open	Source Sound Level	Window Closed	Window Half-Open	Window Open
f (Hz)	**TL (dB)**						**L_{ext}(dB)**	**L_{in}(dB)**		
50	17	16.4	15	**16.6**	14.7	13.4	54.8	41.4	43.3	44.6
63	16	21.7	19	**17.6**	15.3	13.8	56	41.6	43.9	45.4
80	20	22.8	18	**20.7**	16.8	14.8	57.5	40	43.9	45.9
100	26	27.1	18	**25**	18.1	15.6	58.9	37	43.9	46.5
125	30	31.8	19	**28**	18.6	15.8	59.3	34.4	43.8	46.6
160	34	36	28	**33.8**	18.9	16	59	28.4	43.2	46.2
200	37	39.3	26	**35.1**	19	16	58.5	26.6	42.7	45.7
250	39	41.3	28	**37**	19	16	57.5	23.6	41.7	44.6
315	41	42.5	31	**39.4**	19	16	56.5	20.3	40.7	43.6
400	43	46.1	39	**43.4**	19.1	16	55.8	15.5	39.9	42.9
500	44	48.4	41	**44.8**	19.1	16.1	55.2	13.5	39.3	42.3
630	46	50.8	44	**47**	19.1	16.1	54.6	10.8	38.7	41.7
800	47	55.4	47	**48.7**	19.1	16.1	53.7	8.2	37.8	40.8
1000	48	58.7	49	**49.9**	19.1	16.1	52.5	5.8	36.6	39.6
1250	49	61.6	50	**51**	19.1	16.1	51.2	3.4	35.3	38.3
1600	50	64.2	52	**52.1**	19.1	16.1	49.6	0.7	33.7	36.7
2000	49	64	51	**51.1**	19.1	16.1	47.4	-0.5	31.5	34.5
2500	45	63.4	53	**47.4**	19.1	16.1	45.6	1.4	29.7	32.7
3150	45	65.9	53	**47.4**	19.1	16.1	43.3	-1	27.3	30.3
4000	49	71.2	43	**49.9**	19.1	16.1	40.2	-6.8	24.1	27.1
5000	52	76.4	45	**52.6**	19.1	16.1	34.3	-15.5	18	21
STC	46	52	41							
OITC	36.4	39	29	36	19	16				
				Outdoor Sound Level		dBA	62			
				Indoor Sound Level				26	46	49
				A-wtd Level Reduction				36	16	13

IBANA-Calc Composite Model with STC 41 window and double gypsum board wall

```
    Aircraft Noise Sound Insulation Scenario Calculation Results


Project:
ProjectID:
Date:1/13/2014
Outdoor level:    NEF 30  or Leq24 62  or Ldn 63 dBA

Source Spectrum details:

     100% Standard Aircraft
Corrections:


Receiving room:

     Floor Area:    90 ft²
     Absorbtion:    150% of floor area

Construction Description:

Element 1:  SHN3_BPAP0.7_OSB11_RHWT1626_GFB152_G13

     Construction Type:    RHWT Roof
     Area:    90.00 ft²
     Test ID:    TLF-98-097a
     Test Date:  11/19/1998

     Asphalt shingles, building paper, 11 mm OSB, raised heel wood trusses with
glass fibre cavity insulation, 1 of 13 mm gypsum board, no vents installed.

Element 2:  test house - mixed humid - double gypboard

     Construction Type:    Custom Wall
     Area:    137.00 ft²
     Test ID:
     Test Date:  1/13/2014

     fibercement: 7/16", OSB: 7/16", 2x4 wood studs, 24" O.C.
fibergalss insula
tion: 3.5", gyp board: 1" (gypboard: 1/2" + gypboard: 1/2")

Element 3:  SilentGuard 7100 Double Glazed Vinyl Window [STC 41]

     Construction Type:    Custom Window
     Area:    15.00 ft² / 12.00 ft² (half-open) / 9.00 ft² (fully open)
     Test ID:
     Test Date:  10/21/2013

     48" W x 60" H
1/8" (3.2 mm) glazing - 11/16" (18 mm) gap/space - 1/8" (3.2
 mm) glazing

Element 4:  OPENING

     Construction Type:    Window
     Area:    3.00 ft² (half-open) / 6.00 ft² (fully open)
     Test ID:
     Test Date:  12:00:00 AM

     Opening
```

Table B.4: IBANA-Calc model with STC 41 window and double gypsum board wall

				Composite Model				Indoor Sound Level		
	Wall	RHWT roof	Window	Window Closed	Window Half-Open	Window Open	Source Sound Level	Window Closed	Window Half-Open	Window Open
f (Hz)	**TL (dB)**						**L_{ext}(dB)**	**L_{in}(dB)**		
50	16	16.4	15	**16.1**	14.3	13.1	54.8	41.3	43	44.2
63	25	21.7	19	**22.9**	17.6	15.3	56	35.7	41	43.3
80	29	22.8	18	**24.4**	18	15.5	57.5	35.7	42.1	44.6
100	31	27.1	18	**26.7**	18.4	15.8	58.9	34.8	43	45.7
125	34	31.8	19	**29**	18.7	15.9	59.3	32.8	43.1	45.9
160	37	36	28	**35.2**	19	16	59	26.4	42.6	45.5
200	39	39.3	26	**35.7**	19	16	58.5	25.4	42.1	45.1
250	41	41.3	28	**37.7**	19	16	57.5	22.4	41	44
315	43	42.5	31	**40.1**	19	16	56.5	19	40	43
400	45	46.1	39	**44.6**	19.1	16.1	55.8	13.7	39.2	42.2
500	46	48.4	41	**46.1**	19.1	16.1	55.2	11.7	38.7	41.7
630	48	50.8	44	**48.4**	19.1	16.1	54.6	8.8	38.1	41.1
800	49	55.4	47	**50.2**	19.1	16.1	53.7	6	37.2	40.2
1000	50	58.7	49	**51.6**	19.1	16.1	52.5	3.5	36	39
1250	51	61.6	50	**52.7**	19.1	16.1	51.2	1.1	34.7	37.7
1600	53	64.2	52	**54.7**	19.1	16.1	49.6	-2.6	33	36.1
2000	52	64	51	**53.8**	19.1	16.1	47.4	-3.8	30.9	33.9
2500	47	63.4	53	**49.3**	19.1	16.1	45.6	-1.1	29.1	32.1
3150	47	65.9	53	**49.3**	19.1	16.1	43.3	-3.6	26.7	29.7
4000	50	71.2	43	**50.6**	19.1	16.1	40.2	-8	23.4	26.5
5000	54	76.4	45	**53.7**	19.1	16.1	34.3	-17.3	17.4	20.4
STC	48	52	41							
OITC	42	39	29	38	19	16				
				Outdoor Sound Level		dBA	62			
				Indoor Sound Level				24	45	48
				A-wtd Level Reduction				38	17	14

APPENDIX C

RT60 MEASUREMENTS

Table C.1: Reverberation time measurements for each construction iteration

	RT60 (sec)			
f (Hz)	**STC 31**	**STC 25**	**STC 41**	**STC 41 + dbl gyp**
12.5	4.770	6.665	1.870	3.637
16	4.246	1.220	2.230	1.010
20	2.677	4.048	2.213	2.637
25	1.806	4.126	2.098	3.015
31.5	0.300	-	5.285	0.890
40	3.664	1.120	2.000	1.312
50	0.330	1.180	0.764	0.933
63	1.159	0.689	1.120	0.239
80	0.340	1.542	0.837	0.201
100	0.950	1.328	2.037	0.447
125	0.822	1.588	0.496	0.988
160	1.224	0.743	1.246	0.610
200	1.352	0.499	1.591	0.491
250	0.520	0.576	0.704	0.436
315	0.284	0.234	0.417	0.239
400	0.180	0.193	0.342	0.191
500	0.229	0.238	0.167	0.191
630	0.203	0.196	0.128	0.172
800	0.152	0.206	0.147	0.165
1000	0.159	0.125	0.123	0.114
1250	0.127	0.099	0.195	0.174
1600	0.157	0.121	0.132	0.139
2000	0.153	0.163	0.110	0.110
2500	0.135	0.133	0.170	0.141
3150	0.178	0.127	0.189	0.147
4000	0.150	0.106	0.146	0.149
5000	0.140	0.114	0.176	0.146
6300	0.130	0.135	0.140	0.150
8000	0.133	0.145	0.141	0.134
10000	0.141	0.130	0.151	0.136
12500	0.137	0.134	0.147	0.131
16000	0.133	0.123	0.141	0.130
20000	0.145	0.123	0.126	0.212

*Values relevant to study (315 Hz – 5000 Hz) highlighted in blue

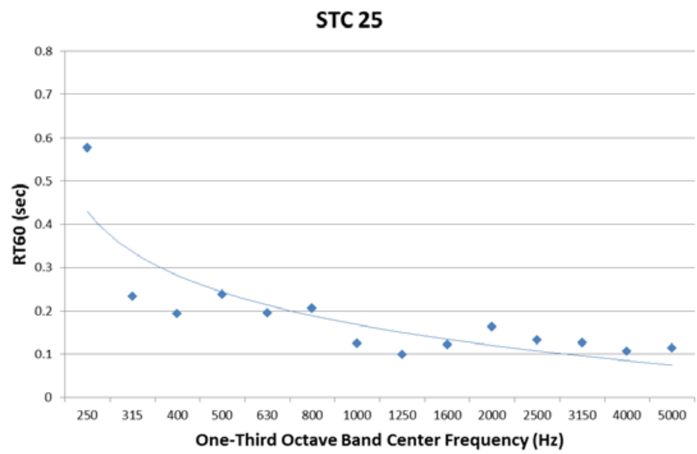


Figure C.1: Measured RT_{60} for test house with STC 25 window

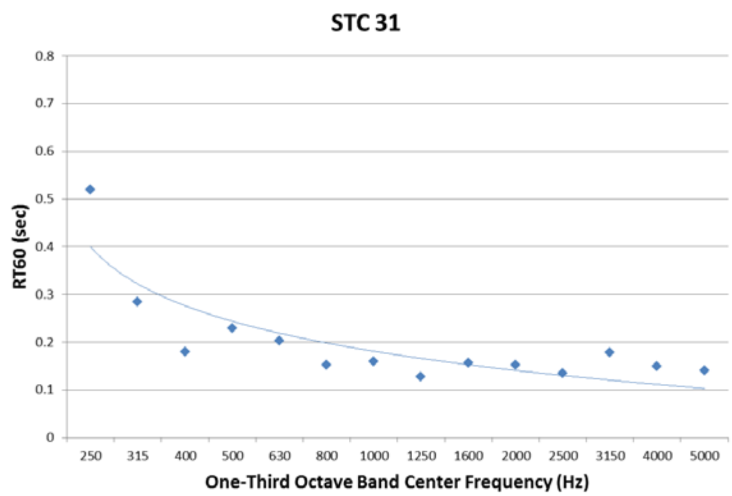


Figure C.2: Measured RT_{60} for test house with STC 31 window

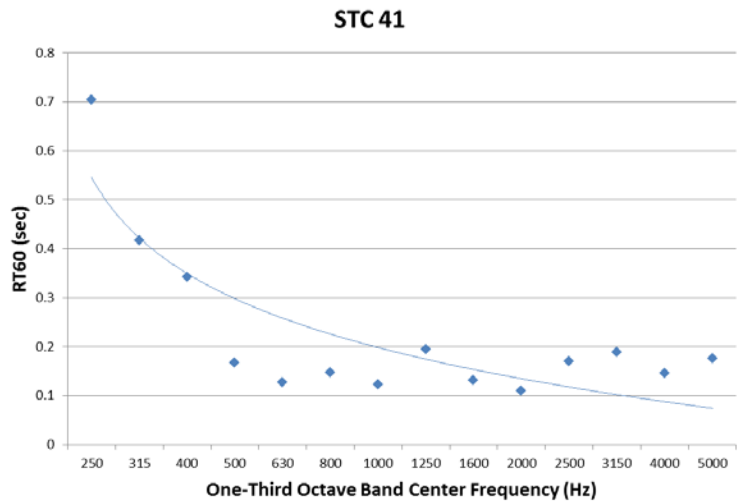


Figure C.3: Measured RT_{60} for test house with STC 41 window

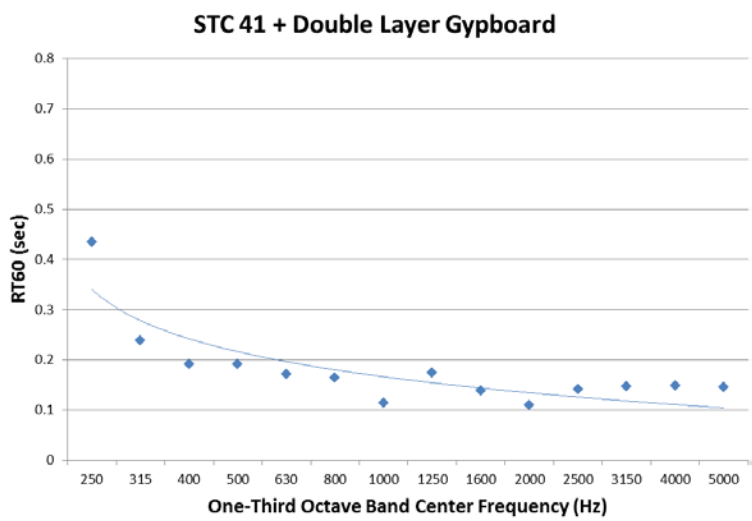


Figure C.4: Measured RT_{60} for test house with STC 41 window and double gypsum board

APPENDIX D

NR MEASUREMENTS

Table D.1: Measured noise reduction across frequency for every iteration

Msmt number	1	2	3	4	5	6	7	8	9	10
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	jet	pink	pink	pink	pink	pink	pink	pink	pink
Ext msmt	flush	near	near	near	near	near	near	near	near	near
Window STC	31	31	31	31	31	31	31	31	31	31
Open/Closed	closed	closed	closed	closed	closed	closed	half	open	closed	closed
Theta (deg)	45	45	45	15	30	45	45	45	45	60
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	**Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)**									
50	17.6	16.8	17.3	13.6	11.9	14.3	10.3	10.2	16.6	20.1
63	15.8	14.4	15.5	10.5	10.3	11.2	6.5	6.5	13.7	16.4
80	22.0	19.8	20.7	15.7	18.2	16.8	9.8	8.3	18.8	20.5
100	25.1	23.5	24.9	18.6	18.4	20.1	16.3	15.3	21.3	25.8
125	25.9	22.9	24.0	21.4	18.4	21.2	8.0	8.5	22.3	24.8
160	26.0	21.8	22.0	17.1	18.7	20.1	7.6	8.0	23.9	24.8
200	19.7	18.3	19.8	15.2	18.7	15.8	12.1	8.0	22.3	25.2
250	26.9	29.7	29.8	20.0	27.4	26.1	15.8	13.0	31.0	34.1
315	26.7	27.0	28.1	21.1	24.5	24.2	18.5	18.3	29.1	30.2
400	33.9	33.1	35.7	28.3	28.6	30.4	19.2	18.0	32.8	35.8
500	37.0	35.7	36.9	30.5	31.7	32.5	19.6	10.2	35.0	36.9
630	40.2	37.7	38.7	30.6	33.1	35.2	15.2	7.5	37.3	41.4
800	41.6	38.7	41.6	31.0	35.9	36.5	11.1	8.6	41.5	40.4
1000	40.9	39.5	41.3	34.0	36.1	37.3	14.1	10.6	40.0	43.4
1250	44.1	43.1	45.3	33.0	36.9	39.8	17.7	10.1	42.9	44.5
1600	44.6	41.9	43.3	33.9	38.8	36.4	13.7	8.3	41.6	44.2
2000	44.0	41.4	41.1	33.0	38.3	38.4	13.9	10.0	41.7	42.4
2500	43.9	42.4	43.5	35.5	38.1	38.0	14.3	10.5	41.9	42.6
3150	43.3	41.3	42.5	34.8	37.7	37.6	15.4	11.8	40.2	41.8
4000	42.1	39.3	40.1	26.3	34.1	36.3	14.9	10.5	39.5	40.8
5000	42.8	39.0	42.8	30.5	29.5	38.1	14.9	11.5	40.4	43.8
6300	44.8	33.0	43.3	38.4	39.0	39.8	15.1	11.1	42.5	47.9
8000	43.3	21.3	39.3	40.1	43.8	36.4	16.1	10.5	40.1	48.3
10000	44.4	9.4	44.1	39.6	43.1	41.9	15.8	11.6	43.8	47.3
12500	38.7	2.3	40.8	36.9	40.6	39.8	18.7	12.2	39.9	42.8
16000	31.9	0.4	34.7	30.3	34.5	34.1	16.7	11.9	34.8	38.1
20000	16.1	-0.7	20.5	14.1	19.4	19.2	16.0	11.7	20.6	23.4
Outdoor Sound Level (dBA)	81.9	89.9	78.2	74.0	76.5	76.4	76.5	76.3	78.4	81.5
Indoor Sound Level (dBA)	37.7	57.0	38.0	42.4	41.8	40.5	59.9	64.0	38.9	40.0
A-wtd Level Reduction (dBA)	44.2	32.9	40.2	31.6	34.7	35.8	16.5	12.2	39.5	41.5

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	11	12	13	14	15	16	17	18	19	20
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	Peavey	Peavey	Peavey
Source Signal	pink	pink	pink	pink	pink	pink	pink	jet	pink	jet
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	31	31	31	31	31	31	31	31	31	31
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	75	90	105	120	135	150	165	45	45	45
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.75	3.75	5
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	20.1	20.0	16.5	14.6	15.4	16.3	16.5	17.2	18.4	17.3
63	14.6	15.1	11.3	11.1	10.6	12.2	12.9	15.4	15.5	14.7
80	21.1	20.3	17.4	16.2	15.6	16.8	16.7	19.1	20.2	19.3
100	28.3	27.4	24.4	23.6	24.0	19.2	17.4	22.4	23.4	21.7
125	27.5	27.8	19.9	19.8	19.6	20.5	18.2	21.9	24.0	24.2
160	27.9	28.5	19.4	20.3	24.3	22.8	14.7	20.4	23.2	24.1
200	22.3	25.2	22.6	19.0	20.1	19.4	11.0	22.5	20.2	19.6
250	31.3	33.5	30.0	26.0	25.7	26.2	23.0	28.9	30.1	31.4
315	31.8	30.2	27.3	26.4	25.4	23.2	23.3	26.3	29.4	29.1
400	34.5	35.5	30.8	32.4	31.1	31.9	31.4	34.5	32.7	32.2
500	36.0	39.9	33.1	34.0	29.8	28.8	26.3	34.6	35.8	33.7
630	41.0	41.0	37.4	33.8	32.7	33.9	30.2	34.5	38.8	37.4
800	39.6	42.1	37.7	36.4	36.3	35.6	30.8	39.3	38.8	40.0
1000	42.5	44.6	41.4	39.0	38.0	36.7	30.9	40.8	42.0	41.5
1250	42.4	44.4	40.6	37.4	39.4	36.3	32.2	43.2	41.2	40.5
1600	39.2	43.4	38.1	35.9	37.6	37.4	31.8	40.3	37.8	38.7
2000	39.7	40.8	38.9	35.3	38.6	37.0	32.1	41.7	41.0	41.9
2500	39.0	39.9	36.5	35.0	38.1	38.9	31.6	41.8	41.8	41.6
3150	39.7	41.3	38.0	35.4	36.6	37.7	32.5	40.6	39.2	40.8
4000	38.2	39.0	34.2	33.8	36.9	35.2	24.3	39.8	39.6	40.5
5000	42.3	43.3	39.3	37.3	37.1	30.4	28.9	41.0	41.1	42.5
6300	46.3	46.8	42.6	41.0	39.1	38.2	35.3	39.8	44.1	38.7
8000	47.4	48.4	44.5	43.6	37.5	44.1	38.4	28.5	38.0	26.8
10000	45.3	46.8	44.6	44.2	42.7	44.4	39.5	18.4	47.0	16.5
12500	42.0	43.5	42.7	40.0	41.8	42.2	36.8	13.3	48.9	10.5
16000	36.9	39.0	37.0	35.9	36.4	36.5	31.4	7.2	43.0	5.1
20000	22.4	24.3	21.8	20.5	21.1	17.1	13.5	2.6	32.7	0.1
Outdoor Sound Level (dBA)	81.1	82.8	80.0	78.2	79.1	78.7	75.4	93.3	88.0	93.2
Indoor Sound Level (dBA)	41.5	41.7	42.9	42.3	43.3	44.4	45.2	61.8	49.1	62.2
A-wtd Level Reduction (dBA)	39.6	41.1	37.1	36.0	35.8	34.2	30.1	31.5	38.8	31.0

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	21	22	23	24	25	26	27	28	29	30
Sound Source	Peavey	Peavey	Peavey	Peavey	Peavey	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	jet	pink	jet	pink	pink	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	flush	near	near	near	near
Window STC	31	31	31	31	31	25	25	25	25	25
Open/Closed	closed	closed	closed	closed	closed	closed	closed	half	open	closed
Theta (deg)	45	45	45	45	45	45	45	45	45	15
Source Height (ft)	5	7	7	8	8	3.4	3.4	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	17.2	18.2	18.2	16.3	19.1	13.4	14.5	10.6	9.9	15.8
63	14.7	13.6	15.6	13.1	13.5	11.5	11.2	7.2	5.6	12.9
80	18.4	18.1	19.4	18.1	17.2	17.6	16.6	10.6	7.2	17.8
100	21.3	23.0	22.6	21.8	22.8	22.4	20.7	16.9	14.6	21.0
125	22.8	23.9	26.5	24.9	24.7	21.0	21.5	8.4	6.8	22.7
160	23.6	22.8	24.5	24.7	22.2	18.7	21.5	7.0	7.3	23.0
200	22.9	16.1	17.1	15.0	15.0	20.1	22.0	11.7	13.1	24.9
250	29.1	27.4	30.9	29.9	27.6	17.9	20.5	14.6	16.7	20.9
315	27.0	28.2	28.0	27.9	29.6	17.0	17.4	18.0	16.8	21.8
400	35.4	34.3	35.1	33.4	33.1	23.6	22.8	20.9	11.9	21.6
500	31.8	31.5	32.9	34.4	32.2	28.8	28.8	16.4	10.6	28.5
630	38.2	36.2	37.3	36.3	35.9	30.4	31.0	12.2	10.4	30.6
800	40.1	38.4	40.7	40.1	38.4	30.8	32.0	12.2	9.2	30.0
1000	41.4	39.7	40.8	41.0	40.3	34.6	36.1	14.9	10.4	33.4
1250	41.9	41.2	41.5	41.8	40.9	38.9	39.0	15.4	9.8	34.3
1600	38.7	40.2	44.4	41.3	38.8	41.7	39.0	13.1	8.9	36.6
2000	40.7	40.9	44.7	42.4	39.7	40.4	38.6	14.2	9.5	36.9
2500	39.9	38.6	40.4	40.0	40.2	41.6	39.2	15.1	11.0	39.2
3150	40.2	38.8	40.2	39.6	39.5	41.1	39.4	16.0	10.6	40.3
4000	41.3	38.3	38.6	39.4	38.2	40.6	40.5	14.5	9.8	39.8
5000	43.9	40.1	41.8	39.8	41.9	40.0	39.6	15.5	10.2	36.0
6300	45.2	35.5	42.0	30.6	42.7	42.0	41.0	16.2	9.4	34.7
8000	39.8	24.7	37.7	20.3	38.4	43.3	42.6	15.8	10.3	44.2
10000	47.2	14.9	44.7	14.4	39.7	41.6	42.5	16.2	11.3	42.3
12500	49.3	8.4	44.4	7.6	38.4	35.8	39.5	18.0	11.8	37.4
16000	41.3	2.9	32.8	2.5	30.5	29.5	34.6	18.2	11.1	30.7
20000	29.6	-0.1	22.4	-0.6	18.1	12.9	20.3	16.2	11.1	15.6
Outdoor Sound Level (dBA)	87.1	92.4	85.0	92.0	82.9	79.3	76.3	76.0	76.2	75.8
Indoor Sound Level (dBA)	48.8	64.2	49.1	63.3	49.3	42.6	42.7	59.5	64.1	43.2
A-wtd Level Reduction (dBA)	38.3	28.2	35.9	28.8	33.5	36.8	33.5	16.5	12.1	32.5

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	31	32	33	34	35	36	37	38	39	40
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	Peavey
Source Signal	pink	pink	pink	pink	pink	pink	pink	pink	pink	jet
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	25	25	25	25	25	25	25	25	25	25
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	30	60	75	90	105	120	135	150	165	45
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.75
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	15.0	19.0	19.9	19.5	18.4	18.0	18.6	18.5	18.5	17.8
63	12.8	16.6	14.7	14.8	14.7	13.4	12.3	15.4	15.8	15.2
80	20.5	20.8	21.4	20.7	19.9	20.1	16.5	20.5	19.2	20.8
100	21.9	25.6	30.1	28.9	27.0	27.4	24.9	23.6	20.4	23.7
125	22.4	24.0	29.4	28.9	24.5	22.0	22.0	23.1	22.2	22.6
160	20.9	24.6	29.3	27.7	23.9	24.6	22.1	22.7	23.5	19.7
200	24.7	29.6	30.2	29.0	29.6	30.3	27.1	25.5	23.8	24.0
250	24.2	26.6	23.1	24.6	24.5	23.4	24.5	23.7	20.3	23.9
315	18.7	24.6	23.2	22.6	21.6	21.3	22.6	24.3	20.0	22.6
400	22.2	26.3	28.3	29.3	29.7	24.5	25.0	21.8	19.3	24.0
500	29.3	32.5	33.2	34.6	33.0	32.2	31.7	29.2	26.4	30.9
630	31.4	35.0	36.8	35.6	36.1	34.2	33.8	31.1	30.5	33.4
800	33.4	39.5	40.4	40.9	39.5	39.4	36.4	32.1	28.9	35.5
1000	36.9	43.5	42.3	42.5	41.6	41.8	40.5	35.4	30.6	38.2
1250	39.0	43.5	42.8	41.8	40.5	42.9	40.2	35.3	33.8	40.4
1600	40.1	42.7	42.7	42.1	38.1	43.8	41.4	37.9	34.2	39.3
2000	40.0	43.7	42.7	44.6	41.1	44.4	43.0	39.8	34.9	40.8
2500	41.9	44.8	44.7	45.8	44.1	43.8	43.8	41.4	37.9	42.6
3150	42.0	43.9	44.5	44.9	44.4	44.2	43.2	44.5	38.8	42.4
4000	42.3	44.6	44.4	45.2	44.4	44.4	44.0	42.6	37.0	44.2
5000	41.5	44.9	45.8	45.3	45.2	45.3	43.8	41.5	33.5	44.1
6300	40.2	46.5	45.4	46.0	45.5	46.7	44.3	39.1	30.6	38.3
8000	42.3	48.1	49.1	49.8	49.0	47.3	46.8	42.1	42.9	27.7
10000	43.6	45.9	47.5	48.0	47.4	46.1	45.3	45.6	42.4	18.0
12500	38.8	41.9	42.6	43.5	42.5	41.2	40.6	40.2	36.9	12.4
16000	31.7	36.4	37.3	37.7	37.0	36.0	35.5	34.1	31.3	6.4
20000	16.8	22.9	23.3	23.7	21.8	20.9	21.7	17.9	14.3	1.7
Outdoor Sound Level (dBA)	77.2	80.2	81.1	81.8	81.0	79.9	79.7	79.0	76.3	94.3
Indoor Sound Level (dBA)	42.9	42.0	43.4	43.5	43.4	43.2	43.7	45.5	46.4	66.0
A-wtd Level Reduction (dBA)	34.4	38.2	37.7	38.3	37.6	36.7	35.9	33.5	30.0	28.3

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	41	42	43	44	45	46	47	48	49	50
Sound Source	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	JBL	JBL	JBL
Source Signal	pink	jet	pink	jet	pink	jet	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	flush	near	near
Window STC	25	25	25	25	25	25	25	41	41	41
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	half
Theta (deg)	45	45	45	45	45	45	45	45	45	45
Source Height (ft)	3.75	5	5	7	7	8	8	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	18.3	17.0	18.4	17.7	17.5	18.4	18.3	17.5	17.3	13.8
63	14.7	14.3	15.2	13.5	15.0	14.5	14.2	14.8	15.1	8.9
80	18.8	19.1	20.2	17.0	18.8	19.7	17.3	21.0	20.3	11.5
100	23.4	22.6	23.2	22.2	22.5	22.6	22.8	24.4	23.2	19.1
125	23.6	22.6	23.0	23.3	24.4	23.4	24.9	30.2	29.3	14.9
160	24.2	22.9	20.4	25.7	23.0	23.2	26.3	24.7	22.9	12.7
200	26.7	27.2	26.0	23.9	23.1	25.1	23.3	27.4	26.6	15.0
250	25.3	20.9	23.2	22.0	20.9	21.4	23.4	26.8	29.3	22.1
315	23.4	22.0	22.3	23.5	24.0	22.2	23.2	31.2	30.8	26.0
400	25.2	23.7	24.9	21.4	23.0	21.5	22.1	39.7	37.8	24.3
500	33.5	30.8	32.3	32.1	31.5	27.9	30.8	40.0	40.8	19.4
630	32.7	33.8	33.3	34.3	34.0	33.1	34.9	40.8	41.7	17.3
800	36.5	36.2	37.1	35.1	35.3	33.2	35.5	41.3	41.0	14.4
1000	39.0	39.5	39.2	38.4	39.0	36.7	39.2	43.5	44.3	18.8
1250	42.0	41.2	40.5	41.1	40.8	40.1	41.1	45.6	44.9	18.7
1600	39.5	37.9	39.3	42.1	43.5	41.8	43.0	48.0	44.3	15.6
2000	42.1	41.4	40.9	43.5	44.6	42.6	43.9	46.9	45.3	17.9
2500	45.2	44.6	43.6	42.5	44.0	43.5	43.9	47.2	46.8	18.1
3150	44.6	42.6	42.8	42.8	42.5	43.3	43.8	47.1	45.8	19.0
4000	46.1	45.6	45.3	43.5	44.3	43.7	45.0	47.5	46.3	17.5
5000	44.2	44.9	44.9	41.7	42.2	42.1	44.2	47.9	48.1	19.2
6300	47.1	37.0	44.6	29.2	41.1	32.3	42.5	49.9	48.9	20.3
8000	51.7	25.3	49.3	19.4	44.8	21.2	44.3	47.0	47.5	19.0
10000	51.0	15.4	50.0	12.5	42.2	13.9	42.7	43.8	44.8	18.0
12500	50.2	9.6	45.8	7.1	39.5	7.6	38.8	36.9	39.6	18.1
16000	44.7	3.6	40.4	2.2	32.3	2.5	29.8	30.7	33.7	17.3
20000	34.5	-0.3	28.7	-0.5	22.3	-0.6	21.0	16.3	19.2	15.5
Outdoor Sound Level (dBA)	88.4	94.0	86.9	92.8	85.0	92.0	83.9	81.0	77.2	77.6
Indoor Sound Level (dBA)	51.4	66.4	52.1	65.5	52.0	65.5	51.5	34.2	34.4	57.7
A-wtd Level Reduction (dBA)	37.1	27.6	34.7	27.3	33.1	26.5	32.4	46.8	42.7	19.9

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	51	52	53	54	55	56	57	58	59	60
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	pink	pink	pink	pink	pink	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	41	41	41	41	41	41	41	41	41	41
Open/Closed	open	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	45	15	30	60	75	90	105	120	135	150
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	12.9	13.8	14.1	19.0	19.2	19.6	18.8	19.8	20.3	21.6
63	8.3	11.3	12.7	15.1	11.4	14.4	12.9	14.3	14.8	16.3
80	10.0	16.4	20.5	17.7	18.1	18.6	17.7	19.3	19.2	20.2
100	18.1	19.1	20.9	23.1	27.6	26.4	23.9	28.8	27.3	21.3
125	11.7	20.6	25.4	29.5	25.7	31.6	26.7	28.7	28.9	23.1
160	12.5	18.7	19.9	26.4	25.1	27.7	23.0	26.3	28.3	21.6
200	17.5	23.5	22.7	32.1	30.7	29.2	32.0	34.6	33.8	28.1
250	19.2	26.1	26.5	30.3	33.9	33.8	33.1	33.2	32.8	31.3
315	20.6	31.1	30.3	34.7	34.5	36.8	33.9	34.7	35.1	36.7
400	17.5	32.4	35.3	37.7	38.4	38.1	39.6	42.0	41.0	39.6
500	12.5	35.3	37.9	39.5	37.7	38.5	39.3	40.3	41.2	40.4
630	12.4	37.2	36.6	41.2	40.7	40.7	40.3	42.4	42.8	40.3
800	14.2	35.5	39.3	43.2	42.8	45.5	43.5	45.7	45.4	39.8
1000	14.3	36.3	40.1	45.9	44.8	44.4	45.0	46.8	47.6	43.7
1250	12.9	39.3	41.7	47.1	44.5	44.8	45.3	47.9	48.9	43.4
1600	12.1	39.4	43.2	47.3	44.1	45.8	46.7	47.8	50.7	45.4
2000	14.0	38.3	42.2	46.6	44.8	47.1	44.6	50.2	47.2	45.9
2500	14.5	39.9	42.7	47.3	45.4	48.6	46.9	49.4	50.3	46.7
3150	14.2	41.8	44.1	47.0	45.2	47.5	46.8	49.4	51.1	49.0
4000	13.0	40.7	43.3	48.0	47.6	48.5	46.8	51.2	51.5	48.5
5000	14.5	44.4	43.8	51.0	50.2	52.2	50.7	51.2	52.6	47.8
6300	13.9	45.8	46.3	52.2	50.6	52.6	50.9	52.4	54.3	48.8
8000	13.5	45.1	45.7	50.7	49.6	51.8	50.0	51.1	51.8	48.9
10000	13.3	42.9	44.5	48.7	48.6	49.7	48.5	48.5	49.9	46.5
12500	11.8	38.9	40.6	45.5	44.0	45.9	44.2	43.6	45.0	41.4
16000	10.6	31.9	33.9	39.7	38.6	40.8	38.9	37.7	39.6	35.5
20000	10.3	16.1	18.5	25.0	23.1	25.3	23.5	22.4	25.4	19.4
Outdoor Sound Level (dBA)	77.7	73.6	75.2	79.8	79.2	80.9	79.5	79.7	80.8	78.4
Indoor Sound Level (dBA)	62.0	36.6	35.7	36.1	36.8	37.2	37.2	34.1	34.9	36.8
A-wtd Level Reduction (dBA)	15.7	37.0	39.5	43.7	42.4	43.6	42.3	45.6	45.9	41.6

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	61	62	63	64	65	66	67	68	69	70
Sound Source	JBL	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey
Source Signal	pink	jet	pink	jet	pink	jet	pink	jet	pink	pink
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	41	41	41	41	41	41	41	41	41	41
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	165	45	45	45	45	45	45	45	45	45
Source Height (ft)	3.4	3.75	3.75	5	5	7	7	8	8	3.75
Layers gypboard	1	1	1	1	1	1	1	1	1	2
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	20.2	17.6	18.4	18.2	18.5	17.1	19.3	18.1	17.7	15.4
63	17.2	13.7	15.9	14.3	15.6	13.4	15.5	13.5	14.0	9.8
80	21.2	19.4	20.1	19.2	19.8	17.4	19.6	18.5	17.9	14.5
100	22.2	22.5	22.6	23.2	22.3	21.0	24.0	21.0	21.2	20.5
125	26.4	28.9	28.1	28.0	26.3	24.7	27.0	24.0	25.1	23.8
160	26.1	22.9	23.5	23.5	24.7	24.5	23.9	26.3	25.1	22.4
200	25.4	27.0	27.9	27.0	29.7	32.2	28.6	33.3	32.1	27.0
250	26.5	28.2	28.6	29.9	31.8	30.6	31.0	30.9	29.8	26.5
315	31.4	30.2	31.6	33.6	33.6	33.4	33.3	32.3	33.5	29.5
400	37.8	38.9	38.1	39.0	38.8	39.2	39.1	38.1	39.4	35.9
500	39.9	39.6	39.7	40.3	39.7	38.9	38.6	38.9	39.6	37.5
630	38.5	42.3	39.9	39.1	42.7	39.5	41.2	38.8	39.2	39.5
800	37.5	41.0	43.6	43.3	44.5	41.5	43.3	42.1	43.1	38.8
1000	40.2	43.8	44.6	44.0	45.6	43.2	43.6	43.7	44.0	40.4
1250	42.5	45.2	46.1	44.0	44.9	42.4	43.6	44.0	43.9	40.7
1600	44.0	43.0	42.7	40.7	43.5	43.4	46.0	45.0	45.4	40.5
2000	43.3	45.3	44.9	45.4	45.6	46.0	48.7	46.2	47.7	42.1
2500	45.5	48.4	47.6	49.2	49.2	47.3	49.2	47.5	47.6	45.0
3150	47.1	46.7	47.0	47.4	48.3	46.6	47.1	46.2	46.6	43.1
4000	44.3	48.9	49.6	48.7	50.8	47.5	49.6	47.0	49.4	46.5
5000	49.0	50.5	53.1	49.4	52.2	46.8	52.0	44.8	51.1	48.1
6300	49.1	43.1	57.9	41.0	57.2	35.4	53.2	33.3	52.0	40.7
8000	49.6	30.0	50.8	27.9	52.8	23.9	50.0	22.8	48.4	27.7
10000	47.0	19.6	56.3	17.6	53.2	14.7	48.4	15.7	43.7	18.0
12500	41.1	13.7	53.1	11.5	49.8	8.7	42.5	8.5	41.2	13.9
16000	34.3	7.8	44.9	4.8	42.8	3.4	31.8	3.2	31.3	8.3
20000	15.3	2.5	33.1	0.5	30.6	-0.1	22.6	-0.4	21.5	2.9
Outdoor Sound Level (dBA)	77.2	94.7	88.2	94.4	87.3	93.0	84.8	92.5	83.5	93.1
Indoor Sound Level (dBA)	37.0	59.8	45.5	58.8	43.9	57.6	43.1	57.0	43.0	60.0
A-wtd Level Reduction (dBA)	40.2	34.9	42.8	35.6	43.4	35.4	41.6	35.5	40.5	33.1

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	71	72	73	74	75	76	77	78	79	80
Sound Source	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	JBL	JBL	JBL
Source Signal	jet	pink	jet	pink	jet	pink	jet	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	flush	near	near
Window STC	41	41	41	41	41	41	41	41	41	41
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	half
Theta (deg)	45	45	45	45	45	45	45	45	45	45
Source Height (ft)	3.75	5	5	7	7	8	8	3.4	3.4	3.4
Layers gypboard	2	2	2	2	2	2	2	2	2	2
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	16.1	15.1	16.1	15.0	15.8	17.8	14.9	16.9	16.6	13.7
63	12.5	11.3	10.5	10.0	11.2	11.8	9.6	13.9	13.4	9.3
80	16.7	16.3	14.4	14.5	15.9	13.1	14.5	20.9	19.2	10.2
100	21.5	19.5	21.9	17.5	20.3	24.8	16.9	25.7	24.1	18.9
125	23.0	21.4	23.9	21.1	21.8	23.8	21.5	27.1	24.6	13.6
160	21.2	20.7	23.3	21.9	23.0	20.9	21.7	25.2	22.6	12.9
200	27.6	26.0	27.5	29.1	26.8	29.1	31.1	27.0	31.5	16.5
250	28.6	30.3	29.2	30.7	27.9	28.9	31.0	27.9	31.1	20.0
315	31.4	30.3	33.3	30.5	31.6	29.1	32.4	33.4	34.8	20.4
400	38.4	36.5	36.7	34.9	37.5	37.7	37.8	40.0	39.7	25.1
500	36.0	37.5	38.1	36.1	36.4	34.1	35.0	40.2	40.1	20.1
630	36.6	37.8	35.8	36.1	37.9	35.3	37.5	41.1	39.7	18.1
800	41.2	38.6	41.3	36.8	39.8	39.2	39.6	41.8	42.8	13.7
1000	40.6	40.7	41.7	38.8	40.3	38.5	38.1	43.6	43.1	20.0
1250	41.7	38.4	38.8	36.9	39.2	39.7	39.3	43.8	44.5	19.1
1600	40.5	39.8	39.0	38.7	42.4	44.0	43.3	48.1	45.0	16.7
2000	41.9	42.7	42.6	43.1	45.1	45.5	45.2	46.5	45.8	16.7
2500	46.0	44.1	44.6	44.7	45.0	44.4	43.8	46.3	45.9	19.2
3150	43.3	42.3	44.3	43.1	43.5	44.0	42.4	47.2	45.5	18.2
4000	47.7	45.1	47.3	45.1	45.9	43.7	43.8	47.8	47.7	17.9
5000	50.8	46.3	50.9	44.2	48.7	41.6	46.1	49.0	49.2	18.5
6300	54.6	37.7	52.8	33.0	49.1	30.6	45.1	50.6	49.4	20.0
8000	51.7	25.7	46.8	21.3	46.4	20.3	42.7	48.1	47.6	19.1
10000	55.7	16.3	49.6	14.2	43.2	14.4	41.5	44.9	44.9	18.0
12500	53.8	11.6	45.7	9.2	41.0	9.0	36.4	37.0	40.1	18.5
16000	45.5	5.8	37.1	3.9	34.3	4.1	27.8	29.1	33.9	16.9
20000	34.5	0.5	23.8	-0.1	23.4	-0.4	17.9	13.7	19.5	16.8
Outdoor Sound Level (dBA)	86.9	92.7	81.7	91.6	83.3	91.3	78.5	80.9	77.6	77.6
Indoor Sound Level (dBA)	45.9	59.6	40.9	58.9	44.6	58.7	40.7	33.8	34.0	57.7
A-wtd Level Reduction (dBA)	41.0	33.1	40.8	32.7	38.8	32.6	37.9	47.1	43.6	19.9

Table D. (cont.): Measured noise reduction across frequency for every iteration

Msmt number	81	82	83	84	85	86	87	88	89	90	91
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	pink	pink	pink	pink	pink	pink	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	near	near	near	near
Window STC	41	41	41	41	41	41	41	41	41	41	41
Open/Closed	open	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	45	15	30	60	75	90	105	120	135	150	165
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Layers gypboard	2	2	2	2	2	2	2	2	2	2	2
f (Hz)	Measured Noise Reduction (dB) at 1/3 Octave Band Center Frequencies (Hz)										
50	13.4	13.6	13.4	12.2	17.8	15.1	16.3	16.3	16.1	16.2	19.5
63	10.1	8.8	10.3	13.7	11.6	11.3	15.0	13.3	14.0	15.8	16.2
80	10.2	16.4	19.4	17.1	18.1	18.6	19.8	18.2	19.4	22.0	20.4
100	18.6	20.5	21.4	23.3	29.2	26.6	27.0	26.7	29.4	25.3	21.3
125	13.9	21.6	23.0	25.4	24.9	24.5	29.4	26.5	27.8	26.9	24.6
160	14.9	17.7	22.3	27.1	24.9	26.2	29.2	25.6	28.7	26.5	27.1
200	13.2	23.5	28.0	31.8	29.3	30.4	30.4	25.5	34.2	28.0	30.0
250	18.0	25.0	27.7	32.2	35.8	34.5	32.9	32.8	32.8	29.4	31.7
315	21.7	31.1	33.0	35.1	36.0	35.0	34.7	32.7	36.4	35.1	31.6
400	19.7	36.5	37.2	37.9	40.6	37.5	39.7	37.2	42.1	39.5	37.6
500	14.4	35.9	37.5	38.7	36.4	37.6	39.1	38.2	41.0	41.1	39.3
630	14.0	35.1	37.7	41.5	40.7	40.6	45.1	39.5	42.2	38.6	36.8
800	14.3	34.9	37.2	43.2	42.4	43.0	44.9	43.3	43.6	39.9	36.4
1000	15.6	37.0	39.0	43.6	43.9	43.0	43.7	44.2	44.8	41.9	39.2
1250	14.9	38.6	43.1	46.7	44.0	42.6	45.6	44.5	46.9	40.7	38.6
1600	13.7	39.1	44.2	44.9	43.9	44.8	46.3	43.9	47.1	43.0	41.6
2000	14.7	38.9	41.1	44.1	44.1	44.6	46.4	42.5	43.8	44.5	41.4
2500	15.3	38.4	42.7	44.5	45.2	44.6	46.5	44.7	45.8	44.7	42.1
3150	15.8	41.7	44.8	46.0	45.9	45.5	47.9	49.1	47.4	48.1	44.2
4000	15.9	39.7	44.3	46.9	47.2	45.3	47.2	50.6	47.7	46.1	42.0
5000	16.1	41.8	44.1	47.5	49.8	47.1	48.5	51.2	49.0	46.6	46.6
6300	17.1	41.3	47.0	47.2	49.3	45.7	47.4	51.3	48.3	46.1	46.3
8000	16.2	39.5	46.8	44.9	48.4	45.0	46.0	50.0	45.4	45.2	46.0
10000	15.1	37.1	44.9	43.0	47.4	43.0	43.3	47.7	43.1	41.8	44.1
12500	15.6	32.9	41.0	39.3	42.7	38.5	37.6	42.5	37.8	36.1	38.3
16000	15.6	26.3	33.8	33.5	36.6	32.3	32.4	36.8	32.8	29.6	33.1
20000	14.6	11.7	18.7	19.0	21.9	16.7	16.6	22.1	19.4	12.6	17.4
Outdoor Sound Level (dBA)	77.7	68.5	75.9	74.1	78.3	73.8	75.2	80.2	74.8	73.8	76.6
Indoor Sound Level (dBA)	60.4	31.4	35.8	31.3	35.8	31.9	31.3	37.4	30.2	32.4	37.1
A-wtd Level Reduction (dBA)	17.3	37.1	40.0	42.8	42.5	41.9	43.8	42.7	44.6	41.4	39.5

APPENDIX E

TL MEASUREMENTS

Table E.1: Measured transmission loss across frequency for every iteration

Msmt number	1	2	3	4	5	6	7	8	9	10
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	jet	pink	pink	pink	pink	pink	pink	pink	pink
Ext msmt	flush	near	near	near	near	near	near	near	near	near
Window STC	31	31	31	31	31	31	31	31	31	31
Open/Closed	closed	closed	closed	closed	closed	closed	half	open	closed	closed
Theta (deg)	45	45	45	15	30	45	45	45	45	60
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	**Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)**									
50	27.8	27.0	27.4	19.4	20.5	24.5	20.4	20.4	26.8	31.1
63	31.4	30.0	31.1	21.8	24.5	26.8	22.1	22.1	29.3	32.9
80	32.3	30.1	31.0	21.7	27.0	27.2	20.1	18.6	29.1	31.7
100	39.9	38.3	39.6	29.0	31.7	34.8	31.1	30.0	36.1	41.4
125	40.0	37.0	38.1	31.1	31.0	35.3	22.1	22.6	36.5	39.9
160	41.8	37.7	37.9	28.6	33.0	36.0	23.5	23.8	39.8	41.5
200	36.0	34.6	36.1	27.1	33.5	32.1	28.4	24.3	38.6	42.4
250	39.1	41.8	41.9	27.8	38.1	38.3	27.9	25.1	43.1	47.1
315	40.1	40.4	41.5	30.1	36.4	37.6	31.9	31.7	42.5	44.5
400	44.4	43.6	46.2	34.5	37.6	40.9	29.8	28.5	43.3	47.2
500	45.6	44.3	45.5	34.7	38.8	41.1	28.2	18.8	43.6	46.4
630	48.2	45.8	46.8	34.3	39.7	43.3	23.2	15.6	45.4	50.4
800	48.4	45.6	48.4	33.4	41.2	43.3	17.9	15.4	48.3	48.1
1000	49.3	48.0	49.8	38.1	43.1	45.8	22.6	19.1	48.5	52.8
1250	50.1	49.2	51.4	34.7	41.4	45.9	23.7	16.1	48.9	51.4
1600	51.5	48.8	50.3	36.5	44.3	43.3	20.6	15.3	48.6	52.0
2000	50.9	48.3	47.9	35.5	43.7	45.3	20.8	16.9	48.6	50.1
2500	50.2	48.7	49.8	37.4	42.9	44.3	20.6	16.8	48.2	49.8
3150	50.8	48.8	50.0	38.0	43.7	45.1	22.9	19.3	47.7	50.2
4000	48.9	46.1	46.8	28.7	39.3	43.1	21.7	17.3	46.2	48.4
5000	49.3	45.5	49.2	32.6	34.4	44.5	21.3	18.0	46.9	51.1
6300	50.9	39.1	49.5	40.2	43.6	45.9	21.2	17.3	48.7	54.9
8000	49.6	27.5	45.6	42.0	48.5	42.6	22.3	16.7	46.3	55.4
10000	50.8	15.9	50.6	41.7	48.1	48.4	22.3	18.0	50.3	54.6
12500	45.0	8.6	47.2	38.9	45.5	46.2	25.1	18.6	46.3	50.0
16000	38.1	6.6	40.9	32.2	39.2	40.4	23.0	18.1	41.1	45.2
20000	22.7	5.9	27.1	16.3	24.5	25.8	22.6	18.3	27.2	30.9
Outdoor Sound Level (dBA)	81.9	89.9	78.2	74.0	76.5	76.4	76.5	76.3	78.4	81.5
Indoor Sound Level (dBA)	37.7	57.0	38.0	42.4	41.8	40.5	59.9	64.0	38.9	40.0
A-wtd Level Reduction (dBA)	44.2	32.9	40.2	31.6	34.7	35.8	16.5	12.2	39.5	41.5

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	11	12	13	14	15	16	17	18	19	20
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	Peavey	Peavey	Peavey
Source Signal	pink	pink	pink	pink	pink	pink	pink	jet	pink	jet
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	31	31	31	31	31	31	31	31	31	31
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	75	90	105	120	135	150	165	45	45	45
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.75	3.75	5
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	31.7	31.7	28.1	25.6	25.6	25.0	22.3	27.4	28.6	27.5
63	31.6	32.2	28.3	27.6	26.3	26.3	24.1	31.0	31.2	30.3
80	32.8	32.1	29.0	27.4	25.9	25.6	22.7	29.4	30.5	29.6
100	44.4	43.7	40.6	39.2	38.8	32.4	27.8	37.1	38.2	36.4
125	43.0	43.5	35.4	34.8	33.8	33.1	28.0	36.1	38.1	38.4
160	45.2	45.9	36.7	37.0	40.2	37.2	26.2	36.3	39.1	39.9
200	39.9	43.0	40.3	36.2	36.4	34.2	22.9	38.8	36.5	35.9
250	44.8	47.2	43.5	39.0	37.9	36.8	30.7	41.0	42.2	43.6
315	46.5	45.1	42.0	40.7	38.8	35.1	32.3	39.7	42.8	42.5
400	46.4	47.5	42.7	43.8	41.7	41.0	37.6	45.0	43.3	42.8
500	45.9	50.0	43.1	43.5	38.4	35.9	30.6	43.2	44.4	42.3
630	50.4	50.6	46.8	42.8	40.8	40.5	33.9	42.6	46.9	45.5
800	47.8	50.4	45.9	44.1	43.2	40.9	33.2	46.1	45.6	46.9
1000	52.3	54.6	51.2	48.4	46.5	43.7	35.0	49.3	50.4	50.0
1250	49.8	51.9	48.0	44.3	45.4	40.8	33.8	49.2	47.2	46.5
1600	47.5	51.8	46.4	43.7	44.5	42.9	34.4	47.2	44.8	45.6
2000	47.9	49.2	47.1	43.0	45.4	42.4	34.6	48.6	47.8	48.7
2500	46.7	47.7	44.2	42.2	44.4	43.7	33.6	48.1	48.1	47.9
3150	48.6	50.3	46.8	43.7	44.1	43.6	35.6	48.1	46.7	48.3
4000	46.3	47.2	42.3	41.4	43.7	40.5	26.7	46.6	46.4	47.2
5000	50.2	51.2	47.2	44.7	43.5	35.4	30.9	47.5	47.5	49.0
6300	53.8	54.5	50.1	48.0	45.2	42.9	37.1	45.9	50.2	44.9
8000	55.0	56.2	52.1	50.7	43.7	48.8	40.3	34.7	44.2	33.0
10000	53.1	54.8	52.4	51.5	49.2	49.4	41.7	24.9	53.5	22.9
12500	49.7	51.4	50.4	47.3	48.1	47.0	38.8	19.6	55.2	16.9
16000	44.5	46.7	44.5	43.0	42.6	41.2	33.3	13.4	49.2	11.3
20000	30.3	32.4	29.8	28.0	27.7	22.2	15.7	9.2	39.3	6.8
Outdoor Sound Level (dBA)	81.1	82.8	80.0	78.2	79.1	78.7	75.4	93.3	88.0	93.2
Indoor Sound Level (dBA)	41.5	41.7	42.9	42.3	43.3	44.4	45.2	61.8	49.1	62.2
A-wtd Level Reduction (dBA)	39.6	41.1	37.1	36.0	35.8	34.2	30.1	31.5	38.8	31.0

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	21	22	23	24	25	26	27	28	29	30
Sound Source	Peavey	Peavey	Peavey	Peavey	Peavey	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	jet	pink	jet	pink	pink	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	flush	near	near	near	near
Window STC	31	31	31	31	31	25	25	25	25	25
Open/Closed	closed	closed	closed	closed	closed	closed	closed	half	open	closed
Theta (deg)	45	45	45	45	45	45	45	45	45	15
Source Height (ft)	5	7	7	8	8	3.4	3.4	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	27.4	28.4	28.4	26.5	29.3	29.1	30.2	26.3	25.6	27.2
63	30.3	29.3	31.3	28.7	29.2	24.8	24.6	20.5	19.0	21.9
80	28.7	28.4	29.7	28.4	27.5	34.5	33.4	27.5	24.1	30.3
100	36.0	37.7	37.4	36.6	37.6	38.6	36.9	33.1	30.8	32.9
125	36.9	38.1	40.7	39.1	38.9	38.0	38.5	25.5	23.8	35.4
160	39.5	38.6	40.4	40.6	38.1	32.4	35.2	20.7	21.0	32.4
200	39.2	32.4	33.4	31.3	31.3	32.0	34.0	23.7	25.0	32.5
250	41.2	39.5	43.0	42.1	39.8	30.5	33.1	27.2	29.3	29.1
315	40.4	41.6	41.4	41.3	43.0	25.6	26.1	26.7	25.5	26.1
400	45.9	44.9	45.6	44.0	43.7	31.5	30.7	28.8	19.7	25.1
500	40.4	40.1	41.5	43.0	40.8	37.6	37.6	25.2	19.3	32.9
630	46.3	44.3	45.3	44.4	44.0	38.3	38.9	20.1	18.3	34.1
800	46.9	45.2	47.5	46.9	45.2	39.0	40.2	20.3	17.4	33.7
1000	49.9	48.1	49.2	49.5	48.8	40.6	42.1	20.9	16.3	35.0
1250	48.0	47.2	47.5	47.8	46.9	43.9	43.9	20.3	14.7	34.9
1600	45.6	47.1	51.4	48.2	45.8	47.5	44.8	18.9	14.7	38.0
2000	47.6	47.7	51.5	49.2	46.5	47.6	45.7	21.3	16.6	39.7
2500	46.2	44.9	46.7	46.3	46.5	47.8	45.5	21.3	17.2	41.0
3150	47.7	46.3	47.7	47.1	47.0	47.1	45.4	22.0	16.6	41.9
4000	48.0	45.0	45.4	46.1	45.0	45.9	45.8	19.8	15.0	40.7
5000	50.4	46.6	48.3	46.2	48.3	45.6	45.1	21.0	15.7	37.2
6300	51.4	41.6	48.1	36.8	48.8	48.3	47.3	22.5	15.7	36.6
8000	46.1	30.9	43.9	26.6	44.6	49.9	49.2	22.4	16.9	46.4
10000	53.7	21.4	51.2	20.9	46.2	47.7	48.6	22.3	17.4	44.1
12500	55.7	14.7	50.7	14.0	44.7	42.1	45.7	24.3	18.1	39.3
16000	47.5	9.2	39.1	8.8	36.7	35.4	40.5	24.1	17.0	32.2
20000	36.2	6.6	29.0	6.0	24.7	18.8	26.2	22.1	17.0	17.1
Outdoor Sound Level (dBA)	87.1	92.4	85.0	92.0	82.9	79.3	76.3	76.0	76.2	75.8
Indoor Sound Level (dBA)	48.8	64.2	49.1	63.3	49.3	42.6	42.7	59.5	64.1	43.2
A-wtd Level Reduction (dBA)	38.3	28.2	35.9	28.8	33.5	36.8	33.5	16.5	12.1	32.5

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	31	32	33	34	35	36	37	38	39	40
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	Peavey
Source Signal	pink	pink	pink	pink	pink	pink	pink	pink	pink	jet
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	25	25	25	25	25	25	25	25	25	25
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	30	60	75	90	105	120	135	150	165	45
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.75
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	29.2	35.6	37.0	36.7	35.5	34.6	34.3	32.7	29.9	33.5
63	24.7	30.9	29.5	29.7	29.5	27.6	25.6	27.2	24.8	28.6
80	35.9	38.5	39.6	39.0	38.1	37.9	33.4	35.8	31.7	37.7
100	36.6	42.7	47.7	46.7	44.6	44.5	41.2	38.3	32.2	39.9
125	37.8	41.9	47.8	47.4	42.8	39.8	39.0	38.6	34.8	39.6
160	33.1	39.2	44.4	42.9	38.9	39.2	35.8	34.9	32.8	33.5
200	35.2	42.4	43.5	42.5	42.9	43.2	39.0	36.0	31.4	35.9
250	35.3	40.1	37.1	38.7	38.5	36.9	37.1	34.8	28.5	36.5
315	25.8	34.2	33.2	32.8	31.6	30.9	31.3	31.5	24.4	31.3
400	28.6	35.0	37.5	38.6	38.9	33.2	32.9	28.2	22.8	31.9
500	36.6	42.2	43.3	44.9	43.2	41.8	40.5	36.4	30.8	39.6
630	37.8	43.8	46.1	45.0	45.3	43.0	41.7	37.6	34.0	41.3
800	40.0	48.5	49.9	50.5	49.0	48.4	44.5	38.7	32.6	43.6
1000	41.4	50.3	49.6	49.9	48.9	48.7	46.5	39.8	32.2	44.2
1250	42.4	49.3	49.1	48.2	46.8	48.7	45.2	38.7	34.4	45.4
1600	44.4	49.4	49.9	49.5	45.3	50.5	47.3	42.2	35.6	45.2
2000	45.6	51.7	51.1	53.2	49.6	52.4	50.2	45.4	37.7	47.9
2500	46.6	51.9	52.3	53.6	51.7	50.9	50.0	46.1	39.8	48.8
3150	46.5	50.8	51.9	52.4	51.8	51.1	49.2	49.0	40.4	48.4
4000	46.1	50.7	51.0	51.9	51.0	50.5	49.2	46.3	37.9	49.4
5000	45.5	51.3	52.7	52.4	52.1	51.7	49.3	45.6	34.7	49.7
6300	45.0	53.7	53.1	53.8	53.1	53.8	50.6	43.9	32.5	44.6
8000	47.4	55.6	57.1	57.9	56.9	54.8	53.4	47.2	45.2	34.3
10000	48.3	53.0	55.0	55.6	54.9	53.2	51.5	50.2	44.2	24.1
12500	43.5	49.0	50.3	51.3	50.1	48.3	46.8	44.9	38.8	18.7
16000	36.1	43.1	44.6	45.1	44.2	42.8	41.4	38.5	32.9	12.3
20000	21.2	29.7	30.5	31.1	29.1	27.7	27.6	22.3	15.9	7.6
Outdoor Sound Level (dBA)	77.2	80.2	81.1	81.8	81.0	79.9	79.7	79.0	76.3	94.3
Indoor Sound Level (dBA)	42.9	42.0	43.4	43.5	43.4	43.2	43.7	45.5	46.4	66.0
A-wtd Level Reduction (dBA)	34.4	38.2	37.7	38.3	37.6	36.7	35.9	33.5	30.0	28.3

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	41	42	43	44	45	46	47	48	49	50
Sound Source	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	JBL	JBL	JBL
Source Signal	pink	jet	pink	jet	pink	jet	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	flush	near	near
Window STC	25	25	25	25	25	25	25	41	41	41
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	half
Theta (deg)	45	45	45	45	45	45	45	45	45	45
Source Height (ft)	3.75	5	5	7	7	8	8	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	34.0	32.7	34.2	33.4	33.2	34.2	34.0	31.3	31.1	27.6
63	28.1	27.7	28.6	26.9	28.4	27.9	27.6	30.3	30.6	24.4
80	35.7	35.9	37.0	33.8	35.7	36.5	34.2	35.2	34.6	25.7
100	39.6	38.8	39.5	38.4	38.7	38.8	39.0	42.5	41.3	37.2
125	40.6	39.6	40.0	40.3	41.4	40.4	41.9	42.2	41.2	26.8
160	37.9	36.6	34.1	39.4	36.7	36.9	40.0	40.7	38.9	28.7
200	38.7	39.2	38.0	35.9	35.1	37.1	35.2	44.4	43.7	32.0
250	37.9	33.5	35.8	34.6	33.5	34.0	36.0	40.2	42.8	35.6
315	32.1	30.7	30.9	32.2	32.7	30.9	31.9	43.6	43.2	38.4
400	33.0	31.6	32.8	29.2	30.8	29.4	29.9	50.0	48.2	34.6
500	42.3	39.6	41.0	40.8	40.3	36.6	39.5	49.7	50.4	29.1
630	40.6	41.7	41.2	42.2	42.0	41.1	42.8	46.9	47.8	23.4
800	44.6	44.3	45.2	43.3	43.4	41.4	43.6	51.1	50.8	24.3
1000	45.0	45.4	45.2	44.4	44.9	42.7	45.2	53.7	54.5	29.0
1250	46.9	46.1	45.4	46.0	45.7	45.1	46.0	53.5	52.8	26.6
1600	45.3	43.8	45.1	48.0	49.4	47.6	48.8	54.2	50.5	21.8
2000	49.2	48.5	48.0	50.6	51.8	49.7	51.1	52.3	50.7	23.3
2500	51.5	50.8	49.8	48.8	50.2	49.7	50.1	54.5	54.1	25.4
3150	50.7	48.6	48.8	48.8	48.5	49.3	49.9	54.9	53.5	26.8
4000	51.4	50.9	50.5	48.7	49.6	49.0	50.2	54.1	52.9	24.1
5000	49.7	50.4	50.5	47.2	47.8	47.7	49.7	55.3	55.6	26.6
6300	53.4	43.3	50.9	35.5	47.4	38.6	48.8	56.4	55.3	26.8
8000	58.3	31.9	55.9	26.0	51.4	27.8	50.9	53.5	53.9	25.5
10000	57.2	21.6	56.1	18.6	48.3	20.0	48.8	50.6	51.6	24.8
12500	56.5	15.9	52.0	13.3	45.7	13.9	45.1	43.6	46.3	24.8
16000	50.6	9.5	46.3	8.1	38.2	8.4	35.7	37.2	40.2	23.8
20000	40.4	5.6	34.6	5.4	28.1	5.3	26.9	22.3	25.2	21.5
Outdoor Sound Level (dBA)	88.4	94.0	86.9	92.8	85.0	92.0	83.9	81.0	77.2	77.6
Indoor Sound Level (dBA)	51.4	66.4	52.1	65.5	52.0	65.5	51.5	34.2	34.4	57.7
A-wtd Level Reduction (dBA)	37.1	27.6	34.7	27.3	33.1	26.5	32.4	46.8	42.7	19.9

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	51	52	53	54	55	56	57	58	59	60
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	pink	pink	pink	pink	pink	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	41	41	41	41	41	41	41	41	41	41
Open/Closed	open	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	45	15	30	60	75	90	105	120	135	150
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Layers gypboard	1	1	1	1	1	1	1	1	1	1
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	26.7	23.2	26.4	33.7	34.4	34.9	34.0	34.5	34.1	33.9
63	23.8	22.4	26.7	31.5	28.2	31.4	29.8	30.7	30.3	30.3
80	24.2	26.3	33.2	32.8	33.6	34.3	33.3	34.4	33.4	33.0
100	36.2	32.8	37.5	42.1	47.1	46.0	43.3	47.8	45.4	37.8
125	23.7	28.2	35.8	42.3	39.0	45.0	40.0	41.5	40.9	33.5
160	28.5	30.3	34.4	43.3	42.4	45.1	40.3	43.2	44.2	36.0
200	34.5	36.2	38.2	50.0	49.1	47.7	50.4	52.5	50.8	43.6
250	32.7	35.2	38.5	44.6	48.7	48.7	47.9	47.6	46.2	43.3
315	33.0	39.1	41.2	48.0	48.3	50.7	47.6	48.0	47.4	47.6
400	27.8	38.4	44.2	48.9	50.1	49.9	51.2	53.3	51.4	48.4
500	22.2	40.7	46.1	50.1	48.8	49.7	50.3	50.9	50.9	48.6
630	18.5	38.9	41.2	48.2	48.2	48.3	47.8	49.4	48.8	44.9
800	24.1	40.9	47.6	53.9	54.0	56.8	54.7	56.4	55.2	48.1
1000	24.5	42.2	48.8	57.0	56.4	56.1	56.6	57.9	57.8	52.4
1250	20.8	42.8	48.1	55.9	53.8	54.2	54.6	56.7	56.8	49.8
1600	18.3	41.2	47.9	54.4	51.6	53.5	54.2	54.9	56.9	50.0
2000	19.4	39.3	46.1	52.9	51.6	54.0	51.3	56.5	52.6	49.8
2500	21.8	42.8	48.5	55.5	54.0	57.4	55.5	57.6	57.6	52.5
3150	22.0	45.2	50.3	55.7	54.3	56.8	55.9	58.1	58.9	55.2
4000	19.6	43.0	48.5	55.5	55.6	56.7	54.8	58.7	58.2	53.6
5000	22.0	47.5	49.7	59.3	59.0	61.1	59.5	59.5	60.0	53.7
6300	20.3	47.9	51.2	59.6	58.5	60.6	58.7	59.7	60.7	53.8
8000	19.9	47.3	50.7	58.1	57.5	59.8	57.8	58.5	58.3	53.9
10000	20.0	45.3	49.8	56.4	56.7	58.0	56.7	56.2	56.7	51.7
12500	18.5	41.2	45.8	53.0	52.0	54.1	52.2	51.2	51.6	46.6
16000	17.1	34.0	38.9	47.0	46.4	48.7	46.7	45.1	46.0	40.5
20000	16.3	17.8	23.0	31.9	30.4	32.8	30.8	29.3	31.4	23.9
Outdoor Sound Level (dBA)	77.7	73.6	75.2	79.8	79.2	80.9	79.5	79.7	80.8	78.4
Indoor Sound Level (dBA)	62.0	36.6	35.7	36.1	36.8	37.2	37.2	34.1	34.9	36.8
A-wtd Level Reduction (dBA)	15.7	37.0	39.5	43.7	42.4	43.6	42.3	45.6	45.9	41.6

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	61	62	63	64	65	66	67	68	69	70
Sound Source	JBL	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey
Source Signal	pink	jet	pink	jet	pink	jet	pink	jet	pink	pink
Ext msmt	near	near	near	near	near	near	near	near	near	near
Window STC	41	41	41	41	41	41	41	41	41	41
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	165	45	45	45	45	45	45	45	45	45
Source Height (ft)	3.4	3.75	3.75	5	5	7	7	8	8	3.75
Layers gypboard	1	1	1	1	1	1	1	1	1	2
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	29.7	31.5	32.2	32.0	32.3	31.0	33.2	31.9	31.5	30.1
63	28.3	29.1	31.4	29.7	31.1	28.9	31.0	29.0	29.5	18.6
80	31.0	33.7	34.3	33.4	34.1	31.6	33.8	32.7	32.1	22.5
100	36.0	40.5	40.7	41.3	40.4	39.1	42.0	39.1	39.3	32.0
125	34.0	40.9	40.1	39.9	38.2	36.6	38.9	35.9	37.0	38.7
160	37.7	38.8	39.4	39.5	40.6	40.5	39.9	42.3	41.1	35.3
200	38.0	44.0	44.9	44.0	46.7	49.2	45.6	50.3	49.1	38.9
250	35.6	41.7	42.1	43.4	45.3	44.1	44.5	44.4	43.3	37.9
315	39.5	42.6	43.9	46.0	46.0	45.7	45.7	44.7	45.8	38.2
400	43.8	49.3	48.4	49.3	49.2	49.5	49.4	48.5	49.7	43.7
500	45.2	49.3	49.4	50.0	49.4	48.6	48.3	48.6	49.3	47.2
630	40.2	48.3	45.9	45.1	48.8	45.5	47.2	44.9	45.2	46.8
800	42.9	50.8	53.4	53.2	54.3	51.3	53.1	51.9	52.9	46.0
1000	46.1	54.0	54.8	54.2	55.9	53.4	53.8	53.9	54.3	46.0
1250	46.1	53.1	54.0	51.9	52.8	50.3	51.5	51.9	51.8	48.1
1600	45.8	49.2	48.9	46.9	49.7	49.6	52.2	51.2	51.6	47.0
2000	44.4	50.7	50.3	50.8	51.0	51.5	54.1	51.6	53.1	47.5
2500	48.4	55.7	54.9	56.5	56.5	54.6	56.5	54.8	54.9	51.5
3150	50.4	54.4	54.8	55.2	56.0	54.4	54.9	54.0	54.4	49.8
4000	46.6	55.5	56.3	55.3	57.4	54.1	56.2	53.6	56.1	53.2
5000	52.1	58.0	60.6	56.9	59.6	54.3	59.5	52.2	58.6	54.8
6300	51.2	49.6	64.4	47.4	63.7	41.9	59.7	39.8	58.5	47.4
8000	51.8	36.5	57.3	34.4	59.3	30.4	56.5	29.3	54.9	34.0
10000	49.4	26.4	63.1	24.3	60.0	21.4	55.1	22.5	50.4	24.3
12500	43.4	20.4	59.8	18.1	56.5	15.3	49.2	15.2	47.8	20.1
16000	36.5	14.3	51.4	11.3	49.3	9.9	38.3	9.7	37.8	14.5
20000	16.9	8.5	39.1	6.5	36.6	5.9	28.6	5.6	27.5	11.2
Outdoor Sound Level (dBA)	77.2	94.7	88.2	94.4	87.3	93.0	84.8	92.5	83.5	93.1
Indoor Sound Level (dBA)	37.0	59.8	45.5	58.8	43.9	57.6	43.1	57.0	43.0	60.0
A-wtd Level Reduction (dBA)	40.2	34.9	42.8	35.6	43.4	35.4	41.6	35.5	40.5	33.1

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	71	72	73	74	75	76	77	78	79	80
Sound Source	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	Peavey	JBL	JBL	JBL
Source Signal	jet	pink	jet	pink	jet	pink	jet	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	flush	near	near
Window STC	41	41	41	41	41	41	41	41	41	41
Open/Closed	closed	closed	closed	closed	closed	closed	closed	closed	closed	half
Theta (deg)	45	45	45	45	45	45	45	45	45	45
Source Height (ft)	3.75	5	5	7	7	8	8	3.4	3.4	3.4
Layers gypboard	2	2	2	2	2	2	2	2	2	2
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)									
50	30.8	29.8	30.8	29.7	30.5	32.5	29.6	31.6	31.3	28.4
63	21.3	20.1	19.2	18.8	20.0	20.5	18.4	22.7	22.2	18.1
80	24.7	24.3	22.4	22.5	23.9	21.2	22.5	28.9	27.2	18.2
100	33.0	31.0	33.4	29.0	31.8	36.3	28.4	37.2	35.6	30.4
125	37.9	36.4	38.9	36.0	36.7	38.7	36.4	42.0	39.6	28.6
160	34.1	33.6	36.2	34.7	35.9	33.7	34.5	38.1	35.4	25.7
200	39.5	37.9	39.4	41.0	38.7	41.1	43.0	38.9	43.4	28.4
250	40.0	41.7	40.6	42.1	39.3	40.3	42.4	39.2	42.5	31.4
315	40.2	39.1	42.1	39.2	40.4	37.9	41.2	42.2	43.6	29.1
400	46.2	44.3	44.5	42.7	45.3	45.5	45.6	47.8	47.5	32.9
500	45.8	47.3	47.9	45.9	46.2	43.9	44.7	50.0	49.9	29.9
630	43.9	45.1	43.2	43.4	45.3	42.6	44.9	48.5	47.0	25.5
800	48.4	45.8	48.5	43.9	47.0	46.4	46.8	49.0	50.0	20.9
1000	46.2	46.3	47.2	44.4	45.8	44.1	43.7	49.2	48.7	25.5
1250	49.1	45.8	46.2	44.3	46.6	47.1	46.7	51.2	51.9	26.5
1600	46.9	46.2	45.4	45.2	48.8	50.4	49.8	54.6	51.4	23.1
2000	47.3	48.1	48.1	48.5	50.5	50.9	50.6	51.9	51.2	22.1
2500	52.5	50.6	51.1	51.2	51.5	50.9	50.2	52.8	52.4	25.7
3150	50.0	48.9	51.0	49.7	50.2	50.7	49.0	53.8	52.2	24.9
4000	54.4	51.8	54.0	51.8	52.6	50.4	50.5	54.5	54.5	24.7
5000	57.4	52.9	57.5	50.9	55.4	48.3	52.8	55.6	55.8	25.1
6300	61.4	44.4	59.5	39.7	55.9	37.3	51.9	57.3	56.2	26.8
8000	57.9	32.0	53.1	27.6	52.6	26.6	49.0	54.3	53.8	25.4
10000	62.0	22.7	55.9	20.6	49.5	20.8	47.8	51.2	51.2	24.3
12500	59.9	17.8	51.9	15.4	47.2	15.2	42.6	43.2	46.3	24.6
16000	51.7	11.9	43.2	10.1	40.4	10.2	33.9	35.3	40.0	23.0
20000	42.8	8.8	32.1	8.2	31.6	7.9	26.2	22.0	27.8	25.0
Outdoor Sound Level (dBA)	86.9	92.7	81.7	91.6	83.3	91.3	78.5	80.9	77.6	77.6
Indoor Sound Level (dBA)	45.9	59.6	40.9	58.9	44.6	58.7	40.7	33.8	34.0	57.7
A-wtd Level Reduction (dBA)	41.0	33.1	40.8	32.7	38.8	32.6	37.9	47.1	43.6	19.9

Table E.1 (cont.): Measured transmission loss across frequency for every iteration

Msmt number	81	82	83	84	85	86	87	88	89	90	91
Sound Source	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL	JBL
Source Signal	pink	pink	pink	pink	pink	pink	pink	pink	pink	pink	pink
Ext msmt	near	near	near	near	near	near	near	near	near	near	near
Window STC	41	41	41	41	41	41	41	41	41	41	41
Open/Closed	open	closed	closed	closed	closed	closed	closed	closed	closed	closed	closed
Theta (deg)	45	15	30	60	75	90	105	120	135	150	165
Source Height (ft)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Layers gypboard	2	2	2	2	2	2	2	2	2	2	2
f (Hz)	Measured Transmission Loss (dB) at 1/3 Octave Band Center Frequencies (Hz)										
50	28.1	24.0	26.6	27.8	33.8	31.3	32.3	31.8	30.8	29.3	29.9
63	18.9	13.2	17.6	23.3	21.7	21.6	25.2	22.9	22.7	23.1	20.6
80	18.2	20.0	25.9	26.0	27.5	28.1	29.2	27.1	27.5	28.5	24.1
100	30.1	27.6	31.4	35.6	42.0	39.6	39.9	39.1	40.9	35.3	28.5
125	28.8	32.2	36.4	41.3	41.2	40.9	45.7	42.3	42.8	40.3	35.2
160	27.8	26.1	33.7	40.9	39.1	40.5	43.4	39.3	41.6	37.8	35.6
200	25.1	31.0	38.4	44.5	42.6	43.9	43.7	38.3	46.1	38.4	37.5
250	29.4	32.0	37.6	44.5	48.5	47.4	45.7	45.1	44.2	39.2	38.8
315	30.5	35.5	40.3	44.7	46.2	45.2	44.8	42.3	45.2	42.4	36.0
400	27.5	40.0	43.5	46.5	49.8	46.8	48.8	45.9	49.9	45.8	41.0
500	24.2	41.4	45.8	49.3	47.5	48.9	50.2	48.8	50.8	49.3	44.8
630	21.3	38.1	43.6	49.7	49.4	49.4	53.8	47.7	49.6	44.4	39.8
800	21.4	37.7	42.9	51.3	51.0	51.7	53.4	51.3	50.7	45.6	39.2
1000	21.1	38.2	43.0	50.0	50.8	50.1	50.6	50.7	50.3	46.0	40.4
1250	22.3	41.6	49.0	55.0	52.8	51.5	54.4	52.8	54.3	46.6	41.7
1600	20.1	41.2	49.1	52.2	51.7	52.7	54.1	51.2	53.6	47.9	43.6
2000	20.1	39.9	45.0	50.4	50.9	51.5	53.2	48.8	49.2	48.4	42.5
2500	21.8	40.6	47.7	51.8	53.1	52.6	54.4	52.1	52.3	49.6	44.3
3150	22.5	44.0	50.0	53.6	54.0	53.7	55.9	56.6	54.0	53.2	46.5
4000	22.7	42.0	49.5	54.5	55.3	53.5	55.2	58.2	54.5	51.3	44.3
5000	22.7	44.1	49.2	55.1	57.7	55.2	56.5	58.7	55.6	51.8	48.9
6300	23.8	43.7	52.3	54.8	57.4	54.0	55.5	58.9	55.1	51.3	48.7
8000	22.4	41.4	51.5	52.0	56.0	52.7	53.6	57.2	51.6	49.9	47.9
10000	21.4	39.1	49.8	50.3	55.1	50.8	51.0	54.9	49.4	46.6	46.1
12500	21.7	34.7	45.7	46.3	50.2	46.2	45.1	49.6	43.9	40.8	40.1
16000	21.7	28.1	38.4	40.5	44.1	40.0	39.9	43.8	39.0	34.2	34.9
20000	22.9	15.5	25.5	28.1	31.5	26.5	26.2	31.2	27.6	19.3	21.3
Outdoor Sound Level (dBA)	77.7	68.5	75.9	74.1	78.3	73.8	75.2	80.2	74.8	73.8	76.6
Indoor Sound Level (dBA)	60.4	31.4	35.8	31.3	35.8	31.9	31.3	37.4	30.2	32.4	37.1
A-wtd Level Reduction (dBA)	17.3	37.1	40.0	42.8	42.5	41.9	43.8	42.7	44.6	41.4	39.5

APPENDIX F

MEASUREMENT SETUP

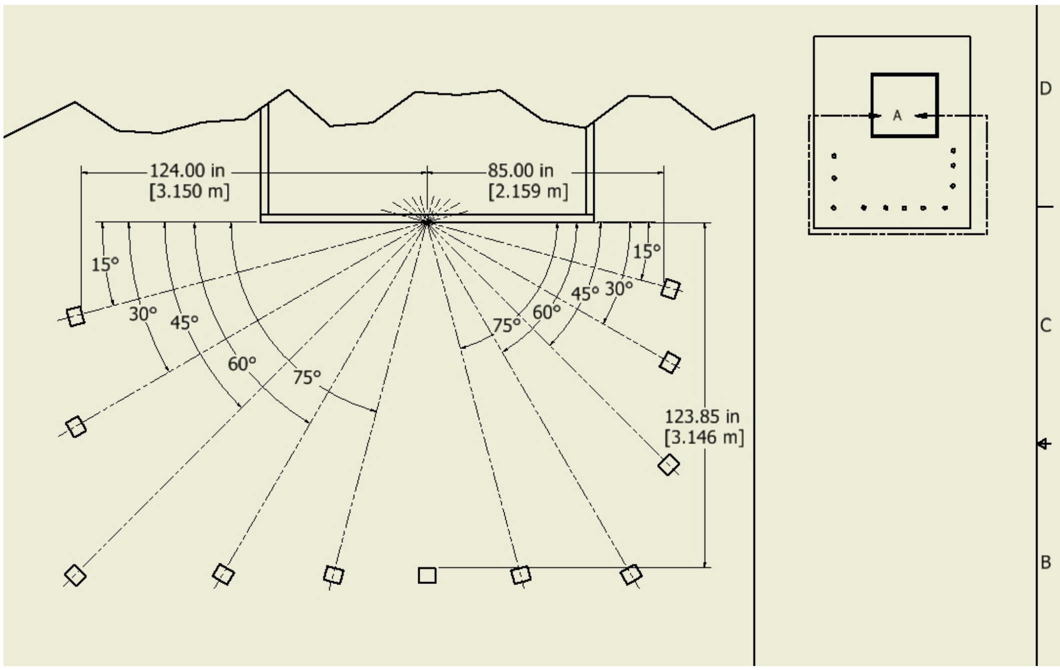


Figure F.1: Sound source placement (Top View) for horizontal incidence angle iterations

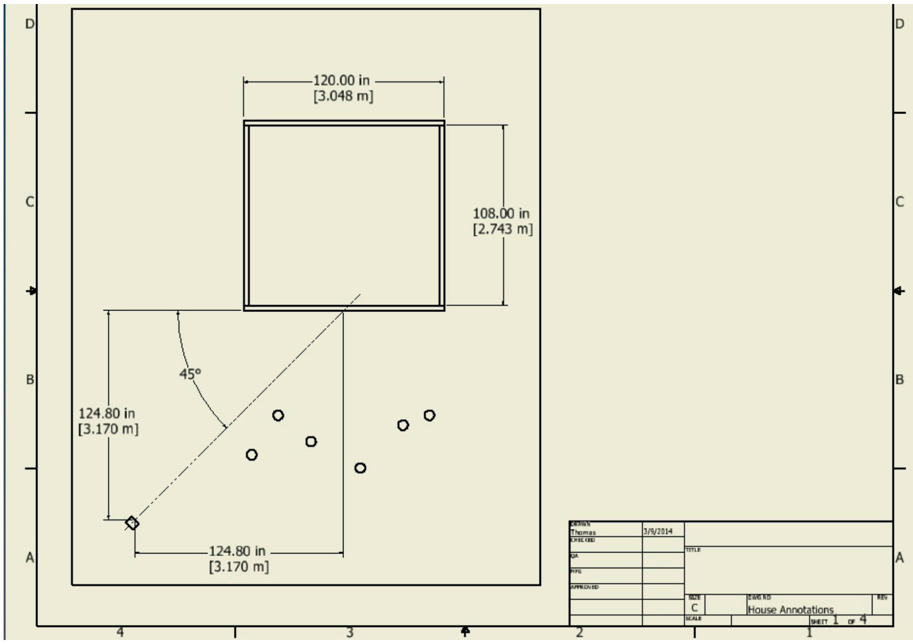


Figure F.2: Sound source placement (Top View) for standard 45 degree incidence

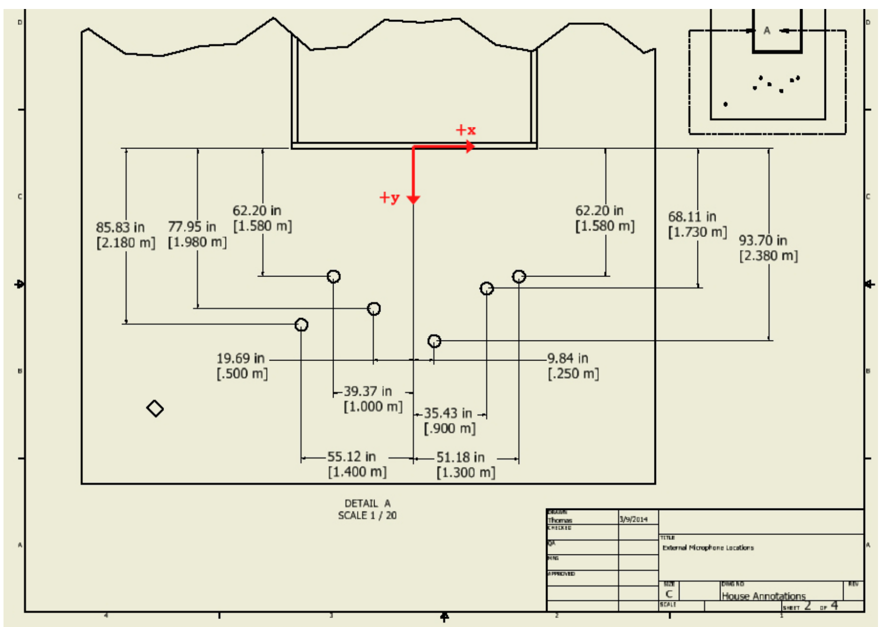


Figure F.3: Microphone placement (Top View) for near average exterior measurements

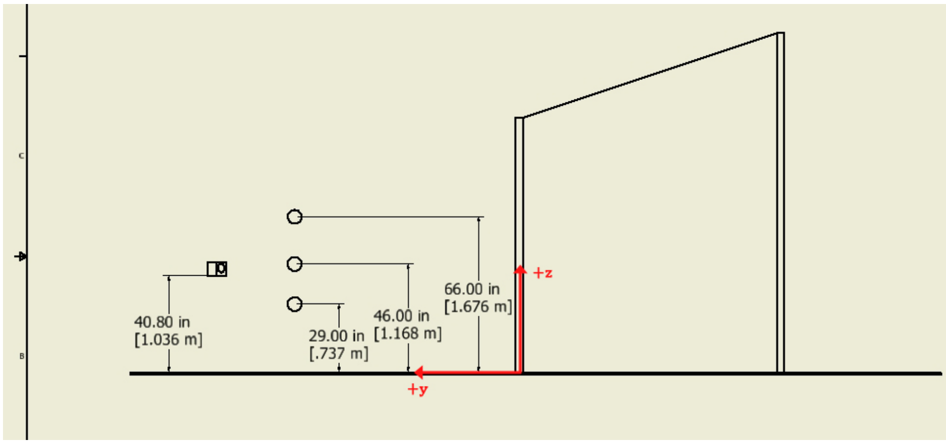


Figure F.4: Fixed microphone heights (Side View) for low, medium, and high exterior configurations

Table F.1: Microphone positions for near average exterior measurements, relative to origin (red) as seen on Figure F.3 and Figure F.4

Position Number	Height Orientation	Microphone Position (in)		
		x	y	z
1	low	-55.12	85.83	29.00
	medium	-55.12	85.83	46.00
	high	-55.12	85.83	66.00
2	low	-39.37	62.20	29.00
	medium	-39.37	62.20	46.00
	high	-39.37	62.20	66.00
3	low	-19.69	77.95	29.00
	medium	-19.69	77.95	46.00
	high	-19.69	77.95	66.00
4	low	9.84	93.70	29.00
	medium	9.84	93.70	46.00
	high	9.84	93.70	66.00
5	low	35.43	68.11	29.00
	medium	35.43	68.11	46.00
	high	35.43	68.11	66.00
6	low	51.18	62.20	29.00
	medium	51.18	62.20	46.00
	high	51.18	62.20	66.00

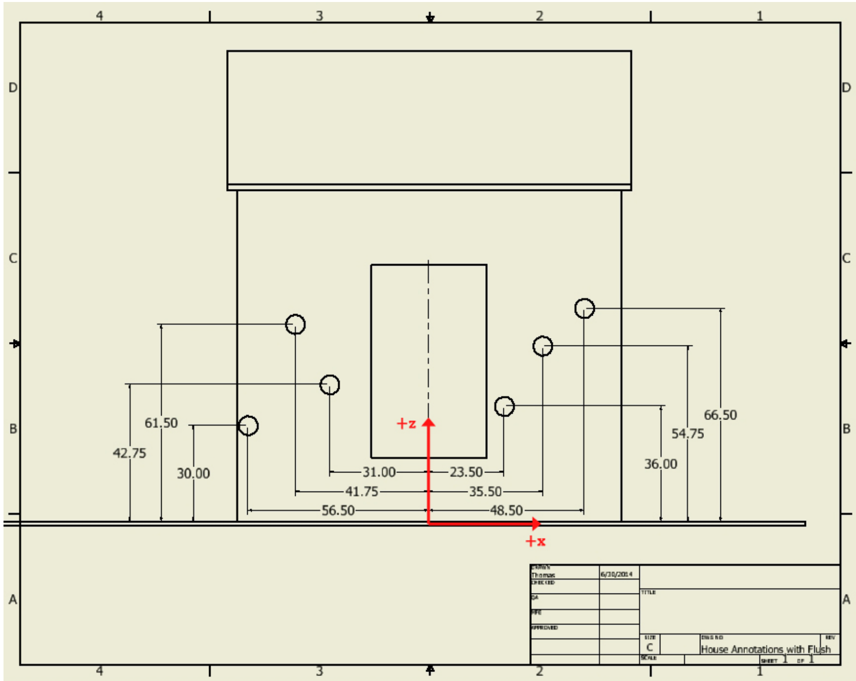


Figure F.5: Microphone placement (Front View) for flush exterior measurements

Table F.2: Microphone positions for flush exterior measurements relative to origin (red) as seen on Figure F.5

Position Number	Microphone Position (in)		
	x	y	z
1	-56.50	0.00	30.00
2	-41.75	0.00	61.50
3	-31.00	0.00	42.75
4	23.50	0.00	36.00
5	35.50	0.00	54.75
6	48.50	0.00	66.50

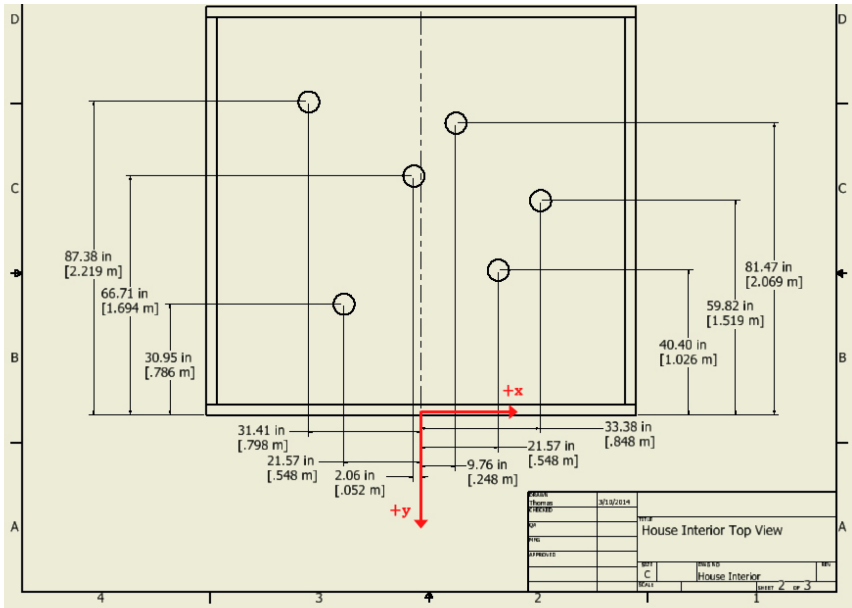


Figure F.6: Microphone placement (Top View) for interior sound level measurements

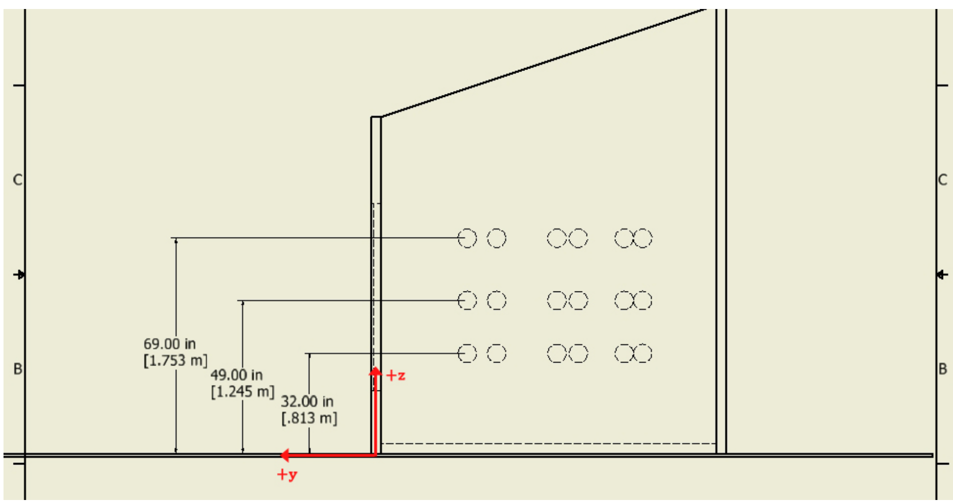


Figure F.7: Fixed microphone heights (Side View) for low, medium, and high interior configurations

Table F.3: Microphone positions for interior sound level measurements relative to origin (red) as seen on Figure F.6 and Figure F.7

Position Number	Height Orientation	Microphone Position (in)		
		x	y	z
1	low	-31.41	-87.38	32.00
	medium	-31.41	-87.38	49.00
	high	-31.41	-87.38	69.00
2	low	-21.57	-30.95	32.00
	medium	-21.57	-30.95	49.00
	high	-21.57	-30.95	69.00
3	low	-2.06	-66.71	32.00
	medium	-2.06	-66.71	49.00
	high	-2.06	-66.71	69.00
4	low	9.76	-81.47	32.00
	medium	9.76	-81.47	49.00
	high	9.76	-81.47	69.00
5	low	21.57	-40.40	32.00
	medium	21.57	-40.40	49.00
	high	21.57	-40.40	69.00
6	low	33.38	-59.82	32.00
	medium	33.38	-59.82	49.00
	high	33.38	-59.82	69.00

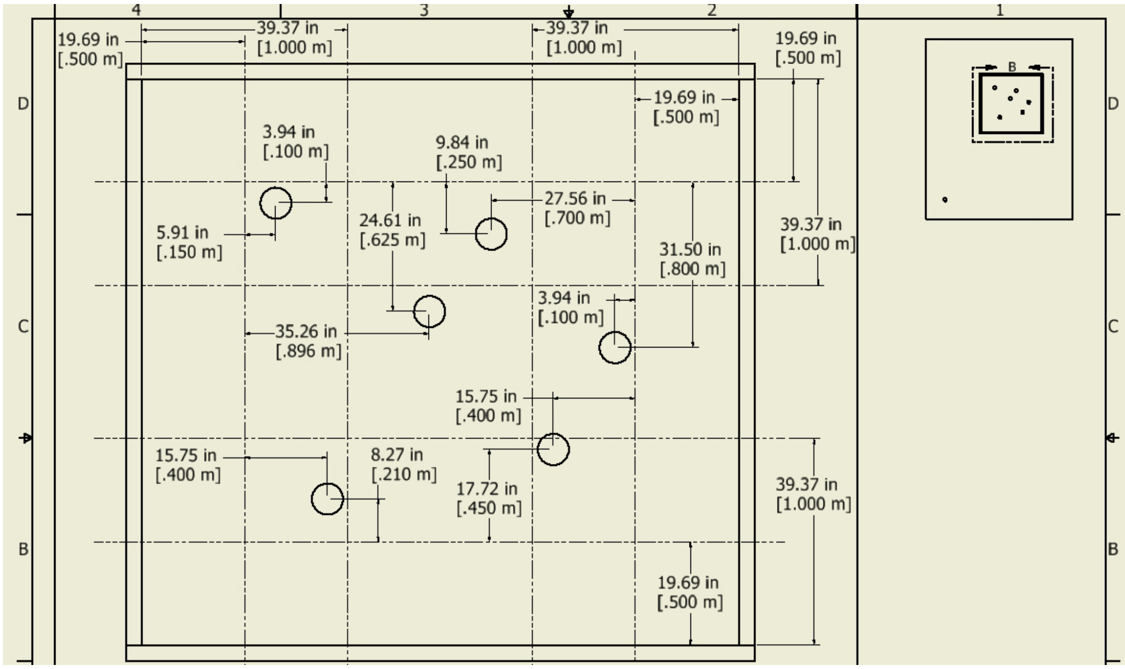


Figure F.8: Microphone placement (Top View) for interior sound level measurements (with planes representing 0.5 m and 1.0 m offset from interior walls)

APPENDIX G

VERIFICATION OF IBANA-CALC CALCULATION

The reported values included in the scenario text file are shown in Table G.1 below to verify the calculation of TL. The modeled room was 9' x 10' x 8' (2.74 m x 3.05 m x 2.44 m) with resulting values of S = 36.6 m^2 and, with 100% floor area absorption, A = 8.36 metric Sabins. It is important to note the 2 dB correction factor, corresponding to the adjustment used in near average exterior level measurements (this was explained in further detail in Section 4.1.3), required to calculate "Indoor Sound Level" L_2 as given by the IBANA-Calc software.

Table G.1: Verification of IBANA-Calc TL and NR calculations

Frequency (Hz)	**Source Sound Level (dB)** L_1 given	**IBANA-Calc TL (dB)** given	**Calculated NR (dB)** NR = TL - 10*log (S/A)	Calculated Indoor Sound Level (dB) $L_2 = L_1$ - NR - 2	**Indoor Sound Level (dB)** L_2 given
50	54.8	10.9	4.5	48.3	**48.2**
63	56.0	11.0	4.6	49.4	**49.3**
80	57.5	21.1	14.7	40.8	**40.7**
100	58.9	26.4	20.0	36.9	**36.8**
125	59.3	30.5	24.1	33.2	**33.0**
160	59.0	33.2	26.8	30.2	**30.1**
200	58.5	26.7	20.3	36.2	**36.1**
250	57.5	31.4	25.0	30.5	**30.4**
315	56.5	34.2	27.8	26.7	**26.6**
400	55.8	35.5	29.1	24.7	**24.6**
500	55.2	39.0	32.6	20.6	**20.5**
630	54.6	41.0	34.6	18.0	**17.9**
800	53.7	42.9	36.5	15.2	**15.1**
1000	52.5	45.4	39.0	11.5	**11.4**

Table G.1 (cont.): Verification of IBANA-Calc TL and NR calculations

Frequency (Hz)	**Source Sound Level (dB)** L_1 given	**IBANA-Calc TL (dB)** given	**Calculated NR (dB)** NR = TL - 10*log (S/A)	Calculated Indoor Sound Level (dB) $L_2 = L_1$ - NR - 2	**Indoor Sound Level (dB)** L_2 given
1250	51.2	47.0	40.6	8.6	**8.5**
1600	49.6	48.1	41.7	5.9	**5.8**
2000	47.4	47.1	40.7	4.7	**4.7**
2500	45.6	44.2	37.8	5.8	**5.7**
3150	43.3	44.7	38.3	3.0	**2.8**
4000	40.2	41.6	35.2	3.0	**2.7**
5000	34.3	43.7	37.3	-5.0	**-5.5**

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