MODELING THE TRANSMISSION LOSS OF TYPICAL HOME CONSTRUCTIONS EXPOSED TO AIRCRAFT NOISE

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MODELING THE TRANSMISSION LOSS OF TYPICAL HOME CONSTRUCTIONS EXPOSED TO AIRCRAFT NOISE

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LIST OF SYMBOLS AND ABBREVIATIONS

A_{Roof}	Roof Area (ft^2)
A_{Wall}	Wall Area (ft^2)
A_{Window}	Window Area (ft^2)
AlC	Aluminum Casement Window
AlC1SW	Aluminum Casement Window plus 1” Airgap and Storm Window
AlC3SW	Aluminum Casement Window plus 3” Airgap and Storm Window
AlOSB	Aluminum Siding with Oriented Strand Board
ANCA	Aircraft Noise and Capacity Act
ASNA	Aviation Safety and Noise Abatement Act
ASTM	American Society for Testing and Materials
BP	Blood Pressure
DNL	Day-Night Level (dB)
DOD	Department of Defense
DOJ	Department of Justice
DOT	Department of Transportation
EPA	Environmental Protection Agency
EU	European Union
FAA	Federal Aviation Administration
FHA	Federal Housing Authority
FICAN	Federal Interagency Committee on Aviation Noise
FICON	Federal Interagency Committee on Noise
FICUN	Federal Interagency Committee on Urban Noise

GAO	Government Accountability Office
GT	Georgia Tech (Georgia Institute of Technology)
HD	Hot-Dry Climate Region
HUD	Housing and Urban Development
HYENA	Hypertension and Exposure to Noise near Airports
IBANA	Insulating Buildings Against Aircraft Noise
ICAO	International Civil Aviation Organization
MD	Mixed-Dry Climate Region
MSE	Mean Square Error
NASA	National Aeronautics and Space Administration
NE	Northeast
NR	Noise Reduction (dB)
NRC-IRC	National Research Council-—Institute for Research in Construction
NW	Northwest
OC	On Center
OITC	Outdoor-Indoor Transmission Class
OSB	Oriented Strand Board
RT	Reverberation Time (s)
SAC1	Specialty Acoustic Window 1
SAC2	Specialty Acoustic Window 2
SE	Southeast
STC	Sound Transmission Class
StDev	Standard Deviation
SW	Southwest
TL	Transmission Loss (dB)

US (also U.S.)	United States
VA	Veterans Administration
VDS	Vinyl Double Slider Window
VDS1SW	Vinyl Double Slider Window plus 1” Airgap and Storm Window
WHO	World Health Organization
WS	Wood Slider Window
XPS	Extruded Polystyrene (Rigid Foam Insulation)

SUMMARY

Current aircraft noise guidelines are based primarily on outdoor sound levels. However, human perception is highly related to indoor response, particularly for residences. A research project has been conducted that provides insight into how typical residential dwelling envelopes affect sound transmitted indoors. A focus has been placed on the effect of residential dwelling envelopes on subsonic civil aircraft noise. Typical construction types across the United States have been identified and used to develop model predictions of outdoor-to-indoor transmission loss. While it was initially hypothesized that these construction types could be grouped by climate region, it was found that these constructions are better grouped according to their outermost construction layer. Further, the impact of systematically altering construction variables (such as the construction materials used and the ratio of window area to wall area) has been investigated. Results will be used to better understand trends for expected noise reduction for typical construction types around the United States. Additionally, comparisons have been made between the effect of older and more modern wall construction techniques on whole-house performance.

CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

As air travel transitioned from a rare luxury to a commonplace mode of transportation, the noise from aircraft became less a sign of progress and more of a disturbance. With more air traffic came higher noise levels, with takeoffs, landings, and overflights occurring at a greater rate. Although steps have been taken to reduce the noise emitted by aircraft, aircraft noise continues to be a significant problem. Not only is annoyance a major concern, but so are the health impacts. A literature review describing annoyance due to aircraft noise, the impact of noise on health, and government standards regarding aircraft noise is contained in Appendix A. Current aircraft noise guidelines are based upon outdoor noise levels, but problematic exposure to aircraft noise also occurs within homes. As such, it is important to quantify the noise transmission properties of typical home constructions in order to better understand the noise levels inside homes. To that end, various typical construction types were identified and modeled in order to generate a set of typical transmission loss curves for these constructions.

1.1 Sound Transmission into Homes

Sound can be transmitted into homes in two ways—either directly through the air or through the building's structure [1]. Since sound can enter a home essentially any way air can enter, openings in doors, windows, vents, leaks, etc. will allow for easy transmission of sound. For example, the vents in a roof (and other leaks) will permit sound to enter, but the sound can also cause the roof to vibrate and thus radiate acoustical energy into the home. As one might expect, sound may only enter through the perimeter of the building, meaning that interior rooms will tend to have a lower noise level, as will lower-level rooms with a story above or rooms which are otherwise shielded from the incident noise [1].

The interior noise goal established by the Federal Aviation Administration (FAA) and Environmental Protection Agency (EPA) is 45 dB Day-Night Level (DNL), which is based upon the assumption that the exterior-to-interior noise reduction for a building is 20 dB from the recommended outdoor noise goal of 65 dB DNL [1]. In the real world, however, things aren't quite as simple, with the noise reduction varying in level across frequency depending upon the building elements and construction methods used.

For example, once all openings are sealed (to prevent the transmission of sound directly through air), the component with the lowest transmission loss performance will tend to dominate the performance of the façade as a whole [2]. In many cases, the windows will become the controlling sound paths since they tend to have a lower transmission loss than walls, doors, and other façade elements [3]. For this reason, using acoustical windows often is the most effective means of improving the transmission loss of a building [1]. As can be expected, when the proportion of window area to wall area is increased, the noise reduction will tend to decrease [1].

The poor performance of windows is due to a number of factors, with a lack of mass preventing good low-frequency performance and mass-air-mass resonances interfering with the midrange performance [4]. This can be compounded by low-frequency induced rattling, the presence of which increases the rate of annoyance [5]. Also, Jean and Rondeau suggested that the angle of incidence may affect the transmission of noise through windows [6].

1.1.1 Sound Transmission Metrics

Transmission Loss (TL) describes the sound insulation value of a building element such as a window or wall and is most often determined for different frequency ranges (octave or 1/3 octave bands). The testing method used to determine TL is described in ASTM Standard E90 [7].

Noise Reduction (NR) is simply the difference between outdoor level and indoor level, where the indoor noise level takes into account both the building's transmission loss properties (TL) and the effects of the receiving room, including absorption/reverberation. TL differs from NR in that TL does not take into account the effects of the receiving room (absorption/reverberation). Also, NR is most frequently a single-number value whereas TL is taken across frequency; in this form, it is sometimes referred to as Noise Level Reduction (NLR).

Sound Transmission Class (STC) is a single-number descriptor based upon comparing the TL values at 16 standard octave bands to a series to reference curves; it gives roughly the decibel reduction a building element will provide and is described in ASTM Standard E413 [8]. Its primary intended use is for speech noise being transmitted through interior partitions, and as such is not ideally suited for use with transportation noise through exterior partitions.

Outdoor-Indoor Transmission Class (OITC) is similar to STC in that it is a single-number value used to rate the ability of a façade to insulate against noise, but the primary difference is that OITC was developed to assess the annoyance of transportation noise, but STC was developed to assess interference with speech. As such, OITC takes into account lower frequencies that are commonly found in transportation noise but not in speech. OITC is the preferred single-number descriptor for exterior partitions, whereas STC is more appropriate for indoor partitions. OITC is described in ASTM E1332 [9].

The challenge with using any single-number metric is that two different construction methods or components can produce identical ratings and have wildly different frequency response characteristics, which can result in better or worse perceived performance depending upon how the spectral content of the incident noise correlates with the response of the building element [4]. Because of this, simply selecting a construction method or component on the basis of the highest single-number rating may not result in the best performance.

1.1.2 Home Retrofits

The cost to build a home which is well-insulated acoustically is modestly higher than the cost to build a standard home, but the cost to retrofit an existing home can range from $10,000 to upwards of $50,000 depending on the level of noise reduction required and the existing construction [1].

Governments are providing subsidies to insulate houses and buildings exposed to aircraft noise as an ex post facto remedy. Another tactic is to purchase the affected properties, allowing their owners to relocate [10], with the threshold being based upon the level of noise exposure.

The first airport-sponsored home retrofit program was at Los Angeles International Airport in 1967 [1], but as a result of the Airport Noise and Capacity Act of 1990 (ANCA), there has been a growth in residential sound insulation programs, with billions of dollars having been spent [11]. As just one example of many, the residential sound insulation programs initiated in Illinois to insulate 3900 homes near O'Hare spent almost $130 million through the year 2000 (over $33,000 per home), with another $250 million going to insulate 94 schools [11].

In the late 1980s, the US Dept. of the Navy and the FAA jointly commissioned the preparation of *Guidelines for Sound Insulation of Residences Exposed to Aircraft Operations*, which was completed in 1989 and published more broadly in 1992 [1]. This document provides recommendations for retrofitting homes exposed to aircraft noise.

Since it generally takes a 5 dB improvement in sound insulation in order to be noticeable by occupants [1], retrofits which provide less improvement will not be effective. In some cases where the noise exposure is quite high, there may not be any feasible sound insulation modification which will result in an acceptable noise exposure as it is impractical to provide more than 35-40 dB of noise reduction for a residence [1].

The first (and probably easiest) step in any attempt to reduce sound transmission indoors is to eliminate the direct air transmission paths by sealing gaps and leaks with caulk and good weather stripping, keeping doors and windows closed, and eliminating any flanking paths through ducts, crawl spaces, or plenums [1].

Common retrofits include replacing the windows with new acoustical windows having a higher STC rating (often with thicker glass and/or a larger airspace), adding storm windows, adding a new prime door, adding an acoustical storm door, or even removing a door or window and filling the hole in the wall [1].

Common ceiling retrofits include adding batt insulation above the ceiling, adding layers of gypsyum board (to increase mass), mounting the gypsum board on resilient channels (to add vibration isolation), or replacing a vaulted ceiling with a flat ceiling (to add an air space) [1]; it is also recommended to add additional batt or blown-in insulation to attics with less than six inches of existing insulation.

For walls, it is common to add mass by adding layers of gypsum board, isolate the interior and exterior panels by increasing their separation (and thus the air gap between them), add absorptive materials within that air gap, mount the panels on staggered studs, or resiliently mount the interior panels [1].

1.1.3 Recommendations for New Construction

When designing a new home to minimize aircraft noise transmission, it is advisable to orient the house and certain rooms within to take advantage of natural shielding properties of the home itself. For example, it is better to locate bedrooms and other noise-sensitive rooms on the side of the house facing away from the predominant flight path. Also, upper stories will shield the rooms below from noise (making the first floor of a two-story home quieter than a single-story home). For this reason, it is recommended that unoccupied attic space be incorporated above all living areas; cathedral ceilings are strongly discouraged [1]. Additionally, it is ill-advised to rely upon foliage, such as trees or shrubs, to shield the house and reduce noise, as these techniques provide minimal noise reduction.

The next important factor is to ensure that sound cannot enter the home via direct air transmission [1]. To achieve this, exterior penetrations must be avoided. This includes wall- and window-mounted air conditioning units, pet doors, mail slots, and (of course) opened windows or doors.

Generally, heavier building elements tend to block more noise because it takes more energy to move the greater mass. With wall construction, this takes the form of using exterior materials like brick and multiple layers of drywall for the interior. Adding absorption in the air cavity, resiliently mounting the interior panels, and using staggered stud construction are means to further improve the performance of the wall. 2"x6" studs should be used in place of 2"x4" studs [1].

The overall building façade performance can be seriously weakened if any of the components used has poor sound insulation properties [1]. For this reason, it is imperative to take into account the weaker elements (such as windows) and the relative size of the components. As a rule, the size of poorer performing elements should be kept to a minimum. For this reason, it is advised to avoid overly large windows.

Also, it is a misconception that high thermal insulation performance equates to high acoustic performance. For example, many thermal windows provide significantly less sound insulation than acoustical windows, and are often the poorest performing façade element [1].

1.1.4 Transmission Loss Resources

While much information exists and is readily available to describe the problem of aircraft noise, the community response to it, the negative health implications of it, government standards regarding it, and industry “best-practices” to help mitigate it, less information is available regarding the actual transmission loss information of exterior home wall constructions across frequency. While many resources exist which describe the noise transmission performance of building construction elements, only a few give transmission loss information across frequency for common home exterior wall constructions. The most comprehensive resource identified was the National Research Council Canada—Institute for Research in Construction’s IR-818 [12], whose database of exterior wall construction transmission loss information was included within the IBANA-Calc software used for this research [13].

Many potential references were suggested by the acoustics community and investigated. While some of these did contain transmission loss information across frequency, it was usually not for typical exterior walls used in residential construction (often either concrete masonry or interior drywall-lined wood framing); some that did have information across frequency were lacking detailed construction information (e.g. “Brick” without any dimensions or other layer information). The resources which referenced common exterior residential constructions typically did not have transmission loss information across frequency, instead reporting single-number values (STC and/or OITC).

An ideal database would consist of the following components:

- Transmission Loss (TL) data across frequency (1/3 Octave Band preferable), not simply single-number ratings
- Detailed construction information, including all layers and dimensions
- Typical exterior home constructions, organized by climate region, not interior partitions or non-typical constructions
- Both older and more modern constructions
- Widely available to the public, not out of print or difficult to obtain

A full listing of all the resources investigated showing the type of information they contained is located in Appendix A.

1.2 Hypothesis

As transmission loss information across frequency is not readily available for common residential exterior partitions beyond the few specific constructions included in the aforementioned IR-818 [12], it is hypothesized that a set of “typical exterior constructions” could be identified for various home constructions in the United States and the transmission loss properties of these building exteriors be modeled in order to generate a set of predicted transmission loss curves. While it was initially hypothesized that these construction types could be grouped by climate region, it was found that these constructions are better grouped according to their outermost construction layer. Taking noise measurements at homes located near airports in order to gather field data was determined to be outside of the scope of this project; thus, its focus shall be on generating computer models of these construction types.

CHAPTER 2

OVERVIEW AND DISCUSSION OF MODELING TECHNOLOGIES

Two software packages were used for this research project: Insul, a commercial software package developed by Marshall Day Acoustics in New Zealand, and IBANA-Calc, a non-commercial software package developed by the National Research Council Canada. A review of the IBANA-Calc software was performed to investigate its functionality for modeling whole-house constructions. Additionally, wall models were generated in Insul and then compared against the corresponding entries in the IBANA-Calc database to validate the two programs against each other.

2.1 IBANA-Calc Overview

In 1998, the Canadian NRC-IRC (National Research Council—Institute for Research in Construction) commissioned the IBANA (Insulating Buildings Against Noise from Aircraft) project. As part of this project, a piece of software was written called IBANA-Calc. Its purpose was to calculate how different building constructions affected sound insulation against aircraft noise and then generate predicted indoor noise levels for different aircraft noises and building constructions. Additionally, IBANA-Calc includes a large database of transmission loss data for various building façade elements (collected as part of the project) as well as a database of source noise spectra. The intent for the software was to be a more convenient tool than look-up tables and single number ratings for calculating the effect of different sound insulation designs. It is available free-of-charge from the NRC-IRC.

2.1.1 IBANA-Calc Features/Capabilities

IBANA-Calc calculates the combined sound insulation of different construction components of each part of the building façade. Construction components are selected from an included database, and the user inputs the surface area of each selected component. The program provides both graphical output (of the outdoor and indoor levels, as well as the transmission loss) and auralizations when given an incident noise source. In addition to using the noise sources and building construction elements included in the software's database, users can easily add new ones. For new sources (aircraft or otherwise), the user enters the 1/3 octave-band (OB) spectrum of the source; for building construction elements, the user enters the 1/3OB transmission loss information for that building element. Additionally, the program includes several optional correction factors that affect the incident noise spectrum or the transmission loss of the building façade due to the angles of incidence from the noise source to the building façade elements.

2.1.2 IBANA-Calc Validation Summary

In 2002, the NRC-IRC released a Validation Study of the IBANA-Calc software in which noise measurement were taken at buildings near airports and then compared to the software's model predictions [14]. The testing sites included an older home near Vancouver Airport, offices in a Vancouver Airport building, and new homes near Toronto Airport. In 3 of the 4 measured cases from the new houses near Toronto Airport, the measured overall A-weighted noise level reductions matched the predictions within 1 dB. Nine of the 10 cases were predicted within 3 dB, but it must be noted that reducing these predictions to overall A-weighted values allows positive and negative errors to cancel each other out. When the actual predicted transmission loss curves are compared to the measured TL across frequency, the differences are much more significant (generally within +/-6 dB, but as much as a 15 dB over-prediction at high frequencies).

The validation study found that the primary contributors to the aforementioned error were a lack of laboratory sound transmission loss data for some constructions and large differences between laboratory and field conditions for windows (near the mass-air-mass resonance frequency, the TL of the windows was highly sensitive to the angle of incidence) and common wood-stud walls (low frequency resonances aren't as significant in the field, making actual TL higher than predicted). Bradley suggested that "[t]hese differences may also be related to differences in angles of incidence between laboratory and field situations. Alternatively they may be influenced by the different edge or mounting conditions for the walls that also differ greatly between laboratory and field situations" [14]. Furthermore, due to a lack of high frequency noise at the test sites near Toronto Airport (labeled the "Oakview" and "Summerhill" houses) and given the level of background noise in the buildings, the measured noise level reductions at higher frequencies were lower than what they should be. This effect was especially noticed at 3.15kHz and above, but it may have extended as low as 2kHz. Thus, the software has not been adequately verified at higher frequencies [14].

2.1.3 IBANA-Calc Correction Factors

Included within the IBANA-Calc software are several correction factors: Air Absorption, Vertical Angle, Horizontal Angle, Horizontal Angle of View, and Ground Reflection [13]. Of these, only the Vertical Angle correction factor affects the transmission loss of the scenario when applied. The Horizontal Angle factor has not been implemented in the software; the remaining three correction factors adjust the noise source, which in turn affects the indoor noise, but the transmission loss of the building façade remains the same. The Vertical Angle, Horizontal Angle of View, and Ground Reflection correction factors are all based upon very limited data, and the software's creators recommend that they be used with extreme caution [14]. When using these correction factors (with the exception of 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. For this reason, as well as the difficulty of use in having to model each surface separately, the correction factors contained in the IBANA-Calc software have not been used in this research.

2.2 Insul Overview

Insul is a commercial software package developed by Marshall Day Acoustics in New Zealand that is designed to predict the sound insulation in walls, floors, and ceilings. It allows the user to generate composite wall constructions, layer-by-layer, with up to two unique layers on each side of a stud cavity. Insul gives the transmission loss (TL) of the composite wall construction and the individual panels themselves in 1/3 octave bands, as well as STC (sound transmission class) and OITC (outdoor-indoor transmission class). Version 6.4 was used in this research.

2.2.1 Insul Features/Capabilities

Insul includes a built-in database of commonly used construction materials, as well as numerous options for developing the models: the type and thickness of each panel layer, the shape of the panel profile, the number of duplicate layers of each type within a single panel, the stud size and spacing, the size and type of cavity insulation, and several options for stud construction (wood/steel, staggered, double wall, etc.). While the software does include modeling for ceiling constructions, it is limited to constant-depth joist construction, hampering its usefulness for roof applications. The roof model in Insul is limited to predicting the sound intensity level due to rainfall, and has the same construction limitation as the ceiling model. Both use the same layer-based approach as the wall models. Note also that Insul's built-in database of materials does not include common roofing materials (such as asphalt shingles or clay tiles).

2.2.2 Insul Validation Summary

Insul utilizes classical theoretical models of transmission loss. To validate the software's methodology, Ballagh (2004) compared the theoretical models against experimental measurements, including over 240 walls and floors compiled by National Research Council (NRC) in Canada [15] [16]. The models were found to be sufficiently accurate for engineering purposes, although the models for wall constructions did tend to slightly over-predict transmission loss at low frequencies and under-predict at midrange/high frequencies, shown in Figure 2.1 [17].

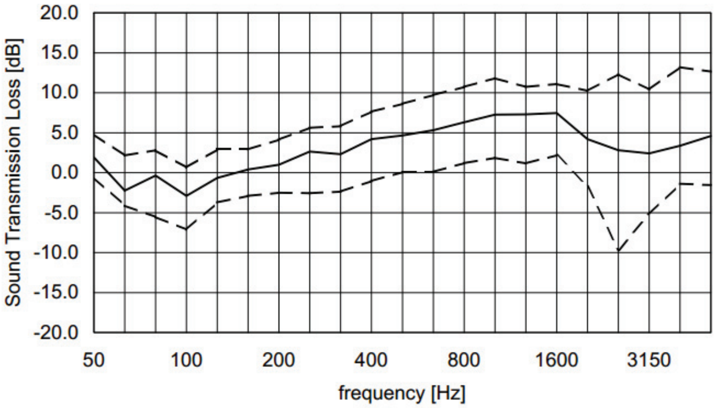


Figure 2.1: Insul Validation Error Study, showing measured less predicted for 112 walls from [15]. Solid line indicates median error; dashed lines indicate 10% and 90% limits. Figure reproduced from [17]

2.3 Re-Creation of Validation Study with Insul-Modeled Wall

The scenarios tested in the IBANA-Calc Validation Study were recreated internally in this research project using the IBANA-Calc software and compared with the predictions from the Validation Study. The re-creation of the IBANA-Calc Validation Study predictions was primarily an effort to ensure correct operation of the software and to better understand its limitations.

Specifically, the Oakview and Summerhill houses shown in Figure 2.2 were modeled in the IBANA-Calc software and compared to the predictions from the Validation Study [14]. The Brown house was not modeled due to a lack of sufficient data in the IBANA-Calc transmission loss database for its wall and window construction types. Additionally, as the focus of this research is on homes exposed to aircraft noise, the scenario involving the Vancouver Airport office building was not recreated internally.

Figure 2.2: Houses Used in IBANA-Calc Validation Study (Oakview-left, Summerhill-right.) Reproduced from [14].

By entering the room size and façade element information (type and surface area) for each of four rooms (two from the Oakview house; two from the Summerhill house), models were generated which matched the Validation Study configurations. Ultimately, the TL values predicted in IBANA-Calc for the re-created scenarios very closely matched the TL values published in the Validation Study (to within 1 dB). Thus, correct use of the IBANA-Calc software was demonstrated.

To compare the modeling capabilities of Insul against the measured transmission loss database contained within IBANA-Calc, the walls used for the Validation Study were modeled in Insul. The resulting transmission loss curve demonstrated the same trends as were identified in Ballagh (2004), with an over-prediction of TL at low frequencies, and an under-prediction at midrange and higher frequencies, shown in Figure 2.3. These differences are similar to those seen between the validation study measured and predicted values, meaning that this Insul model more closely approximates the real-world wall conditions than the TL data in the IBANA-Calc database for this wall.

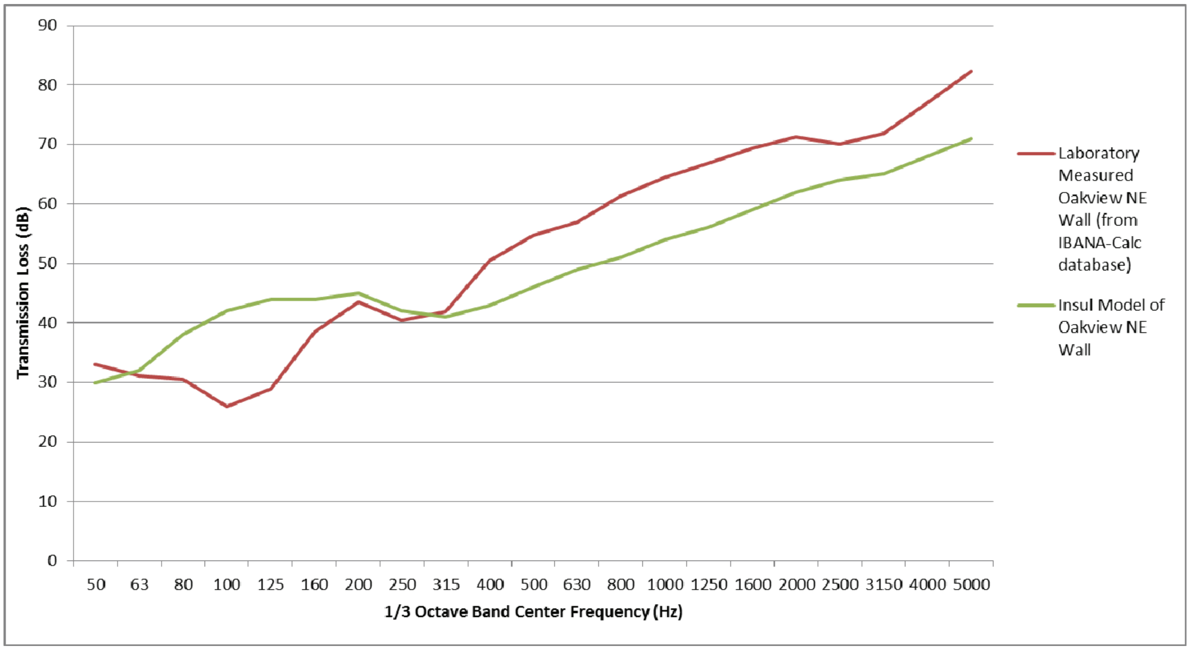


Figure 2.3: Insul Model of IBANA-Calc Wall ("G13_WS140(406)_GFB152_OSB11_ AIR16_BRI89," which indicates wall construction of 13 mm thick gypsum board, 140 mm thick wood studs spaced 406 mm on center with 152 mm thick glass fiber insulation, an 11 mm thick layer of oriented strand board, a 16 mm airgrap, and 89 mm thick brick)

To demonstrate the effect of this error on a composite room model, the Insul-modeled wall TL data was used in place of the IBANA-Calc database walls and compared against the composite room models which used the database walls. The room Noise Reduction (NR, the difference in dB between outdoor and indoor sound levels, here in 1/3 Octave Bands) which resulted from this additional scenario was plotted alongside the Validation Study predicted and measured NR for comparison. The differences were generally negligible, save for a small difference near 100Hz (within 3 dB), which could be due to the differences between how Insul models panel resonances versus how they occurred in the laboratory measurements.

Additional details are provided in the following sections.

2.3.1 Oakview House Modeling Overview

The Oakview house, located near the Toronto airport, has two bedrooms located on the north side of the second floor of the house, which faces the passing aircraft. As the floors in the two tested rooms were hardwood, the “Absorption as % of Floor Area” parameter was set to 50% (its minimum selectable value; not a function of frequency). The other surface area values were either read out of the relevant tables reproduced in Tables 2.1 and 2.3 or calculated from the dimensions listed on the floor plans shown in Figures 2.4 and 2.6. As the study was performed in Canada, all room dimensions are in meters. Wall construction dimensions are mixed between metric and imperial units. Construction information used in the model re-creations is given in Tables 2.2 and 2.4. Comparisons between the validation study results and the re-created model results are shown in Figures 2.5 and 2.7, along with models featuring Insul-modeled walls instead of the IBANA-Calc walls. The validation study predicted NR and the re-creation predicted NR agreed with one another within 1 dB, which means that the validation study predictions were accurately re-created, with the differences being due to rounding. The models featuring the Insul-modeled walls generally matched the other predicted NR values, with the error not exceeding 2 dB. Differences between the predicted NR values and the validation study field measured NR values are discussed in section 2.1.2.

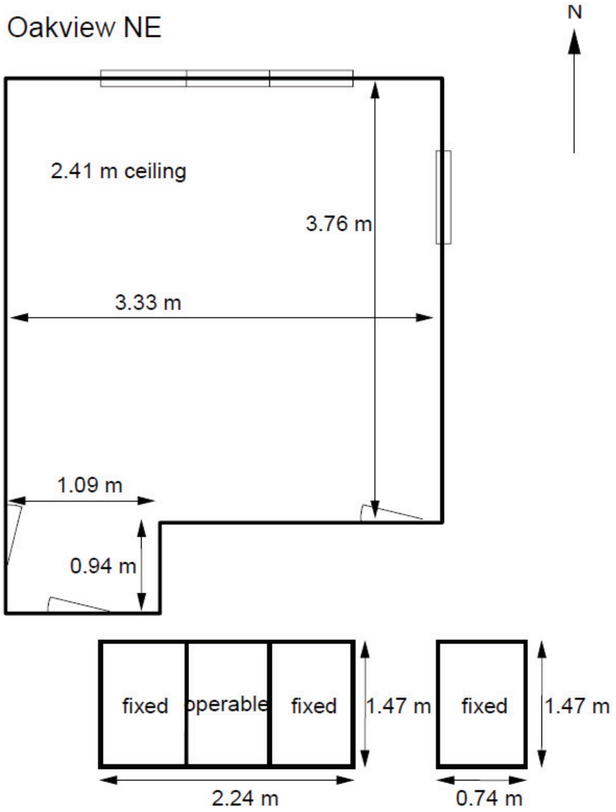


Figure 2.4: Plan of Oakview Northeast (NE) Bedroom. North and East walls exposed to aircraft noise. Reproduced from [14].

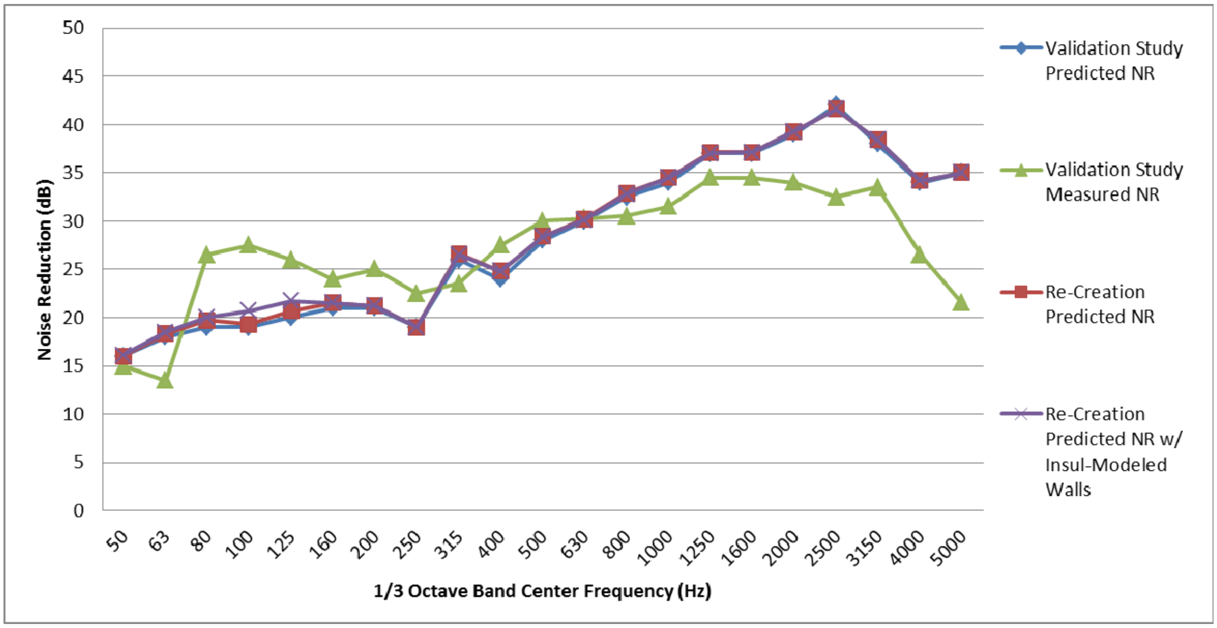


Figure 2.5: Measured and predicted NR for Oakview NE Bedroom, plus re-creation predicted NR and re-creation predicted NR generated using Insul wall model instead of IBANA-Calc wall.

Table 2.1: Oakview Northeast (NE) Construction Information from Validation Study[14].

Floor Area, m^2	13.6 m^2
Room Volume, m^3	32.7 m^2
Window Area, m^2	3.29 + 1.09 m^2
Average RT, s	0.9 s
Walls	Single layer of 13mm gypsum board on 2"x6" wood studs, with sheathing, brick exterior, and cavity thermal insulation.
Windows	Vinyl casement, 2 layers 3mm glass with 13mm air space.
Roof/Ceiling	Asphalt shingles on wood truss with R40 glass fibre. Double layer 13mm gypsum board ceiling.
Floor	Hardwood
Other	Light weight drapes.

Table 2.2: Oakview NE Construction Information Coding Used in Re-Creation

Parameter	Surface Area (m^2)	IBANA-Calc Façade Element
Walls	12.71	G13_WS140(406)_GFB152_OSB11_AIR16_BRI89
Roof	13.6	SHN3_BPA0.7_OSB11_RHWT1626_GFB264_2G13
Windows	4.38	GL3_AIR13_GL3 [Vinyl casement (seals not taped)]
Floor Area	13.6	N/A
Absorption as % of Floor Area	50%	N/A

Table 2.3: Oakview Northwest (NW) Construction Information from Validation Study[14]

Floor Area, m^2	14.1 m^2
Room Volume, m^3	34.0 m^2
Window Area, m^2	2.14 m^2
Average RT, s	0.7 s
Walls	Single layer of 13mm gypsum board on 2"x6" wood studs, with sheathing, brick exterior, and cavity thermal insulation.
Windows	Vinyl casement, 2 layers 3mm glass with 13mm air space.
Roof/Ceiling	Asphalt shingles on wood truss with R40 glass fibre. Double layer 13mm gypsum board ceiling.
Floor	Hardwood
Other	Light weight drapes.

Table 2.4: Oakview NW Construction Information Coding Used in Re-Creation

Parameter	Surface Area (m^2)	IBANA-Calc Façade Element
Walls	16.06	G13_WS140(406)_GFB152_OSB11_AIR16_BRI89
Roof	14.1	SHN3_BPA0.7_OSB11_RHWT1626_GFB264_2G13
Windows	2.14	GL3_AIR13_GL3 [Vinyl casement (seals not taped)]
Floor Area	14.1	N/A
Absorption as % of Floor Area	50%	N/A

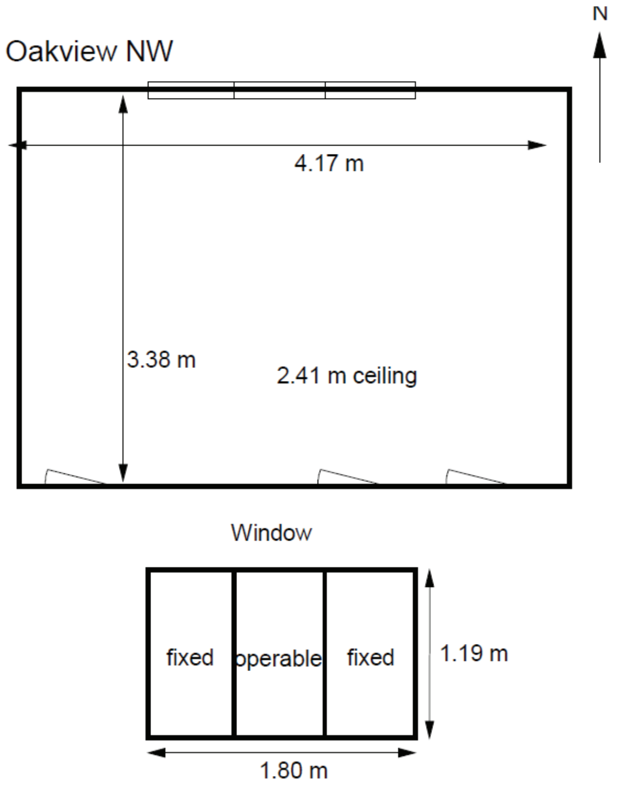


Figure 2.6: Plan of Oakview Northwest (NW) Bedroom. North and West walls exposed to aircraft noise. Reproduced from [14].

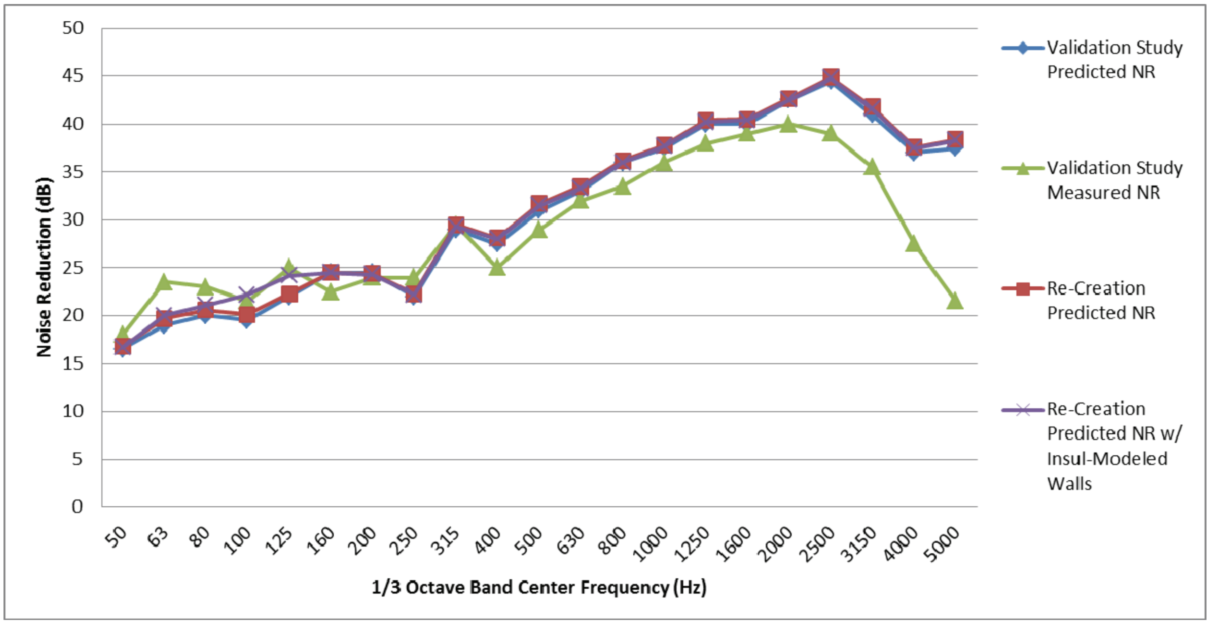


Figure 2.7: Measured and predicted NR for Oakview NW Bedroom, plus re-creation predicted NR and re-creation predicted NR generated using Insul wall model instead of IBANA-Calc wall.

2.3.2 Summerhill House Modeling Overview

The Summerhill house, also located near the Toronto airport, has two bedrooms located on the north side of the second floor of the house, which faces the passing aircraft. The geometries of the two bedrooms in the Summerhill house were more complicated than with the Oakview house. The NE bedroom had a peaked ceiling, while the NW bedroom had a semicircular exterior wall. Both required additional effort to properly calculate the appropriate surface areas. As the floors in the two tested rooms were carpeted, the "Absorption as % of Floor Area" parameter (not a function of frequency) was set to 100%. The other surface area values were either read out of the relevant tables reproduced in Tables 2.5 and 2.7 or calculated from the dimensions listed on the floor plans shown in Figures 2.8 and 2.10. As the study was performed in Canada, all dimensions are in meters. Wall construction dimensions are mixed between metric and imperial units. Construction information used in the model re-creations is given in Tables 2.6 and 2.8. Comparisons between the validation study results and the re-created model results are shown in Figures 2.9 and 2.11, along with models featuring Insul-modeled walls instead of the IBANA-Calc walls. The validation study predicted NR and the re-creation predicted NR agreed with one another within 1 dB, which means that the validation study predictions were accurately re-created, with the differences being due to rounding. The models featuring the Insul-modeled walls generally matched the other predicted NR values, with the error not exceeding 2 dB. Differences between the predicted NR values and the validation study field measured NR values are discussed in section 2.1.2.

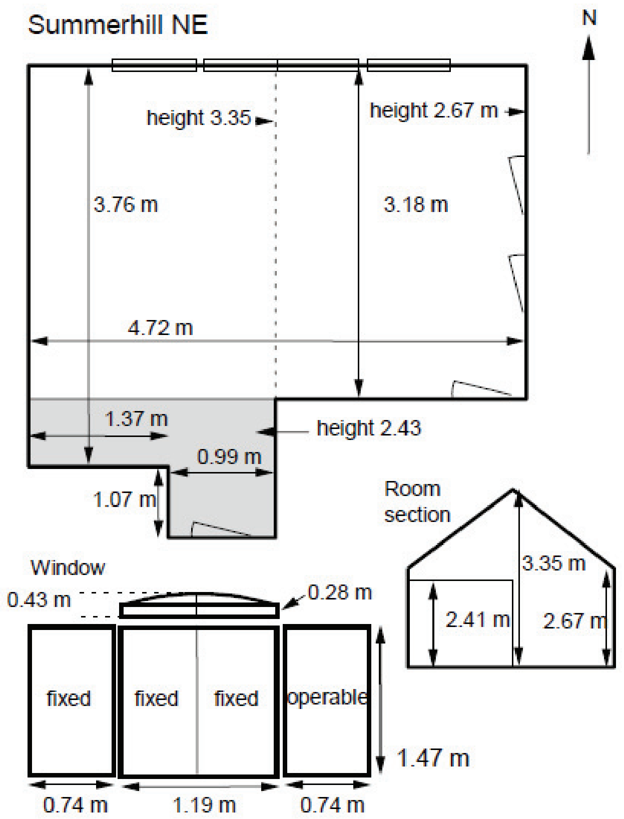


Figure 2.8: Plan of Summerhill Northeast (NE) Bedroom. North and East walls exposed to aircraft noise. Reproduced from [14].

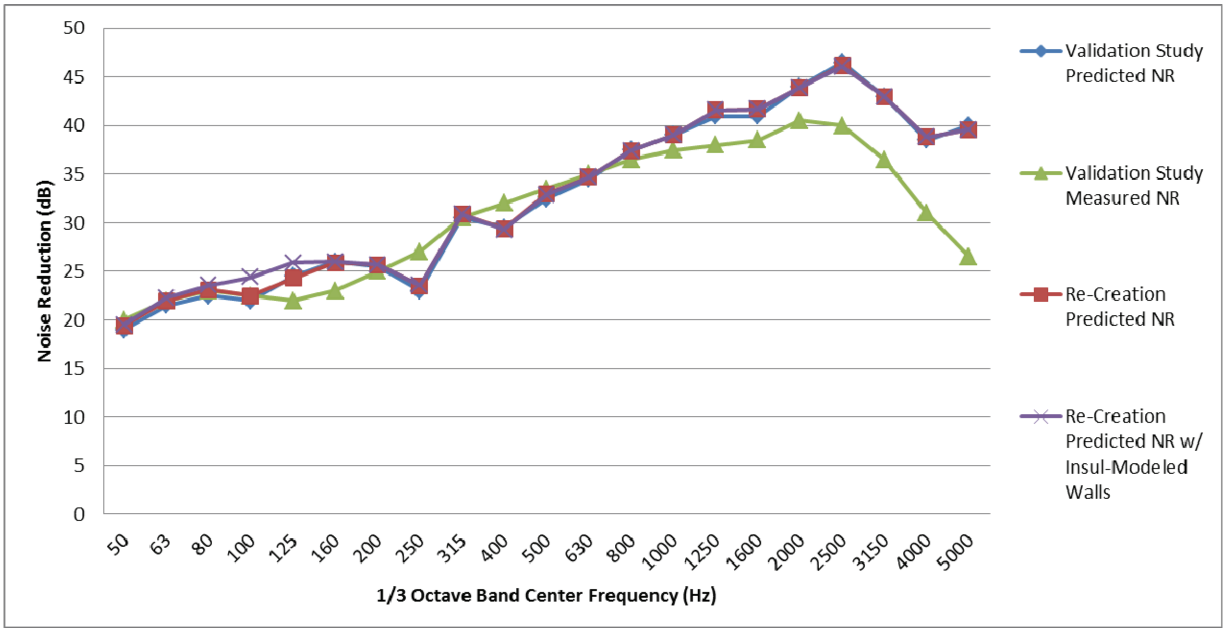


Figure 2.9: Measured and predicted NR for Summerhill NE Bedroom, plus re-creation predicted NR and re-creation predicted NR generated using Insul wall model instead of IBANA-Calc wall.

Table 2.5: Summerhill NE Construction Information from Validation Study [14].

Floor Area, m^2	17.4 m^2
Room Volume, m^3	51.0 m^2
Window Area, m^2	3.92 m^2
Average RT, s	0.5 s
Walls	Single layer of 13mm gypsum board on 2"x6" wood studs, with sheathing, brick exterior, and cavity thermal insulation.
Windows	Vinyl casement, 2 layers 3mm glass with 13mm air space.
Roof/Ceiling	Asphalt shingles on wood truss with R40 glass fibre. Double layer 13mm gypsum board ceiling.
Floor	Carpet
Other	Light weight drapes.

Table 2.6: Summerhill NE Construction Information Coding Used in Re-Creation

Parameter	Surface Area (m^2)	IBANA-Calc Façade Element
Walls	20.18	G13_WS140(406)_GFB152_OSB11_AIR16_BRI89
Roof	17.05	SHN3_BPA0.7_OSB11_RHWT1626_GFB264_2G13
Windows	3.92	GL3_AIR13_GL3 [Vinyl casement (seals not taped)]
Floor Area	17.4	N/A
Absorption as % of Floor Area	100%	N/A

Table 2.7: Summerhill NW Construction Information from Validation Study [14].

Floor Area, m^2	14.9 m^2
Room Volume, m^3	35.9 m^2
Window Area, m^2	2.14 m^2
Average RT, s	0.4 s
Walls	Single layer of 13mm gypsum board on 2"x6" wood studs, with sheathing, brick exterior, and cavity thermal insulation.
Windows	Vinyl casement, 2 layers 3mm glass with 13mm air space.
Roof/Ceiling	Asphalt shingles on wood truss with R40 glass fibre. Double layer 13mm gypsum board ceiling.
Floor	Carpet
Other	Light weight drapes.

Table 2.8: Summerhill NW Construction Information Coding Used in GT Re-Creation

Parameter	Surface Area (m^2)	IBANA-Calc Façade Element
Walls	15.45	G13_WS140(406)_GFB152_OSB11_AIR16_BRI89
Roof	14.9	SHN3_BPA0.7_OSB11_RHWT1626_GFB264_2G13
Windows	2.14	GL3_AIR13_GL3 [Vinyl casement (seals not taped)]
Floor Area	14.9	N/A
Absorption as % of Floor Area	100%	N/A

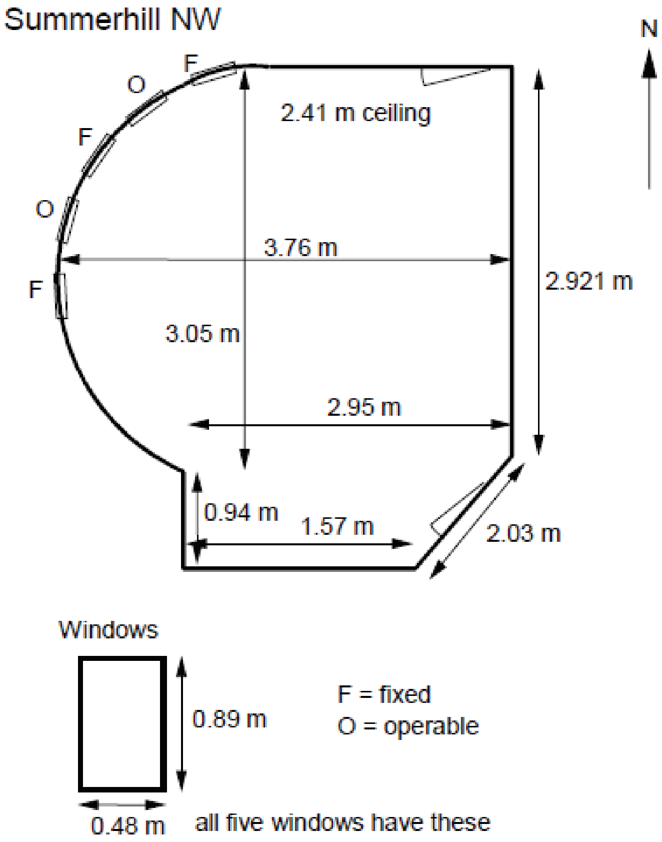


Figure 2.10: Plan of Summerhill Northwest (NW) Bedroom. North and West walls exposed to aircraft noise. Reproduced from [14].

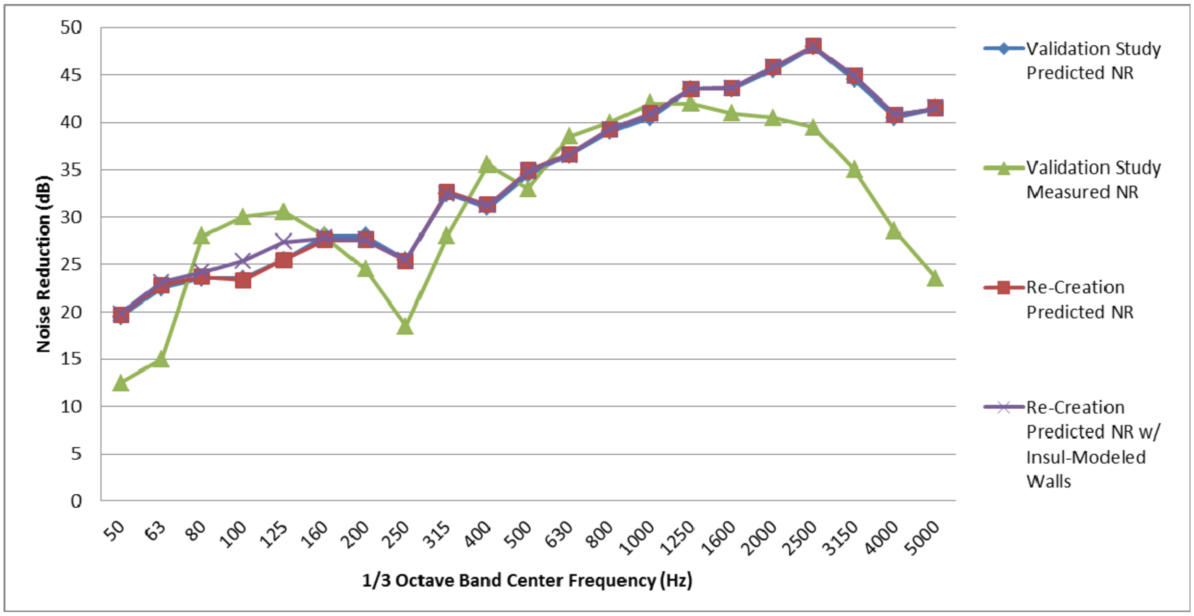


Figure 2.11: Measured and predicted NR for Summerhill NW Bedroom, plus re-creation predicted NR and re-creation predicted NR generated using Insul wall model instead of IBANA-Calc wall.

2.3.3 Validation Study Re-Creation Discussion and Conclusions

By using the data from the IBANA-Calc Validation Study, re-creation models were generated which demonstrated correct use of the software. These re-creation models matched the Validation Study models within 1 dB. The error seen between the Insul-modeled wall and its IBANA-Calc counterpart was higher than expected, but the nature of the error was consistent with that found in the Validation Study between the measured NR data and the IBANA-Calc predicted NR, namely that IBANA-Calc under-predicted TL performance at low frequencies and over-predicted it at high frequencies when compared to field measurements [14]. The implication of this is that the Insul models are potentially a better predictor of wall transmission loss in the field than the laboratory measurements used in IBANA-Calc. It should be noted that for the composite room models, the differences between the IBANA-Calc wall and the Insul wall resulted in no more than a 2 dB difference in noise reduction at any frequency. The models generated in Insul therefore achieved sufficient accuracy when compared to the data contained within IBANA-Calc to warrant its use as a modeling technology in this research.

CHAPTER 3

TYPICAL REGIONAL CONSTRUCTION TYPES MODELING

In order to better model the transmission of aircraft noise into homes near airports, typical home constructions in different regions of the US were identified. The primary differentiator in this research was exterior wall construction, as many homes around the U.S. have asphalt shingle roofs and there are inherent limitations in the software roof modeling as described in Chapter 2. The identified typical wall constructions were modeled using Insul and used alongside other building façade elements from the IBANA-Calc database to systematically generate whole-house models. These whole-house models were analyzed, and patterns were identified in which a building façade element appeared to "dominate" the composite transmission loss performance of the whole-house model. These patterns were found to be consistent with the analytical formula for computing composite transmission loss.

3.1 Climate Regions in North America

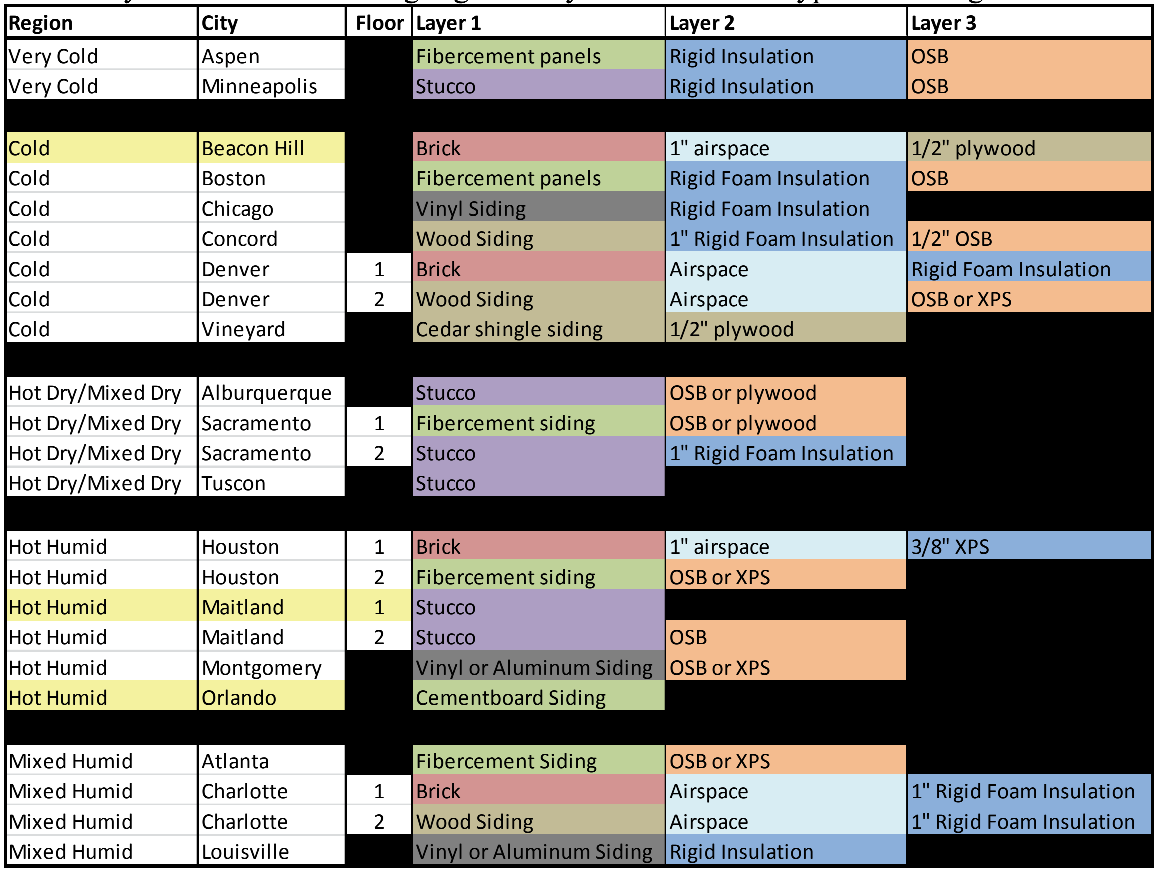
The United States has a diverse set of climate regions. As such, the U.S. Department of Energy has divided the country (as well as the rest of North America) into the eight different climate regions shown in Figure 3.1: hot-humid, hot-dry, mixed humid, marine, mixed-dry, cold, very cold, and subarctic/arctic [18]. The Building Science Corporation has developed recommended building profiles for new construction appropriate for 18 cities in several of these climate regions [19]. No profiles were provided for the subarctic/arctic or marine regions. It should be noted that these building profiles were not designed to have exceptionally high thermal performance; rather, they were recommendations for new construction with merely "good" thermal performance. These profiles represent more modern techniques but are not necessarily representative of existing (older) home constructions located near airports. Table 3.1 shows the acoustically significant exterior construction layers noted in the Building Science data for these constructions. Layers such as building paper, which were neither massive nor thick, were ignored due to their acoustical insignificance. Nearly all the constructions shared the same type of framing/ interior sheathing (2"x6" studs, 24" OC, with fiberglass cavity insulation; ½" drywall interior sheathing); constructions highlighted in yellow in Table 3.1 were the exceptions:

- Cold – Beacon Hill: 4" spray foam cavity insulation
- Hot Humid – Maitland: masonry wall with interior rigid foam insulation
- Hot Humid – Orlando: 6" SIPS wall panel

Some constructions lacked a shear-layer (e.g. plywood or OSB), and as such are unlikely to meet most building codes. They are included in this analysis to give an example of worst-case transmission loss performance. The inclusion of these building profiles in this research is not intended to be an endorsement of their design or recommendation for their use; all home constructions should be built to comply with local building codes.

Figure 3.1: North American Climate Regions. Reproduced from [18].

Table 3.1: Wall Layer Information as Presented by Building Science [19]. Colors indicate similar layers. Constructions highlighted in yellow featured atypical framing.



Region	City	Floor	Layer 1	Layer 2	Layer 3
Very Cold	Aspen		Fibercement panels	Rigid Insulation	OSB
Very Cold	Minneapolis		Stucco	Rigid Insulation	OSB
Cold	Beacon Hill		Brick	1" airspace	1/2" plywood
Cold	Boston		Fibercement panels	Rigid Foam Insulation	OSB
Cold	Chicago		Vinyl Siding	Rigid Foam Insulation	
Cold	Concord		Wood Siding	1" Rigid Foam Insulation	1/2" OSB
Cold	Denver	1	Brick	Airspace	Rigid Foam Insulation
Cold	Denver	2	Wood Siding	Airspace	OSB or XPS
Cold	Vineyard		Cedar shingle siding	1/2" plywood	
Hot Dry/Mixed Dry	Alburquerque		Stucco	OSB or plywood	
Hot Dry/Mixed Dry	Sacramento	1	Fibercement siding	OSB or plywood	
Hot Dry/Mixed Dry	Sacramento	2	Stucco	1" Rigid Foam Insulation	
Hot Dry/Mixed Dry	Tuscon		Stucco		
Hot Humid	Houston	1	Brick	1" airspace	3/8" XPS
Hot Humid	Houston	2	Fibercement siding	OSB or XPS	
Hot Humid	Maitland	1	Stucco		
Hot Humid	Maitland	2	Stucco	OSB	
Hot Humid	Montgomery		Vinyl or Aluminum Siding	OSB or XPS	
Hot Humid	Orlando		Cementboard Siding		
Mixed Humid	Atlanta		Fibercement Siding	OSB or XPS	
Mixed Humid	Charlotte	1	Brick	Airspace	1" Rigid Foam Insulation
Mixed Humid	Charlotte	2	Wood Siding	Airspace	1" Rigid Foam Insulation
Mixed Humid	Louisville		Vinyl or Aluminum Siding	Rigid Insulation	

3.2 Wall Modeling in Insul

Using the Building Science data, wall models were generated in Insul. This required selecting the appropriate building materials and knowing their appropriate thicknesses. While many common construction materials were already contained in Insul's database, some were not; it was necessary to supplement Insul's built-in database of construction materials with others commonly used for residential exterior partitions. This required inputting several material properties for each (i.e., Young's modulus, density, and damping factor), which were found across numerous material property databases. While ranges were given for some of these values, testing revealed these variations had a generally negligible effect on the end results. These new construction materials were used alongside those in Insul's existing database to construct composite exterior wall partitions, layer-by-layer.

Table 3.2: Material Property Data used in Insul modeling. All contained within built-in Insul database except Stucco [20], Vinyl [21], and Rigid Foam[22].

Material	Density (lbs/ft^3)	Young's Modulus (psi)	Thicnkess (in)	Surface Density (lbs/ft^2)	Surface Density (kg/m^2)
Brick	100	1.29E+06	3.5	29.2	142.4
Fibercement	97	1.06E+06	0.375	3.0	14.8
Stucco	123	1.62E+06	0.875	9.0	43.8
Vinyl	39	4.77E+05	0.05	0.2	0.8
Aluminum	181	1.24E+07	0.019	0.3	1.4
Oak	40	1.82E+06	1.0	3.3	16.3
Pine	31	7.18E+05	1.0	2.6	12.6
Rigid Foam	2	2.18E+04	1.0	0.2	0.8
Plywood	35	6.34E+05	0.5	1.5	7.1
OSB	35	5.53E+05	0.5	1.5	7.1
Drywall	40	2.38E+05	0.5	1.7	8.1

Although the dimensions of some layers were specified in the Building Science database, others were not. For some materials, default typical thicknesses were available in Insul. For others, research was necessary in order to identify that information. For instance, stucco is commonly applied in three coats which total 7/8" thick [23]. For cases where two options were given for a particular layer (OSB or XPS, for instance), the material with the higher transmission loss was chosen (OSB in this case). This was an arbitrary decision designed to reduce the number of models needed compared to modeling each option separately. As the range of thicknesses for various construction materials varies greatly, it was necessary to decide upon a method to determine the thicknesses selected for modeling. Airspaces and rigid foam insulation were modeled at 1" thick (unless otherwise specified) to be consistent with the majority of the explicitly specified Building Science recommendations; OSB was modeled at ½" thick [24]. Aluminum and vinyl siding thicknesses were found from internet searches of various manufacturers; the thickest commonly available was modeled since it was relatively easy to identify and modeling other commonly-available thicknesses resulted in no more than 1 dB poorer TL performance.

To summarize the aforementioned Insul model assumptions (used unless otherwise noted by Building Science):

- Stucco 7/8” thick
- OSB chosen in lieu of XPS when given the option due to higher TL
- Airspaces 1” thick
- Rigid foam 1” thick
- OSB ½” thick
- Aluminum siding 0.019” thick
- Vinyl siding 0.05” thick

The construction types which are highlighted yellow in the Table 3.1 indicate constructions with atypical framing; these wall constructions were not modeled in Insul. Table 3.3 below shows the wall constructions as modeled. Detailed step-by-step documentation on the generation of Insul wall construction models is available in Appendix B. In total, 20 typical wall types for 16 cities in 5 climate regions were modeled.

Table 3.3: Wall Constructions as Modeled in Insul

Region	**City**	**Floor**	**Layer 1**	**Layer 2**	**Layer 3**
Cold	Boston		0.375" Fibercement	1" Rigid Foam	1/2" OSB
Cold	Chicago		0.05" Vinyl	1" Rigid Foam	
Cold	Concord		1" Oak	1" Rigid Foam	1/2" OSB
Cold	Denver	1	3.5" Brick	1" airspace	1" Rigid Foam
Cold	Denver	2	1" Oak	1" airspace	1/2" OSB
Cold	Vineyard		1" Pine	1/2" plywood	
Hot Dry/Mixed Dry	Alburquerque		0.875" Cement Stucco	1/2" OSB	
Hot Dry/Mixed Dry	Sacramento	1	0.375" Fibercement	1/2" OSB	
Hot Dry/Mixed Dry	Sacramento	2	0.875" Cement Stucco	1" Rigid Foam	
Hot Dry/Mixed Dry	Tuscon		0.875" Cement Stucco		
Hot Humid	Houston	1	3.5" Brick	1" airspace	3/8" Rigid Foam
Hot Humid	Houston	2	0.375" Fibercement	1/2" OSB	
Hot Humid	Maitland	2	0.875" Cement Stucco	1/2" OSB	
Hot Humid	Montgomery		0.019" Aluminum	1/2" OSB	
Mixed Humid	Atlanta		0.375" Fibercement	1/2" OSB	
Mixed Humid	Charlotte	1	3.5" Brick	1" airspace	1" Rigid Foam
Mixed Humid	Charlotte	2	1" Oak	1" airspace	1" Rigid Foam
Mixed Humid	Louisville		0.019" Aluminum	1" Rigid Foam	
Very Cold	Aspen		0.375" Fibercement	1" Rigid Foam	1/2" OSB
Very Cold	Minneapolis		0.875" Cement Stucco	1" Rigid Foam	1/2" OSB

3.2.1 Transmission Loss of Wall Models

There is a large amount of variation in the transmission loss performance of the various wall constructions shown in Figure 3.2. For each wall construction, the city, climate region, and outermost construction layer are given (City_Region_Ext.Layer). The bulk of these wall transmission loss curves are loosely clustered together, particularly at lower frequencies, but there are exceptions: the walls with brick as their outermost layer (Denver1st_Cold_Brick, Houston1st_HotHumid_Brick, and Charlotte1st_MixedHumid_Brick) have much higher performance due to the added mass, while the walls which only contained vinyl or aluminum siding and 1” of rigid foam (Chicago_Cold_Vinyl and Louisville_MixedHumid_Aluminum) performed much more poorly than the rest, especially at lower frequencies, simply due to a lack of mass. Notably, these wall constructions exhibited an average difference of 38 dB between their performance at 50Hz and 5kHz, demonstrating the importance of analyzing transmission loss performance across frequency and not just in single-number values.

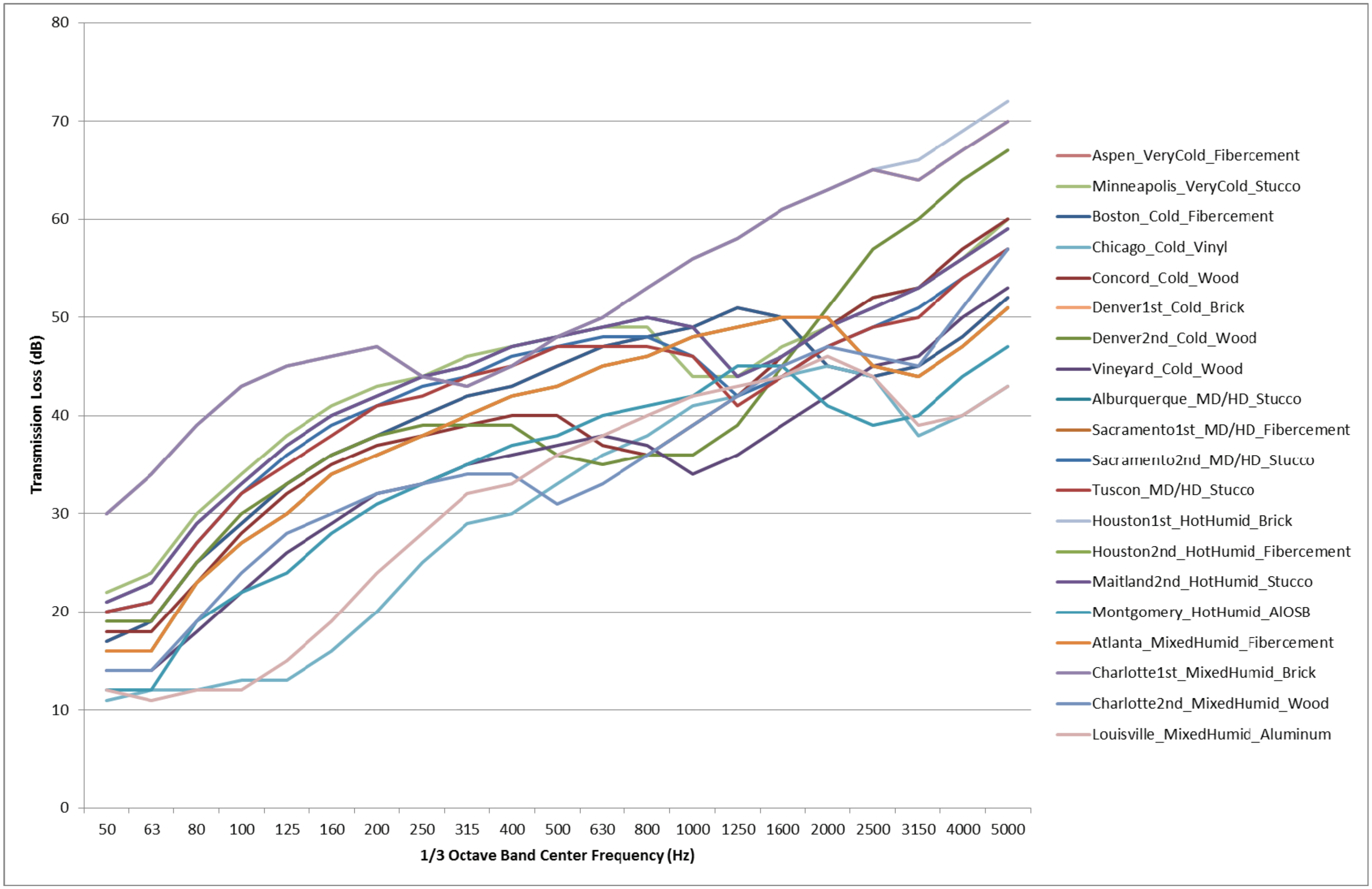


Figure 3.2: Transmission Loss of all wall constructions modeled in Insul (City_Region_Ext.Layer), ordered by climate region

3.2.1.1 TL Organized by Region

One of the primary goals of this research was to identify and then model different regional construction types used across the United States. In Figures 3.3-3.7, the modeled wall constructions have been broken up by region.

Note the very large variance across the different constructions used in the Cold region in Figure 3.3. With as much as 32 dB between the best and worst performers at low frequencies and as much as 27 dB difference at higher frequencies, it is impossible to specify a single "Cold" transmission loss curve. Even taking the mean of the six wall constructions still gives a curve which is as much as +17/-16 dB off. Selecting any of the six wall constructions or even the mean to represent all the constructions used in the Cold region is impractical.

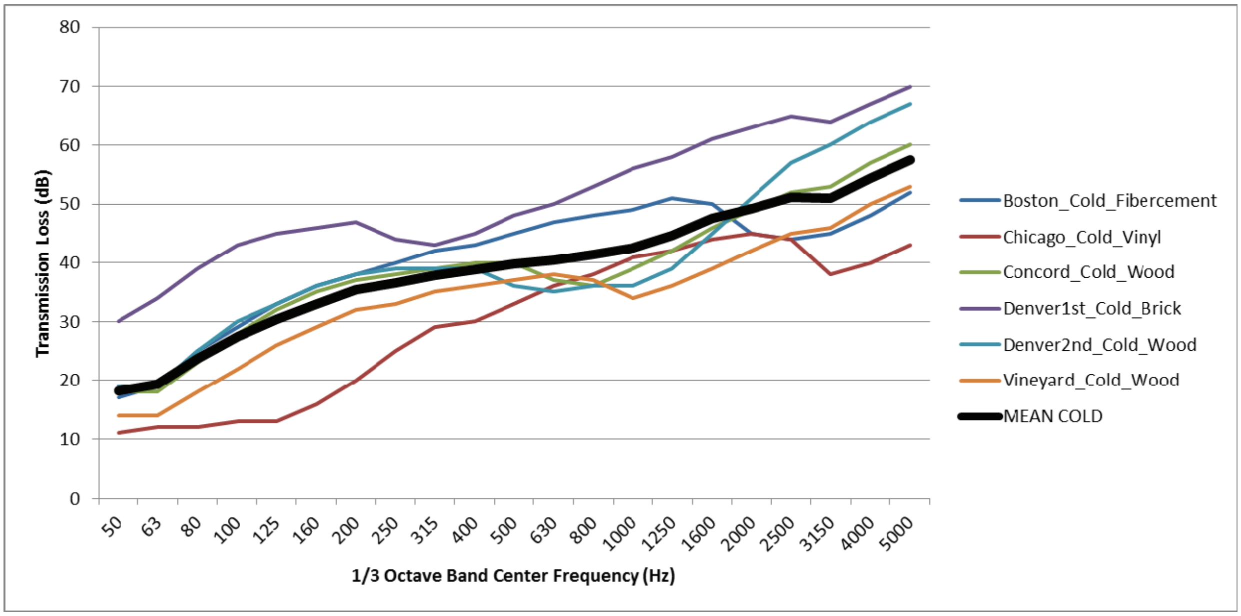


Figure 3.3: Transmission Loss of Insul Modeled Cold Region Walls (City_Region_Ext.Layer)

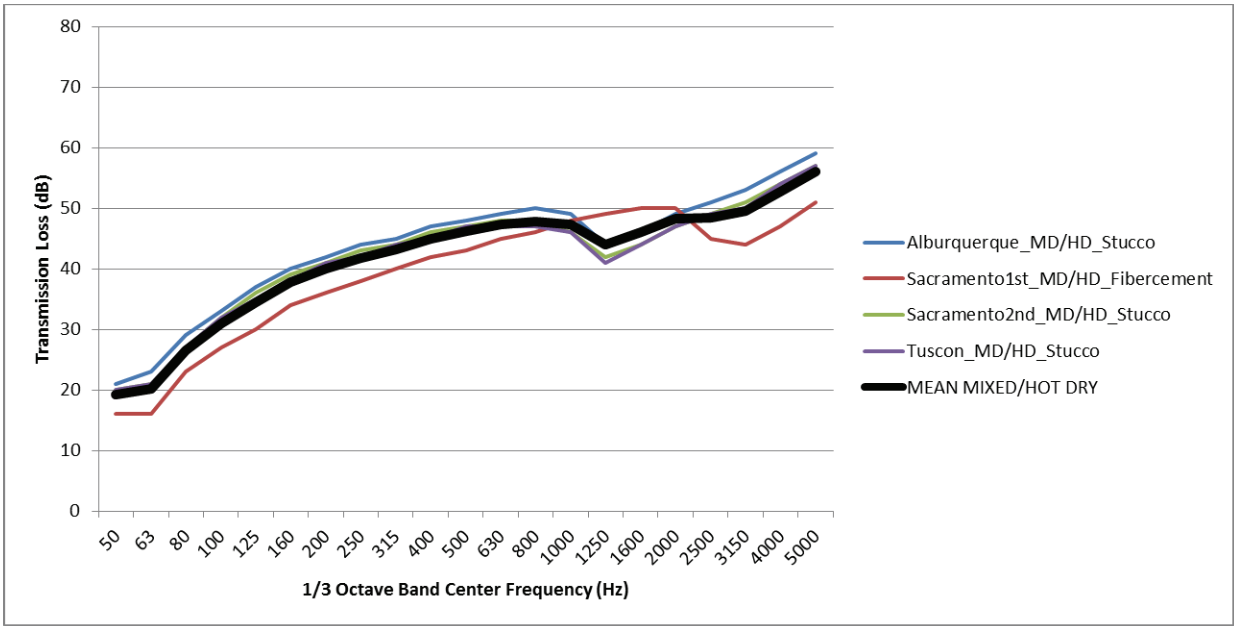


Figure 3.4: Transmission Loss of Insul Modeled MD/HD Region Walls (City_Region_Ext.Layer)

In contrast to the Cold region, the Mixed Dry/Hot Dry region shown in Figure 3.4 shows a farily tight clustering of TL curves. The lone exception is the wall which uses fibercement siding instead of the stucco used in all the other regional wall constructions (labeled "Sacremento1st_MD/HD_Fibercement"). The small variance seen across the stucco walls is due to the presence (or lack) of rigid insulation and/or OSB. Generally, though, the mean could be a viable representative of this region's construction types for recommended new constructions.

The Very Cold region, shown in Figure 3.5, is similar to the Mixed Dry/Hot Dry region as it also has a fairly small variance (+/- ~3 dB).

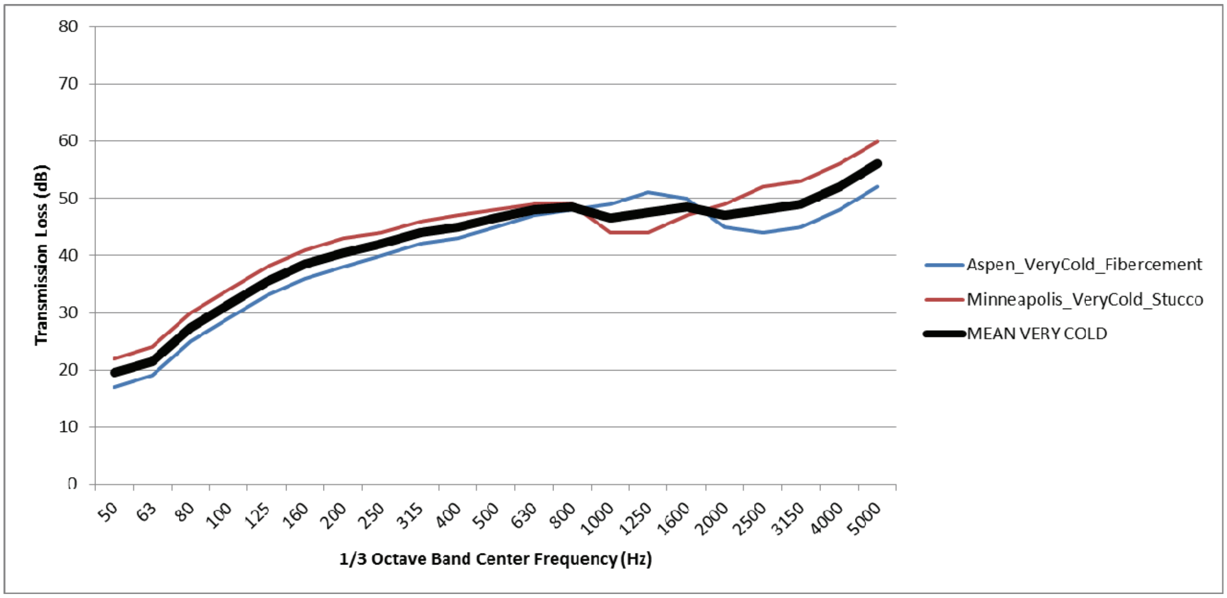


Figure 3.5: Transmission Loss of Insul Modeled Very Cold Region Walls (City_Region_Ext.Layer)

Although the Hot Humid region, shown in Figure 3.6, has less variance than the Cold region, particularly at low frequencies, it is still fairly large (~15 dB at low frequencies up to just over 20 dB at high frequencies). The mean for this region also is not an adequate representation of the constructions seen in this region, making it much more difficult to identify a representative regional construction type than with the Mixed Dry/Hot Dry region.

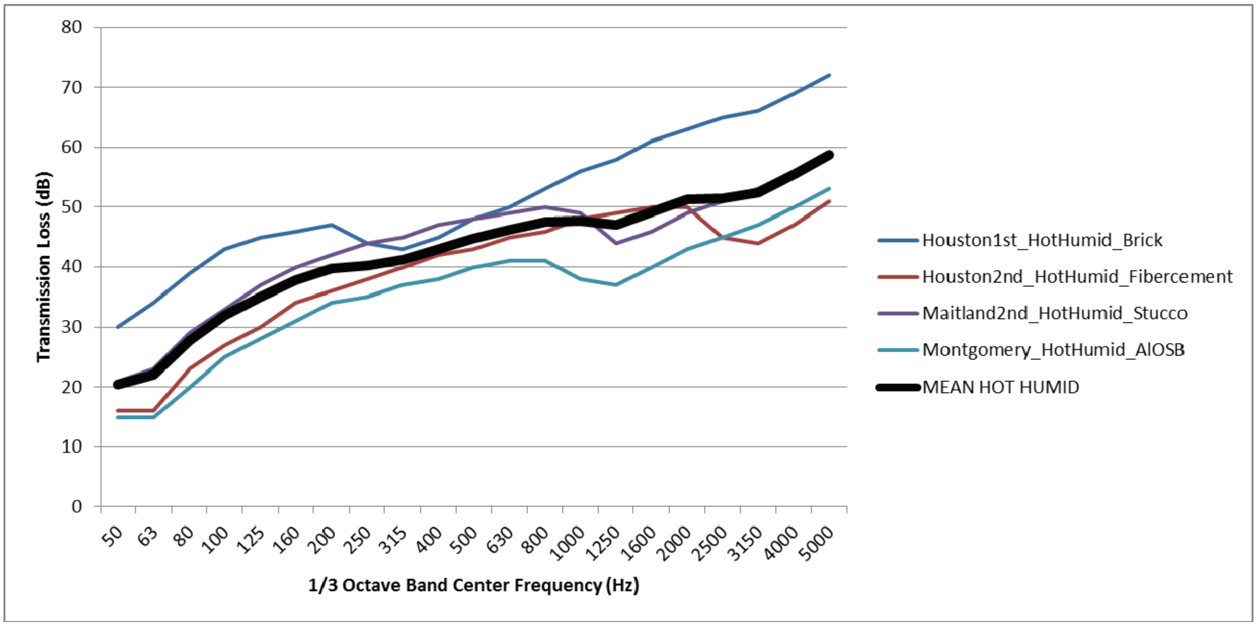


Figure 3.6: Transmission Loss of Insul Modeled Hot-Humid Region Walls (City_Region_Ext.Layer)

The same trends that have previously been seen hold true with the Mixed Humid region shown in Figure 3.7. With >30 dB difference between the best and worst performers at low frequencies (and 20 dB at high frequencies), again a representative transmission loss curve cannot be identified.

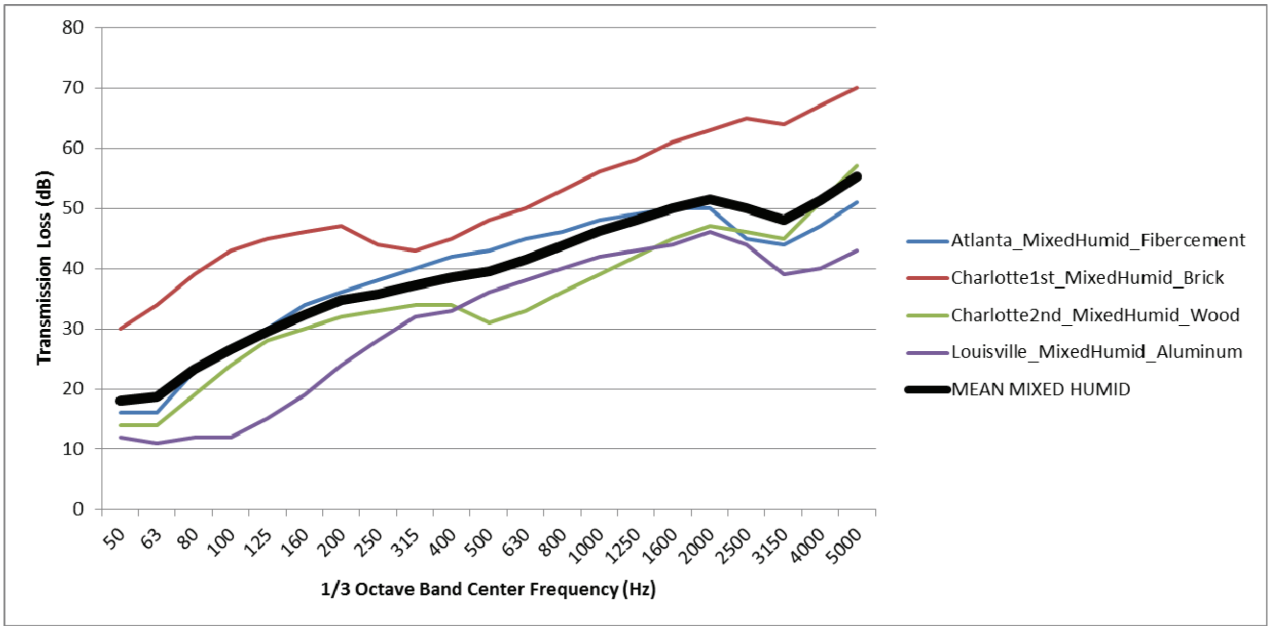


Figure 3.7: Transmission Loss of Insul Modeled Mixed-Humid Region Walls (City_Region_Ext.Layer)

Table 3.4 shows that when reduced to a single-number value, whether STC (not generally appropriate for exterior partitions but still commonly used) or OITC (more appropriate for exterior partitions), the same pattern seen across most of the climate region TL graphs is seen here as well: for most regions, there is a considerably large variation between the highest and lowest performing wall constructions (and thus high standard deviation), making it impractical to identify a single regional construction type to use for whole-house modeling. However, the very tight clustering seen in the Mixed Dry/Hot Dry region amongst the constructions featuring stucco as their outermost wall construction layer demonstrates that perhaps this research would be better served by grouping constructions by their (readily identifiable) outermost layers instead of their climate region. Most climate regions featured a large amount of variation in the constructions used; the Mixed Dry/Hot Dry region was the major exception. While the Cold region did feature three constructions with wood as the outermost layer, it also included constructions featuring brick, fibercement, and vinyl siding.

Table 3.4: STC and OITC for wall constructions, organized by climate region.

Climate Region	**City**	***STC***	***OITC***
Very Cold	Aspen	***47***	***40***
Very Cold	Minneapolis	***48***	***44***
MEAN VERY COLD		**48**	**42**
VERY COLD STDEV		**0.7**	**2.8**
Cold	Boston	***47***	***40***
Cold	Chicago	***35***	***23***
Cold	Concord	***42***	***37***
Cold	Denver 1st	***53***	***48***
Cold	Denver 2nd	***40***	***37***
Cold	Vineyard	***39***	***32***
MEAN COLD		**43**	**36**
COLD STDEV		**6.4**	**8.3**
Mixed Dry/Hot Dry	Alburquerque	***48***	***43***
Mixed Dry/Hot Dry	Sacramento 1st	***46***	***37***
Mixed Dry/Hot Dry	Sacramento 2nd	***46***	***41***
Mixed Dry/Hot Dry	Tuscon	***45***	***41***
MEAN MIXED/HOT DRY		**46**	**41**
MIXED/HOT DRY STDEV		**1.3**	**2.5**
Hot Humid	Houston 1st	***53***	***48***
Hot Humid	Houston 2nd	***46***	***37***
Hot Humid	Maitland 2nd	***48***	***43***
Hot Humid	Montgomery	***41***	***35***
MEAN HOT HUMID		**47**	**41**
HOT HUMID STDEV		**5.0**	**5.9**
Mixed Humid	Atlanta	***46***	***37***
Mixed Humid	Charlotte 1st	***53***	***48***
Mixed Humid	Charlotte 2nd	***39***	***33***
Mixed Humid	Louisville	***37***	***25***
MEAN MIXED HUMID		**44**	**36**
MIXED HUMID STDEV		**7.3**	**9.6**

3.2.1.2 TL organized by Exterior Layer Type

When Table 3.3 is re-arranged by outermost construction layer instead of region, it can be noted that many of the wall constructions are extremely similar, with several even being exact duplicates of those seen in other regions (re-ordering shown in Table 3.5). The implication of this is that rather than developing a model for each region that may be as much as 20+ dB off depending on the construction actually used, models could be generated based upon the outermost wall construction layer to a much higher degree of accuracy. The graphs and tables that follow serve to validate this hypothesis.

Table 3.5: Wall Constructions by Exterior Layer Type (i.e. Layer 1 Column)

Region	City	Floor	Layer 1	Layer 2	Layer 3
Hot Dry/Mixed Dry	Alburquerque		0.875" Cement Stucco	1/2" OSB	
Hot Dry/Mixed Dry	Sacramento	2	0.875" Cement Stucco	1" Rigid Foam	
Hot Dry/Mixed Dry	Tuscon		0.875" Cement Stucco		
Hot Humid	Maitland	2	0.875" Cement Stucco	1/2" OSB	
Very Cold	Minneapolis		0.875" Cement Stucco	1" Rigid Foam	1/2" OSB
Cold	Boston		3/8" Compressed Fibercem	1" Rigid Foam	1/2" OSB
Hot Dry/Mixed Dry	Sacramento	1	5/16" Fibercement	1/2" OSB	
Hot Humid	Houston	2	5/16" Fibercement	1/2" OSB	
Mixed Humid	Atlanta		5/16" Fibercement	1/2" OSB	
Very Cold	Aspen		3/8" Compressed Fibercem	1" Rigid Foam	1/2" OSB
Cold	Concord		1" Oak	1" Rigid Foam	1/2" OSB
Cold	Denver	2	1" Oak	1" airspace	1/2" OSB
Cold	Vineyard		1" Pine	1/2" plywood	
Mixed Humid	Charlotte	2	1" Oak	1" airspace	1" Rigid Foam
Cold	Denver	1	3.5" Brick	1" airspace	1" Rigid Foam
Hot Humid	Houston	1	3.5" Brick	1" airspace	3/8" Rigid Foam
Mixed Humid	Charlotte	1	3.5" Brick	1" airspace	1" Rigid Foam
Cold	Chicago		0.05" Vinyl	1" Rigid Foam	
Hot Humid	Montgomery		0.019" Aluminum	1/2" OSB	
Mixed Humid	Louisville		0.019" Aluminum	1" Rigid Foam	

Table 3.6: STC & OITC for wall constructions, organized by exterior wall layer.

Exterior Construction Layer	City	*STC*	*OITC*
Stucco	Alburquerque	***48***	***43***
Stucco	Sacramento 2nd	***46***	***41***
Stucco	Tuscon	***45***	***41***
Stucco	Maitland 2nd	***48***	***43***
Stucco	Minneapolis	***48***	***44***
MEAN STUCCO		**47**	**42**
STUCCO STDEV		**1**	**1**
Fibercement	Boston	***47***	***40***
Fibercement	Sacramento 1st	***46***	***37***
Fibercement	Houston 2nd	***46***	***37***
Fibercement	Atlanta	***46***	***37***
Fibercement	Aspen	***47***	***40***
MEAN FIBERCEMENT		**46**	**38**
FIBERCEMENT STDEV		**1**	**2**
Wood	Concord	***42***	***37***
Wood	Denver 2nd	***40***	***37***
Wood	Vineyard	***39***	***32***
Wood	Charlotte 2nd	***39***	***33***
MEAN WOOD		**40**	**35**
WOOD STDEV		**1**	**3**
Brick	Denver 1st	***53***	***48***
Brick	Houston 1st	***53***	***48***
Brick	Charlotte 1st	***53***	***48***
MEAN BRICK		**53**	**48**
BRICK STDEV		**0**	**0**
Vinyl	Chicago	***35***	***23***
Aluminum w/ OSB	Montgomery	***41***	***35***
Aluminum	Louisville	***37***	***25***
MEAN VINYL/ALUMINUM		**38**	**28**
VINYL/ALUMINUM STDEV		**3**	**6**

Note that when grouped by exterior wall layer in Table 3.6, all the single number values are generally within a limit of 3 dB. This is validated by the low standard deviations seen in most cases. The exceptions will be discussed below.

In Figure 3.8, the tight grouping of transmission loss in the various stucco-sheathed constructions can be seen. The variations that can be seen are due to the presence or lack of OSB and/or rigid foam insulation. Even still, the greatest difference is only 5 dB, with most being 3 dB or less.

The same can be seen in Figure 3.9 with the constructions featuring fiber cement as their outer-most layer. The difference in transmission loss between constructions does not exceed 5 dB and is primarily due to the coincidence dip shifting lower because of the addition of a 1” layer of rigid foam insulation that causes a significant increase in the wall thickness.

In contrast to the previous two examples, the wood-sheathed constructions in Figure 3.10 exhibit a larger variation in transmission loss, albeit still less than what was seen with most regional groupings. The reason for this larger variation is simply due to the larger variation in the layers found between the exterior wood sheathing and the studs (detailed in Table 3.5): foam plus OSB, airspace plus OSB, just plywood, and airspace plus rigid foam. While it is more difficult to decide what an adequate representative of this particular construction should be, the mean provides a good place to start (generally well within 5 dB of the individual wall TL curves at lower and midrange frequencies). At higher frequencies, the wall construction TL curves spread apart, with the highest- and lowest-performing walls up to 8 dB off from the mean. Do note, however, that the mean is nearly directly on top of the Concord TL curve for most of the frequency range, making that wall type a potentially viable representative.

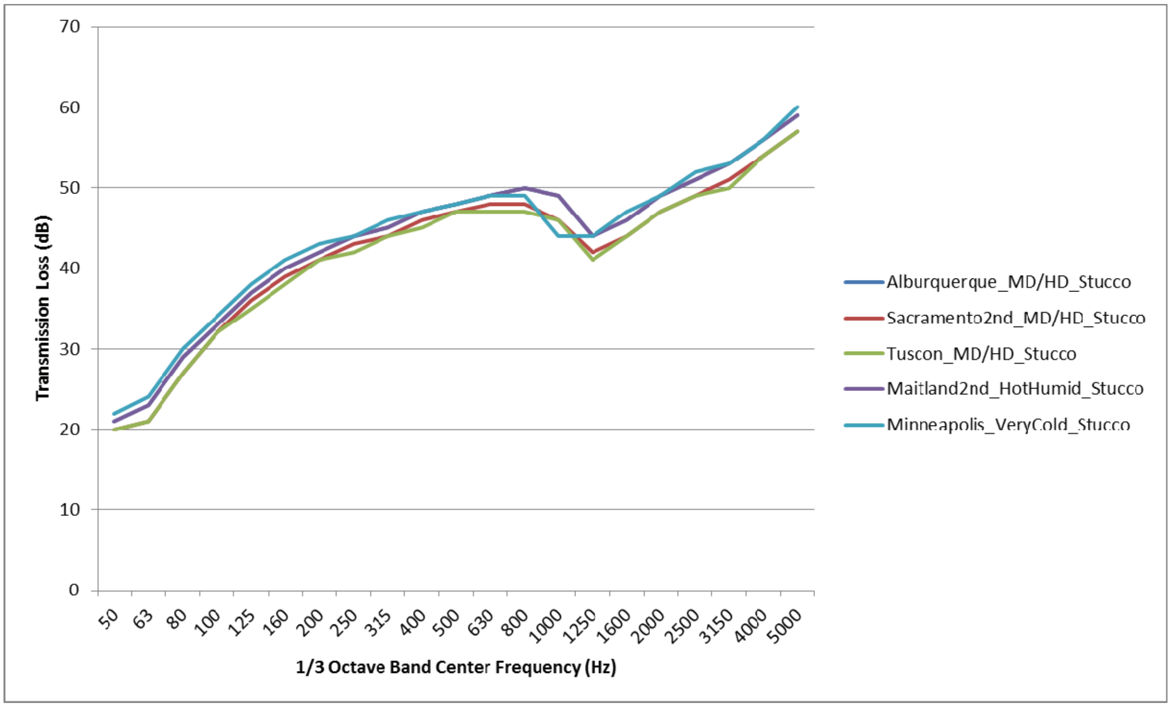


Figure 3.8: Transmission Loss of Insul Modeled Stucco-Sheathed Walls (City_Region_Ext.Layer)

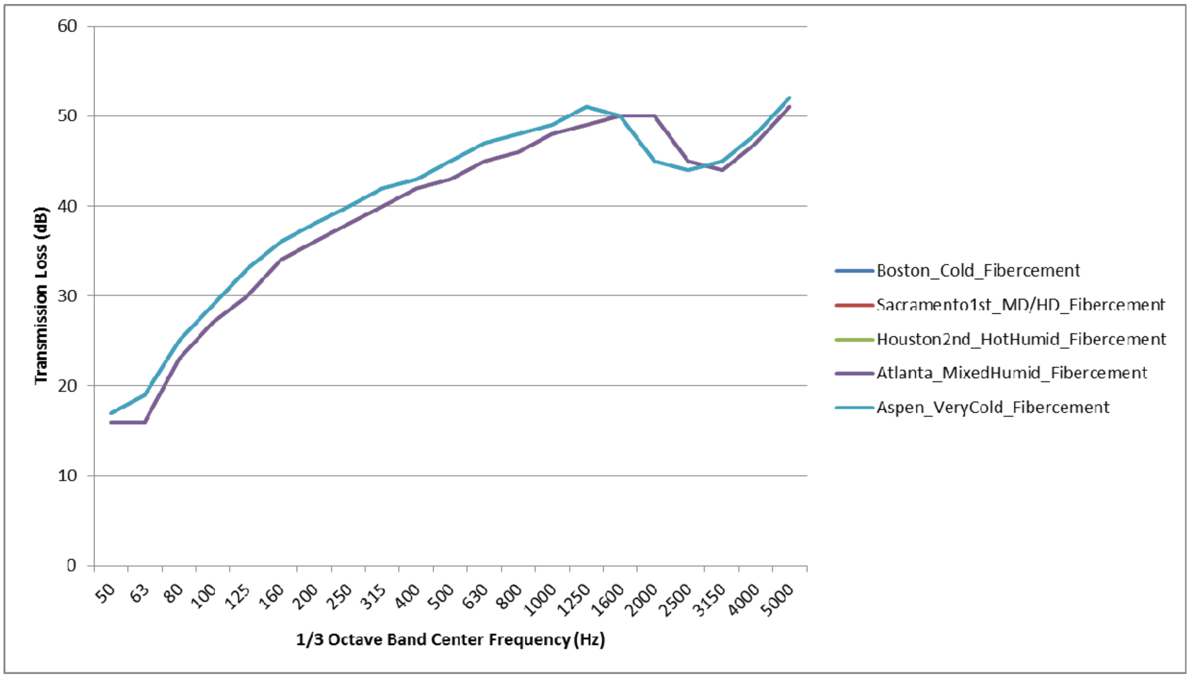


Figure 3.9: Transmission Loss of Insul Modeled Fiber Cement-Sheathed Walls (City_Region_Ext.Layer)

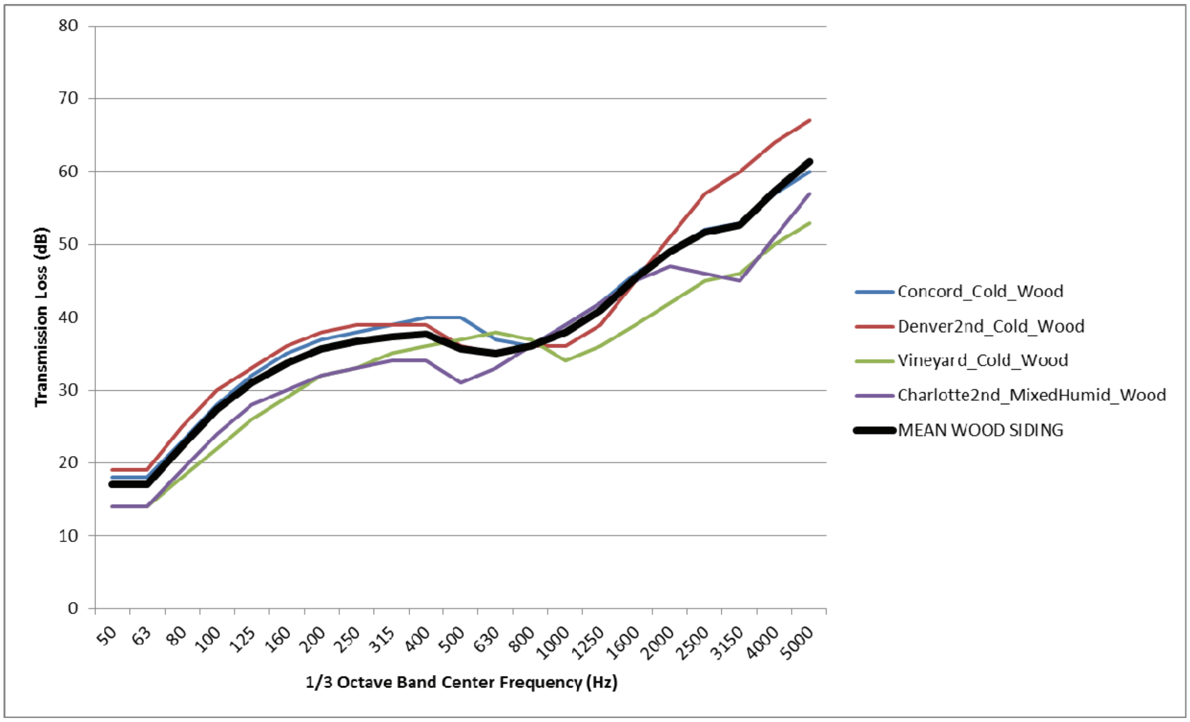


Figure 3.10: Transmission Loss of Insul Modeled Wood-Sheathed Walls (City_Region_Ext.Layer)

The transmision loss of the brick wall constructions shown in Figure 3.11 are nearly identical to one another, with the only difference being at the highest frequencies due to the difference in the thickness of the rigid foam insulation (and by extension the thickness of the wall as a whole).

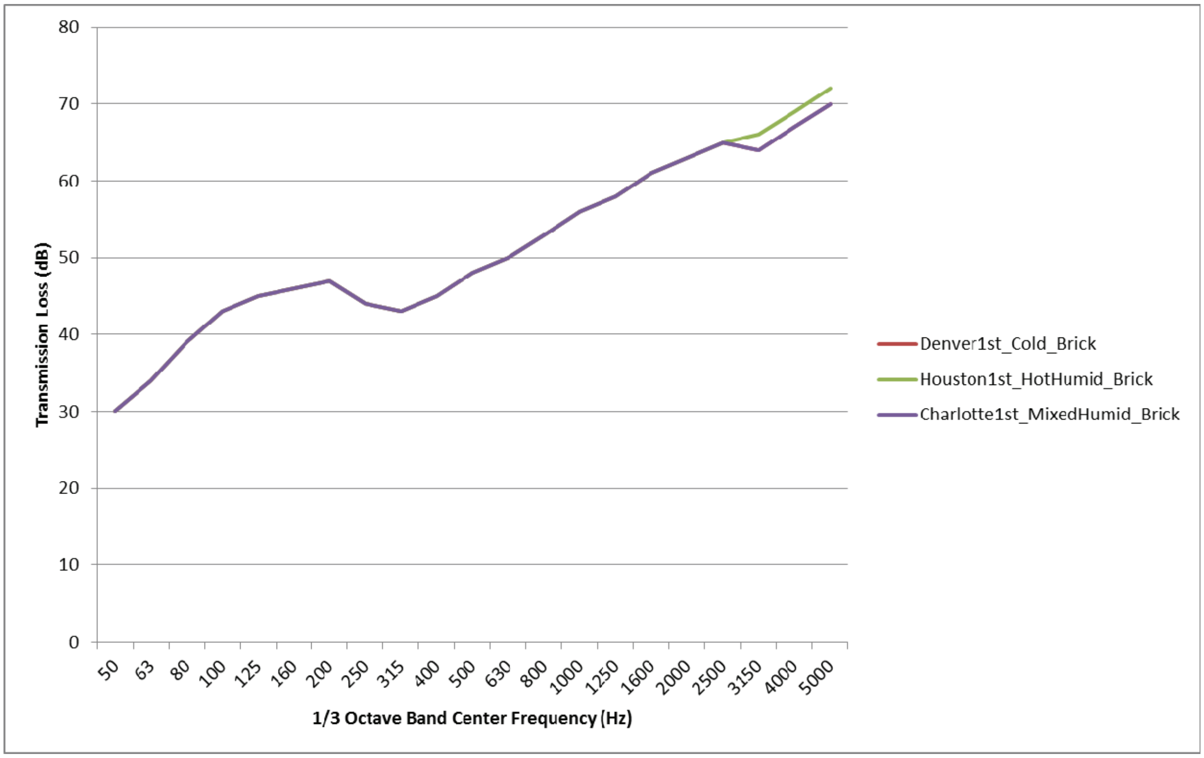


Figure 3.11: Transmission Loss of Insul Modeled Brick-Sheathed Walls (City_Region_Ext.Layer)

Figure 3.12 shows that the TL curves of the constructions featuring vinyl and aluminum siding were grouped together, and while the Louisville and Chicago wall constructions featured aluminum and vinyl siding respectively (plus a layer of rigid foam insulation), the difference between the two transmission loss curves is no more than 3 dB. In contrast, the Montgomery wall construction has a layer of OSB in place of the rigid foam insulation, whose mass significantly improves the wall's transmission loss performance (1/2" OSB on its own has 3 times the surface mass of the aluminum siding plus 1" rigid foam insulation). The large standard deviation seen in Table 3.6 for this grouping necessitates the separation of the Montgomery construction type from this group. Doing so lowers the standard deviation to 1 point (not shown in table) for both STC and OITC between the Chicago and Louisville wall models.

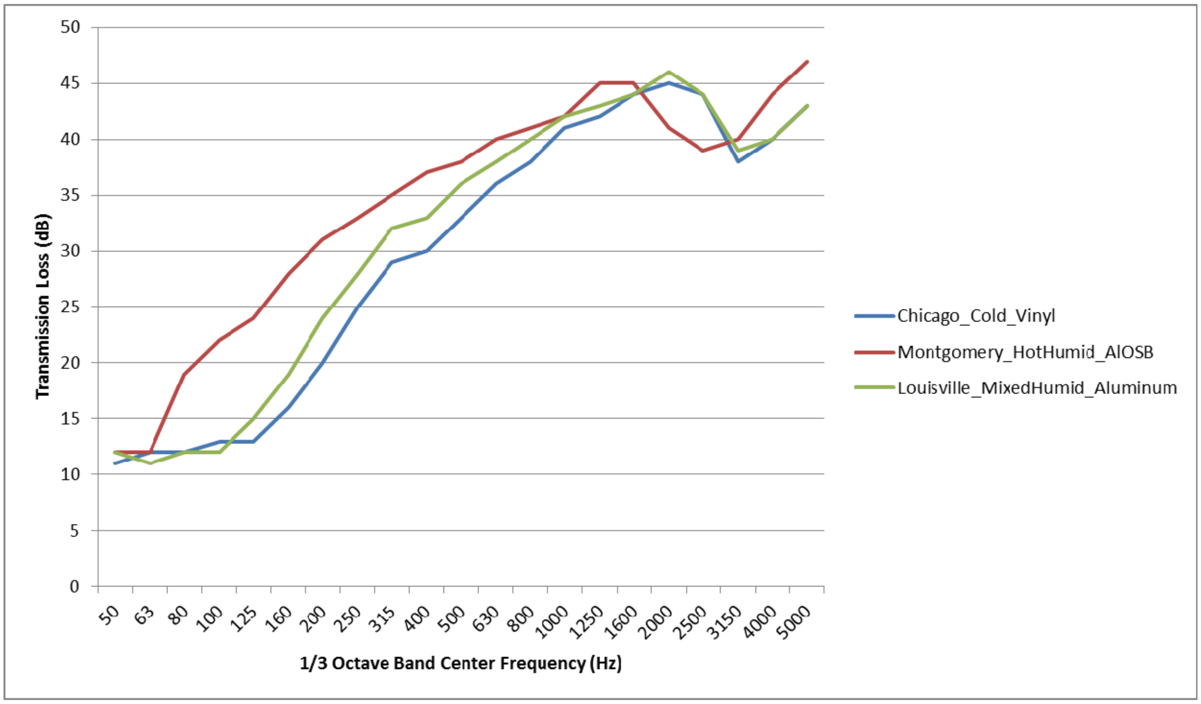


Figure 3.12: Transmission Loss of Insul Modeled Vinyl/Aluminum Siding-Sheathed Walls (City_Region_Ext.Layer)

3.3 Composite Façade Modeling in IBANA-Calc

Each wall partition was used in conjunction with other building elements (roof, windows) to construct a composite building envelope in IBANA-Calc (see Appendix C for a detailed accounting of this process).

3.3.1 Roof Construction

As currently available modeling technologies do not allow for detailed modeling of roof constructions due to their high complexity and the sheer number of different ways a roof can be built (even within a single climate region), a single roof was selected from the IBANA-Calc database to be used for all the regional construction models. The roof selected was consistent with the recommendations from Building Science for the majority (63%) of its building construction types: "Asphalt shingles, building paper, 11 mm OSB, raised heel wood trusses with glass fibre (sic) cavity insulation, 1 of 13 mm gypsum board, no vents installed.” This roof was similar to the one found in the Canadian homes modeled for the IBANA-Calc Validation Study, except those homes’ roofs had two layers of gypsum board. Construction profiles with vastly different roof constructions (including clay tiles and roof constructions which featured continuous soffit vents) were excluded from use in the whole house models.

3.3.2 Windows

Eight total window types were used in the composite models (see list in section 3.3.4). The TL data from six were from the built-in IBANA-Calc database and two were from manufacturer data. Three basic windows were selected from the IBANA-Calc database: Wood Slider (WS), Vinyl Double Slider (VDS), and Aluminum Casement (AlC), each consisting of two 3 mm panes of glass separated by a 13 mm airspace. The database also included data for some windows with storm windows added. As such data was available for the Vinyl Double Slider and Aluminum Casement windows, it was added to this round of modeling in order to examine the effect of this relatively straight-forward modification. Both windows had data available for storm windows with a 1” airgap between the regular window glass and the storm window; they are notated as VDS1SW and AlC1SW, respectively. In addition, data was available for the Aluminum Casement window with a 3” airgap between it and the storm window, giving us an additional window type: AlC3SW. To give an example of the upper limits of retrofit performance, two specialty acoustic windows with higher transmission loss performance were also included in the modeling, SAC1 and SAC2. The transmission loss data for these two windows was provided from the manufacturers, who are not being identified since the purpose of their inclusion is simply to present an example of high-performance acoustic windows and not to validate their specific performance against any other particular options.

3.3.3 Selecting Wall Constructions

Six total wall types were used in the composite models (see the list in section 3.3.4). As many of the modeled wall constructions have very similar transmission loss properties, it was deemed unnecessary to model composite room TL for all 20 of them. Instead, six representative wall constructions were selected to represent the six different outermost wall construction layers. In addition to “Brick”, “Fibercement”, “Stucco”, “Wood”, and “Vinyl”, a sixth type, called “AlOSB” was modeled; this was due to the drastic difference caused by replacing the layer of rigid foam insulation in the Louisville aluminum siding model with OSB in the Montgomery model. Practically speaking, it makes little difference whether one uses vinyl or aluminum siding (in their standard thicknesses); the big difference comes with whether OSB is used in place of rigid foam insulation or not. As such, it was deemed important to model both cases. The vinyl siding model (Chicago) was chosen over the aluminum siding model (Louisville) for inclusion in the whole-house modeling due to the Louisville construction profile not being one of the 63% of profiles having the same roof as described in section 3.3.1.

Similarly, Albuquerque was selected to represent the “Stucco” wall type since several of the other southwestern city profiles featured clay roofing tiles instead of the asphalt shingles found in the roof selected for the whole-house modeling. Concord was chosen to represent the “Wood” type due to its being nearly identical to the mean of all the “Wood” constructions as discussed previously. The Houston 1st floor wall was selected as the representative of the “Brick” construction type over the alternatives to serve as the best-case scenario in this modeling process. The Houston 2nd floor wall construction was selected to represent the “Fibercement” walls simply out of the convenience of using it alongside its first floor model as the other available “Fibercement” walls did not differ significantly (if at all) from the Houston 2nd floor wall in TL performance. Finally, as discussed above, the Chicago profile is representing the

“Vinyl” construction type, while Montgomery is representing “AlOSB”. A graph comparing these selected models to those not selected is shown in Figure 3.13.

3.3.4 Room Configurations

To avoid needing to significantly increase the number of composite room models, only four total room configurations were used for the composite models (see the list in section 3.3.4). The room sizes selected were 8’x12’ and 12’x15’; these were selected to approximate a very small bedroom and a medium-sized bedroom, respectively. The window areas were based upon either one or two 3’x4’ windows (12 sq. ft. or 24 sq. ft., respectively). This resulted in four room configurations with window areas ranging from 5.9% to 17.6% of the wall area.

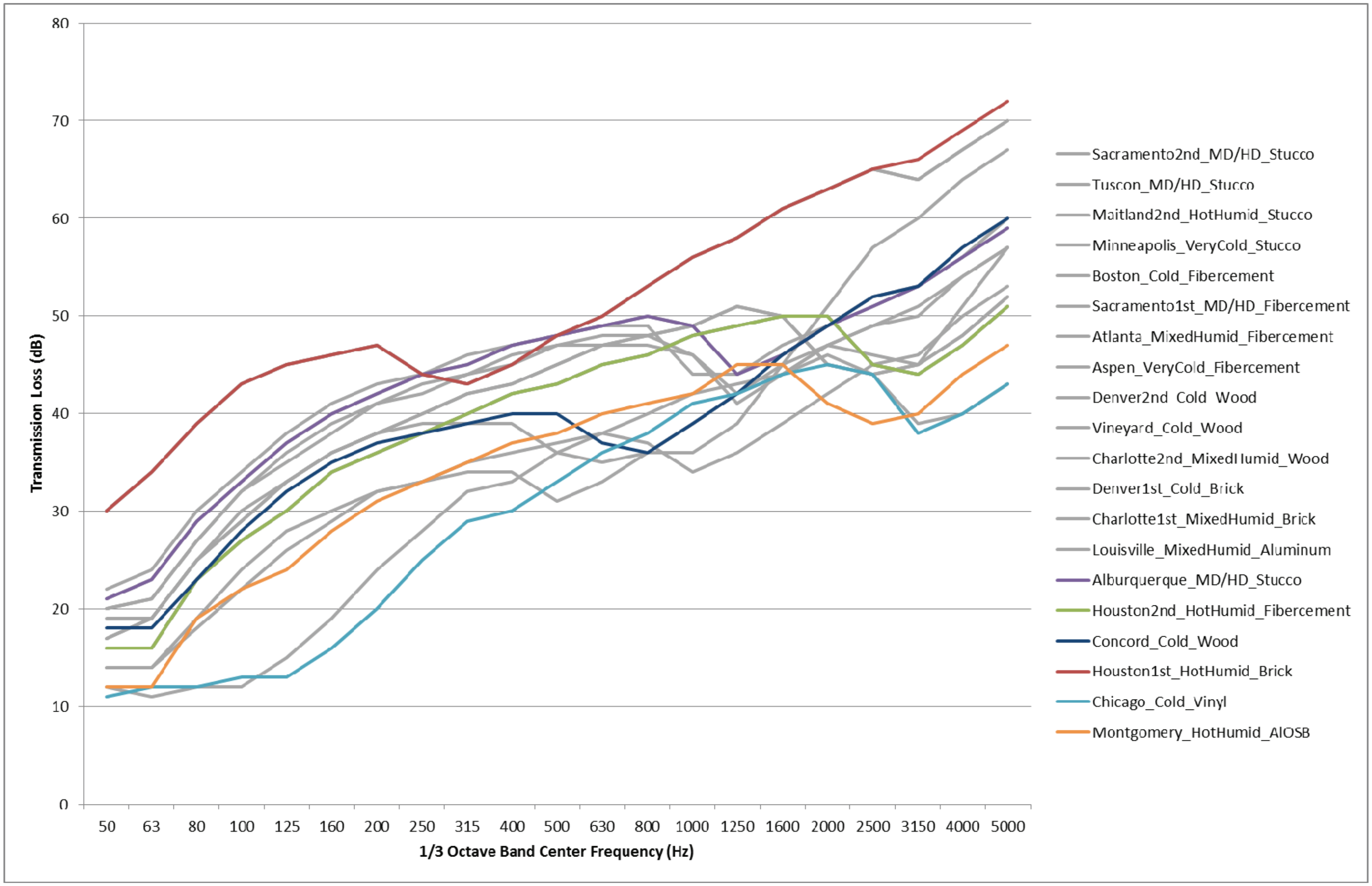


Figure 3.13: Transmission Loss of wall constructions modeled with Insul, with those used for whole-house modeling colored and those not used shown in gray (City_Region_Ext.Layer); ordered by exterior construction layer, with those used for whole house modeling listed last.

3.3.5 Methodology for Generating Composite Façade Models

Once wall constructions were identified and modeled, a number of systematic iterations were introduced for generating composite façade models, centered around four primary variables: window type, exterior wall construction, room size, and window area:

- Windows (8 total)
    - 3 basic types
        - Wood Slider (“WS”, OITC 22)
        - Vinyl Double Slider (“VDS”, OITC 23)
        - Aluminum Casement (“AlC”, OITC 23)
    - 3 types with storm windows
        - VDS with Storm Window, 1” Airgap (“VDS1SW”, OITC 27)
        - AlC with Storm Window, 1” Airgap (“AlC1SW”, OITC 25)
        - AlC with Storm Window, 3” Airgap (“AlC3SW”, OITC 30)
    - 2 specialty acoustic types
        - Specialty Acoustic Window #1 (“SAC1”, OITC 33)
        - Specialty Acoustic Window #2 (“SAC2”, OITC 43)
- Walls (6 total)
    - 6 typical wall constructions w/ various exterior sheathing, 2”x6” studs 24” OC with 4” of cavity insulation, 1/2” sheet of gypsum board
        - “Chicago_Cold_Vinyl”, OITC 23
        - “Houston2nd_HotHumid_Fibercement”, OITC 34
        - “Montgomery_HotHumid_AlOSB”, OITC 35
        - “Concord_Cold_Wood”, OITC 37
        - “Alburquerque_MixedDry_Stucco”, OITC 43
        - “Houston1st_HotHumid_Brick”, OITC 48

- Room Size/Window Area Combinations (4 total)
  - 2 room sizes with 2 window area sizes (“length x width – [window area]”) in feet and square feet, respectively
    - “8x12-[12]”, 8.1% window area
    - “8x12-[24]”, 17.6% window area
    - “12x15-[12]”, 5.9% window area
    - “12x15-[24]”, 12.5% window area

As one of the common problems with aircraft noise is sleep disturbance (see section 1.2.2), all scenarios were modeled as if they were upper-level corner bedrooms. This provided a “worst-case” scenario for noise transmission since the rooms would have two exterior walls through which sound could be transmitted, as well as the roof overhead. It was assumed that any sound transmitted into the rooms in question from interior partitions would be negligible compared to the exterior noise, and as such, no interior partitions were modeled. In the case of the Houston 1st floor brick wall model, it was treated as though it were the upper-most (or only) level, having a roof overhead instead of another story; this could plausibly be seen in a split-level home, for example. All models used the common asphalt shingled raised heel wood truss roof from the IBANA-Calc database. The absorption parameters in IBANA-Calc were set to “Bedroom” (120%).

A detailed step-by-step description of the composite façade modeling process with IBANA-Calc is available in Appendix C.

3.3.6 Composite Façade Transmission Loss Results

As 192 separate scenarios were modeled, some effort to condense the data was deemed necessary for its inclusion in the body of this thesis. Each of the following graphs in Figures 3.14-3.22 shows the four room and window size configurations for each wall/window combination. Graphed separately alongside them are the individual transmission loss curves of the window, wall, and roof. Refer to section 3.4 for analysis.

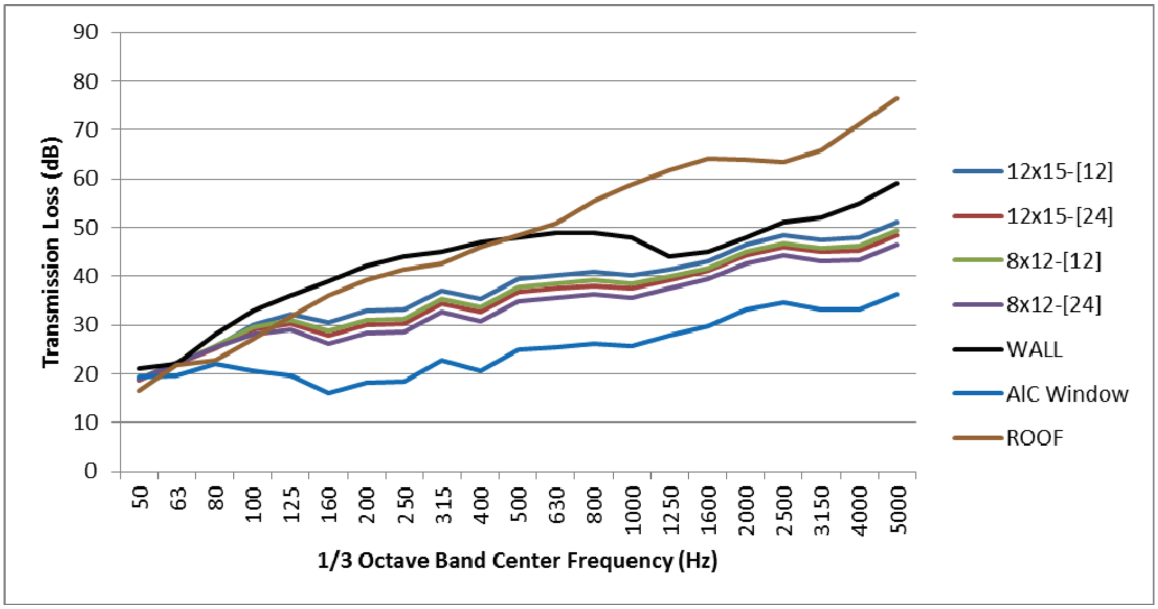


Figure 3.14: Composite room transmission loss for four room configurations, each featuring Alburquerque_MixedDry_Stucco walls (OITC 43) with aluminum casement (AlC) windows (OITC 23). Individual wall, window, and roof TL also shown for reference. Room configurations given by "length x width – [window area]", in ft. and sq. ft.

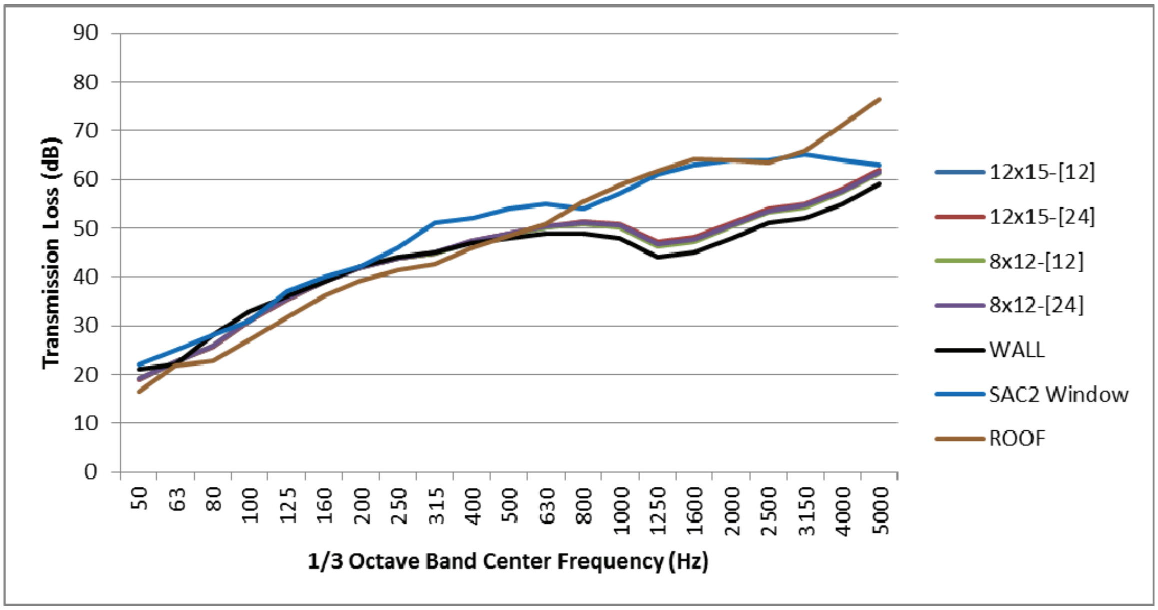


Figure 3.15: Composite room transmission loss for four room configurations, each featuring Alburquerque_MixedDry_Stucco walls (OITC 43) with Specialty Acoustic 2 (SAC2) windows (OITC 43). Individual wall, window, and roof TL also shown for reference. Room configurations given by "length x width – [window area]", in ft. and sq. ft.

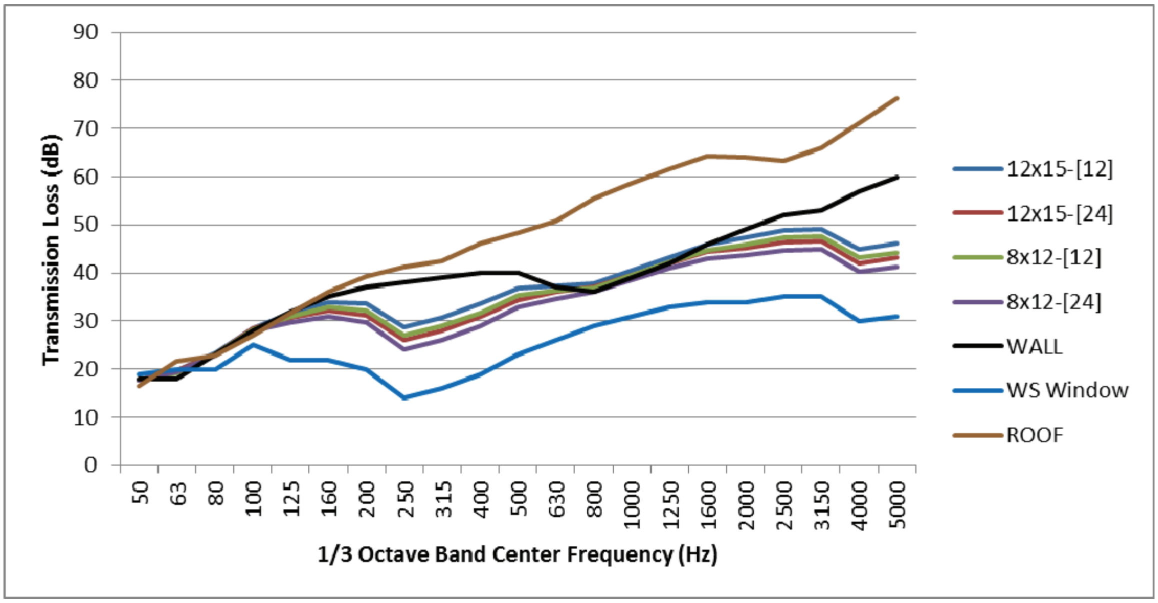


Figure 3.16: Composite room transmission loss for four room configurations, each featuring Concord_Cold_Wood walls (OITC 37) with Wood Slider (WS) windows (OITC 22). Individual wall, window, and roof TL also shown for reference. Room configurations given by “length x width – [window area]”, in ft. and sq. ft.

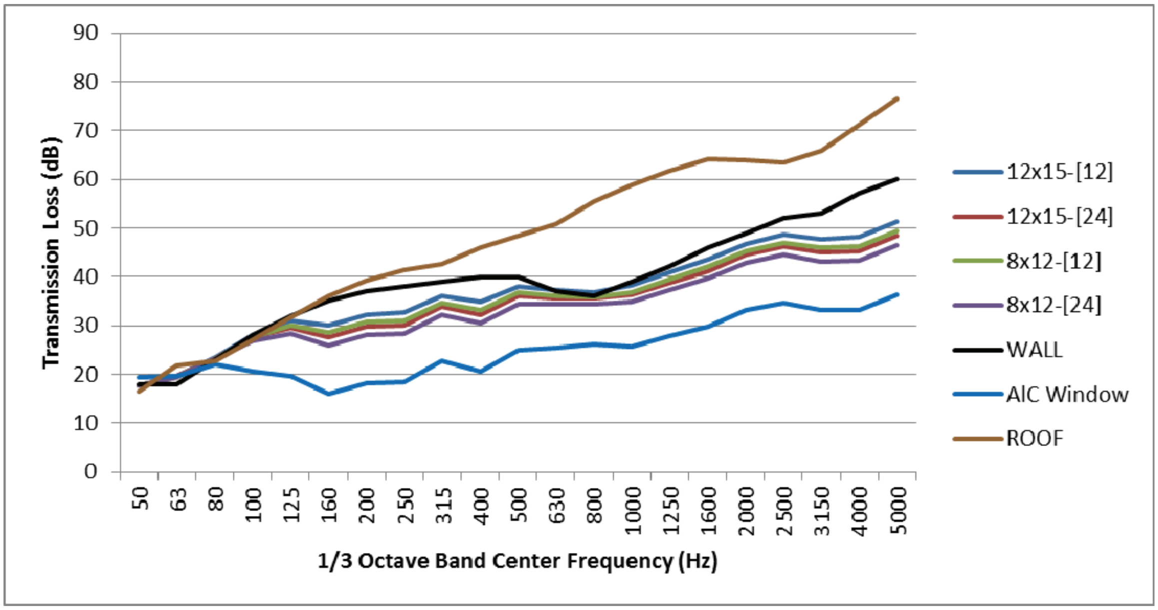


Figure 3.17: Composite room transmission loss for four room configurations, each featuring Concord_Cold_Wood walls (OITC 37) with Aluminum Casement (AlC) windows (OITC 23). Individual wall, window, and roof TL also shown for reference. Room configurations given by “length x width – [window area]”, in ft. and sq. ft.

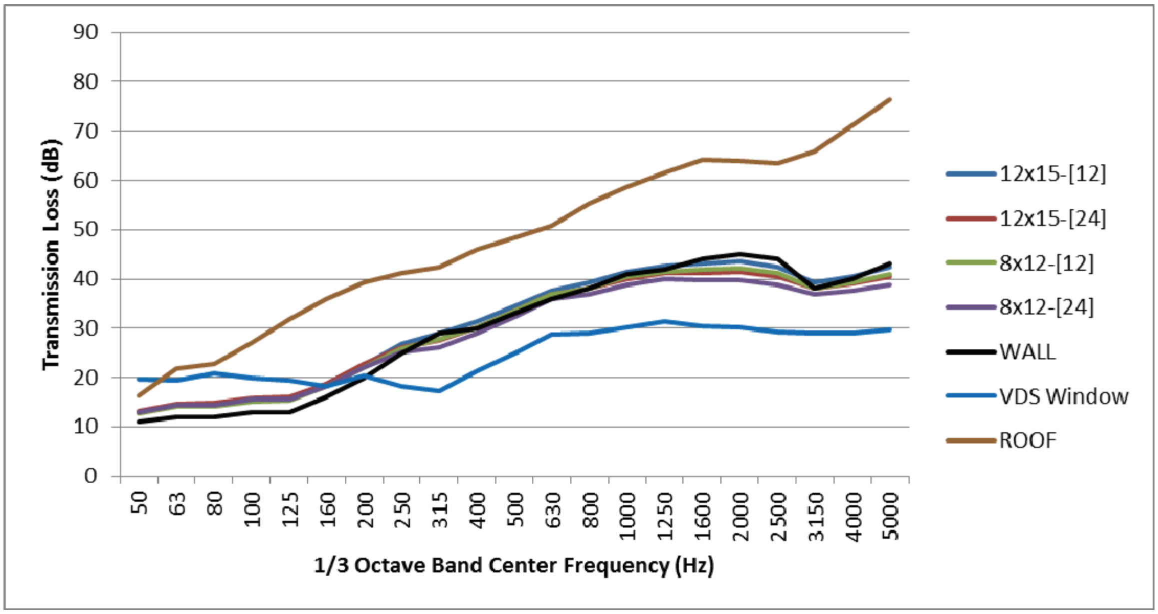


Figure 3.18: Composite room transmission loss for four room configurations, each featuring Chicago_Cold_Vinyl walls (OITC 23) with Vinyl Double Slider (VDS) windows (OITC 23). Individual wall, window, and roof TL also shown for reference. Room configurations given by "length x width – [window area]", in ft. and sq. ft.

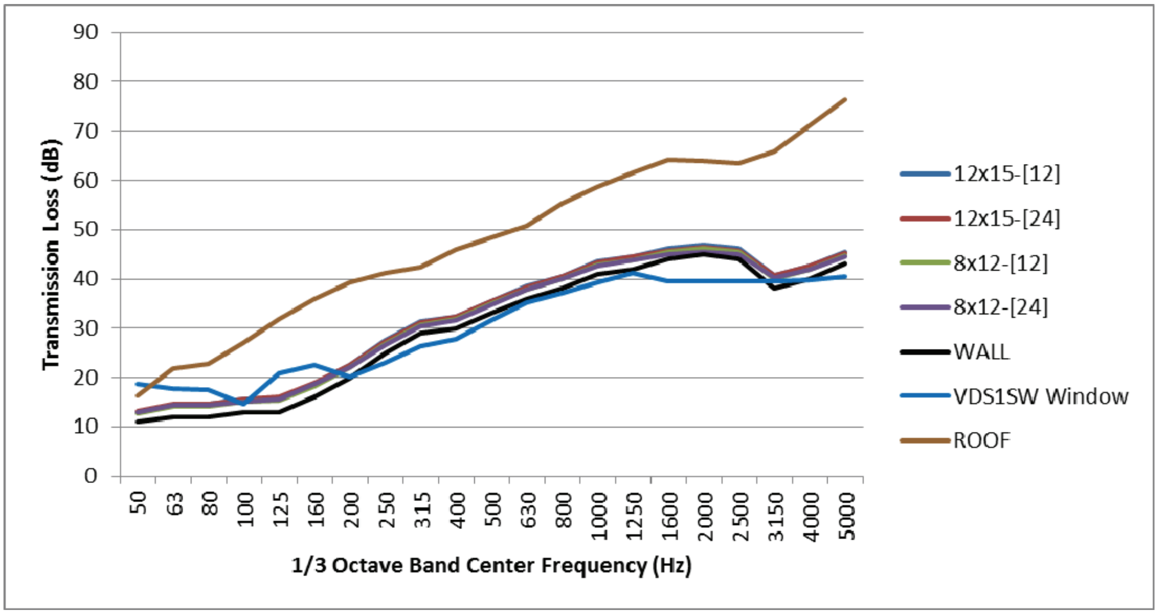


Figure 3.19: Composite room transmission loss for four room configurations, each featuring Chicago_Cold_Vinyl walls (OITC 23) with Vinyl Double Slider windows w/1" Airgap and storm window (OITC 27). Individual wall, window, and roof TL also shown for reference. Room configurations given by "length x width – [window area]", in ft. and sq. ft.

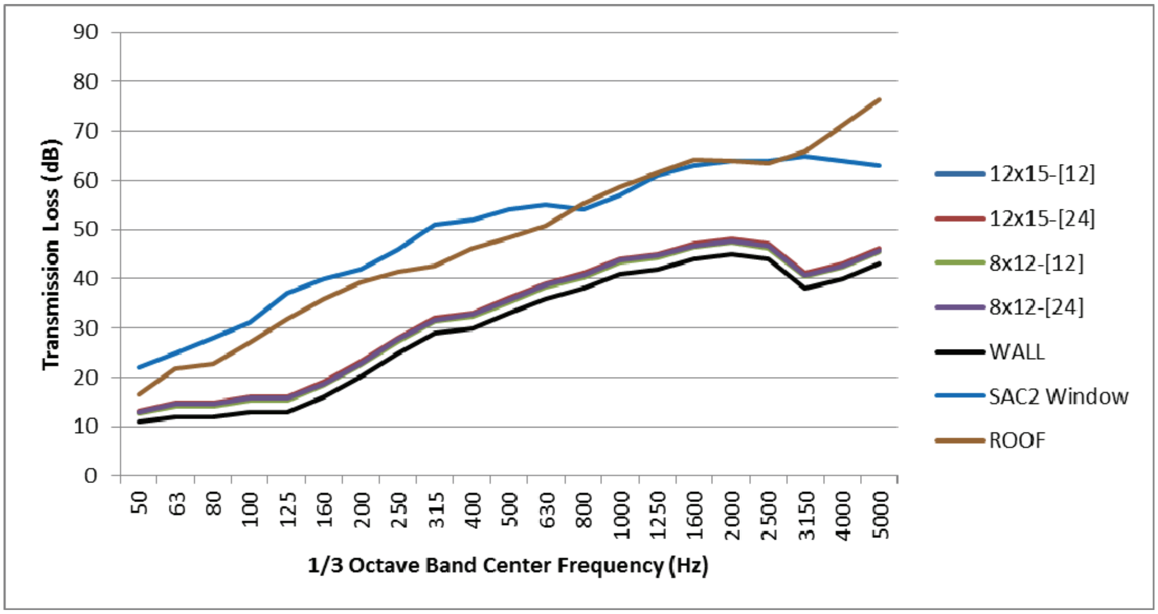


Figure 3.20: Composite room transmission loss for four room configurations, each featuring Chicago_Cold_Vinyl walls (OITC 23) with Specialty Acoustic 2 (SAC2) windows (OITC 43). Individual wall, window, and roof TL also shown for reference. Room configurations given by “length x width – [window area]”, in ft. and sq. ft.

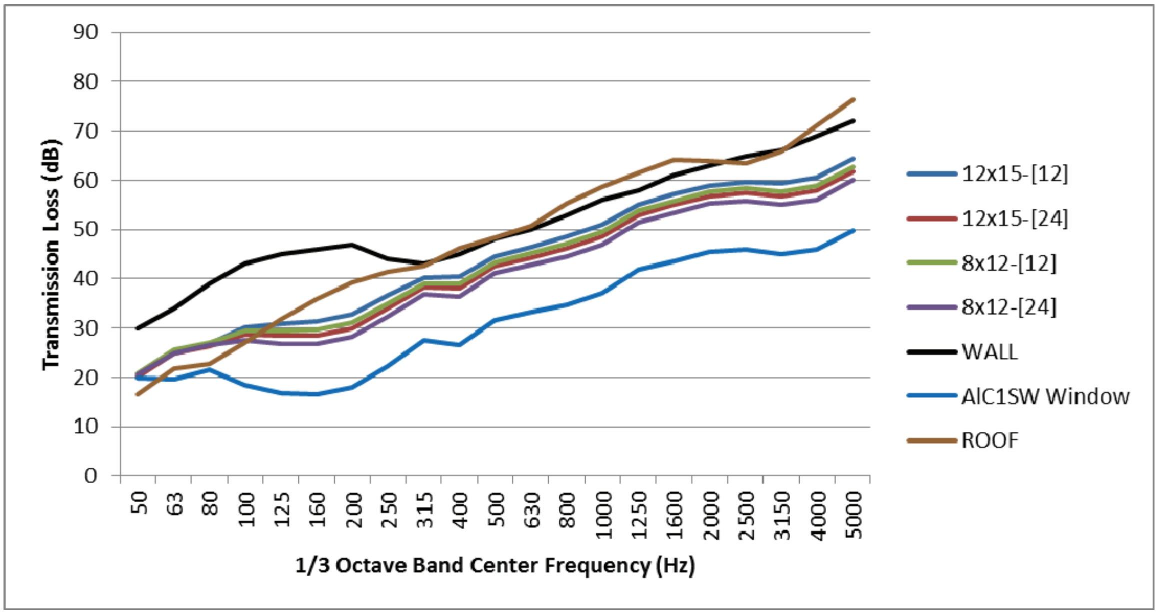


Figure 3.21: Composite room transmission loss for four room configurations, each featuring Houston1st_HotHumid_Brick walls (OITC 48) with Aluminum Casement windows w/ 1” Airgap and storm window (OITC 23). Individual wall, window, and roof TL also shown for reference. Room configurations given by “length x width – [window area]”, in ft. and sq. ft.

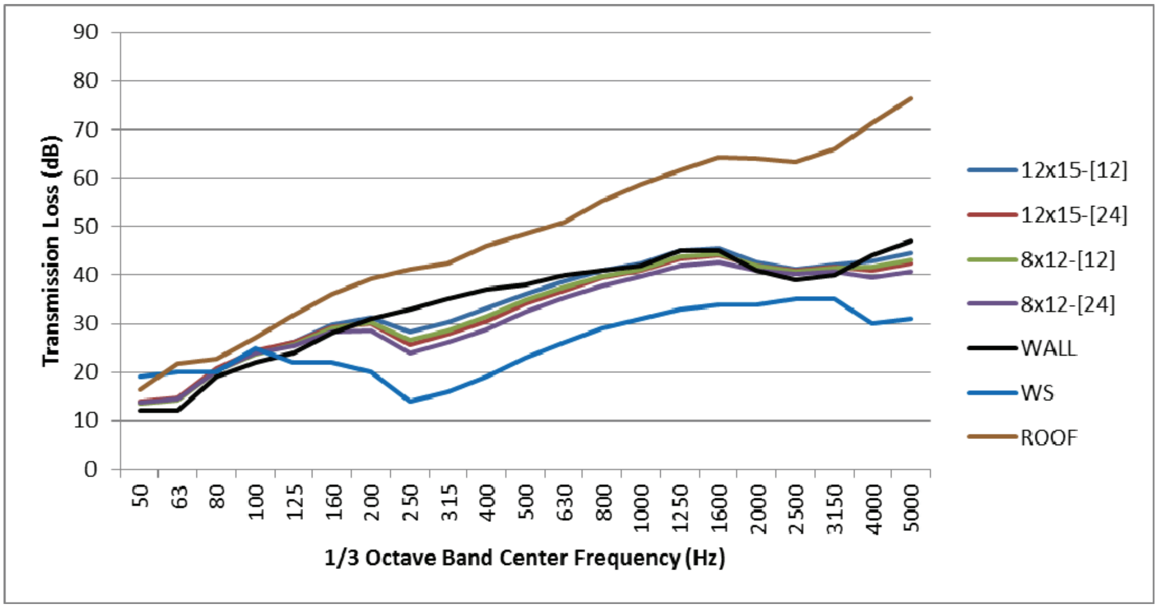


Figure 3.22: Composite room transmission loss for four room configurations, each featuring Montgomery_HotHumid_AlOSB walls (OITC 35) with Wood Slider (WS) windows (OITC 22). Individual wall, window, and roof TL also shown for reference. Room configurations given by “length x width – [window area]”, in ft. and sq. ft.

3.3.6.1 Single-Number A-weighted Noise Reduction (NR_A)

It is commonly useful to condense large amounts of information to single-number values for making comparisons. As reducing transmission loss information to a single-number value discards all frequency content information, it is dangerous to rely solely upon the single-number values since it is possible for different frequency response curves to produce the same single-number value. Although other single-number values exist for describing the transmission of noise through partitions (STC & OITC), A-weighted Noise Reduction (NR_A) was selected to better describe a real-world scenario. The NR_A is found using Equation 3.1 below:

$$NR_A = L_1 - L_2 \qquad \text{(dBA)} \qquad \text{Eqn. 3.1}$$

Where L_1 is the outdoor incident sound level and L_2 is the room-averaged indoor received level. Both L_1 and L_2 are A-weighted equivalent sound pressure levels (in dBA). The indoor received level (L_2), a function of both the building’s transmission loss properties (TL) and the receiving room effects, as described by Equation 3.2:

$$L_2 = L_1 - TL + 10log\left(\frac{S}{A}\right) \qquad \text{(dBA)} \qquad \text{Eqn. 3.2}$$

Where TL is the building's sound transmission loss (in dBA), S is the surface area sound is being transmitted through (in m^2), and A is the total absorption in the receiving room (in m^2). Note that in field measurements of NR_A both TL and the room effect term (S/A) would be automatically accounted for when indoor sound level (L_2) is measured, but calculations or predictions of NR_A would need to specifically include these two factors.

To achieve the single-number NR_A values, IBANA-Calc was used with its "Standard Aircraft Source", which is a mixture of several different aircraft noise signatures taken in the field. Also of note is that the absorption does come into play with Noise Reduction; as was stated previously, IBANA-Calc was set to "Bedroom" absorption for all scenarios ("Absorption as a percentage of floor area" = 120%). The NR_A values are shown in Table 3.7, with a range of values encompassing the four room size/window area configurations for each window/wall combination.

Table 3.7: A-Weighted Noise Reduction (NR_A) in dB(A) of whole-house IBANA-Calc models for varying window types (WS, VDS, etc.) ; range indicates varying performance across the four modeled room/window size configurations

Wall Type and OITC Rating	Range of A-Weighted Noise Reduction (NR_A) in dB(A) for Whole-House Models							
	Window Type and OITC Rating							
(City_Region_ExteriorLayer)	*WS, OITC 22*	*VDS, OITC 23*	*VDS1SW, OITC 27*	*AIC, OITC 23*	*AIC1SW, OITC 25*	*AIC3SW, OITC 30*	*SAC1, OITC 33*	*SAC2, OITC 43*
Alburquerque_MixedDry_Stucco, OITC 43	29-34	30-35	34-38	30-35	33-37	37-40	39-41	41-42
Chicago_Cold_Vinyl, OITC 23	24-26	24-26	25-26	24-26	25-26	25-26	25-26	25-26
Concord_Cold_Wood, OITC 37	28-33	29-34	33-36	29-33	32-35	34-36	35-37	36-37
Houston1st_HotHumid_Brick, OITC 48	29-34	30-35	34-39	30-35	33-38	37-41	40-42	43
Houston2nd_HotHumid_Fibercement, OITC 37	28-32	29-33	32-35	29-33	31-34	34-36	35-36	35-37
Montgomery_HotHumid_AlOSB, OITC 35	28-32	29-33	32-35	29-33	31-34	33-35	34-36	35-36

Additionally, for the sake of comparison outside of those particular noise source/receiving room conditions, IBANA-Calc's reported OITC values for the different scenarios are given in Table 3.8.

Table 3.8: OITC of whole-house IBANA-Calc models for varying window types (WS, VDS, etc.) ; range indicates varying performance across the four modeled room/window size configurations

Wall Type and OITC Rating	Range of Outdoor-Indoor Transmission Class (OITC) Ratings for Whole-House Models							
	Window Type and OITC Rating							
(City_Region_ExteriorLayer)	*WS, OITC 22*	*VDS, OITC 23*	*VDS1SW, OITC 27*	*AIC, OITC 23*	*AIC1SW, OITC 25*	*AIC3SW, OITC 30*	*SAC1, OITC 33*	*SAC2, OITC 43*
Alburquerque_MixedDry_Stucco, OITC 43	32-36	33-37	36-39	33-37	35-38	38-40	39-41	42
Chicago_Cold_Vinyl, OITC 23	25-26	25-26	26	25-26	25-26	26	26	26
Concord_Cold_Wood, OITC 37	32-35	33-36	35-37	32-36	34-36	36-37	37-38	38-39
Houston1st_HotHumid_Brick, OITC 48	32-37	33-37	36-39	33-37	35-39	38-41	40-42	43-44
Houston2nd_HotHumid_Fibercement, OITC 37	31-34	32-34	33-35	32-34	33-35	34-35	35-36	36
Montgomery_HotHumid_AlOSB, OITC 35	31-34	32-35	34-35	32-34	33-35	35-36	36	36-37

3.4 Discussion and Analysis

The most noticeable pattern observed in the previous figures was that in many cases, the composite room transmission loss curve bore a striking resemblance to the shape of the window TL curve used for that model such as in most of Figures 3.14, 3.16, 3.17, 3.21, & 3.22. As expected from [1], it was also apparent that in these circumstances, the greater the window area, the poorer the performance of the composite room (and the nearer to the actual window TL curve the composite room TL curve was). A doubling of window area resulted in nearly a 3 dB worsening of composite room TL performance at each frequency.

In some cases, where the TL curve of the window more closely approached that of the wall such as ~800-1250Hz in Figure 3.16 & ~400-800Hz in Figure 3.18, it was observed that the composite room TL curves ceased to follow the shape of the window TL curve and instead hugged tightly to the wall TL curve over that frequency range, not really exceeding the wall TL curve by any significant margin. In this case, the TL of the windows was functionally offset by the TL of the roof, resulting in a composite room TL roughly equivalent to that of the wall TL curve. The final case was when the window TL curve was within only a few dB of the wall curve (or even above it); in those cases, the composite TL curve tended to be largely identical to that of the wall, albeit with a 2-3 dB vertical shift above the wall curve due to the contributions of the higher roof TL curve. This can be seen above 630Hz in Figure 3.15 and below 200Hz in Figures 3.19-3.20. Many scenarios featured some or all of these cases at some frequency or another, depending on the differences in transmission loss of the various building façade elements relative to one another at different frequencies.

3.4.1 Analytical Formula for Computing Composite TL

These patterns are not unexpected when analyzing the formula for composite transmission loss,

$$TL_{Comp} = 10\log_{10}\frac{\sum_i A_i}{\sum_i A_i * 10^{-TL_i/10}} \qquad \text{(dBA)} \qquad \text{Eqn. 3.3}$$

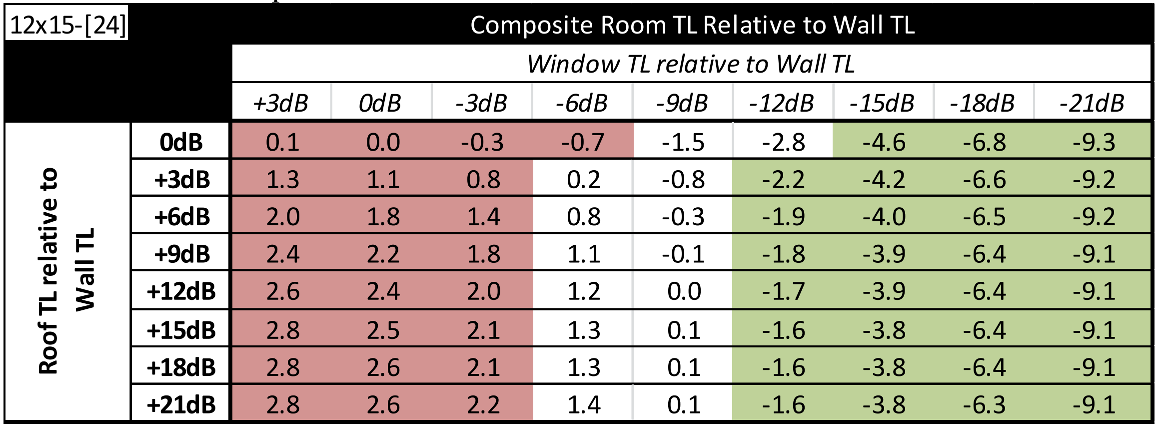
where $TL_{Composite}$ is the composite transmission loss, and A_i & TL_i are the area and transmission loss values of each individual element respectively (all TL values are positively signed). If this formula for composite transmission loss is used for this application, the following equation is generated:

$$TL_{Comp} = 10\log_{10}\frac{A_{Wall} + A_{Roof} + A_{Win}}{A_{Roof} * 10^{-TL_{Roof}/10} + A_{Wall} * 10^{-TL_{Wall}/10} + A_{Win} * 10^{-TL_{Win}/10}}. \qquad \text{(dBA)} \qquad \text{Eqn. 3.4}$$

As it is challenging to visualize how changing one parameter will affect the resulting composite transmission loss curve, several tables and figures were generated using this formula. While these tables and figures were generated for all four room size/window area configurations, for the sake of brevity, only those for the 12x15-[24] configuration are shown; the other configurations produced similar results.

Tables 3.9 and 3.10 contain identical data but are colored differently to better identify patterns in terms of different variables. In these tables, all TL values are relative to the TL of the wall, which is given as a reference level of 0 dB. In Table 3.9, note that with roof TL held constant, when the window TL curve is near that of the wall (generally within +/-3 dB), changes of 3 dB result in ≤0.5 dB change in composite transmission loss; changes of 6 dB result in ≤0.7 dB. However, when the window curve is much farther away (generally more than 12 dB below that of the wall), 3 dB changes in window level result in ≥2 dB changes in composite TL.

Table 3.9: Composite room transmission loss, relative to transmission loss of wall (0 dB), for various combinations of window and roof TL, shown relative to wall TL. Red indicates that a change in 3 dB in window TL results in a change of 0.5 dB or less in composite TL, for each given roof TL level. Green indicates that a change in 3 dB in window TL results in a change of 2 dB or greater in composite TL, for each given roof TL level. Room configuration shown is for 12x15-[24]. The other room configurations used in this research produced similar results.



12x15-[24]		Composite Room TL Relative to Wall TL								
		Window TL relative to Wall TL								
		+3dB	0dB	-3dB	-6dB	-9dB	-12dB	-15dB	-18dB	-21dB
Roof TL relative to Wall TL	0dB	0.1	0.0	-0.3	-0.7	-1.5	-2.8	-4.6	-6.8	-9.3
	+3dB	1.3	1.1	0.8	0.2	-0.8	-2.2	-4.2	-6.6	-9.2
	+6dB	2.0	1.8	1.4	0.8	-0.3	-1.9	-4.0	-6.5	-9.2
	+9dB	2.4	2.2	1.8	1.1	-0.1	-1.8	-3.9	-6.4	-9.1
	+12dB	2.6	2.4	2.0	1.2	0.0	-1.7	-3.9	-6.4	-9.1
	+15dB	2.8	2.5	2.1	1.3	0.1	-1.6	-3.8	-6.4	-9.1
	+18dB	2.8	2.6	2.1	1.3	0.1	-1.6	-3.8	-6.4	-9.1
	+21dB	2.8	2.6	2.2	1.4	0.1	-1.6	-3.8	-6.3	-9.1

In Table 3.10, when the window TL is held constant, it can be seen that in nearly all cases, changes of 3 dB or more result in ≤0.5 dB change in composite TL. The exceptions to this are generally when the roof, wall, and window TL curves are all close together (non-highlighted rows); even then, the largest difference in composite TL resulting from a change of 3 dB in roof TL is 1.2 dB.

Table 3.10: Composite room transmission loss, relative to transmission loss of wall (0 dB), for various combinations of window and roof TL, shown relative to wall TL. Orange indicates that a change in 3 dB in roof TL results in a change of 0.5 dB or less in composite TL, for each given window TL level. Room configuration shown is for 12x15-[24]. The other room configurations used in this research produced similar results.

12x15-[24]		Composite Room TL Relative to Wall TL								
		Window TL relative to Wall TL								
		+3dB	**0dB**	**-3dB**	**-6dB**	**-9dB**	**-12dB**	**-15dB**	**-18dB**	**-21dB**
Roof TL relative to Wall TL	*0dB*	0.1	0.0	-0.3	-0.7	-1.5	-2.8	-4.6	-6.8	-9.3
	+3dB	1.3	1.1	0.8	0.2	-0.8	-2.2	-4.2	-6.6	-9.2
	+6dB	2.0	1.8	1.4	0.8	-0.3	-1.9	-4.0	-6.5	-9.2
	+9dB	2.4	2.2	1.8	1.1	-0.1	-1.8	-3.9	-6.4	-9.1
	+12dB	2.6	2.4	2.0	1.2	0.0	-1.7	-3.9	-6.4	-9.1
	+15dB	2.8	2.5	2.1	1.3	0.1	-1.6	-3.8	-6.4	-9.1
	+18dB	2.8	2.6	2.1	1.3	0.1	-1.6	-3.8	-6.4	-9.1
	+21dB	2.8	2.6	2.2	1.4	0.1	-1.6	-3.8	-6.3	-9.1

From analysis of Table 3.10, it can be seen that it is not necessary to know the precise transmission loss curve of the roof element since in most cases changes in the transmission loss of the roof had minimal impact on the composite transmission loss. Analysis of Table 3.12 will reveal one additional caveat.

Similarly from analysis of Table 3.9, it is not necessary to know the precise transmission loss curve of the windows in cases where the window TL curve is near that of the wall (within +/-3 dB) due to the minimal effect that varying the window TL curve has on the composite TL. However, it is much more important to know the actual TL curve of the windows in cases when they have much lower transmission loss performance than the wall as changes to the window TL curve more readily impact the composite TL. These same effects may be seen from an alternate perspective in Tables 3.11 and 3.12, where the window TL is used as the 0 dB reference.

In Table 3.11, it can be seen that when the roof TL is held constant and the wall TL is much higher (generally more than 12-15 dB, depending on roof level) than that of the windows, changes of 3 dB in wall TL result in ≤0.5 dB change in composite transmission loss; changes of 6 dB result in ≤0.7 dB. Conversely, when the wall TL curve is nearer that of the window (generally within +/-3 dB), changes of 3 dB in wall TL result in changes of ≥2 dB in composite transmission loss.

Table 3.11: Composite room transmission loss, relative to transmission loss of wall (0 dB), for various combinations of window and roof TL, shown relative to wall TL. Brown indicates that a change in 3 dB in Wall TL results in a change of 0.5 dB or less in composite TL, for each given roof TL level. Blue indicates that a change in 3 dB in wall TL results in a change of 2 dB or greater in composite TL, for each given roof TL level. Room configuration shown is for 12x15-[24]. The other room configurations used in this research produced similar results.

12x15-[24]		Composite Room TL Relative to Window TL								
		Wall TL relative to Window TL								
		+21dB	*+18dB*	*+15dB*	*+12dB*	*+9dB*	*+6dB*	*+3dB*	*0dB*	*-3dB*
Roof TL relative to Window TL	**+21dB**	11.7	11.4	11.0	10.2	9.0	7.3	5.1	2.6	-0.1
	+18dB	11.4	11.2	10.8	10.1	8.9	7.2	5.1	2.6	-0.2
	+15dB	11.0	10.8	10.4	9.8	8.7	7.1	5.0	2.5	-0.2
	+12dB	10.3	10.1	9.8	9.2	8.2	6.8	4.8	2.4	-0.2
	+9dB	9.1	9.0	8.8	8.3	7.5	6.2	4.4	2.2	-0.4
	+6dB	7.5	7.4	7.2	6.9	6.3	5.3	3.8	1.8	-0.6
	+3dB	5.3	5.3	5.2	5.0	4.6	3.9	2.7	1.1	-1.0
	0dB	2.8	2.8	2.8	2.6	2.4	2.0	1.2	0.0	-1.7

Table 3.11 serves to further extrapolate on what was seen in Table 3.9. In cases where the wall is much higher performing than the windows, it is not necessary to know the precise TL curve of the wall, but it is important to know the actual TL performance of the windows. This is apparent upon examining the formula for computing composite TL.

Ignoring the additional factor of area, which would only serve to further decrease the second term relative to the first, it can be seen that since

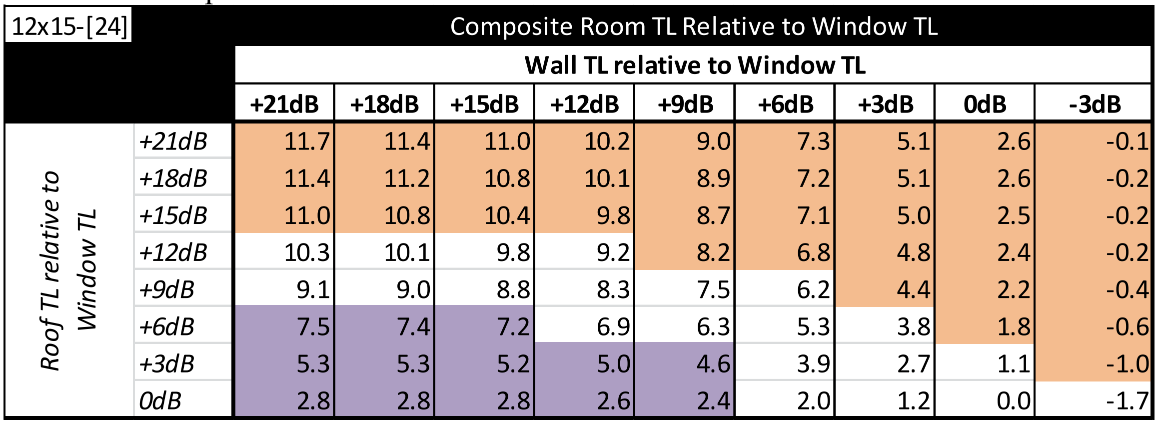
$$10^{TL_{Wall}/10} \gg 10^{(TL_{Wall}-12)/10},$$

$$10^{TL_{Wall}/10} + 10^{(TL_{Wall}-12)/10} \cong 10^{TL_{Wall}/10}.$$

Conversely, when the walls and windows are similar in their TL performance (+/- 3 dB), it is not important to know the precise window TL curve, but it is quite important to know that of the wall. This is due to the much larger surface area the walls have compared with the windows.

Whereas with Table 3.10 it was seen that changes in the roof TL curve had minimal impact on the composite TL in most cases, Table 3.12 shows when the roof TL performance is near that of the windows (within 6 dB) but the wall TL is not, changes of 3 dB in roof TL generally result in changes of ≥2 dB in composite TL. This is due to the much larger area of the roof compared to that of the windows.

Table 3.12: Composite room transmission loss, relative to transmission loss of wall (0 dB), for various combinations of window and roof TL, shown relative to wall TL. Orange indicates that a change in 3 dB in roof TL results in a change of 0.5 dB or less in composite TL, for each given wall TL level. Purple indicates that a change in 3 dB in roof TL results in a change of 2 dB or greater in composite TL, for each given wall TL level. Room configuration shown is for 12x15-[24]. The other room configurations used in this research produced similar results.



12x15-[24]		Composite Room TL Relative to Window TL								
		Wall TL relative to Window TL								
		+21dB	+18dB	+15dB	+12dB	+9dB	+6dB	+3dB	0dB	-3dB
Roof TL relative to Window TL	*+21dB*	11.7	11.4	11.0	10.2	9.0	7.3	5.1	2.6	-0.1
	+18dB	11.4	11.2	10.8	10.1	8.9	7.2	5.1	2.6	-0.2
	+15dB	11.0	10.8	10.4	9.8	8.7	7.1	5.0	2.5	-0.2
	+12dB	10.3	10.1	9.8	9.2	8.2	6.8	4.8	2.4	-0.2
	+9dB	9.1	9.0	8.8	8.3	7.5	6.2	4.4	2.2	-0.4
	+6dB	7.5	7.4	7.2	6.9	6.3	5.3	3.8	1.8	-0.6
	+3dB	5.3	5.3	5.2	5.0	4.6	3.9	2.7	1.1	-1.0
	0dB	2.8	2.8	2.8	2.6	2.4	2.0	1.2	0.0	-1.7

3.4.2 Dominating Features

As was seen in Figures 3.14-3.22 and discussed in the opening of section 3.4, there were many cases where the shape of the composite room transmission loss curve closely resembled that of one of the building façade elements. When this occurs, that building element is said to be the dominating feature as far as transmission loss is concerned. This means that small changes to the TL curves of the other building façade elements do not significantly affect the composite room transmission loss curve.

When the analytical formula for computing composite transmission loss was applied to a range of circumstances, several breakpoints were identified. The threshold for "dominance" was defined as a 3 dB change in the other façade elements producing a resulting change in composite transmission loss of ≤0.5 dB. When using this definition, it was found that for the room and wall configurations considered here:

- The windows were dominant in cases where the roof and wall TL were both >15 dB above the window TL.
- The walls were dominant when the roof TL was >6 dB above the wall TL and the window TL was no more than 3 dB below that of the wall.
- The roof was dominant only when its TL was more than 6 dB below that of the wall and the window TL was not more than 6 dB below that of the roof.

If one allows for a resulting composite TL change of ≤1.0 dB instead of ≤0.5 dB to establish dominance, windows are dominant when the roof and wall TL are both >12 dB above the window TL, walls are dominant when the roof TL is >3 dB above the wall TL and the window TL is no more than 6 dB below that of the wall, but the roof is still only dominant when its TL is more than 6 dB below that of the wall and the window TL is not more than 6 dB below that of the roof.

The practical implications of knowing which feature is dominant are very real for anyone involved in home retrofits. In cases where the wall is dominating, replacing the windows with better performing windows will not significantly improve the overall composite transmission loss, no matter how highly performing the windows may be. Once the window TL is higher than 3 dB below the wall TL, additional improvements do not substantially improve the composite TL performance. The Chicago_Cold_Vinyl models are the perfect example of this. Compare Figures 3.18-3.20 above. Note that despite going from an OITC 23 to an OITC 27 and then to an OITC 43 window, the composite room TL does not substantially change. In fact, while there is some improvement at the upper midrange frequencies, the overall A-weighted level and OITC values given in Tables 3.6 & 3.7 for the composite room do not improve more than 1 or 2 dB.

3.5 Summary of Key Findings

While numerous different typical regional construction types were identified, once they were modeled, it became clear that trying to choose a single representative wall construction for each region would be impractical. Instead, the walls were grouped based upon common exterior layer construction, allowing for the viable selection of representative constructions. Once these constructions were used to generate whole-house models, certain patterns began to appear. It was observed that there were circumstances where certain building façade elements appeared to "dominate" the composite TL. These observations were corroborated by analysis of the analytical formula for computing composite transmission loss.

- For windows dominant, wall TL >+15 dB & roof TL >+15 dB relative to windows.
- For walls dominant, roof TL >+6 dB & window TL >-3 dB (that is, higher than -3 dB, which includes 0 dB, NOT -6 dB) relative to wall.
- For roof dominant, wall TL >+6 dB and window TL >-6 dB (that is, higher than -6 dB, which includes 0 dB, NOT -9 dB) relative to roof.

These breakpoints were identified for the four room configurations considered in this research.

Some disadvantages of using the IBANA-Calc model versus simply applying the analytical formula for computing composite transmission loss were identified and are given below:

- Unable to generate large number of models very quickly

- Does not provide for intuitive user interface
- Export/import process necessary
- Does not give instant “reality check” to help identify potential errors
- Difficult to modify/expand due to closed architecture

The analytical formula was used for all composite façade modeling performed in the following chapter due to these numerous advantages over the previously utilized IBANA-Calc process.

CHAPTER 4

OLDER CONSTUCTION TYPES

Since the modern construction methods used in the previous chapter differ from those used 30+ years ago, a separate set of models must be constructed for these older construction types. As most homes near airports are older constructions, identifying and modeling those constructions is very important, especially for determining potential retrofit impacts. In fact, most retrofit programs will only consider homes over 15 years old [25]. Additionally, modeling older construction types and comparing them against previously published estimated single-number ratings will serve as an additional validation of the methodology used herein.

4.1 Construction Methods for Older Homes

Unfortunately, a database of detailed construction information for older home constructions is not readily available, and extensive searches were unable to locate consistent and reliable data. The one commonality, though, is that unlike the modern construction types discussed in Chapter 3, almost all older homes were constructed with 2”x4” framing, 16” OC and ½” thick drywall [24]. Due to the unavailability of detailed information on the exterior layers of older home constructions, the exterior layers were kept the same as what was used in Chapter 3. As all the building materials used in the modern construction types were available and in use 30+ years ago, this is believed to be a valid assumption for now; further research may allow for the refinement of these models in the future.

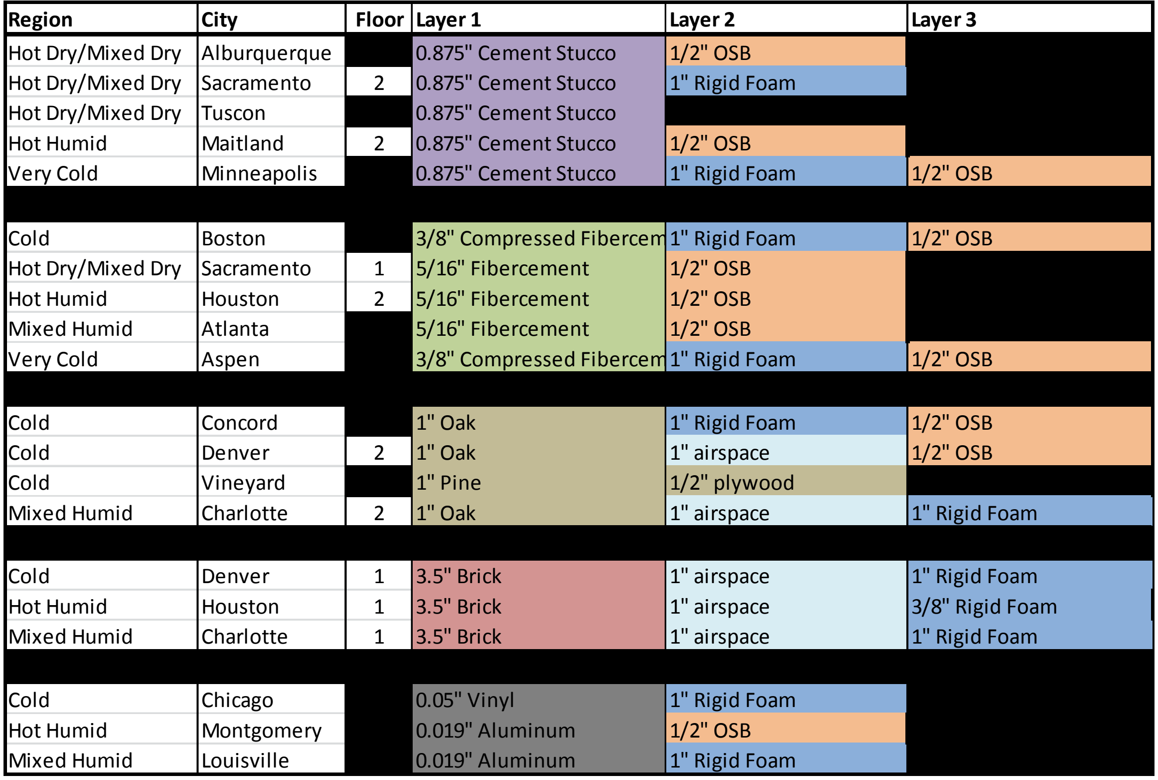
4.2 Modeling Details

Most of the details for the modeling of these older home construction types are the same as were used previously for the modern home constructions. The notable difference is the use of 2”x4”, 16” OC framing in lieu of the 2”x6”, 24” OC framing used in the modern constructions. Of course, with a shallower stud cavity, the depth of the cavity insulation was reduced from 4” to 3”.

4.2.1 Wall Construction Transmission Loss

Once all the wall constructions described in Table 4.1 were modeled in Insul, their transmission loss curves were plotted together in Figure 4.1. At low frequencies, the TL curves range from 11 dB up to 32 dB, and at high frequencies, the range is even larger: from 41 dB to 71 dB.

Table 4.1: Wall Constructions Used for Older Constructions Modeling



Region	City	Floor	Layer 1	Layer 2	Layer 3
Hot Dry/Mixed Dry	Alburquerque		0.875" Cement Stucco	1/2" OSB	
Hot Dry/Mixed Dry	Sacramento	2	0.875" Cement Stucco	1" Rigid Foam	
Hot Dry/Mixed Dry	Tuscon		0.875" Cement Stucco		
Hot Humid	Maitland	2	0.875" Cement Stucco	1/2" OSB	
Very Cold	Minneapolis		0.875" Cement Stucco	1" Rigid Foam	1/2" OSB
Cold	Boston		3/8" Compressed Fibercem	1" Rigid Foam	1/2" OSB
Hot Dry/Mixed Dry	Sacramento	1	5/16" Fibercement	1/2" OSB	
Hot Humid	Houston	2	5/16" Fibercement	1/2" OSB	
Mixed Humid	Atlanta		5/16" Fibercement	1/2" OSB	
Very Cold	Aspen		3/8" Compressed Fibercem	1" Rigid Foam	1/2" OSB
Cold	Concord		1" Oak	1" Rigid Foam	1/2" OSB
Cold	Denver	2	1" Oak	1" airspace	1/2" OSB
Cold	Vineyard		1" Pine	1/2" plywood	
Mixed Humid	Charlotte	2	1" Oak	1" airspace	1" Rigid Foam
Cold	Denver	1	3.5" Brick	1" airspace	1" Rigid Foam
Hot Humid	Houston	1	3.5" Brick	1" airspace	3/8" Rigid Foam
Mixed Humid	Charlotte	1	3.5" Brick	1" airspace	1" Rigid Foam
Cold	Chicago		0.05" Vinyl	1" Rigid Foam	
Hot Humid	Montgomery		0.019" Aluminum	1/2" OSB	
Mixed Humid	Louisville		0.019" Aluminum	1" Rigid Foam	

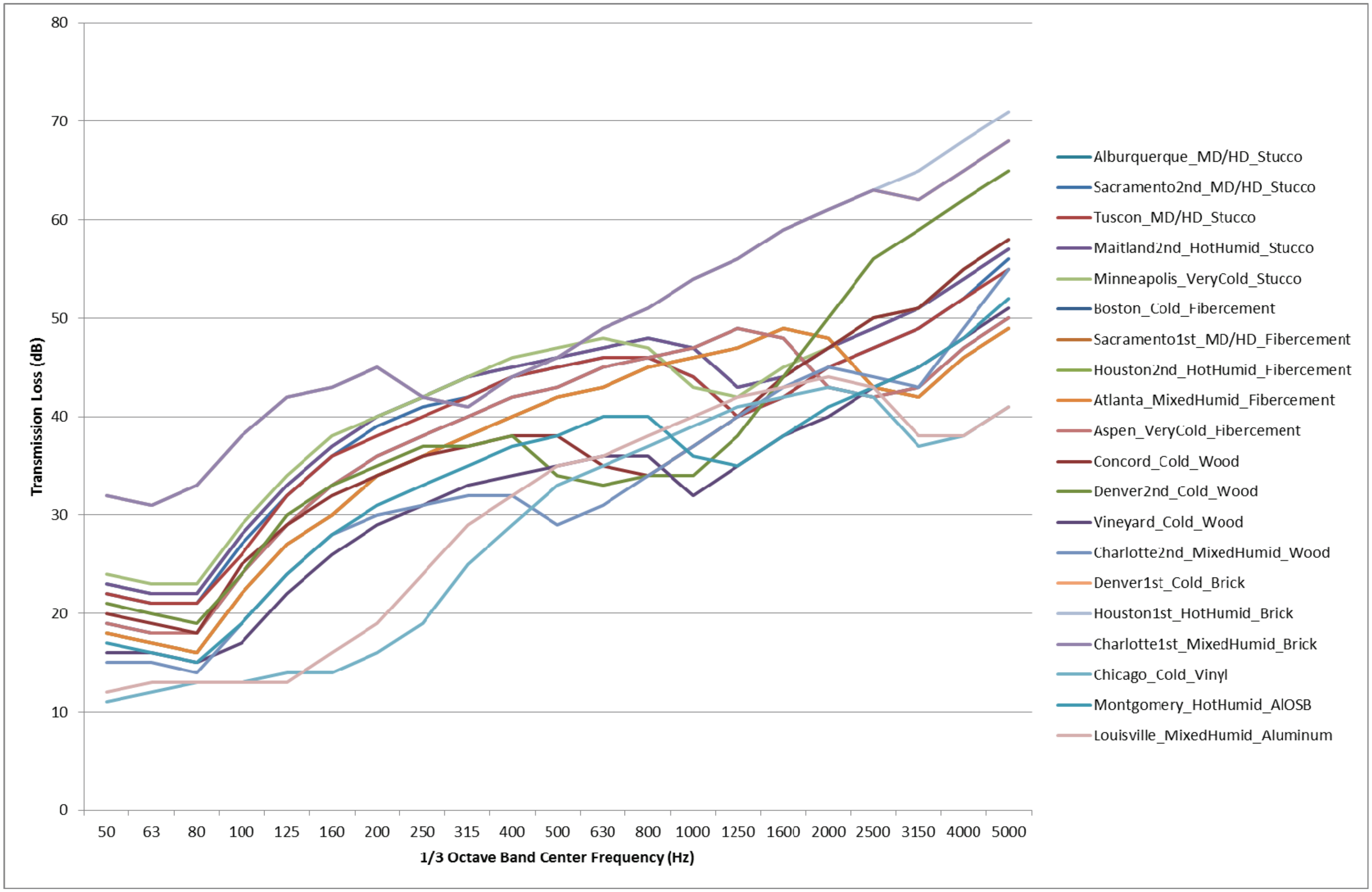


Figure 4.1: Transmission Loss (TL) of all older wall constructions modeled in Insul (City_Region_Ext.Layer), ordered by exterior construction layer

These wall transmission loss curves bear a strong resemblance to those for the modern construction types (and they should, since the bulk of the construction is identical). Despite that, though, there are some differences. Generally speaking, the older construction profiles had 1-2 dB poorer TL performance across the board, with that difference increasing significantly at low frequencies. This can be seen in Figure 4.2. Also, the change in thickness caused the coincidence dip to shift, resulting in some differences at higher frequencies.

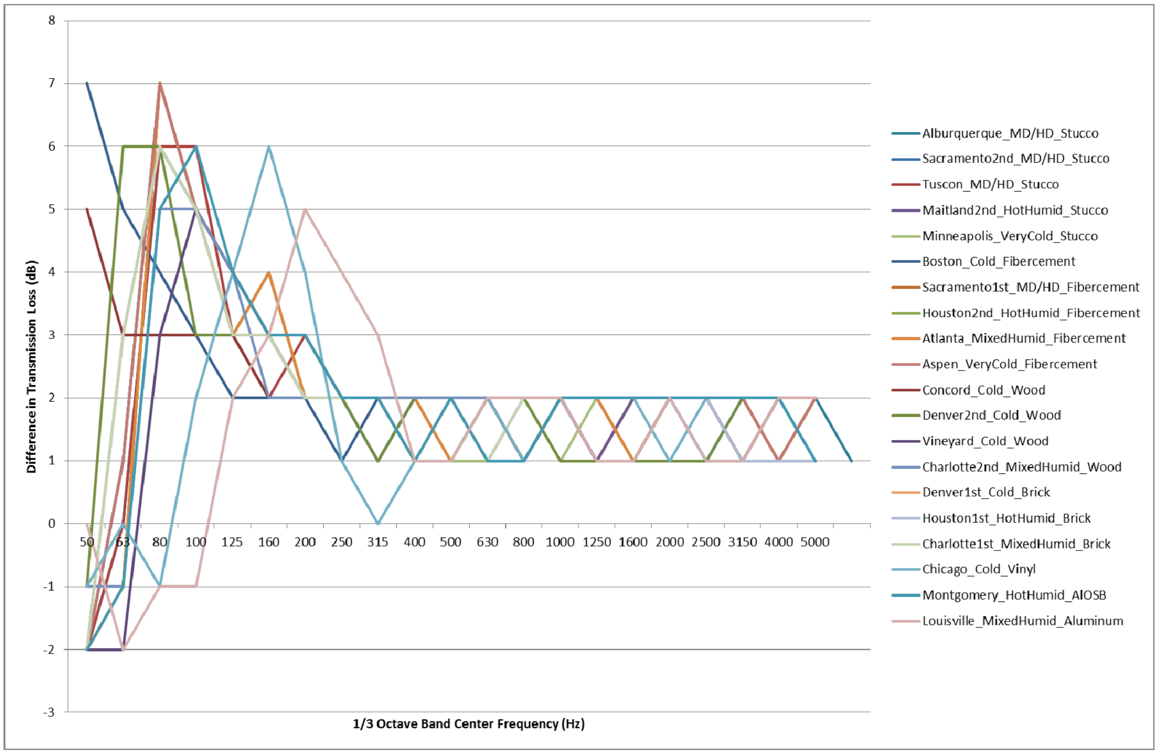


Figure 4.2: Difference in TL between Modern & Older Wall Constructions (City_Region_Ext.Layer), ordered by exterior construction layer

As it is difficult to process the data from 19 different construction profiles simultaneously, the data was condensed down by exterior layer construction type. It was noted that most constructions within each group had very similar difference curves, and so the curves from within each group were averaged together. The resulting graph is shown in Figure 4.3. Note that with the exception of the Vinyl/Aluminum group, most cases could be well represented with a single mean curve, shown in Figure 4.4.

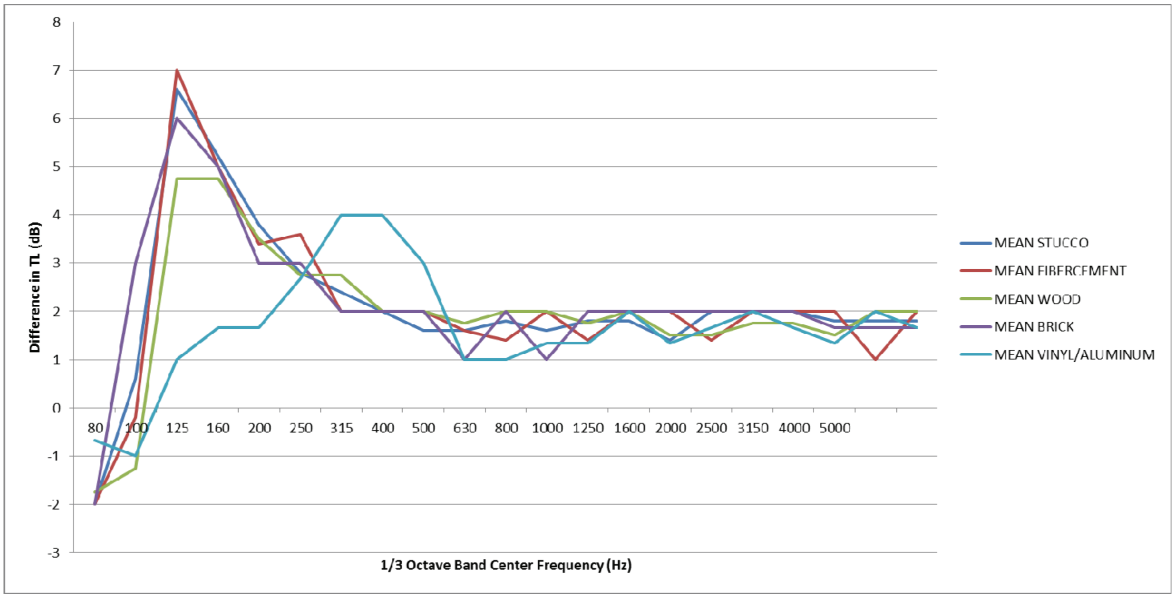


Figure 4.3: Difference in TL between Modern & Older wall constructions when grouped together by outermost construction layer (City_Region_Ext.Layer)

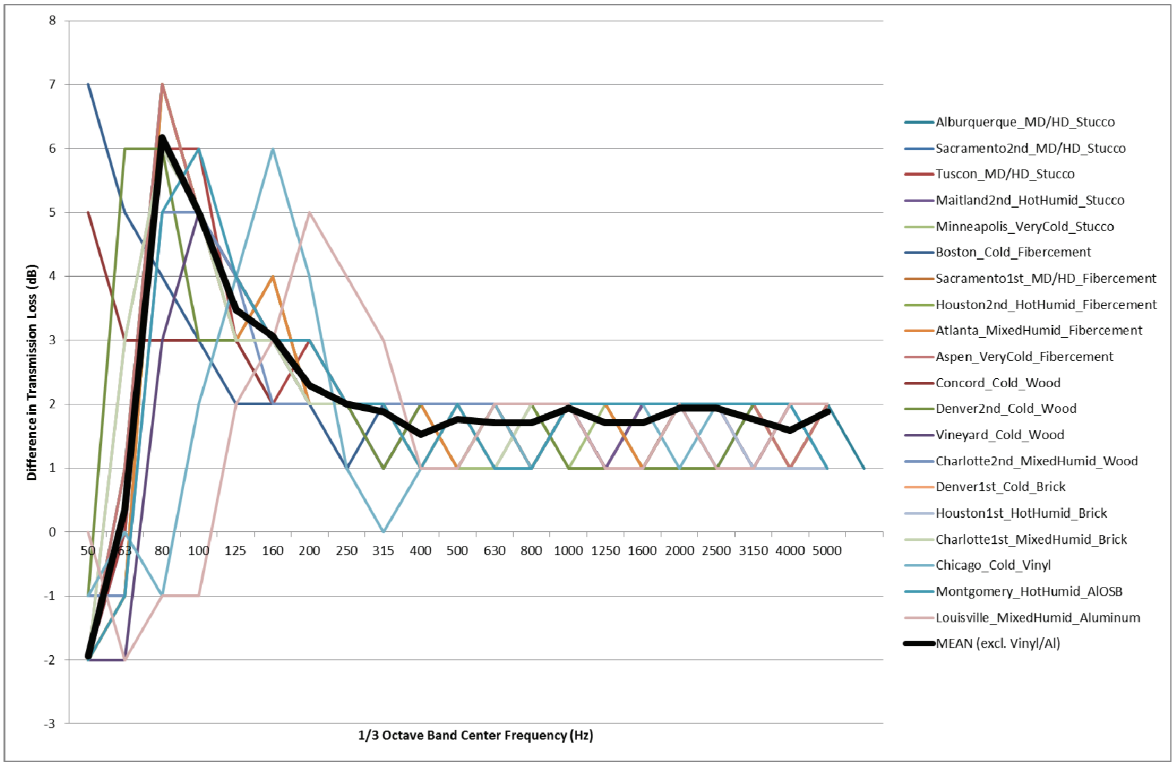


Figure 4.4: Difference in TL between Modern & Older wall constructions w/ mean (mean excludes vinyl and aluminum siding walls). (City_Region_Ext.Layer), ordered by exterior construction layer

Generally, the change from the modern constructions to the older constructions made a minimal difference in the STC rating of the partition (1-2 points), which is to be expected given that the STC metric does not as significantly weight the lower frequencies where most of the differences occurred (see Appendix E for more information on calculating the STC and OITC metrics). Decreasing the stud cavity did make a larger impact on the OITC ratings, with up to 5 points of difference in some cases. The full comparison between the single-number ratings of the modern and older construction types, plus the differences between them can be seen in Table 4.2.

Table 4.2: STC & OITC Comparison between Older & Modern Constructions

City_Region_ExteriorLayer	***Modern-STC***	***Modern-OITC***	***Old-STC***	***Old-OITC***	***Diff-STC***	***Diff-OITC***
Alburquerque_MD/HD_Stucco	48	43	47	38	1	5
Sacramento2nd_MD/HD_Stucco	46	41	44	37	2	4
Tuscon_MD/HD_Stucco	45	41	44	37	1	4
Maitland2nd_HotHumid_Stucco	48	43	47	38	1	5
Minneapolis_VeryCold_Stucco	48	44	46	39	2	5
MEAN STUCCO	47	42	46	38	1.4	4.6
Boston_Cold_Fibercement	47	40	45	35	2	5
Sacramento1st_MD/HD_Fibercement	46	37	44	33	2	4
Houston2nd_HotHumid_Fibercement	46	37	44	33	2	4
Atlanta_MixedHumid_Fibercement	46	37	44	33	2	4
Aspen_VeryCold_Fibercement	47	40	45	35	2	5
MEAN FIBERCEMENT	46	38	44	34	2	4.4
Concord_Cold_Wood	42	37	40	33	2	4
Denver2nd_Cold_Wood	40	37	39	33	1	4
Vineyard_Cold_Wood	39	32	37	29	2	3
Charlotte2nd_MixedHumid_Wood	39	33	37	29	2	4
MEAN WOOD	40	35	38	31	1.75	3.75
Denver1st_Cold_Brick	53	48	52	46	1	2
Houston1st_HotHumid_Brick	53	48	52	46	1	2
Charlotte1st_MixedHumid_Brick	53	48	52	46	1	2
MEAN BRICK	53	48	52	46	1	2
Chicago_Cold_Vinyl	35	23	33	22	2	1
Montgomery_HotHumid_AlOSB	41	35	39	31	2	4
Louisville_MixedHumid_Aluminum	37	25	35	23	2	2
MEAN VINYL/ALUMINUM	38	28	36	25	2	2.33

4.2.2 Noise Reduction of Older Home Constructions

As described in Chapter 3, Eqn. 3.4, the analytical formula for computing composite transmission loss,

$$TL_{Comp} = 10\log_{10}\frac{A_{Wall} + A_{Roof} + A_{Win}}{A_{Roof} * 10^{-TL_{Roof}/10} + A_{Wall} * 10^{-TL_{Wall}/10} + A_{Win} * 10^{-TL_{Win}/10}} \quad \text{(dBA)} \qquad \text{Eqn. 3.4}$$

was used to model the transmission loss for these older constructions instead of IBANA-Calc; as such, the NR values were not explicitly computed. In order to obtain NR values, it was necessary to replicate the process used within IBANA-Calc: subtract the TL from the source level at each frequency, while also accounting for absorption, to find the indoor noise levels; then the indoor levels across frequency were reduced to a single A-weighted level, which was subtracted from the A-weighted level of the source noise to give the noise reduction for that scenario, as already described in Chapter 3, Eqn. 3.1 –2:

$$NR_A = L_1 - L_2 \quad \text{(dBA)} \qquad \text{Eqn. 3.1}$$

where:

$$L_2 = L_1 - TL + 10log\left(\frac{S}{A}\right) \quad \text{(dBA)} \qquad \text{Eqn. 3.2}$$

For the 8’x12’ rooms, setting the absorption parameter in IBANA-Calc to “Bedroom” had the same effect as reducing the transmission loss by 3.5 dB at each frequency; for the 12’x15’ rooms, TL was effectively reduced by 2.6 dB. So, the indoor levels (L_2) at each frequency were calculated as the outdoor levels minus the actual TL values at each frequency, plus either 3.5 dB or 2.6 dB, as shown in Equations 4.1 and 4.2:

8’x12’: $$L_2 = L_1 - TL + 3.5 \quad \text{(dBA)} \qquad \text{Eqn. 4.1}$$

12’x15’: $$L_2 = L_1 - TL + 2.6 \quad \text{(dBA)} \qquad \text{Eqn. 4.2}$$

While the author acknowledges this is a less-than-ideal representation of absorption, it was used to maintain consistency with the previously presented data.

4.2.3 Observations

Generally, the A-weighted noise reduction ($\mathrm{NR_A}$) for these older home constructions, shown in Table 4.3, was very similar to that seen with the more modern constructions. In no cases did the $\mathrm{NR_A}$ values decline more than 3 dB, shown in Table 4.4. This is consistent with the changes seen in Table 4.2 on the previous page, showing the differences between the STC and OITC values of the wall constructions themselves. Note that while OITC values varied as much as 5 points between the older and modern constructions, the $\mathrm{NR_A}$ values were smaller, largely due to the reduced impact of changes in the low-frequency performance of the composite room due to the A-weighting.

Table 4.3: A-Weighted Noise Reduction ($\mathrm{NR_A}$) in dB(A) of older construction whole-house IBANA-Calc models for varying window types (WS, VDS, etc.); range indicates varying performance across the four modeled room/window size configurations

Wall Type and OITC Rating	Range of A-Weighted Noise Reduction ($\mathrm{NR_A}$) in dB(A) for Whole-House Models							
	Window Type and OITC Rating							
(City_Region_ExteriorLayer)	*WS, OITC 22*	*VDS, OITC 23*	*VDS1SW, OITC 27*	*AIC, OITC 23*	*AIC1SW, OITC 25*	*AIC3SW, OITC 30*	*SAC1, OITC 33*	*SAC2, OITC 43*
Alburquerque_MixedDry_Stucco, OITC 43	29-33	30-34	35-38	30-34	33-36	37-39	39-40	40-41
Chicago_Cold_Vinyl, OITC 23	22-23	22-23	23-24	22-23	23-24	23-24	23-24	23-24
Concord_Cold_Wood, OITC 37	28-31	29-32	32-34	29-32	31-34	33-34	34-35	34-35
Houston1st_HotHumid_Brick, OITC 48	29-33	30-34	35-39	30-34	33-37	38-40	40-41	42-43
Houston2nd_HotHumid_Fibercement, OITC 37	28-32	30-33	33-34	29-33	32-34	34-35	35-36	35-36
Montgomery_HotHumid_AlOSB, OITC 35	28-30	29-31	31-32	29-31	30-32	32	32-33	32-33

Table 4.4: Difference between Older & Modern Construction A-Weighted Noise Reduction ($\mathrm{NR_A}$) in dB(A) for varying window types (WS, VDS, etc.) ; range indicates varying performance across the four modeled room/window size configurations

Wall Type and OITC Rating	Range of Differences Between Older & Modern $\mathrm{NR_A}$ for Whole-House Models							
	Window Type and OITC Rating							
(City_Region_ExteriorLayer)	*WS, OITC 22*	*VDS, OITC 23*	*VDS1SW, OITC 27*	*AIC, OITC 23*	*AIC1SW, OITC 25*	*AIC3SW, OITC 30*	*SAC1, OITC 33*	*SAC2, OITC 43*
Alburquerque_MixedDry_Stucco, OITC 43	0-1	0-1	1-0	0-1	0-1	0-1	0-1	1-1
Chicago_Cold_Vinyl, OITC 23	2-3	2-3	2-2	2-3	2-2	2-2	2-2	2-2
Concord_Cold_Wood, OITC 37	0-2	0-2	1-2	0-1	1-1	1-2	1-2	2-2
Houston1st_HotHumid_Brick, OITC 48	3-3	0-1	1-0	0-1	0-1	1-1	0-1	1-0
Houston2nd_HotHumid_Fibercement, OITC 37	0-0	1-0	1-1	0-0	1-0	0-1	0-0	0-1
Montgomery_HotHumid_AlOSB, OITC 35	0-2	0-2	1-3	0-2	1-2	1-3	2-3	3-3

4.3 Additional Considerations

It is important to note that while the modeled transmission loss performance of these older wall constructions was largely similar to their more modern counterparts (generally within 3 dB; lower frequencies up to 7 dB), several factors have not been taken into account. It has been assumed that all other construction variables are the same except the stud cavity; however, other variables for older construction such as leaks and flanking paths should be accounted for in future research. Additionally, aging effects of materials should be considered. There is currently limited data available in this regard, but research on this topic is currently underway through the Airport Cooperative Research Program (ACRP) [26].

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

While the original hypothesis of this project aimed to generate a set of typical regional transmission loss profiles, the modeling process demonstrated that the variance across wall constructions alone within a single region precluded the identification of a typical regional wall type, much less a typical regional transmission loss curve. Instead, the various wall constructions were sorted based upon their outermost construction layer, allowing for the generation of a “typical stucco wall”, for instance. These wall constructions were then used to generate a series of whole-house models with varying window types, window sizes, and room sizes in order to identify and quantify trends that affect the transmission loss performance of building façades. Examination of the analytical formula for composite transmission loss revealed useful breakpoints for identifying the most significant, or “dominant”, building façade element.

As is to be expected, wall constructions which featured thick, massive layers (such as brick) had the best transmission loss performance, ranging from 32 dB at 50Hz to 70+ dB at 5kHz. In contrast, walls with only thin vinyl or aluminum siding as their outermost layer performed poorly, with TL values as low as 11 dB at 50Hz, up to 43 dB at 5kHz. Most walls, however, had between 14 dB and 22 dB of transmission loss at 50Hz, up to 51-60 dB at 5Khz; at midrange frequencies, the walls generally had between around 35 dB and 50 dB of TL.

Most composite whole-house models provided A-weighted noise reduction in the 30-40 dB range. Some home types, particularly those with large, poor-performing windows or very-poor performing walls were as low as 24 dB NR_A. OITC ratings were generally equivalent to the NR_A values or slightly (1-3 points) higher.

Several breakpoints emerged when examining the whole-house models generated in IBANA-Calc which were corroborated by analysis of the analytical formula for calculating transmission loss. These helped to identify the circumstances under which a building element is dominant, namely that 3 dB changes in the TL of the other building façade elements do not result in the composite TL changing more than 0.5 dB. When using this definition, it was found that the windows were dominant in cases where the roof and wall TL were both >15 dB above the window TL. Walls were dominant when the roof TL was >6 dB above the wall TL and the window TL was no more than 3 dB below that of the wall. The roof was dominant only when its TL was more than 6 dB below that of the wall and the window TL was not more than 6 dB below that of the roof.

Despite efforts to locate and use construction information for older homes more typical of those found near airports for this modeling process, reliable data simply were not readily available. Still, to approximate the effect of the more traditional framing techniques likely used in these older homes on composite façade transmission loss, additional models were created and analyzed by modifying the new construction models. The differences were generally within 2 dB for TL above 250Hz and 2 points for STC; at low frequencies, the differences increased by up to 7 dB, which caused the OITC to differ by as much as 5 points. It is also important to note that none of the models took into account field conditions such as aging that should be addressed in future research as described below.

5.2 Future Work

While the modeling performed thus far has provided a useful insight into how differences in wall constructions and window selections affect sound transmission into homes, further work is needed in order to more thoroughly validate the models against real-world constructions, improve and expand the modeling methodology, and extend the work into other areas with significant real-world application.

5.2.1 Development of Excel-Based Tool for Quick TL Estimations

While IBANA-Calc is functional and useful for generating whole-house transmission loss models, it has several major limitations, including the generating and exporting of large numbers of scenarios. Furthermore, one of the major challenges when dealing with predicting the transmission loss performance of existing homes is full knowledge of the layer-by-layer construction of the walls. As was shown in section 3.2.1, when walls are grouped by outermost construction layer, the transmission loss performance for walls featuring differing intermediate layers is quite similar (see Table 3.6 for standard deviations of STC and OITC values). Therefore, a tool could be developed which would allow the user to simply select the outer-most construction layer of the wall in question, the stud size (2x4 vs 2x6), the roof, the windows, and the window/wall areas, and the tool would generate an estimation of the composite room TL performance. This Excel-based tool could easily be disseminated to individuals not wanting to install, learn, and operate IBANA-Calc, especially those working in the field, to allow for quick in-situ estimations of transmission loss performance.

5.2.2 Expanded Modeling

This project provides a good foundation for future research to expand the modeling methodology. In this project, certain elements of the room construction models were simplified (e.g., complexities of various wall constructions) and other aspects were omitted (e.g., variability of roof constructions) in order to realistically achieve the main objectives of the project. While these simplifications and omissions did not detract significantly from the results as presented, there is certainly room to more thoroughly expand the information presented.

5.2.2.1 Indoor Noise Levels

One omission from this round of modeling was quantification of indoor noise levels in the home constructions modeled. It was determined that identifying the transmission loss properties of the building façade was the primary concern and that given the TL of the building façade and the source noise spectrum, the indoor noise levels should be relatively easy to calculate.

5.2.2.1.1 Source Noise Spectra

The greatest challenge in finding the indoor noise levels is determining the nature of the source noise, as different aircraft produce different noise spectra and different sound pressure levels. Also, the state of the aircraft makes a significant difference in both level and spectrum (whether it is taking off, landing, or simply flying overhead). The easiest way to identify the source noise information is by using data collected in the field outside homes exposed to actual aircraft noise, such as the data collected at the "Brick House" as a part of PARTNER Project 1 [27].

5.2.2.1.2 Receiving Room

The properties of the receiving room will also have an effect on the indoor noise levels. While the room dimensions should already be known (needed to model the wall and roof constructions), it is also necessary to identify the absorption properties of the room (or at least make a general assumption due to the room type) in order to find the reverberation time and factor in its effect on the noise levels. Of course, if the background noise in the space exceeds the levels predicted due to the incident aircraft noise, the indoor level will be no lower than that background noise. A basic modal analysis should also be undertaken to identify if any particularly problematic low-frequency modes exist that might be excited by the incident aircraft noise.

5.2.2.2 Additional Regions/Construction Types

While many different regional wall constructions were modeled for this project, numerous other variations exist. Efforts should be made to identify other sources of regional construction information and compare them with that provided by Building Science, both for validation and to identify new constructions to model. Additionally, identifying and modeling older construction types that are more likely to have been used in building the homes located near airports should be a priority. While some older constructions were modeled in this study, the only significant difference between the modern home constructions modeled and the older types was the change in the framing. In actuality, the exterior façade constructions may have been different as well; identifying and modeling those will provide a more substantial database for use with existing homes. Additionally, this study did not account for effects such as leaks, cracks, rattles, old seals, and the potential degradation of the TL properties of building materials, not to mention any potential differences that may have arisen from non- or sub-standard construction techniques. Further work is needed to fully explore this topic.

5.2.2.3 Improved Façade Element Modeling

Improving the model means ensuring the accuracy of the construction information used in the wall construction models, as well as transitioning from using TL data from a single roof construction to modeling various roofs.

5.2.2.3.1 Wall Constructions

While Insul does have some small accuracy concerns, it is still a good method for modeling wall constructions. To keep any accuracy problems to an absolute minimum, it is necessary to ensure that one is providing the most accurate construction information possible. This includes doing more research into the typically used thicknesses of materials which the Building Science database did not explicitly identify. It also includes ensuring the accuracy of the material property information used. It may be necessary to even perform laboratory testing of certain construction materials whose properties are not readily available to obtain the most accurate material property data for use in the model.

5.2.2.3.2 Roof Constructions

Future research should identify a modeling technique that will allow for the modeling of roof constructions instead of simply using transmission loss data contained in a database. This is challenging due to the highly complex and varied nature of roof constructions.

5.2.2.3.3 Windows/Doors/etc.

The current models rely upon window data from the IBANA-Calc database, plus some manufacturer-reported transmission loss data. Expanding this database would allow for more options when modeling actual home constructions. Additionally, as none of the modeled scenarios had exterior doors or other building elements, no effort has been made to identify or model them; these would be best treated on a case-by-case basis rather than expending great effort to identify a large database of such constructions beforehand.

5.2.2.4 Correction Factors

None of the correction factors included in IBANA-Calc were used in any of the models. There is some debate about the significance of the angle of incidence with aircraft noise for mid-high frequencies, but it may be useful to examine the effects of factoring that in. Further testing should be done prior to the use of the included correction factors since IBANA-Calc's creators did not fully validate them prior to its release [14].

5.2.3 Physical Model Testing

As up to this point all results obtained have been due to computer-generated models, it would be immensely useful to compare the models against actual physical constructions, whether in the lab or in the field.

5.2.3.1 Small In-Lab Constructions

While building a full home inside a lab is not a viable option, it is certainly feasible to build a small room inside a hemi-anechoic chamber to compare the computer models against physical constructions. The room could be constructed with framing and an interior layer of drywall that could remain standing but allow for various exterior layers to be used depending on which construction type was in question.

5.2.3.2 Field Testing

Alternately, visiting homes near airports and setting up microphones would be another way to gather real-world data. By taking the difference between the outdoor and indoor noise levels, the NR of the façade could be identified. In order to find the transmission loss, it would be necessary to adjust for the effect of the receiving room on the interior noise level. Since cutting open walls is not a viable option for most homes, some creative sleuthing will be required to identify the wall construction. Examining behind wall power outlets can allow for the identification of the thickness of drywall and cavity insulation used, as well as the type of framing. To identify the exterior layers, it will likely be necessary to find a removable penetration (such as a dryer vent), remove it, and then examine the wall layers. For the windows, it will be necessary to identify the most similar model available in the IBANA-Calc database (or any other database identified). Also, using this method to validate the modeling process as leaks and flanking paths would likely impact results.

5.2.4 Subjective Testing

Much has been written about the annoyance, sleep disturbance, and negative health effects caused by exposure to excessive noise. By using the predicted indoor noise levels (and spectra) identified for various constructions, studies could be undertaken to quantify which construction types result in the greatest annoyance or sleep disturbance. Similarly, studies could be performed to examine the effects of making specific changes to the building construction in order to determine if the improvement in annoyance or sleep disturbance is worth the cost of actually implementing the proposed retrofit. As quite a lot of money is spent on retrofits, quantifying the return-on-investment would help in the cost-benefit analysis for these programs.

5.2.5 Implications of Energy-Efficient Designs

In this day and age, significant focus is placed on energy efficiency with new building construction and retrofits, as well as an emphasis on “green” construction techniques. As was noted previously, sometimes building constructions which have similar thermal insulation properties have drastically different acoustical properties. Other times (such as with windows), the better thermal performer can have *poorer* acoustical performance (with windows, adding multiple panes causes mass-air-mass resonances which reduce the transmission loss performance significantly, often at frequencies where highly annoying noise is present). An effort could be made to compare various recommended energy-efficient construction techniques to quantify the acoustical implications of such constructions.

APPENDIX A

LITERATURE REVIEW

The following is a collection of resources examined during the course of this research, primarily highlighting the effects of aircraft noise on annoyance and health, as well as the history of government and international aircraft noise standards.

A.1 Annoyance Due to Aircraft Noise

High levels of aircraft noise in homes tends to cause annoyance by interfering with daily activities, such as having conversations (whether in person or on the telephone) or listening to the television or radio. This intrusion is perceived as more disturbing than other kinds of noise, most likely due to the sporadic nature of aircraft noise, with individual noise events each having their own distinct rise and fall pattern [1].

This noise-induced annoyance, defined by Passchier-Vermeer and Passchier as “a feeling of resentment, displeasure, discomfort, dissatisfaction, or offense when noise interferes with one’s thoughts, feelings, or actual activities,” [28] has been increasing over time [29]. Many factors have been shown to affect annoyance, including variations in the source signal, background noise, number of events, age, self-reported sensitivity, and more; however, not all such reports agree, and many actually contradict one another. For example, Lim et al. found that when the level of aircraft noise is held constant, people in homes with lower background noise tended to be more highly annoyed [30]. This is in contrast with Taylor et al. who found that the level of background noise present was not significant when examining the level of annoyance to aircraft noise [31]. Studies have found that annoyance increased as did the noise level of the overflights [32, 33], but Fidell et al. found that the level, duration, and spectral content of noise were not sufficient predictors to determine annoyance [34]. Some reports do agree, however:

Pepper et al. found that susceptibility to noise annoyance may depend on the proximity to the source or the frequency of exposure [35]. Bjorkman also found that annoyance increased with the number of overflight events up to a certain breakpoint [33]. Van Gerven et al. found that the most highly annoyed individuals tended to be of middle age, with much fewer individuals of younger and older ages being highly annoyed [36], and Krog and Engdahl found that people who were highly annoyed by aircraft noise at home were more highly annoyed than others when exposed to aircraft noise in recreational areas [37]. Interestingly, in a 2004 study looking at data across three countries, self-reported noise sensitivity became a reliable predictor for annoyance due to aircraft noise, independent of the actual noise level [38].

Natural settings such as national parks have been specifically studied with regards to aircraft noise. There is a large amount of variance in visitor sensitivity to aircraft noise in national parks. For example, the farther visitors hiked away from the parking lot, the more likely they were to be annoyed by aircraft noise [39]. Annoyance increased as the level of the aircraft noise increased with respect to the background sound levels and as the duration of the noise event increased. Visitors who were prepared for the possibility of hearing aircraft noise were less annoyed than those who were not. Repeat visitors to parks tended to be more annoyed by aircraft noise, and visitors were more sensitive to noise from tour aircraft than from high-altitude jet overflights [40].

A.1.1 Dose-Response Relationship

In 1978, Schultz developed a dose-response curve that roughly fit available data from several scattered studies [41]. This helped demonstrate time-weighted average noise exposure as a predictor of community response. Since then, Schultz and others have reanalyzed the data and suggested alternate fitting functions [42]. Schultz’s premise was that he could reliably predict the subjective community response to noise from physical measurements of the noise. He did this by reviewing existing surveys of noise annoyance and adjusting the data to a common scale, and then fitting a curve to the data [41]. This curve showing the relationship between day-night level and percent of people highly annoyed is shown in Figure A.1 on the following page, along with curves showing noise interference with activities and curves showing the percentage of people and locations exposed to various levels of noise.

In a 1992 report, the U.S. Federal Interagency Committee on Noise (FICON) established its own fitting function as the preferred annoyance prediction metric, but the FICON curve was not based on practical noise exposure levels, rather being fit to data points at exposure levels both 20 dB higher and lower than what is typically of practical interest to regulatory bodies. This had the effect of biasing the function to underestimate annoyance at more reasonable noise levels [42]. The result was the establishment of 65 dB DNL, or Day-Night Average Sound Level, as the threshold above which outdoor aircraft noise is unacceptable. FICON has since been succeeded by a similar body named FICAN, which has yet to attempt to improve the accuracy of its prediction metrics.

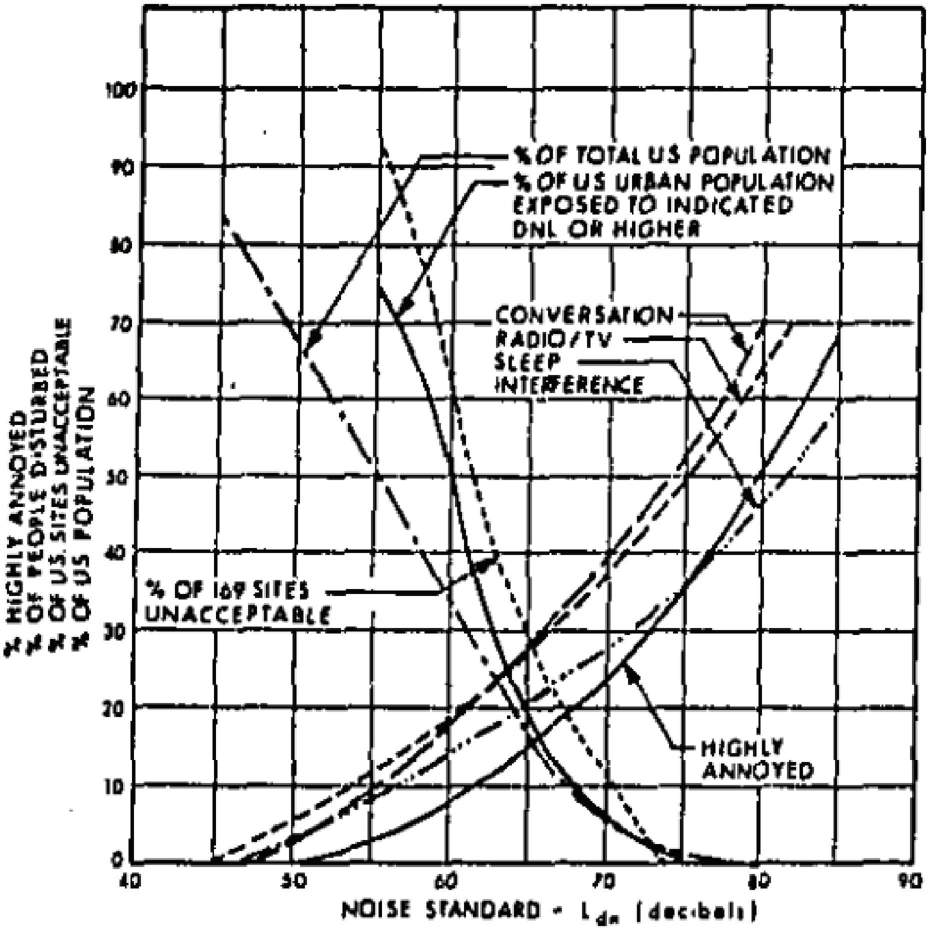


Figure A.1: Schultz Cuve. Reproduced from [41]: "Summary of data from eleven social surveys concerning noise from aircraft, street traffic, highway traffic and railroad traffic: percentage of the local population highly annoyed or activity interference. The consequences of various choices for noise standard are also shown in terms of the percentage of U.S. sites and of U.S. population currently exposed to higher levels."

A.1.1.1 Day-Night Level (DNL)

Since the standard threshold for the acceptability of outdoor aircraft noise is 65 dB DNL [1] [42] , most noise contours in the US are depicted in terms of DNL. DNL is a single-number metric used to give a time-of-day weighted average of the A-weighted sound level of noise events occurring over a 24-hour period. The DNL metric penalizes events occurring between 10:00PM and 7:00AM by 10 dB in order to reflect the greater intrusiveness of nighttime noise [1, 35].

A.1.1.2 Controversy Surrounding Dose-Response Metrics

Despite the 65 dB DNL threshold for most federal regulations, most experimental data does not support 65 dB DNL as being a watershed data point, especially considering that more people are highly annoyed by aircraft noise at 65 dB DNL than FICON predicts [42]. A GAO report from 2000 actually found that most aircraft noise complaints are received from areas *outside* the 65 dB DNL contour surrounding the airports in question [43]. It is becoming increasingly apparent that exclusively using this DNL metric may not fully capture many important attributes of the noise and how it affects the communities [11].

A.1.1.3 Subjectivity of Annoyance

Annoyance is a highly subjective metric. An important thing to consider is that non-acoustic factors can have a large effect on community annoyance levels [1]. Such factors can include the cultural background and attitude of the residents, as well as variations in climate (such as temperature, humidity, and wind). Additionally, since the construction of the home affects the level and spectrum of the sound transmitted indoors, differences in housing construction can, in turn, affect annoyance. There are acoustic factors which are not captured in the DNL metric that can contribute to annoyance, including tonal content and the frequency spectrum of the noise [44]. DNL also does not adequately account for variations in the number and types of aircraft operating, or the time of day that these operations occur. (While DNL has a penalty for sounds at night, there are a very wide range of scenarios possible to achieve the same DNL but which will cause wildly different levels of annoyance [44].) As Elrich et al. state, “There is no simple relationship between DNL and the maximum noise level” [1].

A.2 Impact of Aircraft Noise on Health

A massive study (6,000 persons aged 45-70) undertaken in the EU known as the HYENA study (Hypertension and Exposure to Noise near Airports) aimed to assess the impact of noise on cardiovascular health, primarily relating to high blood pressure (BP) [45]. Additionally, smaller samples were used to examine the effects of noise on saliva cortisol levels (500 persons) and the short-term effects of noise on blood pressure over a 24-hour period (200 persons). Using a standardized questionnaire, the study collected data on annoyance, noise disturbance, and “modifiers of individual exposure, such as the orientation of living and bedroom toward roads, window-opening habits, and sound insulation.”

The aforementioned modifiers, along with previously collected road traffic data, were used to normalize the data collected in the HYENA study [45]. Using data from the HYENA study, Kaltenbach et al. demonstrated a link between aircraft noise and hypertension [46]. Selander et al. noted that saliva cortisol levels were elevated in women exposed to aircraft noise [47]. Goines and Hagler also describe several studies linking psychological and physiological symptoms and noise exposure [48]. Other studies have shown that aircraft noise has a particularly adverse effect on the development and health of children, as described below.

A.2.1 Impact on Children

Babisch et al. found that noise at home had an effect on children’s blood pressure [49], and Hygge et al. found that children living near airports suffered long-term memory and reading impairment [50]. Stansfeld et al. suggested that schools be the primary focus for reducing children’s exposure to noise as nighttime aircraft noise exposure does not additionally impact children’s cognitive performance beyond the level caused by daytime exposure alone [51].

Children from noisy schools tend to have higher blood pressures than those from quieter schools [52]. They are also more likely to fail when given a task or give up before time has elapsed as they were unable to concentrate. In contrast, children in quieter environments were able to concentrate longer and put forth a more determined effort to solve "unsolvable" puzzles [53]. Bullinger et al. also concluded that children living near noisy airports experience a significant decrease in quality of life, which he defined as having "an impaired sense of well-being, a decrease in motivation, and a decrease in their sense of control.

A.2.2 Impact on Sleep

Most complaints about aircraft noise are due to noise events occurring during the night [54], with such events being roughly twice as annoying as those occurring during the daytime [55]. Borsky also found that "the quality of sleep and sleep disturbance is directly related to the intensity of aircraft noise exposure." Basner, however, notes that noise events with the same DNL can wildly differ in their sleep disturbing potential due to how DNL is calculated and how the noise events are perceived [54]. Fyhri and Aasvang (2010) found significant relationships between annoyance due to nighttime noise exposure and sleeping problems [56].

Fidell disagrees, stating, "non-aircraft related awakenings are more common than aircraft noise-induced awakenings in airport neighborhoods and that only small percentages of habitually exposed people in familiar sleeping quarters are regularly awakened by aircraft noise intrusions" [57].

A.2.3 Impact on Animals

The effects of noise aren't just limited to humans. When exposed to loud noises, animals may exhibit changes in behavior patterns. Fright is a common response, but most animals return to normal behavior relatively quickly [35]. For example, aircraft overflights caused the heart rates of mountain sheep to elevate above preflight levels, but they returned to normal within two minutes of the conclusion of the overflight [58]. Harlequin ducks showed elevated alert behavior due to aircraft overflights; physiological responses returned to normal within one minute, but residual behavioral changes did linger for up to two hours afterward [59]. Mexican spotted owls showed limited response to aircraft noise, with any behavioral changes quickly returning to normal; however, it was noted that the owls' responses to the aircraft noise was oftentimes less than that caused by naturally occurring events [60]. Also, it has been shown that military activities can cause bald eagles to flush (quickly leave their nests) [35], which can cause eggs to break or nestlings to fall out before they are able to fly. Chronic noise exposure can impair communication between animals by masking their vocalizations; sometimes animals will go so far as to alter their communication techniques to compensate for the noise masking [61].

A.3 Government Standards Concerning Aircraft Noise

For land to be considered compatible with airport operations by the FAA land use guidelines, the annual outdoor average aircraft noise exposure must be below 65 dB(A) DNL [44]. The goal of most airport noise-compatibility and mitigation programs is to establish and/or maintain compatible land uses in areas at or above that threshold, but this is a difficult proposition since the federal government generally does not control land use (zoning authority is reserved to the states and their subdivisions) [62]. Instead, the FAA works to encourage and guide state and local governments to exercise their authority in a way that serves both the airport and the community.

As of 2000, it was estimated that some 675,000 people lived within the 65 dB DNL contour near 48 of the 50 busiest US airports, but about half of the complaints received at 35 of these airports actually came from people living *outside* the 65 dB DNL contour [43], with some complaints coming from as far as 50 miles away [11]. As a result of this, airports have to wrestle with the conflict between public perception and regulated standards [11].

A.3.1 History of US Standards

The Aircraft Noise Abatement Act of 1968 authorized the FAA to prescribe standards for the measurement of aircraft noise and to establish regulations to abate it [63]. The Noise Control Act of 1972 amended the Aircraft Noise Abatement Act to give the Environmental Protection Agency (EPA) the ability to work with the FAA to establish goals for decreasing noise level exposure. The standards the EPA established are based upon the time of day, with 55 dB during waking hours and 45 dB during sleeping hours [35]. However, the primary responsibility for control of noise rests with state and local governments [63].

The 1976 Aviation Noise Abatement Policy published by the Department of Transportation provided a course of action for reducing aviation noise impact, and along with subsequent legislative and regulatory action, has resulted in a dramatic reduction in the number of Americans exposed to unacceptable levels of aircraft noise [62]. At the time, 6-7 million Americans were exposed to DNL65 or above near airports. The report estimated that by the year 2000, only 500,000 Americans would be exposed to this level of noise. The policy outlined an effort to reduce aircraft noise, primarily by aircraft source-noise reduction. There is continued emphasis to reduce the number of people living within the DNL65 contours around airports.

The Federal Interagency Committee on Urban Noise (FICUN) was formed in 1979 to “develop Federal policy and guidance on noise” [62]. FICUN membership included the Environmental Protection Agency (EPA), Federal Aviation Administration (FAA), Federal Housing Authority (FHA), Department of Defense (DOD), Housing and Urban Development (HUD), and Veterans Administration (VA). FICUN “developed consolidated Federal agency land use compatibility guidelines using Yearly Day-Night

Average Sound Levels (DNL) as the common descriptor of noise levels." In 1980, FICUN issued the Guidelines for Considering Noise in Land Use Planning and Control which established DNL65 as the government's threshold for acceptable noise exposure; this standard had been a part of the Aviation Safety and Noise Abatement Act (ASNA) of 1979.

The National Parks Overflights Act (Public Law 100-91, passed in 1987) declared that aircraft overflight noise impaired the ability of park visitors to use and enjoy the national parks [64]. Because of this, it mandated a noise study to assess damage inflicted upon the wilderness ecosystem. The US Fish and Wildlife Service then established a 500-ft limit on flights over national wildlife refuges [35]. As stated by Girvin (2010), "FAA recognizes that the 65 dB(A) DNL significant noise threshold inadequately addresses the effects of noise in naturally quiet areas such as National Parks and wilderness" [44]. In 1990, the Aircraft Noise and Capacity Act (ANCA) was enacted, causing the responsibilities of regulating and abating excessive noise to fall on the federal government. This policy directed national leadership to decrease aircraft noise and was revisited and reinitiated in 2000 [35].

The Federal Interagency Committee on Noise (FICON) was formed in 1991 to "review technical and policy issues related to assessment of noise impacts around airports" [62]. FICON membership included the DOD, Department of Transportation (DOT), HUD, Department of Justice (DOJ), VA, and the Council on Environmental Quality. The FICON reaffirmed the methodology employing DNL as the noise exposure metric and appropriate dose-response relationships (primarily the Schultz curve for Percent Highly Annoyed) to determine community noise impacts.

Based on policy recommendations from the FICON report, the Federal Interagency Committee on Aviation Noise (FICAN) was formed in 1993 [62]. FICAN served to "facilitate research on methodology development and on the impact of aircraft noise." FICAN membership included the DOD, HUD, DOT, the Department of the Interior, National Aeronautics and Space Administration (NASA), and the EPA.

The FAA's goals in 2000 were to continue to reduce aircraft noise at its source; use new technologies to mitigate noise impacts; bring existing land uses into compatibility with levels of significant noise exposure around airports, and prevent the development of new non-compatible uses in these areas; provide special considerations to locations in national parks; ensure strong financial support for noise compatibility planning and for mitigation projects [62].

In 2001, NASA had a noise-reduction goal that would have enabled the 65 dB DNL contour to be contained entirely within airport-compatible land-use areas by 2011, and the 55 dB DNL contour by 2026 [11]. Unfortunately that effort has been unsuccessful.

A.3.2 History of International Standards

The 1944 Convention on International Civil Aviation, more commonly known as the "Chicago Convention," paved the way for international standards for aircraft and aircraft noise by giving the International Civil Aviation Organization (ICAO) the authority to adopt international standards and recommended practices [65]. Contracting states, including the United States and participating members of the European Union (EU), are required to follow the standards, but only must make a reasonable effort to follow the recommended practices [35, 65].

In 1966, nations experiencing the expansion of air travel and the problems with noise that came with it met at the International Conference on the Reduction of Noise and Disturbance Caused by Civil Aircraft (commonly referred to as the London Noise Conference) and were able to make some conclusions about the problem of aircraft noise [65]. These were introduced to the ICAO at the Fifth Air Navigation Conference in Montreal in 1967, which lead to the ICAO adopting a resolution to address aircraft noise in 1968 at the Sixteenth Session of the Assembly in Buenos Aires. In response to this resolution, the ICAO convened the 1969 Special Meetings on Aircraft Noise in the Vicinity of Aerodromes, whose recommendations lead to Annex 16 to the Chicago Convention being adopted in 1971, which dealt with aircraft noise and engine emissions [65]. The 1969 meetings also lead to the creation of the Committee on Aircraft Noise to "assist ICAO in the development of noise certification requirements for different classes of aircraft [10]." This committee has since been superseded by a broader Committee on Aviation Environmental Protection which reviews and proposes noise standards [10].

The goals of the ICAO are the following: "establishing procedures for describing and measuring aircraft noise; assessing human tolerance to aircraft noise; aircraft noise certification; formulating criteria for establishing noise abatement procedures that address ground run-up of aircraft; and land-use control" [65].

The primary method of regulation used by the ICAO is the certification process for different classes of aircraft and aircraft engines, and the permission or prohibition of their use [65] as "the reduction of aircraft noise at its source has provided the greater amount of noise relief to the public" [62]. By phasing out older, noisier designs, the ICAO aims to reduce the noise emitted by the aircraft, and thus the community noise exposure. Chapter 2 of Volume I of Annex 16 to the Chicago Convention applies to aircraft designs certified prior to 1977; Chapter 3, which has much more stringent standards, applies to designs certified between 1977 and 2006 [65]; Chapter 4, which requires a cumulative reduction of 10 dB below the Chapter 3 standard, applies to aircraft designs certified since 2006 [11]. In the US, these are known as Stage 2/3/4 aircraft. Unfortunately, the reduction of noise from each successive generation of new aircraft is flattening out, making further major gains in noise reduction from the source a challenge [11].

A.3.2.1 World Health Organization WHO

The World Health Organization (WHO) recommends in its Guidelines for Community Noise, that continuous interior background noise levels should not exceed 30 dB (A) to allow for uninterrupted sleep, with individual noise events not exceeding 45 dB (A) [66]. The WHO also recommends that daytime LAeq levels remain below 50 dB (A) outdoors to minimize annoyance, with evening and nighttime levels 5-10 dB lower.

APPENDIX B

DATABASE OF TRANSMISSION LOSS RESOURCES

The following is a collection of resources examined during the search for transmission loss resources. Indications are given as to the nature of the material contained within each resource. An ideal database would consist of the following components:

- Transmission Loss (TL) data across frequency (1/3 Octave Band preferable), not simply single-number ratings
- Detailed construction information, including all layers and dimensions
- Exterior home constructions, organized by climate region, not interior partitions or non-home constructions
- Both older and more modern constructions
- Widely available to the public, not out of print or difficult to obtain

For each resource investigated, the following table gives a "Quick Reference", a "Full Reference", whether the resource gives STC or OITC values (or both), whether the resource gives TL values (1/3 OB or OB), whether the resource gives interior or exterior construction information (or both), whether the resource indicated typical home wall constructions, or whether the resource was unable to be located (or was located but not purchased for investigation).

Table B.1: Database of Potential Transmission Loss Resources and Information Included with Each

Quick Reference	Full Reference	STC/ OITC?	TL?	Interior/ Exterior?	Typical Home Wall Constructions?	Not Located/ Purchased
GREENBOOK	2012 Greenbook: Standard Specifications for Public Works Construction					X
HUD 1967	A guide to airborne, impact, and structure-borne noise control in multifamily dwellings. Rep. FT/TS-24. Washington, D.C: U.S. Department of Housing and Urban Development; 1967.	STC	No	Int	Yes	
NBS-BSS-77	Acoustical and thermal performance of exterior residential walls, doors, and windows. NBS-BSS-77. Washington, DC: U.S. Department of Commerce, National Bureau of Standards; 1975.	STC	1/3OB	Both	Yes	
Parkin (1979)	Acoustics Noise and Buildings; Parkin, Humphreys and Cowell; Faber and Faber; London; 1979	STC	1/3OB	Ext.	No	
FPL-43	Airborne Sound Transmission Loss, Characteristics of Wood Frame Construction; Fred F. Rudder, Jr.; USDA, Forest Service; General Technical Report FPL-43.	STC		Both	Yes	
HUD 1968	Airborne, Impact & Structure borne Noise Control, HUD FT/TS 24,1968, NTIS PB 210849	STC	No	Int.	Yes	
IR-818	Bradley J.S., Birta, J.A. Laboratory Measurements of the Sound Insulation of Building Facade Elements. IRC Internal Report, IRC IR-818, October 2000	Both	1/3OB	Ext.	Yes	
Dupree (1981)	Dupree, R. B., 1981, “Catalog of STC and IIC ratings for wall and floor/ceiling assemblies—With TL and ISPL data plots,” Office of Noise Control, California Department of Health Services					X

Quick Reference	Full Reference	STC/ OITC?	TL?	Interior/ Exterior?	Typical Home Wall Constructions?	Not Located/ Purchased
NIOSH 80-116	Compendium of materials for noise control. Publ. No. 80-116. Cincinnati, OH: U.S. Department of Health, Education, and Welfare, National Institute for Occupational Safety and Health; 1980.		Mixed		No	
Harris (1997)	D. Harris (1997) Noise Control Manual for Residential Buildings (The McGraw-Hil Companies, Inc., New York, New York)	STC	OB	Both	Yes (Int); No (Ext)	
IR-811	Detailed Report for Consortium on Fire Resistance and Sound Insulation of Floors: Sound Transmission and Impact Insulation Data in 1/3Octave Bands, IRC,NRC-CNRC, IR 811, 2000, 237 pages		1/3OB	Int.	No	
IR-761	Gypsum Board Walls - Transmission Loss Data, IRC,NRC-CNRC, IR 761,1998, 365 pages		1/3OB	Int.	No	
Retting (1979)	Handbook of Architectural Acoustics and Noise Control; Michael Retting; Tab Book; Blue Ridge Summit, Pa.; 1979.					X
Riverbank, 1969	Measurements of Sound Transmission Loss in Masonry, Riverbank Acoustical Laboratories, Monograph #1, 1969		1/3OB	Ext.	No	
Sabine (1967)	Octave and one-third-octave TL data, STC, and IIC ratings. Sabine et al (1967)					X
PARTNER 1.5	PARTNER Project 1.5 Report. Daniel H. Robinson, Robert J. Bernhard, Luc G. Mongeau. January 2008. Report No. PARTNER-COE-2008-003	Both	1/3OB	Ext.	No	
NBS 119	Quieting: A Practical Guide to Noise Controls; U.S. Department of Commerce/National Bureau of Standards; NBS Handbook 119; 1976.				No	

Quick Reference	Full Reference	STC/ OITC?	TL?	Interior/ Exterior?	Typical Home Wall Constructions?	Not Located/ Purchased
BBC, 1986	Sound Insulation of partitions in Broadcasting Studio Centers -field measurement data. 1986, BBC 534.833.522 (England)			Int.	No	
NBS m77	Sound Insulation of wall, Floor and Door construction, 1964, NBS monograph 77		1/3OB	Int.	No	
IR-586	Sound Transmission Loss Measurements Through 190 mm and 140 mm blocks with Added Drywall and through Cavity Block Walls. IRC,NRC-CNRC, IR-586 1990		1/3OB	Ext.	No	
NRCC 35545	Sound Transmission Loss Measurements Through two kinds of porous concrete blocks with Attached Drywall. IRC,NRC-CNRC, NRCC 35545, 1991		1/3OB	Ext.	No	
BRN-93	Sound Transmission Loss of Masonry Walls, 12" lightweight Concrete Blocks - comparison of Latex and Plastic Sealers, IRC,NRC-CNRC, BRN-93, 1974		1/3OB	Ext.	No	
BRN-90	Sound Transmission Loss of Masonry Walls, 12" lightweight Concrete Blocks with Various Surface Finishes, IRC ,NRC-CNRC, BRN-90, 1974		1/3OB	Ext.	No	
BRN-217	Sound Transmission Loss of Masonry Walls, Tests on 90,140,240, & 290mmConcrete Block walls with Various Surface Finishes, IRC,NRC-CNRC,BRN-217, 1984		1/3OB	Ext.	No	
JACI, 1978	Sound Transmission Loss through Concrete and Concrete Masonry Walls, J. American Concrete Institute, No 12, Vol 75, Dec 1978. available from PCA		1/3OB	Ext.	No	
NBS GCR 80-250	Ben H. Sharp, Peter K, Kasper, Mark L. Montroll. Sound transmission through building structures : review and recommendations for research (1980) NBS GCR 80-250				N/A	

Quick Reference	Full Reference	STC/ OITC?	TL?	Interior/ Exterior?	Typical Home Wall Constructions?	Not Located/ Purchased
IR-693	Sound Transmission through Gypsum Board Walls: Sound Transmission Results IRC, NRC-CNRC, IR 693, 1995, 83 pages		1/3OB	Int.	No	
NAHB, 2001	Stewart, Noral D., Ph.D (September 19,2001). Measurements of Appartment Sound Insulation of Exterior and Interior Walls (National Association of Home Builders Research Center) Lexington, NC	Both	1/3OB	Both	Yes (Int); No (Ext)	
RR-169	Summary Report for Consortium on Fire Resistance and Sound Insulation of Floors: Sound Transmission and Impact Insulation Data. IRC,NRC-CNRC, RR 169, 2005, 116 pages		1/3OB	Int.	No	
IR-766	Summary Report for Consortium on Fire Resistance and Sound Insulation of Floors: Sound Transmission Class and Impact Insulation Class Results, IRC, NRC-CNRC, IR 766, 1998, 119 pages		1/3OB	Int.	No	
BRN-66	Transmission Loss of Plasterboard Walls. IRC, NRC-CNRC, BRN No. 66, 1970.	STC	1/3OB	Int.	No	

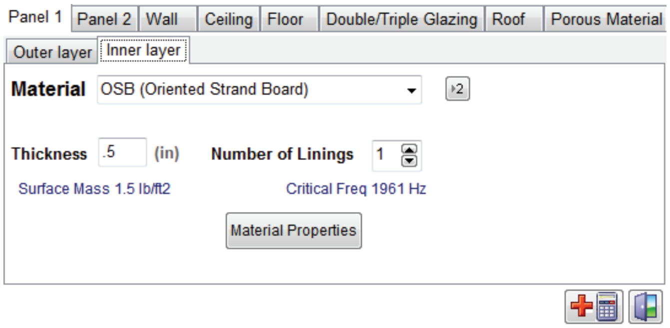
APPENDIX C

GENERATING A WALL MODEL IN INSUL

This appendix illustrates the process of generating a wall model using the commercial software package Insul v6.4 developed by Marshall Day Acoustics in New Zealand.

C.1 Generating a Standard Wall

Modeling a standard wall in Insul is fairly straightforward. Simply select the outer and inner panel layer materials for interior and exterior panels from the drop down boxes and specify the thickness of each layer and the number of such layers. Then switch to the Wall tab and input the framing details, including cavity insulation. Insul automatically generates the wall transmission loss curve and provides the data in a convenient table for ease of exporting.



Material OSB (Oriented Strand Board)

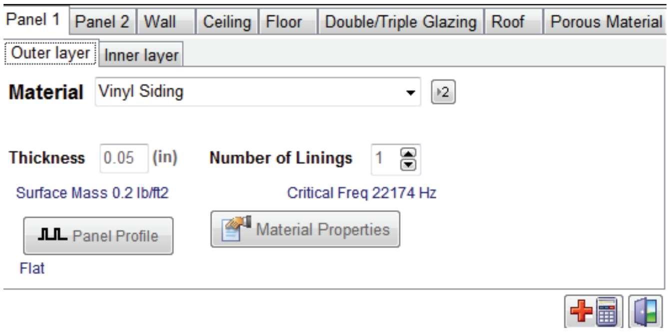
Thickness .5 (in)

Number of Linings 1

Surface Mass 1.5 lb/ft2

Critical Freq 1961 Hz

Figure C.1: Panel 1 Inner Layer



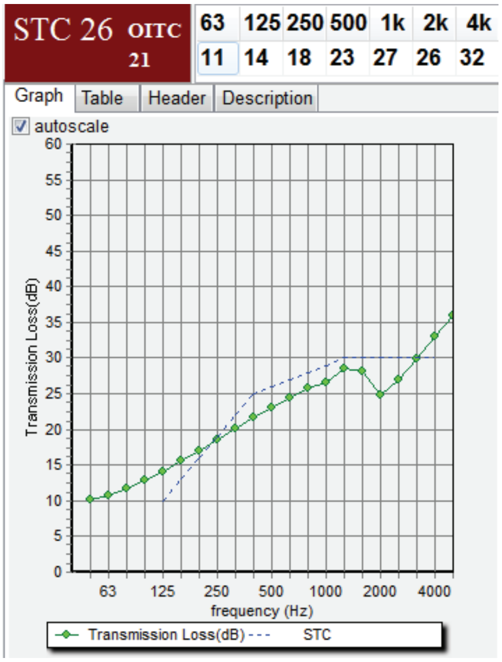
Material Vinyl Siding

Thickness 0.05 (in) **Number of Linings** 1

Surface Mass 0.2 lb/ft2 Critical Freq 22174 Hz

Flat

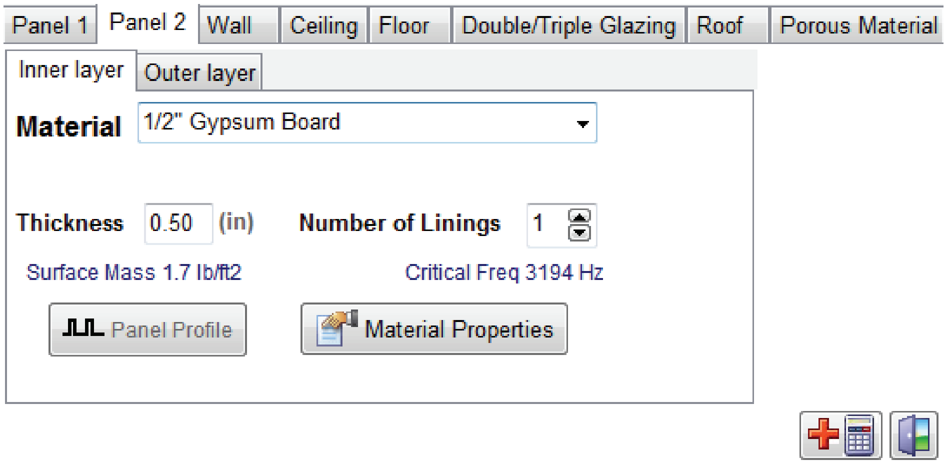
Figure C.2: Panel 1 Outer Layer



STC 26 OITC 21

63	125	250	500	1k	2k	4k
11	14	18	23	27	26	32

Figure C.3: Panel 1 Overall Transmission Loss Curve

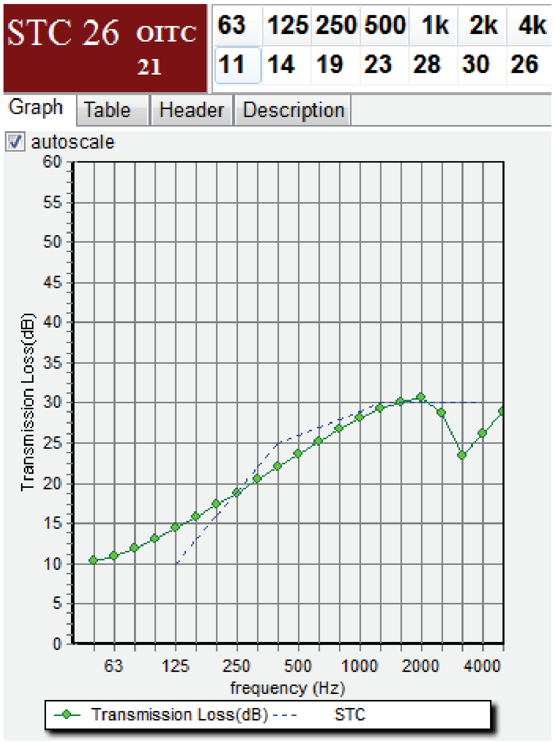


Material 1/2" Gypsum Board

Thickness 0.50 (in) **Number of Linings** 1

Surface Mass 1.7 lb/ft2 Critical Freq 3194 Hz

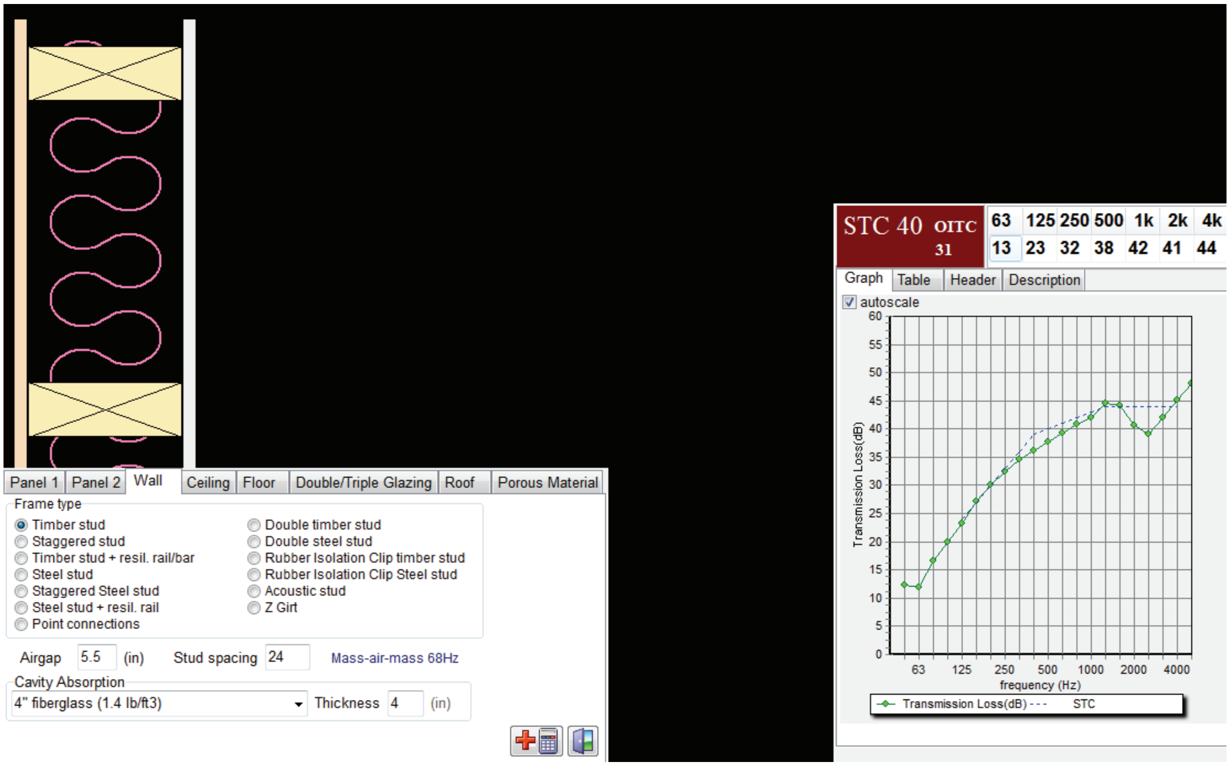
Figure C.4: Panel 2 Inner Layer



STC 26 OITC 21

63	125	250	500	1k	2k	4k
11	14	19	23	28	30	26

Figure C.5: Panel 2 Overall Transmission Loss Curve



Frame type

● Timber stud
○ Staggered stud
○ Timber stud + resil. rail/bar
○ Steel stud
○ Staggered Steel stud
○ Steel stud + resil. rail
○ Point connections
○ Double timber stud
○ Double steel stud
○ Rubber Isolation Clip timber stud
○ Rubber Isolation Clip Steel stud
○ Acoustic stud
○ Z Girt

Airgap 5.5 (in) Stud spacing 24 Mass-air-mass 68Hz

Cavity Absorption

4" fiberglass (1.4 lb/ft3) Thickness 4 (in)

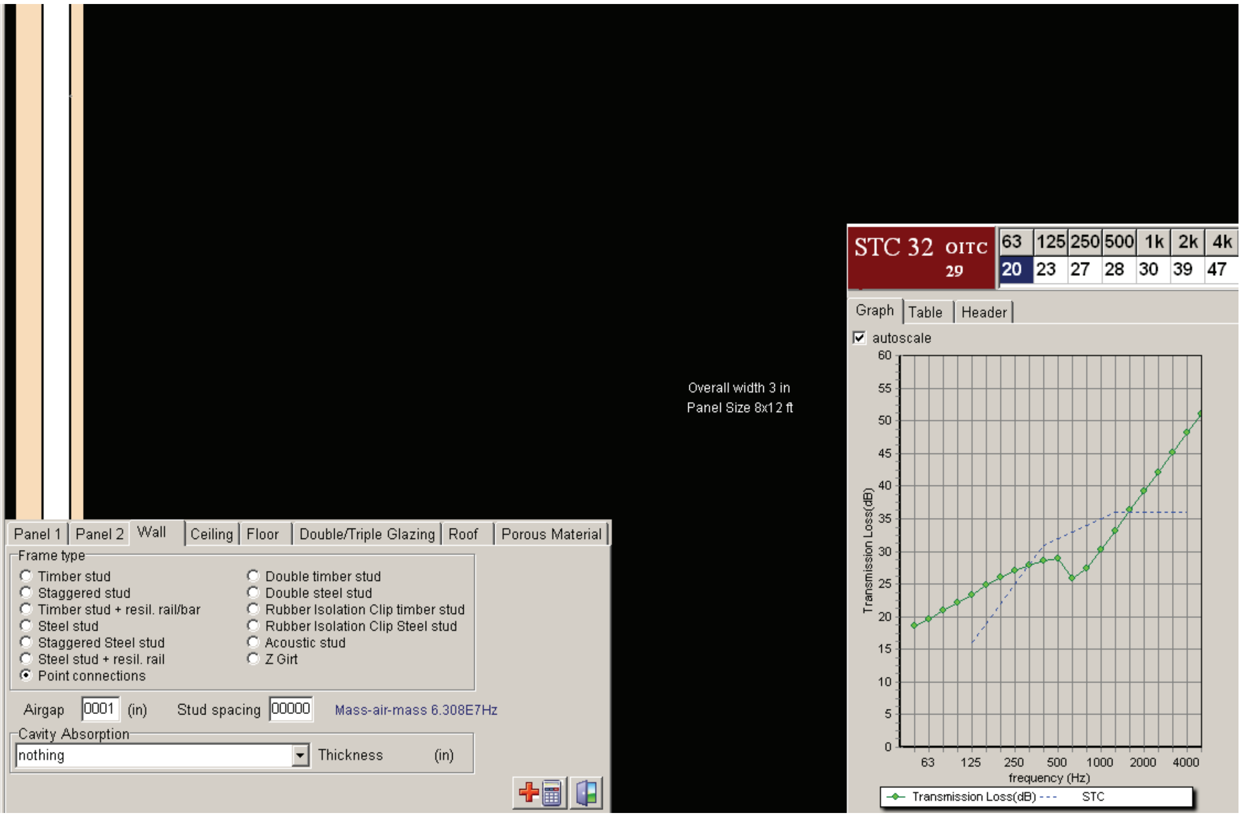
STC 40 OITC 31

63	125	250	500	1k	2k	4k
13	23	32	38	42	41	44

Figure C.6: Whole Wall Model

C.2 Generating a Wall Model with Additional Layers

Although Insul is designed to model partitions with up to two unique layers on each side of the stud cavity, many walls have more acoustically significant layers than this. Currently, the only way to model such wall types is to go through a multi-step process. For a wall with three layers on one side of the stud cavity, first generate a wall model with two of the layers on one side of the stud cavity and the third on the other. Then set the stud cavity to a very small depth and the stud spacing very high. This will most closely approximate the layers being joined together. Copy the transmission loss values generated for this wall from the table; they will be used to generate a new material type which will approximate the three layers. In a new file, create a new elastic core material. Input the material property information for the two outermost layers for Skin 1 and Skin 2 and all known information of the middle layer in the Core Properties. Exit the dialog box and paste the previously copied transmission loss values into the Ref column in the Table and select “Display ref spectrum”. Then re-enter the new material dialog box and edit the Core Properties information until the green TL curve corresponds to the purple reference points. Once this is accomplished, the new material is ready for use and can be used in place of those three layers. The next release of Insul is slated to include functionality to model additional layers on either side of the framing which will render this process unnecessary.



STC 32 OITC 29

63	125	250	500	1k	2k	4k
20	23	27	28	30	39	47

☑ autoscale

Frame type

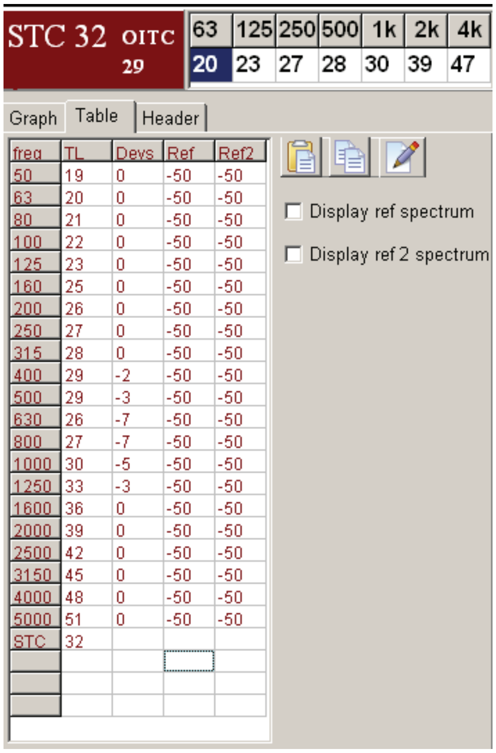
○ Timber stud
○ Staggered stud
○ Timber stud + resil. rail/bar
○ Steel stud
○ Staggered Steel stud
○ Steel stud + resil. rail
● Point connections
○ Double timber stud
○ Double steel stud
○ Rubber Isolation Clip timber stud
○ Rubber Isolation Clip Steel stud
○ Acoustic stud
○ Z Girt

Airgap 0001 (in) Stud spacing 00000 Mass-air-mass 6.308E7Hz

Cavity Absorption

nothing Thickness (in)

Figure C.7: Three-Layer Wall with No Stud Cavity



STC 32 OITC 29

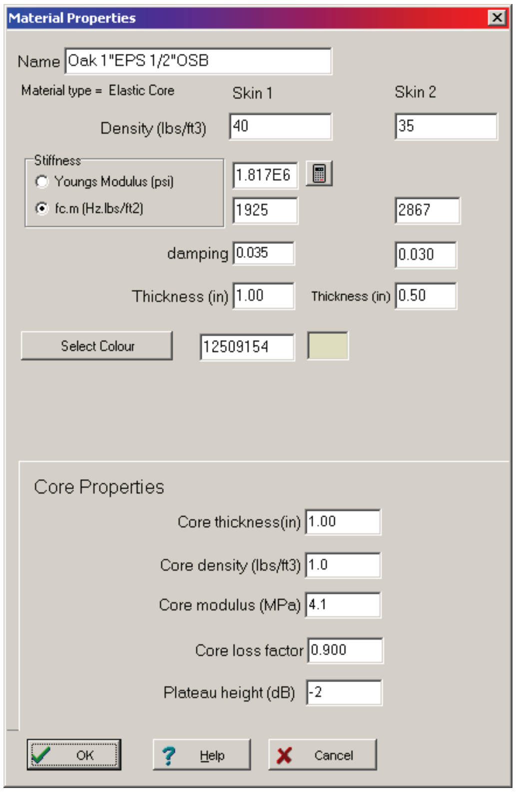
63	125	250	500	1k	2k	4k
20	23	27	28	30	39	47

freq	TL	Devs	Ref	Ref2
50	19	0	-50	-50
63	20	0	-50	-50
80	21	0	-50	-50
100	22	0	-50	-50
125	23	0	-50	-50
160	25	0	-50	-50
200	26	0	-50	-50
250	27	0	-50	-50
315	28	0	-50	-50
400	29	-2	-50	-50
500	29	-3	-50	-50
630	26	-7	-50	-50
800	27	-7	-50	-50
1000	30	-5	-50	-50
1250	33	-3	-50	-50
1600	36	0	-50	-50
2000	39	0	-50	-50
2500	42	0	-50	-50
3150	45	0	-50	-50
4000	48	0	-50	-50
5000	51	0	-50	-50
STC	32			

☐ Display ref spectrum

☐ Display ref 2 spectrum

Figure C.8: Transmission Loss Table



Material Properties

Name: Oak 1"EPS 1/2"OSB

Material type = Elastic Core

	Skin 1	Skin 2
Density (lbs/ft3)	40	35
Stiffness: ○ Youngs Modulus (psi)	1.817E6	
● fc.m (Hz.lbs/ft2)	1925	2867
damping	0.035	0.030
Thickness (in)	1.00	0.50

Select Colour: 12509154

Core Properties

Core thickness(in): 1.00

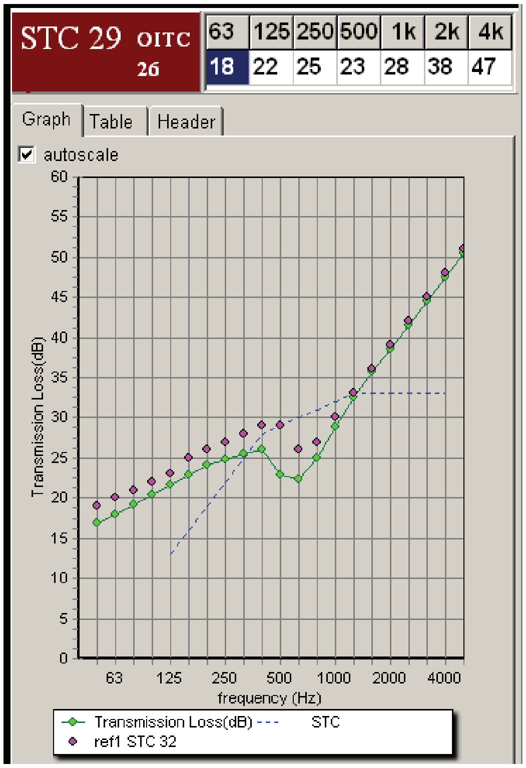
Core density (lbs/ft3): 1.0

Core modulus (MPa): 4.1

Core loss factor: 0.900

Plateau height (dB): -2

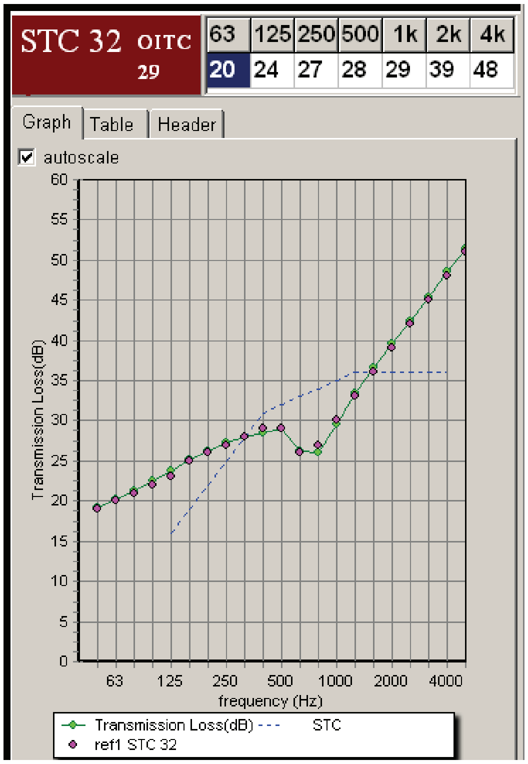
Figure C.9: Elastic Core Material Properties Dialog Box



STC 29 OITC 26

63	125	250	500	1k	2k	4k
18	22	25	23	28	38	47

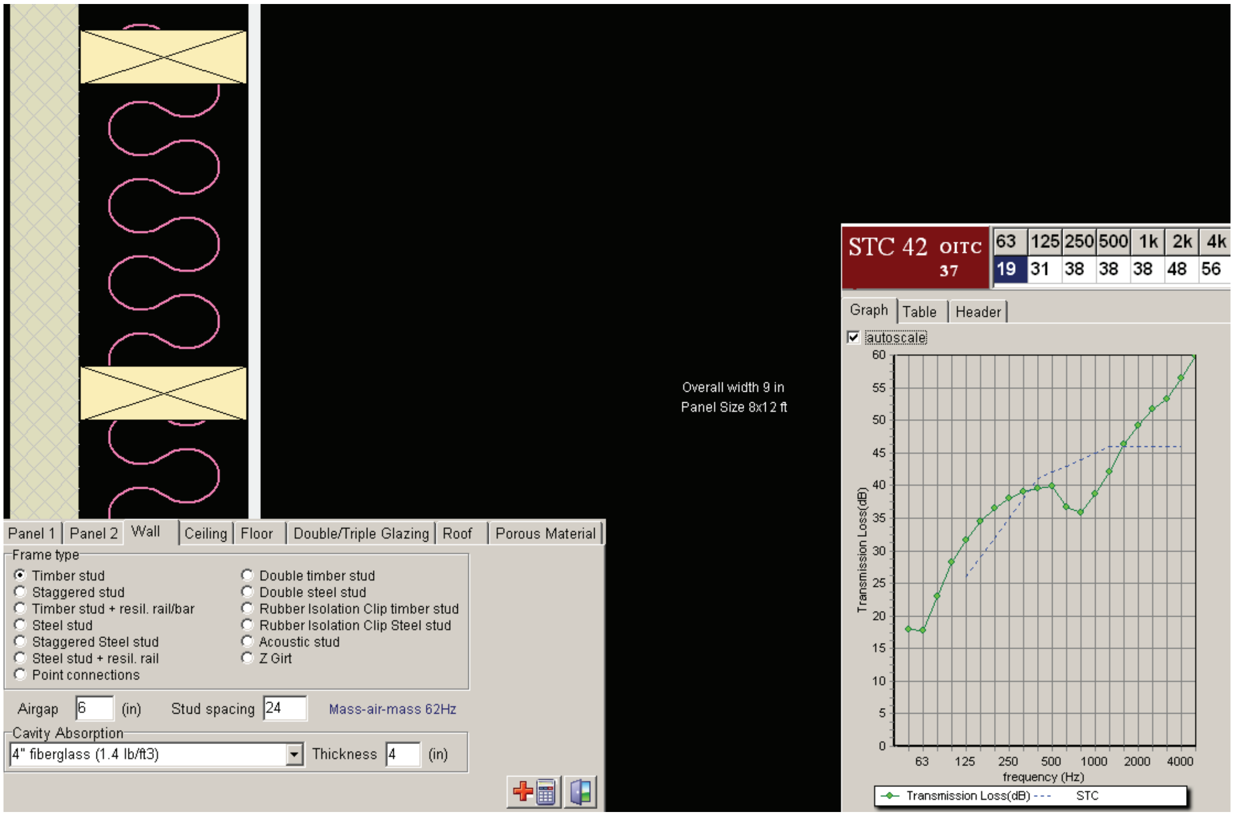
Figure C.10: First Attempt at Approximating Three-Layer Wall (reference in purple)



STC 32 OITC 29

63	125	250	500	1k	2k	4k
20	24	27	28	29	39	48

Figure C.11: Acceptable Approximation of Three-Layer Wall After Adjustments



Overall width 9 in
Panel Size 8x12 ft

Frame type: ● Timber stud

Airgap 6 (in) Stud spacing 24 Mass-air-mass 62Hz

Cavity Absorption: 4" fiberglass (1.4 lb/ft3) Thickness 4 (in)

STC 42 OITC 37

63	125	250	500	1k	2k	4k
19	31	38	38	38	48	56

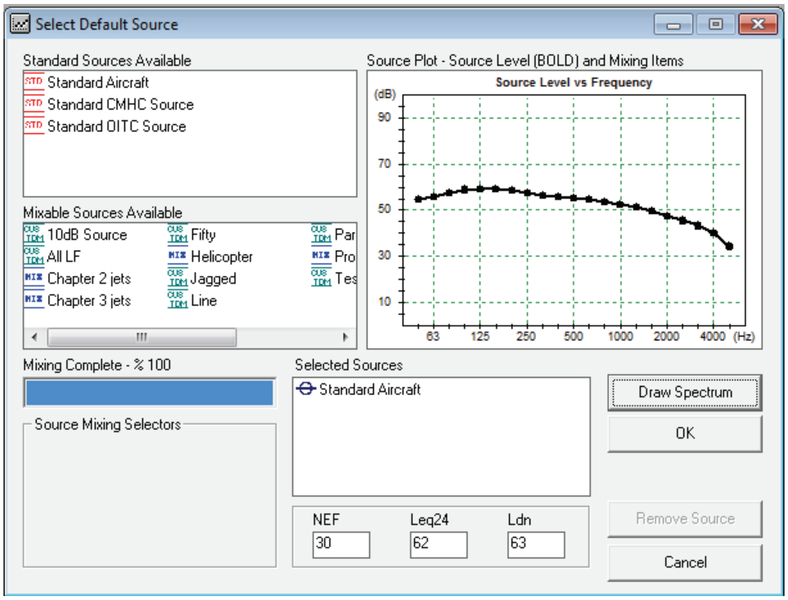
Figure C.12: Whole-Wall Model with Three-Layer Approximation on One Side

APPENDIX D

GENERATING A COMPOSITE ROOM MODEL IN IBANA-CALC

This appendix illustrates the process of generating a composite room model using the program IBANA-Calc, which was developed as part of the IBANA (Insulating Buildings Against Noise from Aircraft) project by the Canadian NRC-IRC (National Research Council—Institute for Research in Construction).

To generate a composite room model, select the noise source (typically the Standard Aircraft source, which is a mixture of measured aircraft noise spectra) and start a new scenario. Enter the room area and set the room absorption. Next, select the room's façade elements and their respective areas. If façade elements beyond the included database are required, they may be easily entered using the Database Editor. The program outputs the composite room transmission loss curve vs. frequency, though other plots are available. For additional information, please reference the IBANA-Calc User's Manual [13].

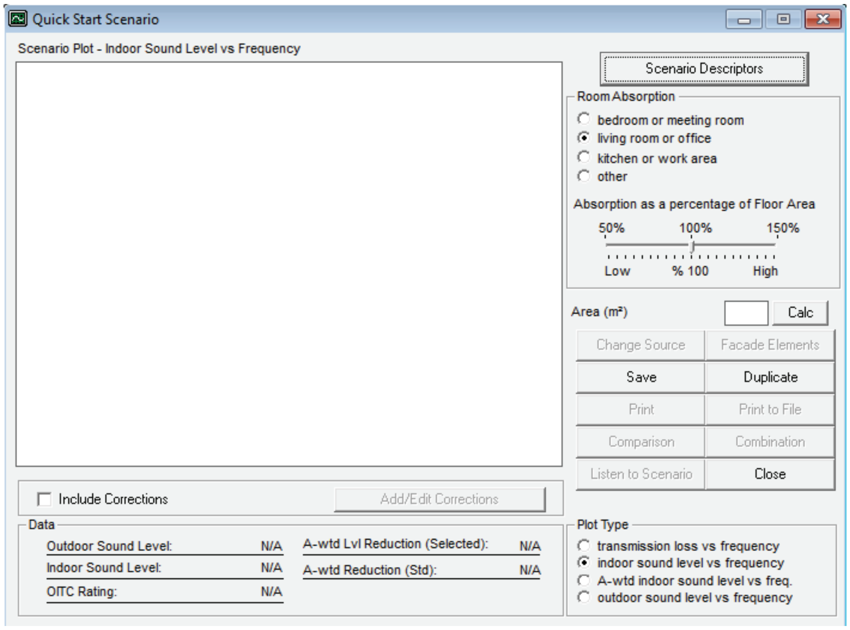


Mixing Complete - % 100

Selected Sources
Standard Aircraft

NEF 30
Leq24 62
Ldn 63

Figure D.1: Default Source Selection



Room Absorption

○ bedroom or meeting room
● living room or office
○ kitchen or work area
○ other

Absorption as a percentage of Floor Area

☐ Include Corrections

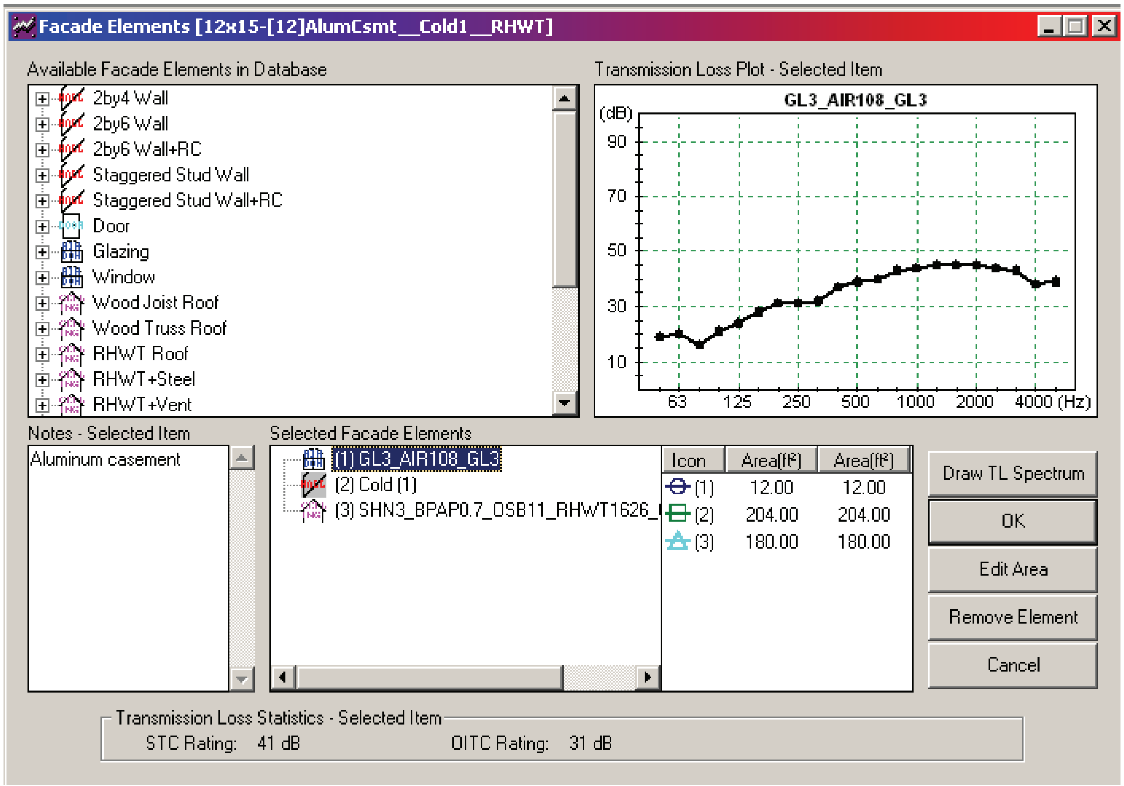
Data

Outdoor Sound Level:	N/A	A-wtd Lvl Reduction (Selected):	N/A
Indoor Sound Level:	N/A	A-wtd Reduction (Std):	N/A
OITC Rating:	N/A		

Plot Type

○ transmission loss vs frequency
● indoor sound level vs frequency
○ A-wtd indoor sound level vs freq.
○ outdoor sound level vs frequency

Figure D.2: New Scenario



Notes - Selected Item

Aluminum casement

Selected Facade Elements

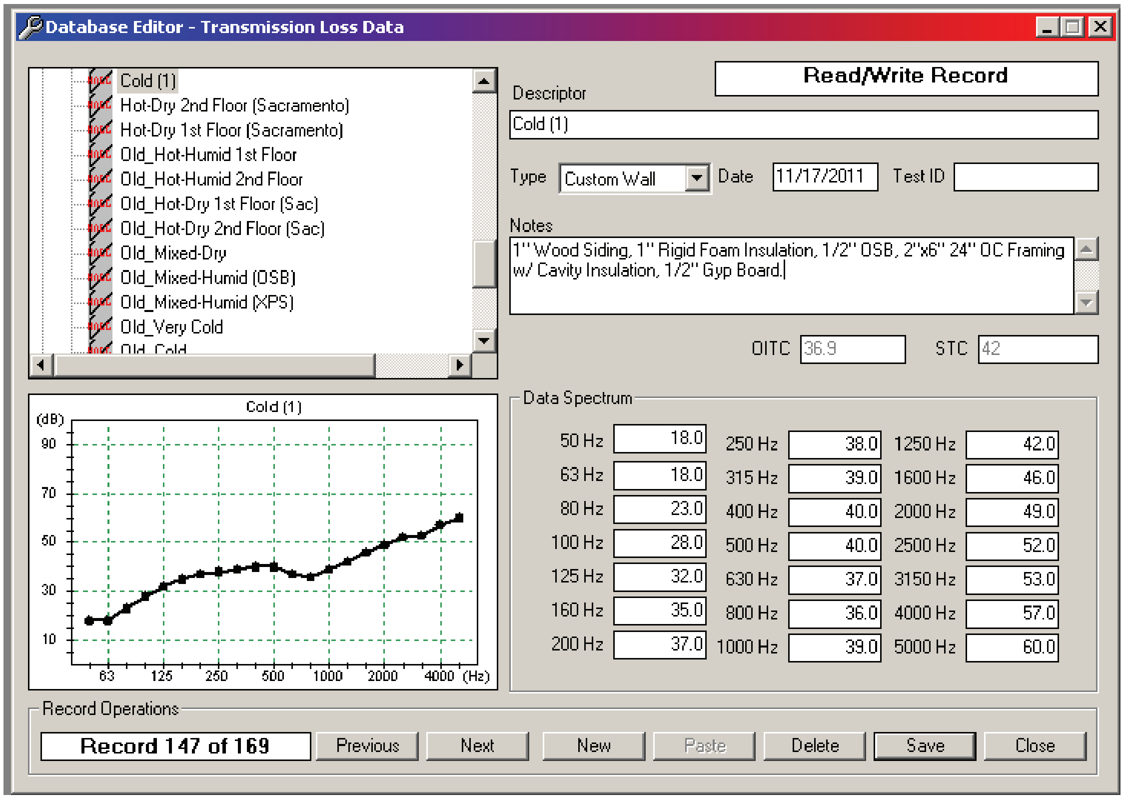
(1) GL3_AIR108_GL3
(2) Cold (1)
(3) SHN3_BPAP0.7_OSB11_RHWT1626_

Icon	Area(ft²)	Area(ft²)
(1)	12.00	12.00
(2)	204.00	204.00
(3)	180.00	180.00

Transmission Loss Statistics - Selected Item

STC Rating: 41 dB OITC Rating: 31 dB

Figure D.3: Façade Element Selection



- Cold (1)
- Hot-Dry 2nd Floor (Sacramento)
- Hot-Dry 1st Floor (Sacramento)
- Old_Hot-Humid 1st Floor
- Old_Hot-Humid 2nd Floor
- Old_Hot-Dry 1st Floor (Sac)
- Old_Hot-Dry 2nd Floor (Sac)
- Old_Mixed-Dry
- Old_Mixed-Humid (OSB)
- Old_Mixed-Humid (XPS)
- Old_Very Cold
- Old_Cold

Descriptor: Cold (1)

Type: Custom Wall
Date: 11/17/2011
Test ID:

Notes: 1" Wood Siding, 1" Rigid Foam Insulation, 1/2" OSB, 2"x6" 24" OC Framing w/ Cavity Insulation, 1/2" Gyp Board.

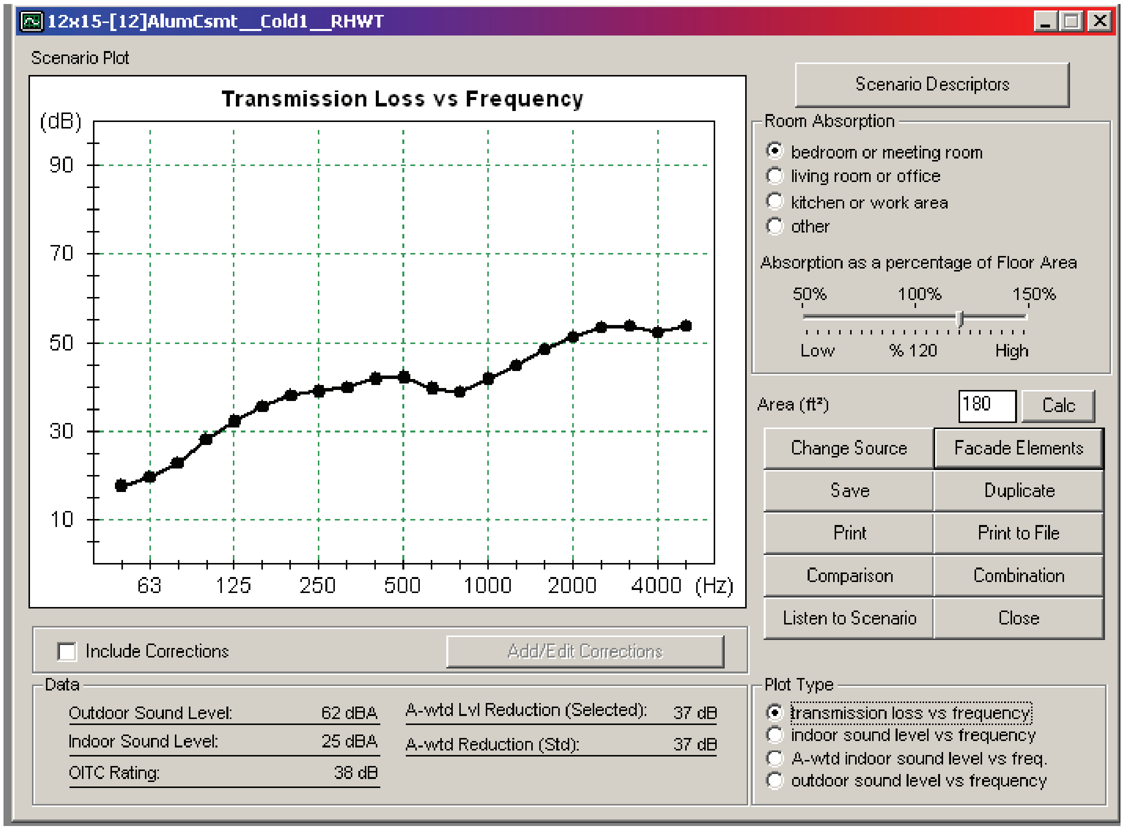
OITC: 36.9
STC: 42

Data Spectrum

50 Hz	18.0	250 Hz	38.0	1250 Hz	42.0
63 Hz	18.0	315 Hz	39.0	1600 Hz	46.0
80 Hz	23.0	400 Hz	40.0	2000 Hz	49.0
100 Hz	28.0	500 Hz	40.0	2500 Hz	52.0
125 Hz	32.0	630 Hz	37.0	3150 Hz	53.0
160 Hz	35.0	800 Hz	36.0	4000 Hz	57.0
200 Hz	37.0	1000 Hz	39.0	5000 Hz	60.0

Record 147 of 169

Figure D.4: Transmission Loss Database Editor



Room Absorption
- ● bedroom or meeting room
- ○ living room or office
- ○ kitchen or work area
- ○ other

Absorption as a percentage of Floor Area: % 120

Area (ft²): 180

☐ Include Corrections

Data

Outdoor Sound Level:	62 dBA
Indoor Sound Level:	25 dBA
OITC Rating:	38 dB
A-wtd Lvl Reduction (Selected):	37 dB
A-wtd Reduction (Std):	37 dB

Plot Type
- ● transmission loss vs frequency
- ○ indoor sound level vs frequency
- ○ A-wtd indoor sound level vs freq.
- ○ outdoor sound level vs frequency

Figure D.5: Completed Whole-Room Model

APPENDIX E

CALCULATING STC AND OITC

Insul and IBANA-Calc both report STC and OITC values for any given transmission loss curve. This appendix documents the process of computing these values and verifies the accuracy of both software packages.

E.1 Calculating STC

The Sound Transmission Class (STC) method, described in ASTM E413 [8], assigns a single number rating to measured Sound Transmission Loss (TL) data obtained in accordance with ASTM E-90 [7] across 1/3 Octave Bands from 125Hz to 4kHz, inclusive. A series of contours are defined across the aforementioned frequency range, with their numbering given by their value at the 500Hz 1/3 OB. The STC rating is given by number of the contour that best fits the data.

To calculate the appropriate STC rating, the STC contour values are added to the transmission loss values at each frequency to achieve the Adjusted TL. A test STC contour is then selected. The difference between that test contour and the Adjusted TL is taken; positive values are known as deficiencies, but negative values are set equal to zero. The total number of deficiencies may not exceed 32, and no single frequency band may have more than 8 deficiencies. A blank worksheet is shown below.

Table E.1: Blank Worksheet for Computing STC Values

1/3 OB Center Frequency(Hz)	STC Contour	Transmission Loss	Adjusted TL	Test STC	Deficiencies
125	16		16		0
160	13		13		0
200	10		10		0
250	7		7		0
315	4		4		0
400	1		1		0
500	0		0		0
630	-1		-1		1
800	-2		-2		2
1000	-3		-3		3
1250	-4		-4		4
1600	-4		-4		4
2000	-4		-4		4
2500	-4		-4		4
3150	-4		-4		4
4000	-4		-4		4
			TOTAL DEFICIENCIES:		**30**

E.2 Calculating OITC

The Outdoor-Indoor Transmission Class (OITC) method, defined in ASTM E1332 [9], assigns a single number rating to measured Sound Transmission Loss (TL) data obtained in accordance with ASTM E 90 [7] across 1/3 Octave Bands from 80Hz to 4kHz, inclusive. The OITC is defined as the A-weighted sound level reduction of a test specimen in the presence of a reference spectrum designed to approximate a mixture of transportation noise sources.

To calculate the appropriate OITC rating, the transmission loss values are subtracted from the A-weighted reference values at each frequency to achieve the Adjusted TL. These Adjusted TL values are then logarithmically summed and subtracted from the log sum of the reference spectrum. The resulting value is the OITC rating. A blank worksheet is shown below.

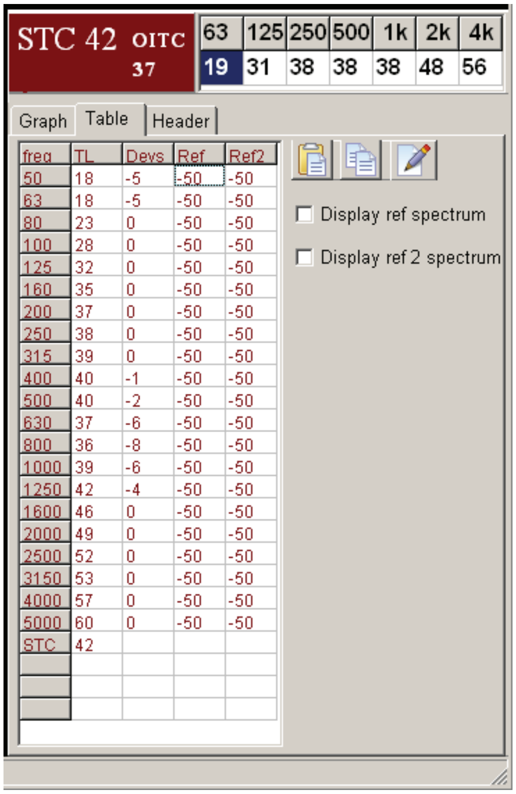
$$OITC = 100.13 - 10 \cdot \log \left\{ \sum_{i=80Hz}^{4000Hz} 10^{\frac{(AWRS_i - TL_i)}{10}} \right\}$$

Table E.2: Blank Worksheet for Computing OITC Values

1/3 OB Center	A-wtd Ref.	Transmission Loss	Adjusted TL
80	80.5		80.5
100	82.9		82.9
125	84.9		84.9
160	84.6		84.6
200	86.1		86.1
250	86.4		86.4
315	87.4		87.4
400	88.2		88.2
500	89.8		89.8
630	89.1		89.1
800	89.2		89.2
1000	89		89
1250	89.6		89.6
1600	89		89
2000	89.2		89.2
2500	88.3		88.3
3150	86.2		86.2
4000	85		85
		OITC:	**0.0**

E.3 Comparisons with Insul and IBANA-Calc

The aforementioned computation methods are compared to the automatic output from IBANA-Calc and Insul. The same TL data is used for both. As can be seen in the following figures and tables, all STC and OITC values agree.



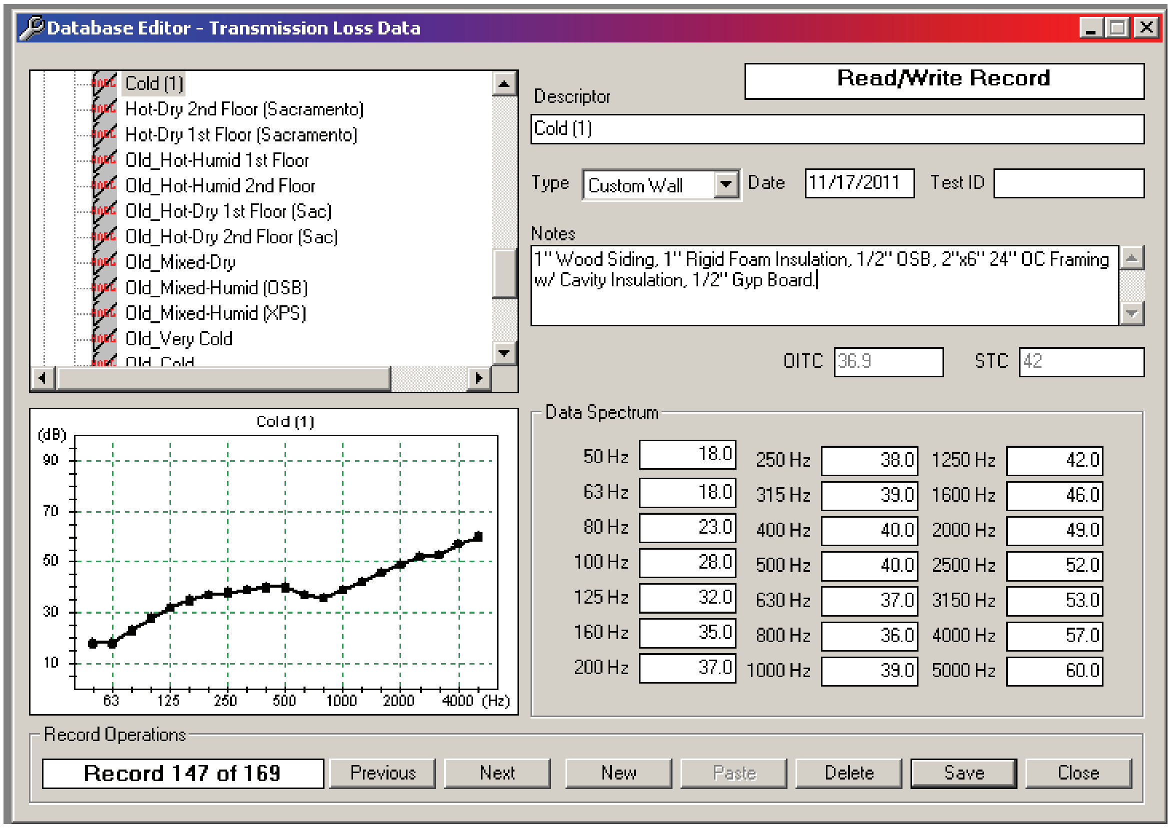
STC 42 OITC 37

63	125	250	500	1k	2k	4k
19	31	38	38	38	48	56

freq	TL	Devs	Ref	Ref2
50	18	-5	-50	-50
63	18	-5	-50	-50
80	23	0	-50	-50
100	28	0	-50	-50
125	32	0	-50	-50
160	35	0	-50	-50
200	37	0	-50	-50
250	38	0	-50	-50
315	39	0	-50	-50
400	40	-1	-50	-50
500	40	-2	-50	-50
630	37	-6	-50	-50
800	36	-8	-50	-50
1000	39	-6	-50	-50
1250	42	-4	-50	-50
1600	46	0	-50	-50
2000	49	0	-50	-50
2500	52	0	-50	-50
3150	53	0	-50	-50
4000	57	0	-50	-50
5000	60	0	-50	-50
STC	42			

☐ Display ref spectrum
☐ Display ref 2 spectrum

Figure E.1: Insul TL, STC, & OITC Data



Descriptor: Cold (1)

Type: Custom Wall Date: 11/17/2011 Test ID:

Notes: 1" Wood Siding, 1" Rigid Foam Insulation, 1/2" OSB, 2"x6" 24" OC Framing w/ Cavity Insulation, 1/2" Gyp Board

OITC: 36.9 STC: 42

Data Spectrum

50 Hz	18.0	250 Hz	38.0	1250 Hz	42.0
63 Hz	18.0	315 Hz	39.0	1600 Hz	46.0
80 Hz	23.0	400 Hz	40.0	2000 Hz	49.0
100 Hz	28.0	500 Hz	40.0	2500 Hz	52.0
125 Hz	32.0	630 Hz	37.0	3150 Hz	53.0
160 Hz	35.0	800 Hz	36.0	4000 Hz	57.0
200 Hz	37.0	1000 Hz	39.0	5000 Hz	60.0

Record Operations

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Figure E.2: IBANA-Calc TL, STC, & OITC Data

Table E.3: Calculating STC Values of Given Transmission Loss Information

1/3 OB Center Frequency(Hz)	STC Contour	Transmission Loss	Adjusted TL	Test STC	Deficiencies
125	16	32	48	42	0
160	13	35	48	42	0
200	10	37	47	42	0
250	7	38	45	42	0
315	4	39	43	42	0
400	1	40	41	42	1
500	0	40	40	42	2
630	-1	37	36	42	6
800	-2	36	34	42	8
1000	-3	39	36	42	6
1250	-4	42	38	42	4
1600	-4	46	42	42	0
2000	-4	49	45	42	0
2500	-4	52	48	42	0
3150	-4	53	49	42	0
4000	-4	57	53	42	0
			TOTAL DEFICIENCIES:		**27**

Table E.4: Calculating OITC Values of Given Transmission Loss Information

1/3 OB Center	A-wtd Ref.	Transmission Loss	Adjusted TL
80	80.5	23	57.5
100	82.9	28	54.9
125	84.9	32	52.9
160	84.6	35	49.6
200	86.1	37	49.1
250	86.4	38	48.4
315	87.4	39	48.4
400	88.2	40	48.2
500	89.8	40	49.8
630	89.1	37	52.1
800	89.2	36	53.2
1000	89	39	50
1250	89.6	42	47.6
1600	89	46	43
2000	89.2	49	40.2
2500	88.3	52	36.3
3150	86.2	53	33.2
4000	85	57	28
		OITC:	**36.9**

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