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EVALUATION OF METHODS IN PREDICTING NOISE LEVEL REDUCTION (NLR)

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TABLE OF CONTENTS

Section 1 Introduction 1
Section 2 Coordination With University Teams 3
2.1 Background 3
2.2 Develop Knowledge Base from Other Studies 3
2.3 Observations from Measurements of Field Test House 4
2.4 Using Georgia Tech Research Measurements vs Modeling Data 5
Section 3 Consultant Modeling Survey 6
3.1 Background 6
3.2 Development of the NLR Modeling Survey 6
3.3 Consultant Response to the NLR Modeling Survey 7
3.4 Results of the NLR Modeling Survey 7
3.4.1 Model 7
3.4.2 Modeling Process 8
3.4.3 Verification of Results 10
3.5 Background on NLR Models 10
3.5.1 Proprietary Models 10
3.5.2 IBANA-Calc Model 11
3.5.3 INSUL 12
Section 4 Modeling Program Evaluation 13
4.1 Background 13
4.2 Modeling Input Data 13
4.3 Overview of Modeled NLR Results 14
4.4 Modeling Survey Observations 14
4.5 Overview of Measured NLR Results 16
4.5.1 NLR Measurement Method 16
4.5.2 Initial Assumptions and Observations of Measured NLR & Critical Elements 21
4.6 Comparison of Modeled NLR Results (Different Models & Using Measured TL Data) 23
4.7 Comparison of Modeled NLR Results (Consultant "A" Model & Using Different TL Data) 24
4.8 Comparison of Modeled NLR Results (IBANA Model & Using Modeled TL Data) 27
4.9 Summary of NLR Modeling Program Evaluation 29
4.10 Discussion Regarding Interior Absorption Assumptions 29
4.11 Modeling Consistency among Consultants 31
4.12 Deviation from Measured NLR among Consultants 32
4.13 Building Self-Shielding Considerations 33
4.14 Angle Above the Horizon Considerations 37
Section 5 Incorporation of ACRP study findings 40
Section 6 Recommendations for short-term Best Practices 42
6.1 NLR Models (General) 42
6.2 Diffuse Sound Field Assumptions of the NLR Model 42
6.3 Exterior Noise Source Input 43
6.4 TL Data Input - Exposed & Critical Elements 43
6.5 Dimensional Data Input 44

TABLE OF CONTENTS *(continued)*

6.6 Interior Room Acoustics Input - Assumptions Regarding Absorption 44
6.7 Modeling Consistency 45
6.8 Comparison to NLR Measurements 45
6.9 Building Self-Shielding Considerations 45
6.10 Angle above the Horizon Considerations 45
6.11 Recommendations for Short-Term Best Practices 46
6.11.1 Use of One Model 46
6.11.2 Noise Exposure and Exposed Surfaces 46
6.11.3 Critical Elements and Leakage 46
6.11.4 Absorption 46
Section 7 recommendations for Future long-term Research 48
7.1 Recommendations for Future Long-Term Research 48
7.1.1 Variation in Modeling Consistency 48
7.1.2 Influence of the Condition of Critical Elements 48
7.1.3 Determining Room Absorption 48
7.1.4 Measurement Method Selection and Future Research 49
Section 8 CONCLUSIONS 50
8.1 Modeling for Design 50
8.2 Modeling for Eligibility 50
8.2.1 Modeling (without On-Site Inspection) 50
8.2.2 Modeling (with On-Site Inspection) 51

Appendices

Appendix A A-1
Appendix B B-1

TABLES

Table 1. List of Acoustical Consultants Contacted for NLR Modeling Survey 7
Table 2. Summary of NLR Modeling 18
Table 3. Measured NLR of Rooms and SIE of Critical Elements 23
Table 4. Summary of NLR Modeling from Different Models & Using Measured TL Data 24
Table 5. Summary of NLR Modeling from Consultant "A" Model Using Different TL Data 26
Table 6. Summary of NLR Modeling From IBANA-Calc Model Using Modeled TL Data 28
Table 7. Summary of NLR Modeling Input Source 29
Table 8. Differences between Measured and Modeled NLR from Different Models & Using Measured TL Data 32
Table 9. Summary of NLR Increases Due to Building Self-Shielding 36
Table 10. Summary of NLR Measurements in Relation to Angle above Horizon 38

FIGURES

Figure 1. Summary of NLR Modeling 19
Figure 2. Measured NLR of Rooms and SIE of Critical Elements 23
Figure 3. Median NLR Modeling from Different Models & Using Measured TL Data (By Room Type) 25
Figure 4. Median NLR Modeling from Different Models & Using Measured TL Data (By Region) 26
Figure 5. Median NLR Modeling from Consultant "A" Model & Using Different TL Data (By Region) 27
Figure 6. Median NLR Modeling From IBANA Model Using Modeled TL Data (By Room Type) 28
Figure 7. Median, 5th and 95th Percentiles of Differences between Measured and Modeled NLR from Different Models & Using Measured TL Data 33
Figure 8. Breakdown of Categories of Exposure due to Building Self-Shielding 36
Figure 9. NLR Increases Due to Building Self-Shielding 37

SECTION 1 INTRODUCTION

The noise reduction of buildings determines the interior noise exposure from an exterior noise source. The Noise Level Reduction (NLR) quantifies how much outdoor noise is reduced inside a room, and is typically used in Residential Sound Insulation Programs (RSIP) to derive interior noise metrics such as Day-Night Average Sound Level (DNL) and Community Noise Equivalent Level (CNEL). The indoor DNL/CNEL is now a definitive factor in the determination of the eligibility for mitigation treatments. As a result, the accurate determination of NLR is important. NLR is typically determined through measurements using various methods and techniques. However, NLR can also be calculated through acoustical modeling. Acoustical consultants use various modeling programs to calculate the NLR and have different approaches to the assumptions for the input of these models. The NLR modeling is left to the individual acoustical consultant since the Federal Aviation Administration (FAA) does not specify a standard approach. Since consultants having different approaches, use different models, and make different assumptions, the final NLR results may differ. The variation of NLR using the different modeling techniques has never been evaluated. This study attempts to obtain insight into the various NLR modeling approaches performed by the various acoustical consultants as well as variation in the results of the different models.

Currently, different consultants may use different models and assumptions for determining the NLR. A number of models have been developed and validity studies have been done for only a few commercially available models. Since modeling may be a cost effective option to performing actual measurements, it is important to have an understanding how the modeled results correlate to measured results. This may depend on the consultant's choice of acoustical models, assumptions taken, and any applied corrections or adjustment factors.

Additional insight may come from recent Georgia Institute of Technology (Georgia Tech) studies which evaluated the validity of modeling results and comparing those results to measurements. Another research study, ACRP 02-51, was recently completed and was released as ACRP Report 152 and could also provide additional insight about the variation in the various measurement methods[1]. In addition, the Burlington NLR Study completed for the FAA in 2013 provides additional insight into this issue[2]. Ultimately, these may all aid in the understanding of differences between modeled and measured results.

[1] Airport Cooperative Research Program (ACRP) Report 152, "Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs", 2016.
[2] Policy, Engineering, Analysis, and Research Support (PEARS), Contract No. DTFAWA-11-D-00019, "Study of Noise Level Reduction (NLR) Variation", April 2013.

The purpose of this study is to review, evaluate, guide (when feasible) and leverage those research efforts and to determine where additional research may be required. The ultimate goal of the results would be practical guidance for modeling the NLR in sound insulation programs. NLR measurements will be discussed as well, particularly on the topic of using measurement data to validate and to calibrate the models.

SECTION 2 COORDINATION WITH UNIVERSITY TEAMS

2.1 Background

One of the important aspects of this study is to collect and review recent or on-going research to gain a thorough understanding of what has been studied previously. It is important to gain as much knowledge as possible from other studies to gain a deeper understanding of the differences between modeled and measured NLR results. This will include a review of the differences between the previous lab testing and prediction.

2.2 Develop Knowledge Base from Other Studies

Georgia Tech is involved with some previous and on-going research for the determination of NLR. Landrum & Brown (L&B) staff participated in a teleconference with Georgia Tech staff to gain a thorough understanding of the previous and on-going modeling studies and data collection efforts. Two of these studies are described below.

PARTNER, the Partnership for AiR Transportation Noise and Emissions Reduction is part of the FAA Center of Excellence, which is sponsored by the FAA, NASA, Transport Canada, the U.S. Department of Defense, and the U.S. Environmental Protection Agency. PARTNER Project 38 focused on evaluating measurement and modeling methodologies using published and laboratory data with a test house in a hemi-anechoic chamber[3].

ASCENT, the Aviation Sustainability Center from the FAA Center of Excellence for Alternative Jet Fuels & Environment is sponsored by the FAA, Washington State University and the Massachusetts Institute of Technology. ASCENT Project 4A is on-going and research is focusing on evaluating measurement and modeling methodologies using field data[4].

Following the teleconference, a daylong meeting was setup with L&B and Georgia Tech staff in December 2014. Staff from the University of Nebraska – Lincoln (UNL) participated by teleconference. FAA staff also participated by teleconference. The first part of the meeting included a presentation by Georgia Tech and UNL staff on the PARTNER Project 38 and ASCENT Project 4A. L&B staff followed with a presentation on consultant best practices for measurement methodologies and NLR modeling techniques. The second part of the Georgia Tech meeting included a visit to the hemi-anechoic chamber where the measurements on the test house for PARTNER Project 38 were undertaken. Next a visit to the outdoor test house was undertaken where research was on-going. The purpose of these tests was to allow

[3] PARTNER Project 38, "Sound Transmission Indoors – Study of Whole Houses".
[4] ASCENT Project 4A, "Estimation of Noise Level Reduction".

field measurements of NLR under limited controlled conditions. L&B staff was able to observe some sample noise measurements being conducted on the field test house using the methods that consultants use in the field. Ideas and observations were shared between the university team and the consultant team on knowledge under actual in-field testing conditions.

2.3 Observations from Measurements of Field Test House

The observations of the measurements of the field test house allowed L&B staff to see the "research" world and the Georgia Tech staff to see the "real" world of sound insulation measurements.

The test house was built by staff and students from the Georgia Tech School of Architecture based on the U.S. Department of Energy climate regions. The test house was a structure that would be typical of a house in a Mixed-Humid Region such as Atlanta. The test house was a single-room structure, approximately six-feet square, with an insulated wood stud wall with two layers of gypsum board on the interior and fiber cement siding on the exterior of the structure. The roof was an insulated asphalt-shingled roof. The house/room had a single window that had varying degrees of acoustical abilities. The windows were either Sound Transmission Class (STC) 25, 31, or 41. Windows were to be replaced and the room retested during the research. Insulation panels were added to the interior of the room to simulate typical interior acoustics of a normal house.

Several observations were noted and these are listed and discussed below:

- *Observation #1 - Placement of the Test House –* The test house location was limited to a site immediately outside of the School of Architecture building. It was not considered a true free-field condition due to the close location to the building, the overhang of the building on the speaker side, and a half height retaining wall immediately behind the house. The placement of the test house is expected to be acceptable for testing relative differences between testing scenarios. *Implication:* The influence of reflections needs to be evaluated before comparing measured and modeled results applied to aircraft noise.
- *Observation #2 – Size of the Test Room –* The relative small size of the test room determines the limit of the NLR measurement accuracy below the Schroeder frequency, measured to be between 200 and 250 Hertz (Hz). Since acoustical models assume perfect stochastic reverberation, deviation from measurements is expected below the Schroeder frequency. In practice, rooms are significantly larger and therefore will have a lower Schroeder frequency. *Implication:* Measured and modeled results applied to aircraft noise needs to be evaluated.
- *Observation #3 – Construction Characteristics -* It was observed by L&B staff that while students and staff built the house following what is required for construction materials in a house in a Mixed-Humid Region, the construction

was not consistent with typical construction of habitable buildings. The existing window that was in place was an ADW Model 9000 Single-Hung Double-Glazed window. The STC rating was not specified, however, it was assumed to be a typical single strength window with an STC rating of approximately 25. With the noise source turned on, noise was audible coming between the window sash and the window frame. Noise was also audible coming between the seal on the upper and lower window sash and the window itself was vibrating and producing a secondary noise source. Noise was also audible coming between the window assembly and the rough building opening. It was confirmed that this space was not insulated. Joints in the gypsum board were sealed on the walls and on the ceiling. However, they were not sealed where the gypsum board ceiling meets the gypsum board walls. Only a rough poor-fitting molding covered the space and noise was very audible coming thru the openings. Similarly, where the walls meet the floors, noise was audible coming between the cracks in this area. In addition, the floors were particle board and the joints were not sealed and noise was heard coming up thru the cracks on the floors. It was believed that the floor joists were not insulated and not well sealed in the front of the room where the floor meets the ground. In the area where the exterior wall panels meet, the seal was rough and open in many places allowing noise to penetrate into the structure. *Implication:* The conditions would likely be acceptable for comparing relative differences between testing scenarios, but would likely be problematic if the measured test results were to be compared to modeled results.

2.4 Using Georgia Tech Research Measurements vs Modeling Data

The measurements being undertaken for ASCENT Project 4A were meant to validate the NLR measurements with the loudspeaker at an array of spatial positions and using various window types. Modeling under these conditions may present differences, brought on by the differences in the construction of a test home and rooms in habitable buildings. However, it is our understanding that funding is presently only available for the measurements and that the modeling portion of this study was not funded.

The goal of the university research team and the consulting team was to understand the knowledge gained from all parties and to work together to develop an understanding how their measured versus modeled results differ from those differences measured using consultant methods. The university was interested comparing manual special averaging microphone method to averaging multiple static microphone locations. L&B recommended improving the construction of the test home to match habitable rooms in buildings more closely and to evaluate the measured and modeled results for the different scenarios. To that end it was a successful collaboration.

SECTION 3 CONSULTANT MODELING SURVEY

3.1 Background

To gain a better understanding of differences in the modeling results used throughout the industry, this task will focus on preparing and distributing a survey for the consulting industry to determine their modeling practices. Unlike the modeling and development of airport noise contours which uses a standard and accepted model by the FAA, the Integrated Noise Model (INM), no such standard model is used throughout the industry to model and determine NLR.

3.2 Development of the NLR Modeling Survey

A limited number of acoustical consultants are involved in the noise mitigation or sound insulation industry. To gain insight of the modeling practices, a survey was developed and distributed to six (6) consultants known to be involved in airport sound insulation programs. The survey was developed to find out the types of models that are used, the consultant modeling practices, the various input and output parameters of the model, the assumptions used, and any applied adjustment/correction factors. Specific questions were asked regarding the model, modelling process and the process of verification of the results. Questions on the survey were as follows:

- Model
    - Type of model used (proprietary/commercially available)
    - Description of the model
    - Describe model limitations
    - Other relevant model details
- Modeling Process
    - Assumption for exterior source spectrum (single aircraft/airport specific/INM mix/pink noise)
    - Room dimensions (plans/measurements)
    - Assumptions (large openings/irregular rooms)
    - Data for Transmission Loss (TL) of elements (lab data/field measured data/calculated data, i.e. INSUL or proprietary model)
    - Application of TL corrections (angle of incidence/poor products)
    - Determination of room absorption (lab data/field measured data)
    - Assumptions for typical rooms
    - Corrections for flight path (room location/angle/shielding)
    - Other relevant modeling process details

- Verification of Results
    - Process to verify accuracy (national average/actual measurements)

A copy of the Consultant NLR Modeling Survey is provided in **Appendix A**.

3.3 Consultant Response to the NLR Modeling Survey

A list of acoustical consultants was developed and each was contacted to inquire whether they would be able to participate in the modeling survey. All consultants expressed a willingness to participate in the survey. A list of the acoustical consultants that were contacted, location, company contact and the date the survey was sent is presented in **Table 1**.

Table 1. List of Acoustical Consultants Contacted for NLR Modeling Survey

Company Name & Location	Company Contact	Date Survey Sent
Acentech, Inc. Cambridge, MA	Roberto Gomez	February 18, 2015
BridgeNet International Irvine, CA	Justin Cook	February 17, 2015
CSDA Design Group San Francisco, CA	Randy Waldeck	February 18, 2015
Harris Miller Miller & Hanson, Inc. Burlington, MA	Eric Cox	February 17, 2015
Landrum & Brown, Inc. Boston, MA & Irvine, CA	Eric Seavey	February 12, 2015
Wyle El Segundo, CA	Joanna Norris	February 12, 2015

The modeling surveys were sent to all six (6) acoustical consultants between February 12 and 18, 2015.

3.4 Results of the NLR Modeling Survey

Ultimately, five (5) responses were received from the acoustical consultant, with no response from Wyle. All five (5) responses were received by April 7, 2015. The results of the surveys are discussed in the following sections

3.4.1 Model

Model - All five (5) consultants seem to use a proprietary model to determine NLR, although some consultants use commercially available IBANA-Calc (IBANA) as a supplemental tool. One (1) consultant seems to favor IBANA for the FAA sound insulation projects and uses their proprietary model for new construction. Some use the INSUL model to calculate TL data for elements to input into their model. Some use measured TL data; some have a proprietary TL model.

Description - The basic concept of the proprietary model is using equations based on calculation of the NLR from the composite transmission loss of exposed surfaces of the building envelope and room constant using the total room absorption and dimensional data. The dimensions of the room are entered, as well as the dimensions of all elements such as the roof, walls, windows, doors, attic configuration and insulation. Each of the elements has a unique TL and the total noise reduction (NR) for each octave band is based on the TL of each of the elements and the area of the element in relation to the total area of the room. Room absorption also is factored into the modeling.

Limitations - While the IBANA model or the proprietary models used by the consultants follow similar principles in the calculation of the NLR all the models have one main limitation which is the determination of the correct TL data for building elements being modeled. Some consultants rely on standard database numbers for elements such as those used in IBANA. Some use calculation models such as INSUL to determine the TL data for elements. Some use measured field data to develop accurate TL data. Some have developed "leakage" TL models to adjust standard data for older elements.

3.4.2 Modeling Process

The modeling process also varies by consultant.

Noise Source Spectrum – The use of the exterior aircraft noise source spectrum seems to vary between consultants. Some use a single aircraft or a departure operation from a single aircraft type based on the INM data while most seem to use an airport-specific spectrum derived from multiple measurements.

Room Measurements **–** Most consultants obtain room measurement data from architect's plans if available or measure in the field if the data is not readily available.

Large Openings/Irregular Rooms – Some consultants do not seem to make any assumptions or adjustments for large openings or irregular rooms. Some treat large openings as absorptive surfaces and assume irregular rooms are standard rectangular rooms.

TL Data for Elements – Some consultants seem to use laboratory data only for the TL data for elements. Some use a combination of measured data and programs such as INSUL or IBANA. Most consultants do not apply corrections to the TL data. One consultant applies correction factors for leaks and slits.

Room Absorption Data – Most consultants calculate room absorption or use standard rates based on field observations. Sometimes, RT60 measurements are performed.

Flight Path Corrections – None of the consultants make any adjustments relative to the flight path of an aircraft, i.e. no shielding from other buildings and no adjustments based on aircraft elevation angle or lateral angle.

3.4.3 Verification of Results

All consultants were asked to describe their process to validate or verify the accuracy of the modeled results. In all cases, they responded by stating that for existing or pre-construction the modeled results are compared to measured pre-construction data and then the each modeled room is adjusted for consistency. This process ensures that the future or post-construction modeled results are consistent when compared to the existing or pre-construction results.

3.5 Background on NLR Models

The acoustical consultants generally use proprietary models that are supplemented by IBANA and INSUL. These are discussed in more detail in the sections below.

3.5.1 Proprietary Models

The proprietary room model that L&B uses for NLR calculations described below is likely similar to the proprietary models used by other acoustical consultants. It is setup using an Excel spreadsheet and uses standard equations to calculate the NLR of a room based on the exterior noise source spectrum, the transmission losses and areas of the surfaces that are exposed to the noise source, and the interior absorptive properties of the room[5,6]. This model allows calculated results to be compared with measured results at a spectral level, for both the pre-test and post-test data.

Dimensional Data **-** The first step in the modeling of a room is to enter the room size and element sizes into the model. Also all exposed surfaces are defined.

Noise Source Input - The calculated NLR depends on the spectrum of the exterior noise source. As a result, the spectral data of the noise source is entered into the model. In addition, the exterior noise metric (DNL, A-weighted Leq, or Lmax) is entered in the model to compute the total interior noise levels.

Transmission Loss Input - TL is the most critical input of room modeling and therefore multiple options are part of the modeling process. Here either measured or laboratory 1/1 or 1/3 octave band data are entered for each exposed element. If the roof is also exposed there is the choice of either modeling the roof TL using the pitched roof transmission loss model or entering the TL spectrum directly. Using the transmission loss model, the TL can also be calculated and entered into the room model. If adjustments from leakage are appropriate, the transmission loss model can take into account the effects of leakage using the slit leakage transmission loss model.

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[5] L. L. Beranek, I. L. Ver, "Noise and Vibration Control Engineering – Principles and Applications".

[6] D. A. Bies, C. H. Hansen, "Noise Control Engineering", Third Edition.

Interior Acoustics Input - The NLR is affected by the amount of absorption in the room and size of the room. All dimensions of interior surfaces and their spectral absorption data are entered into the model. Also air absorption and furniture information is included in the modeling process. Increasing the absorption in a room will increase the NLR.

Measurement Input - Measured pre- and post- construction data can be entered and compared with computed output. The measured pre-construction data is usually used to validate the model. Measured post-construction data can be entered and compared with the projected results to study the performance of the treatments.

Modeling Output – Since the model is designed for validating measurements and the effectiveness of treatments, both pre- and post-construction data can be compared. Also, measurements and modeled data can be compared for pre-and post-construction conditions. The output of the model is the computation of pre- and post-construction Outdoor-Indoor Noise Reduction (OINR). The interior noise levels are computed from the noise source data and OINR. To project the performance of treatments, the TL spectra of replacement windows, doors, improved roof structure, etc. are entered, after modeling the non-treated rooms.

One consultant (L&B) has also developed three additional models. Their use depends upon the available input data. These three models can feed data into the room model and are:

1. **Pitched Roof Transmission Loss Model** that calculates roof TL data[4,5].
2. **Partition Transmission Loss Model** that calculates the TL and STC of single or multi-layered partitions. It has the capability to validate modeled TL from measured data, in a similar manner as the NLR model. Again, structural changes are reflected in the TL that can be entered into the NLR model and used to project changes to the NLR.
3. **Slit Leakage Transmission Loss Model** that adjusts the partition TL model for cracks and leakage around perimeters of the partition such as the TL of windows and doors that are affected by the quality of the seals[7].

3.5.2 IBANA-Calc Model

The IBANA (Insulation Buildings Against Noise from Aircraft) software was initially developed by the acoustics laboratory of the Institute for Research in Construction at the National Research Council of Canada. IBANA contains a database of TL data of building façade elements as well as a database of aircraft noise spectra. IBANA was developed to calculate the effect of sound insulation against aircraft noise and

[7] M.J. Kim, J.H. An, "Effect of Slit Shaped Apertures on Sound Insulation Performance", Noise Control Engineering Journal, Vol. 57, Nr. 5, September 2009.

to provide the user with indoor noise levels for different exterior aircraft noise sources and for different building constructions.

To use IBANA a user first selects the type of outdoor aircraft noise to use from the source database. The source database includes three standard source spectra and four mixable aircraft spectra. It has a "standard aircraft" spectrum for locations near typical commercial airports with significant numbers of jet aircraft operations. It also has "mixable source" spectra for Stage (Chapter) 2 jets, Stage (Chapter) 3 jets, propeller aircraft and helicopters. The program user can create a new source spectra from a mixture of these four source types or can enter their own aircraft source data.

The next step for the user is to define the amount of absorption in the room, and select a construction style and area of each façade element of the building façade from the program's database. IBANA contains a database of laboratory TL measurements for various building façade elements including 50 exterior walls, 50 roof-ceilings, 40 windows and glazing, as well as doors. The user also has the ability to add TL results to the database. The database is divided into several categories and groupings are by type of façade element: wall, roof-ceiling, doors, windows, glazing units. Wall and roof-ceiling assemblies are again subdivided into smaller categories by framing type such as 2x4, 2x6, 2x6 + resilient channels, staggered stud, and staggered stud + resilient channels. Roof-ceilings are subdivided into wood joist, wood truss, raised heel wood trusses and steel decks.

In the last step the combined sound insulation of the selected components is calculated and determines the expected indoor sound levels from the aircraft noise.

3.5.3 INSUL

INSUL is a program for predicting the TL for various façade elements such as walls, floors, roofs, ceilings and windows. Data from INSUL can be used with other programs such as IBANA or proprietary models to determine the NLR of various rooms. INSUL calculates the TL in 1/3 octave bands and STC for use in NLR calculations. INSUL also has a built-in module for calculating noise reduction of rooms. A study is presented in Sound & Vibration that discusses the accuracy of INSUL software and its uses[8].

[8] Sound & Vibration, Daniel M. Horan, "Computer Modeling of STC – Option and Accuracy", December 2014.

SECTION 4 MODELING PROGRAM EVALUATION

4.1 Background

The second part of the modeling survey was to request that the various acoustical consultants model a number of different rooms given a standard set of supplied input data. Section 3 above presents information on the variability of the modeling methodologies used throughout the industry. This section will allow us to better understand the actual differences in the modeling results. Overall this will provide insight about the variation between modeling done by various consultants. This evaluation will supply a standard set of input data and photographs that would include some data from some ongoing projects.

4.2 Modeling Input Data

L&B staff as part of on-going support for sound insulation programs at two airports, collected detailed information for 10 rooms at the two airports. Data for four (4) rooms at Ft. Lauderdale-Hollywood International Airport (FLL) and for six (6) rooms at Ontario International Airport (ONT) were collected. The data collected for each room included:

- Room type;
- Room dimensions;
- Window style and description;
- Window dimensions;
- Exterior door style and description;
- Exterior door dimensions;
- Roof style and description;
- Ceiling style;
- Exterior wall description with number of exposed walls;
- Interior wall description;
- Floor description;
- Number and size of interior openings to adjacent spaces; and
- Number and style of interior furnishings.

Photographs were also provided for both the interior and exterior of all rooms. Data was also provided on the exterior A-weighted aircraft spectra used for both FLL and ONT. Noise measurement data for each of the elements tested was also provided. Information on the room data, source spectra data and element measurement data is provided in **Appendix B**. Photographs of each room were not included in Appendix B.

The modeling data was sent to all six (6) acoustical consultants on March 3, 2015. Reminders were sent out on April 17, 2015 and data was received from five consultants by mid-June, 2015. No responses were received from Wyle. The results of the modeling are discussed in the following sections.

Note: From this point forward, the names of the acoustical consultants have been removed from further discussion in the following sections and will only be referred to as Consultant "A", "B", "C", "D", and "E".

4.3 Overview of Modeled NLR Results

The summary of the NLR modeled results for the ten rooms from the various acoustical consultants are presented in **Table 2**. Table 2 also presents the measured NLR for each room. The measured NLR was based on the method using a loudspeaker on a tripod, manually scanning the external façade and room measurements. In Table 2 column one and two describes the room number and the type of room. Column three presents the measured NLR for each of the 10 rooms. The results of the modeling using the IBANA model are presented in column four to six. Columns seven to fifteen present the results of the modeling performed by the various acoustical consultants. All consultants used their own proprietary model with the exception of Consultant "E". For the TL data for the elements used in the modeling process, consultants either used laboratory data, INSUL data, IBANA data, or the measured data provided. Column sixteen presents the range of modeled NLRs for each room.

The various modeling results from the different consultants and scenarios have also been presented graphically in **Figure 1**. The measured NLR results in Figure 1 have been connected with a black line to aid visual comparison. Also, to aid visual comparison, the colored lines connect median NLR values of different comparable scenario. The colors in Figure 1 have been chosen such that comparable scenarios have different shades or markers shapes of the same color. With a focus on the transmission loss of the doors and windows, red markers indicate that the window and door TL was modeled. The red line shows the median NLR for modeled TL. Orange markers were used to indicate that laboratory TL data were used and the orange line indicates the median NLR for laboratory TL. The green markers reflect modeling using measured window and door TL data and the green line indicates the median NLR for measured TL data. These lines connecting median values of each comparable category have been included in Figure 1.

4.4 Modeling Survey Observations

This section discusses various aspects that influence the modeling results from the different models that consultants used who participated in the survey. The modeled results are compared to each other as well as to the measured NLR. Table 2 presents a summary of the modeled NLRs of ten rooms by the five consultants. In addition, L&B modeled the ten rooms using a proprietary model and IBANA. Also, different transmission loss spectra were modeled and compared. These included measured data, laboratory data, modeled data, and modeled data with

leakage taken into account. Table 2 also includes measured NLR results in the third column that are used for a baseline comparison.

The following briefly discusses initial observations with further details being discussed in following sections.

Exposure – Consultant "A" modeled the rooms based on noise exposure from a speaker on a tripod. Consultant "B" and "D" have also assumed the same noise exposure, thereby leaving out roof exposure. Consultant "E" has included the roof exposure in their modeling process. Consultant "C" has taken one façade into consideration for each room, even though some rooms have two exposed facades. These differences in assumptions are expected to have minor influence on the NLR. Consultant "A" assumes a 45 degree angle of incidence for all modeling. The TL was measured at a 45 degrees angle of incidence, and therefore consultants using the TL data that L&B provided for the windows and doors were also based on a 45 degrees angle of incidence.

Absorption - Taking absorption into account in the modeling process, Consultant "A" measures the main absorptive surfaces in the room, and estimates the surface areas of furniture. The absorptive spectral data is obtained from laboratory measured data and entered into the proprietary model. IBANA uses a slider that increases or decreases the room absorption evenly across the spectrum. The absorption assumptions used in the modeling by Consultant "B", "C" and "D" are not known at this time.

Transmission Loss - The TL of windows and doors was measured and provided to all consultants. All consultants used the measured TL data for the modeling for the survey. Consultant "B" ran an additional set of modeling using TL calculated with INSUL. Consultant "A" ran multiple sets of modeling with different TL spectra. These spectra were TL from laboratory measurements, measured TL, modeled TL using a proprietary model, and modeled TL using INSUL. Using the proprietary model and INSUL, Consultant "A" also took into account leakage or gaps around windows and doors. Laboratory and modeled TL data includes a two (2) dB downward adjustment to reflect a 45 degree angle of incidence TL values[9].

Regions - The measurements can also be categorized into regions. The two measured regions are near Fort Lauderdale International Airport (FLL) and Ontario International Airport (ONT). The structures near FLL (Rooms 1 through 4) have concrete masonry unit (CMU) wall construction with single glazed windows. The structures near ONT (rooms 5 through 10) have insulated frame wall construction with stucco finishing. The windows had insulated glazing.

Room Types - The two room types that were measured were Living Rooms and Bedrooms. The Bedrooms had one or two facades exposed and only had windows. The Living Rooms had either one or two facades exposed and had an exterior door

[9] L.L. Beranek, "Noise and Vibration Control", 1972

in addition to windows. The Living Rooms are typically significantly larger than Bedrooms and have openings leading to other rooms.

Initial Observations - The measured NLR data in Table 2 shows that the FLL region generally had lower NLRs than the ONT region. The Bedrooms in the ONT region generally have higher NLRs than the Living Rooms. These trends are reflected by all consultants using measured TL data. Using Consultant "A" proprietary model, this trend is less pronounced than using laboratory TL data, however, using modeled TL data with Consultant "A" proprietary TL model shows similar trends as those from measured TL data. Taking into account leakage in the modeling process brings the NLR results closer to the measured results. The influence of the TL on the NLR will be analyzed first, followed by influence of the assumptions taken regarding the absorption. The following sections discuss the variations between the different models consultants used, differences of regions and room types, and influence of the transmission loss differences.

4.5 Overview of Measured NLR Results

The modeled data presented in the previous sections is compared to the measured NLR data for each of the ten rooms. The measured NLR values are provided based on measurements undertaken by L&B staff using the loudspeaker measurement (ground loudspeaker) method. While the method is commonly used within the consulting industry, variations amongst consultants may occur due to the application of method variations. Also, measurements conducted using the aircraft flyover method versus loudspeaker method may produce differences. Consultant measurement techniques and setup procedures are also likely to results in some variation when compared to modeled results. The Airport Cooperative Research Program Report 152, "Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs" (ACRP 02-51) has evaluated the various methods. The findings that are incorporated in this study are discussed in Section 5.

4.5.1 NLR Measurement Method

Acoustical Measurement - Sound insulation measurements are based on either using a loudspeaker method or aircraft flyover method. For this study, L&B used a sound insulation measurement technique (ground loudspeaker) based on the use of a loudspeaker method. The loudspeaker method allows measurements to be made during a brief measurement period, independent from aircraft over flights. The measurement procedure described herein has been developed to accurately measure outdoor-to-indoor NLR of rooms.

The procedures *generally* follow those outlined in the American Society for Testing and Materials (ASTM) Standard E966-10[10]. The procedures conform to good

[10] American Society for Testing and Materials (ASTM) Standard E966-10, "Field Measurement of Airborne Sound Insulation of Building Facades and Facade Elements".

practice in sound insulation programs. The efficiency and flexibility of the testing procedures have been adjusted using techniques from other sources. Certain measurements are performed in accordance with "manual microphone scanning" technique from the ASTM Standard E336-08[11]. These are applied, in addition to the ASTM E966 standard to achieve the same level of accuracy.

Measurement Procedure - L&B used a specialized field monitoring kit that includes a signal generator, amplifier, and an equalizer to produce a noise source of equal energy in each octave band (known in the acoustics field as "pink noise"). The use of pink noise lends to accurately measuring all octave bands of interest. The noise source is relayed to a loudspeaker and the amplified pink noise is directed at the room or element of interest. The following equipment was used to perform the acoustical testing:

- Larson Davis 824 Sound Level Meter/One Third Octave Band Analyzer
- Larson Davis CAL200 Acoustic Calibrator
- McCauley AC95-1 Coaxial Loudspeaker (or equivalent)
- Crown XLS 202 Power Amplifier (or equivalent)
- Rolls REQ215 31 Band Graphic Equalizer (or equivalent)
- Goldline PN3B Noise Generator (or equivalent)

The loudspeaker was directed at the room to be measured, with the goal of having a uniform sound field exposed to all of the surfaces of interest. With the loudspeaker pointed at the room, measurements are made both on the exterior and in the interior of the structure. L&B applies the manually scanning method as described in ASTM E336-08 for the interior measurements. Manually scanning method is also used for exterior measurements at approximately three (3) feet from the façade surface. Exterior and interior octave band sound levels were measured and recorded with the loudspeaker in operation. Exterior and interior octave band sound levels were also measured and recorded without the loudspeaker to provide background or ambient sound levels. The transmission loss measurements L&B performs are similar to the "Intensity Method", whereby one microphone is swept the exterior surface approximately three (3) feet from the façade, and another measurement is done where the microphone is swept close to the internal surface of the element being tested. Instead of using an intensity probe, L&B uses a sound level meter. For a plane wave, the sound pressure level is about 0.2 dB different from the intensity level. It is assumed that the transmitted sound approximates a plane wave, and that the reverberation levels are sufficiently low compared to the transmitted levels.

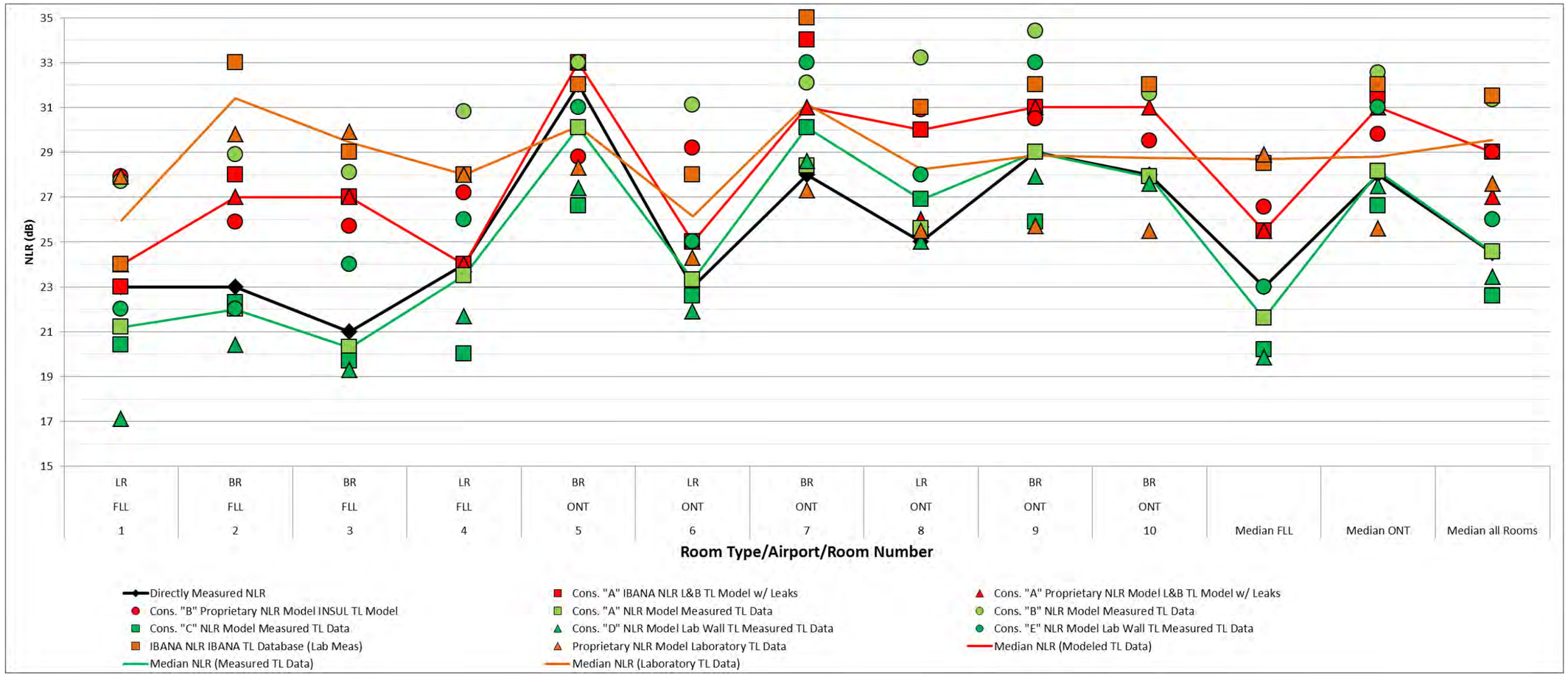
[11] American Society for Testing and Materials (ASTM) Standard E336-08, "Measurement of Airborne Sound Attenuation between Rooms in Buildings".

Table 2. Summary of NLR Modeling

Room No.	Room Type	Measured NLR (dB)	IBANA TL Data	IBANA Modeled TL Data (w/ leaks)	IBANA INSUL TL Data	Cons. "A" Lab. TL Data	Cons. "A" Modeled TL Data	Cons. "A" Modeled TL Data (w/ leaks)	Cons. "A" Measured TL Data (1)	Cons. "B" Measured TL Data (1)	Cons. "B" INSUL TL Data	Cons. "C" Measured TL Data (1)	Cons. "D" Measured TL Data (1)	Cons. "E" Measured TL Data (1)	NLR Range (dB)
1	LR	23	23	23	24	28	25	24	21	28	28	20	20	22	21 - 28
2	BR	23	31	28	33	30	27	27	22	29	26	22	22	22	22 – 34
3	BR	21	33	27	29	30	28	27	20	28	26	20	20	24	20 - 33
4	LR	24	25	24	28	28	25	24	24	31	27	20	20	26	20 - 31
5	BR	32	33	33	32	28	34	33	30	33	29	27	27	31	27 – 34
6	LR	23	25	25	28	24	26	25	23	31	29	23	23	25	23 - 31
7	BR	28	33	34	35	27	32	31	28	32	30	30	30	33	27 – 34
8	LR	25	27	30	31	26	27	26	26	33	31	27	27	28	26 – 34
9	BR	29	31	31	32	26	32	31	29	34	31	26	26	33	26 - 34
10	LR	28	31	32	32	26	32	31	28	32	30	(2)	(2)	(2)	26 - 33

Notes: (1) Used measured TL data for windows/doors & IBANA database for TL data for walls.
(2) Room not modeled

Figure 1. Summary of NLR Modeling



Once the measurements have been completed the Outdoor/Indoor Level Reduction (OINR) of rooms are calculated from the measured exterior and interior sound levels in each octave band, as outlined in ASTM E966-10. The OINR values are then used to compute the outdoor to indoor NLR of aircraft noise based on A-weighted aircraft noise spectrum. The OITL is used to compute the Sound Isolation Effectiveness (SIE) of the measured building elements. The SIE is a single number rating, similar to Outdoor/Indoor Transmission Class rating, where the same aircraft spectrum is used to calculate the NLR. L&B developed this rating as a convenient way to compare noise transmission elements of a room.

Sound levels using the loudspeaker method are used to determine the OINR and OITL in accordance with ASTM E966-10. With the loudspeaker pointed at the room, or element, measurements are made both on the exterior and in the interior of the room. The exterior "near façade" measurements is adjusted to account for the reflected sound off the façade. Definitions according to ASTM E966-10 for room NLR measurements and the element measurements are explained in the following sections.

Aircraft Noise Spectrum - For this acoustical assessment, noise data was collected on a representative sample of aircraft that operate at both FLL and ONT. Aircraft types included commercial jets, regional jets corporate jets and turboprop aircraft. This data was used to develop an average A-weighted noise spectrum of the typical fleet mix operating at both airports and for determining the NLR and SIE of the various rooms and elements measured for this project.

Noise Level Reduction Calculations for Rooms - NLR is a single number rating used for the comparison of the difference in the outdoor-to-indoor noise levels. This number is typically used to judge the overall effectiveness of sound insulation programs.

The NLR of a room is dependent on the exterior noise source spectrum. In aviation sound insulation programs, the NLR is therefore based on aircraft as the noise source. For this program, L&B will use a FLL- and ONT-specific A-weighted average noise spectrum of the fleet mix for the exterior noise source. The noise source spectrum of the fleet mix is A-weighted to resemble human perception and to be consistent with the FAA guidelines for assessing aircraft noise in communities. The indoor A-weighted noise source spectrum for each room tested in the program is obtained by subtracting the measured OINR from each octave band of the exterior A-weighted noise source spectrum. The A-weighted noise level is obtained by summing the energies in each octave band. The A-weighted NLR, based on a typical aircraft noise spectrum, is the difference between the outdoor and indoor A-weighted noise levels.

Sound Isolation Effectiveness Calculations for Elements - Industry-wide various single number ratings have been developed to describe the sound insulating capabilities of elements such as doors, windows, walls, roof structures, etc. L&B measures elements only to provide guidance in providing acoustical support and recommending treatments.

Manufacturers of windows and doors most frequently use the STC rating. This rating was developed for rating the sound insulating capabilities of interior building partitions over the frequencies of human speech. L&B developed a single number rating, SIE, which is used to assess the capability of an element to reduce aircraft noise inside a building. SIE for elements is calculated the same way as the NLR for rooms. For elements, the OITL is subtracted from each octave band of the A-weighted average noise spectrum of the fleet mix. It should be noted that the SIE based on aircraft noise exposure will generally be lower than STC since because aircraft noise has more energy in the low frequencies than the frequencies of human speech.

4.5.2 Initial Assumptions and Observations of Measured NLR & Critical Elements

Acoustically, rooms behave differently in two (2) frequency regions. In the lower frequency region, the space is dominated by standing waves at various frequencies depending on the room size. The frequency where the sound field transitions to a diffuse sound field is approximated by the Schroeder frequency which is determined from the reverberation time and volume of the room. The basic diffuse octave band or 1/3 octave band sound field calculation of noise reduction (NR) is calculated as follows:

- NR = TL - 10log(S/A), where
    - "S" is the size of the sound transmitting partition, and
    - "A" is the total room absorption.

At the lower frequencies, the outdoor-to-indoor noise reduction is expected to be less accurately predicted using the diffuse sound field NR equation. Above the Schroeder frequency, rooms have a relatively diffuse sound field, where it is expected that the diffuse sound field NR equation predicts more accurately. For smaller bedrooms, the Schroeder frequency is approximately 200 Hz, and typically decreases as the room size increases. The dominating octave bands influencing the NLR based on aircraft noise are 250 Hz, 500 Hz, 1 kHz, and 2 kHz, that is typically above the Schroeder frequency. Because the dominating frequencies for determining the NLR are above the Schroeder frequency, a diffuse sound field may be assumed for all octave bands for determining the NLR. The modeling process has been compared to the measured NLR, where the manual spatial scanning measurement method is performed. By moving the microphone through the standing wave patterns of the room, the chances of measuring in a standing wave maximum or minimum is significantly reduced. With these steps taken, is assumed that the modeled NLR using the diffuse sound field equation can be directly compared to the NLR measured using the loudspeaker and manual spatial scanning method.

A total of three (3) variables affect the NR in the diffuse field NR equation; the composite transmission loss of the sound transmitting partition, total absorption and the size of the sound transmitting partition. The three (3) variables are divided into two (2) terms; TL and 10log(S/A). To gain understanding how the parameters

influence the NR, the NLR and TL data are plotted in **Figure 2.** In addition, the Composite SIE of the elements with lower TLs and the difference of the NLR and composite SIE are also included in Figure 2. The solid line in Figure 2 connects the measured NLR results and composite critical element SIE results for visual comparison.

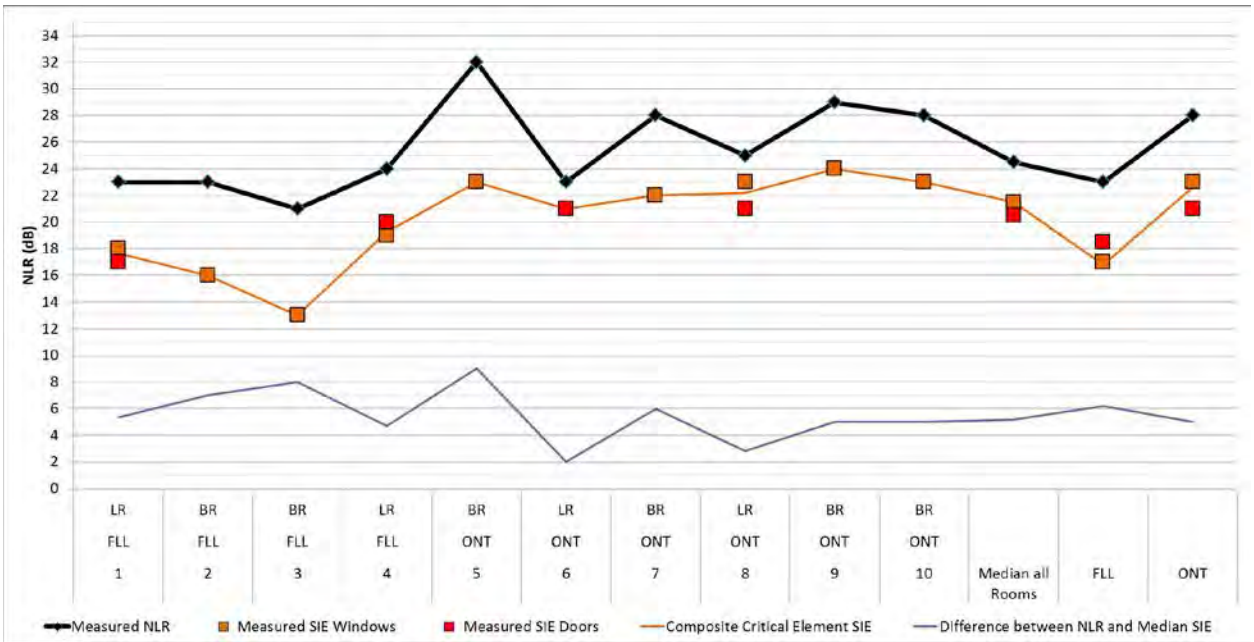
The NLR modeling spreadsheet that L&B uses outputs the contribution of noise from all modeled elements that make up the exposed façade. The contributions to the interior levels through the CMU or stucco wall structures are 10 to 20 dB lower than the contributions through the windows and/or doors. Roof structures have not been directly exposed using the loudspeaker measurement method. The roof structures with attic space of the rooms in this study tend to have higher sound transmission loss and assumed to have minimal influence on the NLR. Noise penetration through vaulted or flat roof structures can be more significant, however, only rooms with attic type roof structures are selected in this study. The TL of windows and doors drive the composite TL, and will be referred to as critical elements. The difference between the NLR and the composite TL is equivalent to the influence of the 10log(S/A) term. This term has ranged from two (2) to nine (9) dB (a range of seven dB) in the rooms that were modeled. The total transmitting partition size was provided to all consultants, and therefore it is expected the only differences in assumptions regarding the total absorption would influence the term. A factor of two (2) difference in absorption between consultants would result in a three (3) dB NLR difference. Information about the furnishing in the rooms has also been provided to all consultants and therefore a difference in total absorption would be expected to be significantly less than a factor two.

Table 3 presents the measured NLRs of the rooms and SIEs of critical elements of the rooms that were modeled. The measured SIEs in Table 3 range from 13 to 24 dB, a range of 11 dB. This range is due to differences in the materials, leakage, element size, etc. The room with the lowest NLR coincides with a critical element with the lowest SIE. The room with the highest NLR has a critical element with second to highest SIE. The modeled NLRs in Table 3 range from 21 to 32 dB, a range of 11 dB. This signifies the importance of how modeling critical elements affect the NLR and confirms that wall structures are less significant. Also, for example, a difference of a less than a factor two in the assumptions of absorption in the room would constitute to less than a three (3) dB change in the NLR. Therefore this study will consider windows and doors critical elements and focus primarily on how the transmission loss performance of windows and doors affect the NLR modeling process.

Table 3. Measured NLR of Rooms and SIE of Critical Elements

Room	Airport	Room Type	NLR (dB)	SIE Window (dB)	SIE Door (dB)
1	FLL	Living Room	23	18	17
2	FLL	Bedroom	23	16	-
3	FLL	Bedroom	21	13	-
4	FLL	Living Room	24	19	20
5	ONT	Bedroom	32	23	-
6	ONT	Living Room	23	21	21
7	ONT	Bedroom	28	22	-
8	ONT	Living Room	25	23	21
9	ONT	Bedroom	29	24	-
10	ONT	Bedroom	28	23	-

Figure 2. Measured NLR of Rooms and SIE of Critical Elements



4.6 Comparison of Modeled NLR Results (Different Models & Using Measured TL Data)

This section discusses the modeled results from the five (5) consultants using different models. All consultants used their proprietary model with the exception of Consultant "E", who used IBANA. All modeling in this section was performed using measured TL data for windows and doors and exterior noise spectra of FLL and ONT. Known differences in the modeling approach are that one consultant included roof exposure, while most only considered one façade exposed. From the previous section, it is assumed that wall and roof exposure will have minimal influence on the NLR. The assumption consultants have taken regarding absorption is not known. **Table 4** presents the modeled NLR results compared to the measured NLR. The results from Consultant "B" seem significantly higher than those from other

consultants. The modeling results from Consultant "C" and "D" differ less than three (3) dB for all of the rooms, and generally are lower than measured NLRs. The majority of the results from IBANA are higher than the measured NLRs. The difference of the results from Consultant "A" model and measured NLRs are less than two (2) dB. The differences between the results amongst consultants can be caused by various reasons that are unknown. **Figure 3** compares the modeled NLRs using measured TL data of the room types among the different consultants. Modeled NLRs of bedrooms show a significantly higher NLR than those of living rooms. This is consistent amongst all consultants and measured NLRs, though the differences that Consultant "B" modeled are smaller. **Figure 4** compares modeled NLRs of two regions amongst different consultants. Modeled NLRs of the FLL region are significantly lower than those from the ONT region. The TL of the windows was also significantly lower in the FLL region than the ONT region. This is consistent amongst all consultants, and measured NLRs. These results are consistent with expectations that the TL of critical elements significantly influences the overall NLR

Table 4. Summary of NLR Modeling from Different Models & Using Measured TL Data

Room No.	Room Type	Measured NLR (dB)	Cons. "A"	Cons. "B"	Cons. "C"	Cons. "D"	Cons. "E"	Median Modeled NLR (dB)
1	LR	23	21	28	20	17	22	21
2	BR	23	22	29	22	20	22	22
3	BR	21	20	28	20	19	24	20
4	LR	24	24	31	20	22	26	24
5	BR	32	30	33	27	27	31	30
6	LR	23	23	31	23	22	25	23
7	BR	28	28	32	30	29	33	30
8	LR	25	26	33	27	25	28	27
9	BR	29	29	34	26	28	33	29
10	LR	28	28	32	(1)	28	(1)	30

Notes: (1) Room not modeled

of the rooms. Variations due to other causes, such as absorption, are unknown. With the addition of roof exposure, the NLR is expected to decrease. This is not directly evident from the results from Consultant "E". It is expected that exposing only one façade for all rooms, that the NLR would increase. This is not directly evident from the modeled results from Consultant "C".

4.7 Comparison of Modeled NLR Results (Consultant "A" Model & Using Different TL Data)

Because the TL of critical elements significantly affects the NLR, different TL spectra was entered into the proprietary model used by Consultant "A". **Table 5** presents

the modeled results using TL data from laboratory measurements and the Consultant "A" proprietary model. The Consultant "A" proprietary model included leakage and field measurements. **Figure 5** compares the median results per region. The laboratory measured and modeled TL data has been corrected to a 45 degree angle of incidence, consistent to the expose for the measured NLRs. IBANA database TL data are measured at random angle of incidence, where the NLR calculations are normalized to a 60 degree angle of incidence plane wave. Although the modeled trends of the two regions are consistent with measured results, the laboratory measured and modeled TL is significantly higher than the measured TL. To account for poor seals that most measured windows and doors had, the TL was modeled with the presences of a slit of around the entire perimeter. The assumed width of the slits around the windows was 0.3 millimeter (mm) wide and 30 mm deep. The width of the slits around the doors was one (1) mm around the sides and top of the door, and two (2) mm at the threshold. The depth of the slit of the doors is assumed to be 50 mm. These results indicate that the modeled NLR trends can be consistent with those that are measured. A detailed observation of the actual leakage dimensions of windows and doors may improve leakage assumptions and NLR correlation with measured results.

Figure 3. Median NLR Modeling from Different Models & Using Measured TL Data (By Room Type)

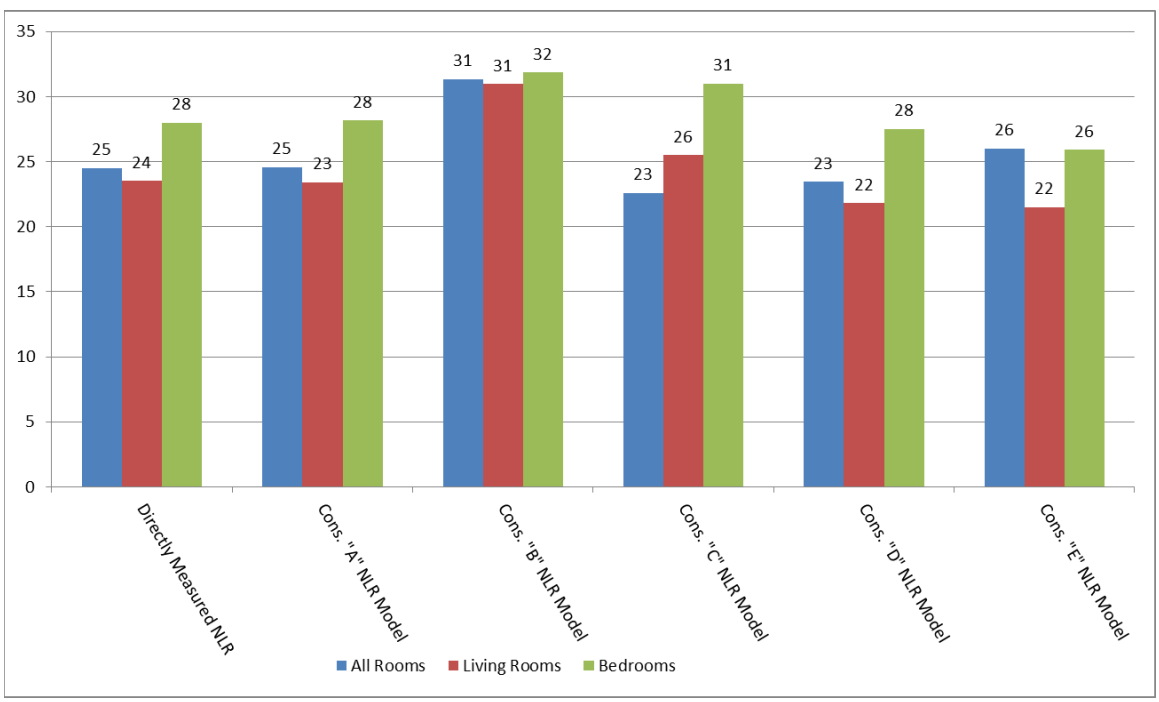


Figure 4. Median NLR Modeling from Different Models & Using Measured TL Data (By Region)

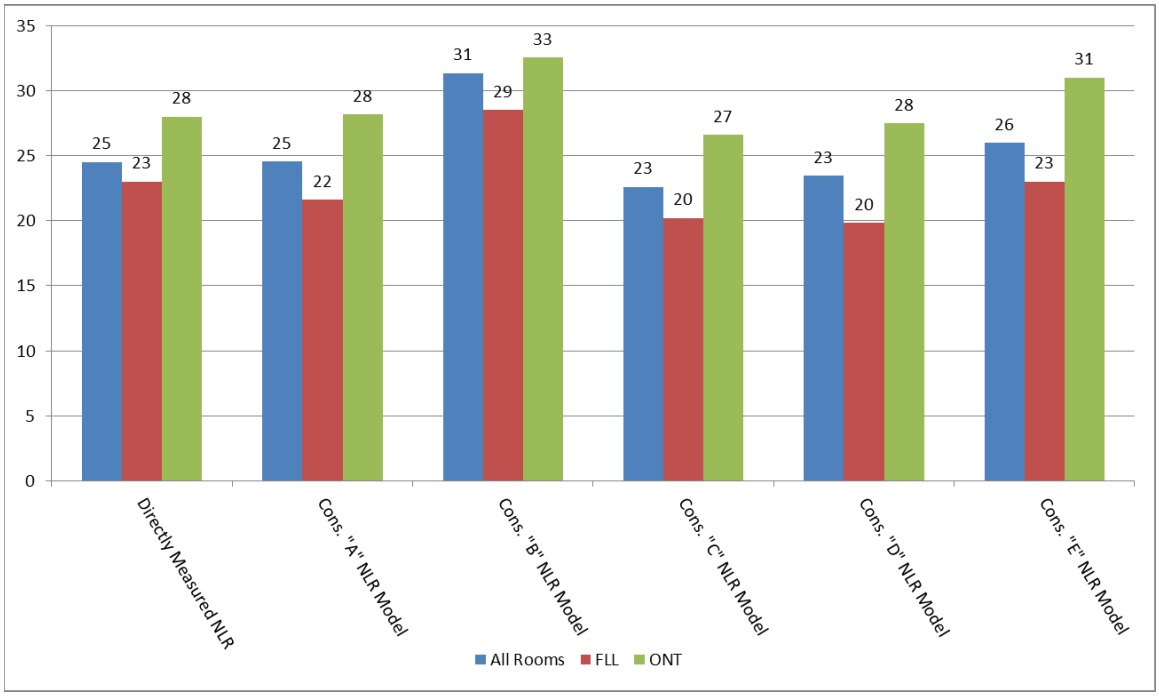
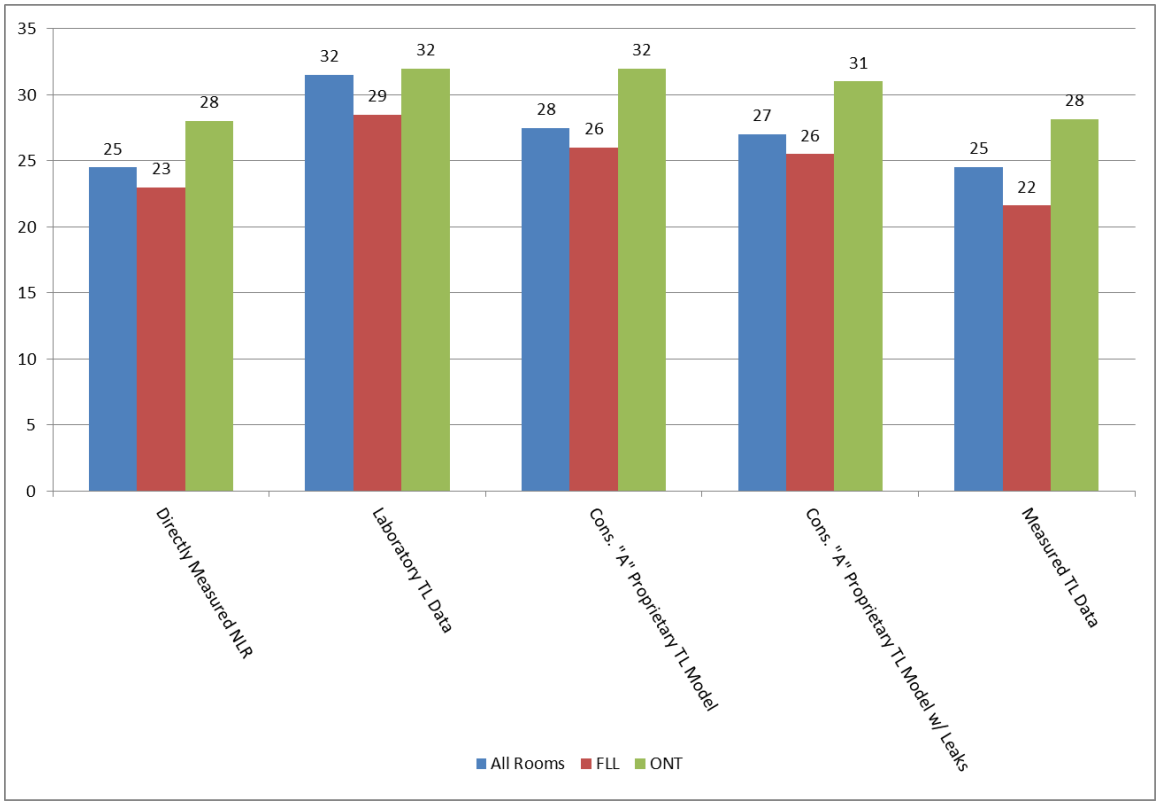


Table 5. Summary of NLR Modeling from Consultant "A" Model Using Different TL Data

Room No.	Room Type	Measured NLR (dB)	Laboratory TL Data	TL Model	TL Model (w/ leakage)	Measured TL Data
1	LR	23	24	25	24	21
2	BR	23	33	27	27	22
3	BR	21	29	28	27	20
4	LR	24	28	25	24	24
5	BR	32	32	34	33	30
6	LR	23	28	26	25	23
7	BR	28	35	32	31	28
8	LR	25	31	27	26	26
9	BR	29	32	32	31	29
10	LR	28	32	32	31	28

Figure 5. Median NLR Modeling from Consultant "A" Model & Using Different TL Data (By Region)



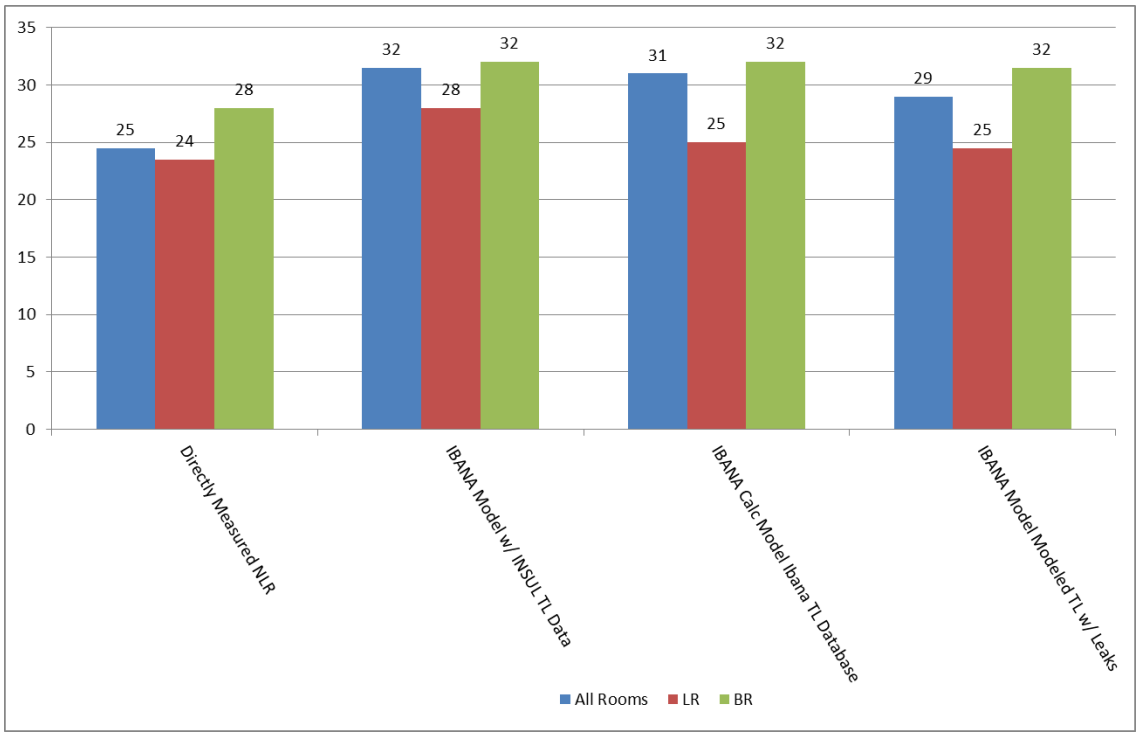
4.8 Comparison of Modeled NLR Results (IBANA Model & Using Modeled TL Data)

This section discusses observations using the IBANA software and compares the results using the TL data included with the software to that of other laboratory TL data. **Table 6** summarizes the modeling in IBANA using different TL data. **Figure 6** presents the median NLR modeled with IBANA using different TL data, broken down by room type. The IBANA model TL database includes an unsealed door selection with significantly lower TL. Using the TL of the unsealed door lowered NLR significantly. The included leakage in both INSUL and L&B TL model also lowered the NLRs. The modeled door leakage in INSUL was based on four (4) meter (m) long slit that was one (1) mm wide and 50 mm deep. The window leakage in INSUL was modeled with a length equal to the perimeter of the window, and 0.3 mm wide slit with 30 mm depth. From these results, influence of leakage is significant. For example, on a study L&B conducted in Phoenix, AZ, a door was tested and re-tested after sealing the edges with putty. The measured SIE increased from 17 to 22 dB and confirms that leakage influences the TL significantly. Given that the TL of critical elements influences the NLR significantly, it is important to understand the condition of critical elements and their seals. The TL data included in the IBANA database uses random angle of incidence, where the NLR calculations are normalized to a 60 degree angle of incidence plane wave. INSUL and the proprietary program from Consultant "A" have calculations that were done at a 45 degree angle of incidence.

Table 6. Summary of NLR Modeling From IBANA-Calc Model Using Modeled TL Data

Room No.	Room Type	Measured NLR (dB)	INSUL TL (w/ leakage)	IBANA TL Database	TL Model (w/ leakage)
1	LR	23	24	23	23
2	BR	23	33	31	28
3	BR	21	29	33	27
4	LR	24	28	25	24
5	BR	32	32	33	33
6	LR	23	28	25	25
7	BR	28	35	33	34
8	LR	25	31	27	30
9	BR	29	32	31	31
10	LR	28	32	31	32

Figure 6. Median NLR Modeling From IBANA Model Using Modeled TL Data (By Room Type)



4.9 Summary of NLR Modeling Program Evaluation

Table 7 below summarizes the NLR modeling input source that was discussed in the previous sections. Column one, two and three presents the section, table and figure where the modeling scenario is discussed. Column four presents the NLR model used which included all models, the Consultant "A" model or IBANA. The fifth column presents information on the source spectra used which in all cases was data that Consultant "A" provided. Column six provides information on the TL data used which is either all data or measured data only. The seventh column presents data on the interior absorption. This information from other consultants is not known.

Table 7. Summary of NLR Modeling Input Source

Section	Table	Figure	NLR Model	Source Spectra	TL Data	Interior Absorption
4.3	2	1	All	Consultant "A" Provided	All	Not all known
4.6	4	3 & 4	All	Consultant "A" Provided	Measured	Not all known
4.7	5	5	Consultant "A"	Consultant "A" Provided	All	Known
4.8	6	6	IBANA	Consultant "A" Provided	Modeled	Known

4.10 Discussion Regarding Interior Absorption Assumptions

The interior absorption of a room affects reverberant sound field in a rooms, thereby affecting the NLR. The influence of extreme changes in absorption has been looked into during previous research studies undertaken by L&B[12]. None of the 11 rooms in that study had furniture. Three rooms had carpeting, and the rest had tiles or wood floors. One of the carpeted rooms had approximately 75% of the carpeting covered with construction debris. The NLR changed one (1) dB by adding batt insulation in the room with construction debris. The NLR of the other carpeted rooms increased up to three (3) dB after adding batt insulation. The median change in the remaining rooms was a three (3) dB NLR increase. The assumptions with regards to absorption are likely to differ amongst consultants. One of the most significant areas that may affect the absorption is how openings between rooms are handled amongst different consultants. These differences are expected to be in less than three (3) dB. Without knowing the assumptions that were made, it is not possible to determine the exact influence of these assumptions amongst the consultants.

[12] Policy, Engineering, Analysis, and Research Support (PEARS), Contract No. DTFAWA-11-D-00019, "Study of Noise Level Reduction (NLR) Variation", April 2013.

4.11 Modeling Consistency among Consultants

While the TL of critical elements has a significant influence on the NLR, other assumptions, such as that related to interior absorption, building exposure or modeling techniques, contribute to differences in the modeled NLR amongst consultants. **Table 8** presents differences between the measured NLR and modeled NLR of all consultants, where the TL of critical elements and exterior source spectrum are consistent. The measured NLR has been chosen to compare modeled NLRs to, even though the measured NLR itself has variation due to various factors. Despite the limitations of using the measured NLR in an absolute sense, the spread amongst the modeling process performed by various consultants is evident. **Figure 7** presents a summary of the median, 5th and 95th percentile of the differences. The median, 5th and 95th percentiles, provide a sense of the distribution of the modeling process in relation to the measured results. A negative difference indicates that the modeled NLR was lower than the measured NLR. Table 8 shows the medians of all consultants having approximately seven (7) dB variation. The reasons for this variation of the modeling results amongst various consultants are unknown. The Consultant "A" model includes 90% of the modeling results in a 2.6 dB range. The 90% of the results of the modeling process performed by Consultant "B" has a 6.0 dB range. Consultant "E" used IBANA, where the range that included 90% of the results is 5.6 dB, 0.4 dB different from Consultant "B". Consultant "C" and "D" have 90% of the results included in a 3.9 and 3.5 dB range respectively. In addition, the spread of the modeling performed by various consultants varies by 3.4 dB. The reasons for these differences are also unknown. With information about the assumptions that were made and knowledge about the models that were used may provide further insight into these differences. It is known however, that Consultant "E" was the only company that also modeled roof exposure even though the roof was not directly exposed due to use of a tripod. Excluding the roof exposure in their modeling process may have resulted in higher NLR results. Consultant "C" modeled exposure to one façade, even though some rooms had two facades exposed. The walls are not considered a critical element, however, the number of exposed facades can affect the NLR. Possibly the median NLR would decease if Consultant "C" had included exposure of all facades. IBANA also uses a single slider to adjust the absorption in the room, with a preset for larger rooms such as living rooms, and another preset for smaller rooms such as bedrooms. This approach has limited accuracy where for example, adjustments to account for tile or carpeted floors are estimated by moving the slider.

Table 8. Differences between Measured and Modeled NLR from Different Models & Using Measured TL Data

Room No.	Room Type	Cons. "A" Prop. NLR Model	Cons. "B" Prop. NLR Model	Cons. "C" Prop. NLR Model	Cons. "D" Prop. NLR Model	Cons. "E" IBANA
1	LR	-1.8	4.7	-2.6	-5.9	-1
2	BR	-1.0	5.9	-0.7	-2.6	-1
3	BR	-0.7	7.1	-1.3	-1.7	3
4	LR	-0.5	6.8	-4.0	-2.3	2
5	BR	-1.9	1.0	-5.4	-4.6	-1
6	LR	0.3	8.1	-0.4	-1.1	2
7	BR	0.4	4.1	2.1	0.6	5
8	LR	0.6	8.2	1.9	0.0	3
9	BR	0.0	5.4	-3.1	-1.1	4
10	LR	-0.1	3.6	-	-0.4	-
Median	**-**	**-0.3**	**5.7**	**-1.3**	**-1.4**	**2**
5th Percentile	**-**	**-1.9**	**2.2**	**-4.8**	**-5.3**	**-1**
95th Percentile	**-**	**0.5**	**8.2**	**2.0**	**0.3**	**4.6**

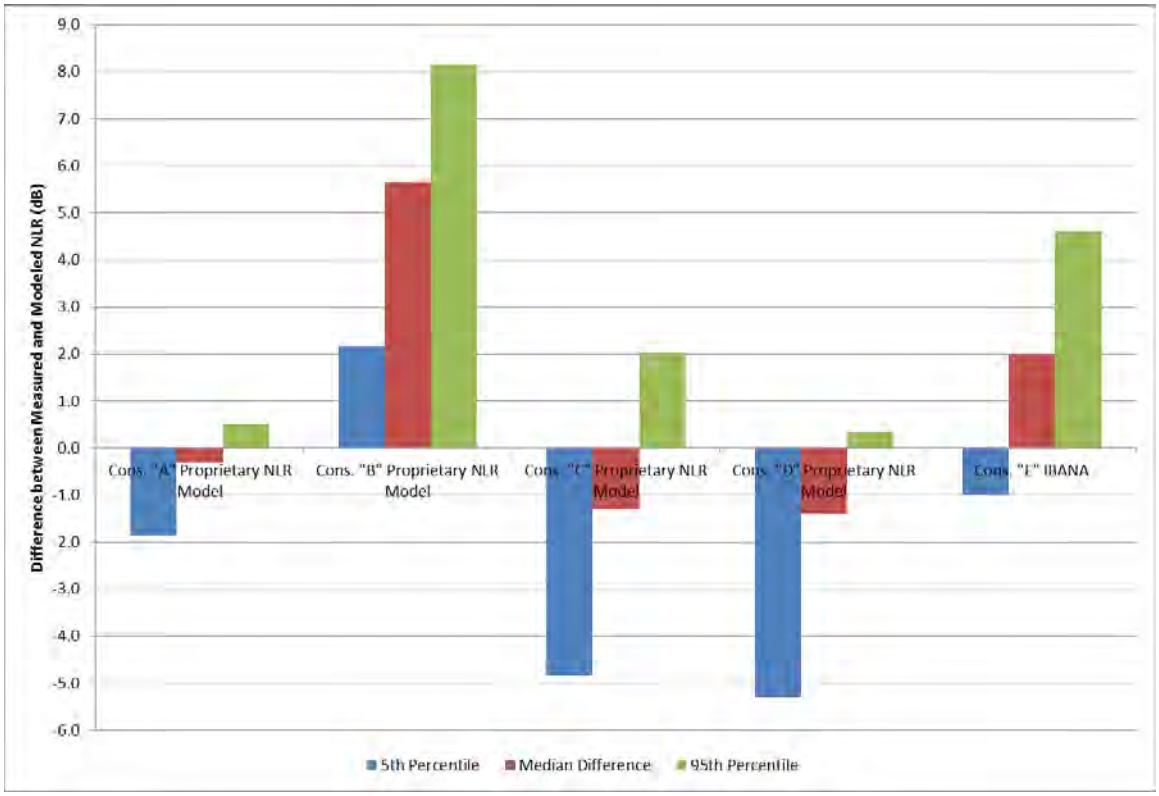
Notes: (1) Room not modeled

4.12 Deviation from Measured NLR among Consultants

As mentioned in the previous section, the variation of the measured NLR is influenced by various factors for which an initial study was performed in 2013. This study, and a further on-going detailed study under ACRP 02-51, is evaluating the measurement methods for measuring NLR. The comparison of modeled results to the measured NLR is used in relative terms only, and absolute error cannot be determined.

From Table 8 and Figure 7, using the Consultant "A" model, the median difference to the measured NLR was -0.3 dB. Consultant "C" and "D" also modeled NLRs with median NLRs lower than the measured NLR, with differences of -1.4 and -1.3 dB; respectively. Consultant "B" and Consultant "E" using the IBANA modeled NLRs that resulted in the medians to be 5.7 and 2.0 dB higher than the measured NLR respectively. The median modeled NLRs were all within two (2) dB from the measured NLR, except for the modeled results from Consultant "B". The following section discusses the study that is ongoing that evaluates various methods of measuring the NLR.

Figure 7. Median, 5th and 95th Percentiles of Differences between Measured and Modeled NLR from Different Models & Using Measured TL Data



The 2013 study that performed sound insulation measurements using real aircraft, resulted in measurements with an elevated noise source using a crane with higher NLR results. A limitation noted in that study was that the aircraft exposure was primarily sideline departures. The ACRP 02-51study is based on a larger sample size, more typical aircraft overflight exposure, and greater variety of regions and construction. This study may gain additional insight of the causes of variation in NLR measurements that may aid to the correlation of the NLR modeling in this study.

4.13 Building Self-Shielding Considerations

The models that were evaluated assumed one or more exterior facades of the room exposed to a noise source. The proprietary model from Consultant "A" and IBANA assumes exposure to a plane wave. The exterior exposure angle of incidence of proprietary models from other consultants is unknown. However, since the TL data was measured at 45 degrees angle of incidence, effectively the angle of incidence of the NLR calculations using that TL data are 45 degrees also. The models are compared to the measured NLR using the loudspeaker method that has been setup to expose all facades to an approximate plane wave. In practice, the noise exposure changes as a function of time, and on the location of the flight track in relation to the location and orientation of the room. Therefore, the NLR also varies as a function of time. The variation of the NLR is especially significant when part of

an aircraft overflight is shielded by the building itself, thereby effectively increasing the NLR during that part of the aircraft overflight. A Wyle report, WR 89-7, in section 2.5, page 2-12, shows diagrams with building shielding attenuation factors for each façade depending on the exposure to the flight track[13]. The report recommends considering the shielding on a case-by-case basis. To help understand the influence of building self-shielding on NLR, L&B has evaluated 95 rooms from the City of Inglewood Sound Insulation Program (Inglewood) at Los Angeles International Airport (LAX), where the NLR was measured using real aircraft. Because the building shielding was not directly measured, a sample of NLR measurements has been statistically evaluated instead. The location and orientation of the rooms have been broken down into three categories, where windows/doors/sliding doors which are considered "weaker elements" have:

1. Category 1 - exposure to the whole fight track;
2. Category 2 - exposure to approximately half of the flight track; and
3. Category 3 - no exposure to the flight track.

These categories are schematically presented in **Figure 8** for rooms with critical elements on one or two facades in relation to the flight tracks in the upper and lower rooms; respectively. In addition, L&B evaluated both pre- and post-construction test data separately. A total of 90 rooms had the roof exposed to the flight track. Five rooms were located on first floors with a second floor above. A total of 95 rooms are included in this evaluation.

Of the 95 evaluated rooms for the LAX Inglewood program, 92 rooms were subjected to pre-construction noise tests and 83 rooms had post-construction noise tests. **Table 9** and **Figure 9** present a summary of the influence of building self-shielding on the NLR. Table 9 shows a statistically increasing trend of the median NLR as a greater part of the flight track is shielded by the building both for the pre- and post-construction noise measurements. Typically rooms that are exposed to the flight tracks are selected when selecting rooms for real aircraft NLR measurements. Therefore the sample size in this evaluation is relatively small for rooms that have no weaker elements exposed to the flight tracks. A smaller NLR increase for the post-construction noise measurement than the pre-construction noise measurements is expected for exposure category 2. Some rooms are corner rooms with weaker elements on one façade only. During the post-test, these critical elements are replaced with acoustical products with higher transmission loss. For these corner rooms, the influence of the partial exposure of the weaker elements is reduced, thereby also reducing the difference between exposure category 1 and 2. A significantly higher NLR is evident when no weaker elements are exposed to the flight track. The sample size of exposure category 3 is too small to make conclusive statements about the differences between the pre-test and post-test measurements.

[13] Wyle Research Report, WR 89-7, "Guidelines for the Sound Insulation of Residences Exposed to Aircraft Operations", November, 1989

Figure 8. Breakdown of Categories of Exposure due to Building Self-Shielding

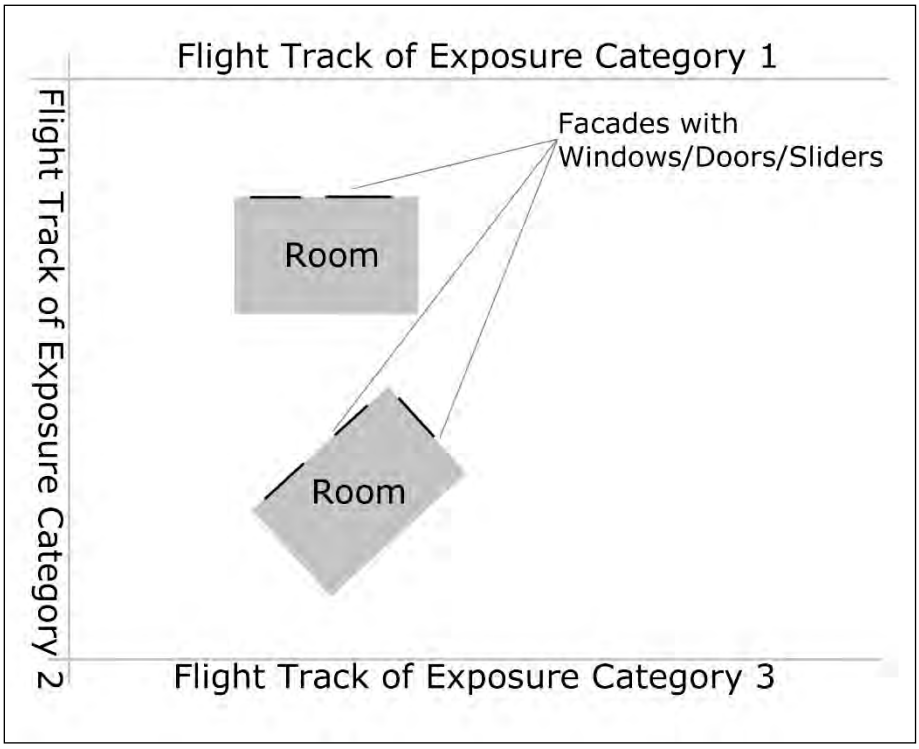


Table 9. Summary of NLR Increases Due to Building Self-Shielding

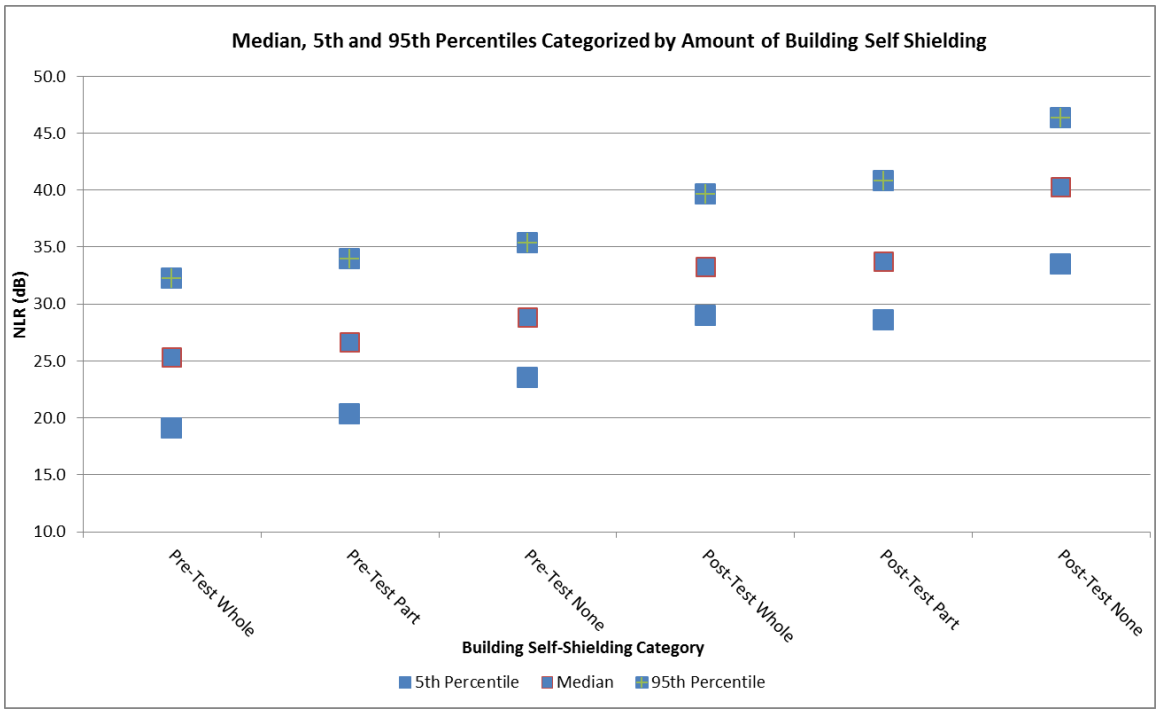
Exposure Category	1 (Pre-Test)	2 (Pre-Test)	3 (Pre-Test)	1 (Post-Test)	2 (Post-Test)	3 (Post-Test)
Median NLR (dB)	25.3	26.6	28.8	33.3	33.7	40.3
Increasing NLR Trend Relative to Building Self-Shielding (dB)	-	1.3	3.5	-	0.5	7.0
Number of Rooms in Sample	45	41	6	40	37	6

IBANA has an option to apply a correction to account for the horizontal angle of view of the flight track. In an attempt to take into account the effect of building self-shielding, partial exposure to the flight track has been approximated in IBANA as 0 and 90 degree angular view to the flight track that is meant to represent exposure category 2. Room No. 1 and 8 from this study were selected for applying corrections in IBANA where the roof exposure has been included so that the modeling is comparable to the Inglewood measurements. The IBANA corrections for a 90 degree angle of view increased the NLR two (2) dB. When the same room is modeled using 1/8”-glass-1/2”-air-1/8”glass windows and wood doors with magnetic seals, the NLR increases one (1) dB when applying corrections. IBANA calculates the angle of view correction based on a corrected source level (Ls”(f)), in the following equation:

$$Ls''(f) = Ls(f) + 10 \log\{ (\varphi / 180) D(f)\} \text{ dB},$$

Where φ is the horizontal angular view of the fly-by and $0 \leq \varphi \leq 180$, and D(f) is a frequency dependent variable that accounts for diffracted energy around the building. The correction is applied to the source levels, and affects all exposed surfaces, including the roof. Typically, façades may be shielded depending on the orientation of the room, however, usually the roof structure is fully exposed.

Figure 9. NLR Increases Due to Building Self-Shielding



4.14 Angle Above the Horizon Considerations

The models are compared to the measured NLR using the loud speaker method that has been setup to expose all facades to an approximate at an angle of incidence of approximately 45 degrees, as well as the TL measurements. In practice, the angle of incidence changes as a function of time, and depending on the location of the aircraft on the flight track in relation to the location and orientation of the room. In this paragraph, the vertical angle to the flight track is evaluated and NLR are evaluated statistically. To help understand the influence of the angle to the flight track on the NLR, L&B has considered 95 rooms from the Inglewood program at LAX, where the NLR was measured using real aircraft. Only rooms with weaker elements exposed to the whole flight track were included in this evaluation. The angle of the closest point to the flight track was calculated using the assumption that only the outer two runways of LAX were used for arrivals, and aircraft approached LAX at a three-degree slope. The angle above the horizon was approximated using the distance to the flight track and elevation of the aircraft. A total of 45 pre-construction noise tests and 40 post-construction noise tests are

included in the evaluation. The median angle above the horizon of all room tested was 35 degrees. In this evaluation, the angles above the horizon categories are divided into:

1. Above 35 degrees
2. Below 35 degrees

Table 10 presents the measured NLRs in relation to the two categories. Both the sets of pre- and post-construction measurements show a lower median NLR as the angle above horizon decreases. This difference seems more prominent in the post-construction measurements.

Angle of Incidence - As the angle above horizon increases, the angle of incidence to the walls decreases, and the angle of incidence to the roof structure increases. The TL theoretically decreases as the angle of incidence decreases. The weaker elements typically drive the NLR, and therefore it may be expected that the NLR would decrease as the angle above the horizons increase. Perhaps post-construction measurements may show the NLR decrease when the angle above the horizon decreases as the influence of the roof becomes more significant.

Slant Distance - Atmospheric absorption affects the source spectrum, and is dependent on the distance to the source. The high frequencies are attenuated more than the lower frequencies. As a result, the NLR will gradually decrease as the slant distance increases. The average slant distance in category 1 and 2 is 1,380 and 1,850 feet; respectively. This represents an average difference of almost 500 feet.

Ground Reflection - When performing NLR measurements with a loudspeaker and manual scanning method for the exterior measurements, the microphone moves through interference patterns. For real aircraft measurements, a static microphone is placed that may be affected by ground reflections that may destructively interfere with incident sound. This interference is affected by the angle above the horizon, and changes throughout the aircraft overflight.

Table 10. Summary of NLR Measurements in Relation to Angle above Horizon

Angle above Horizon	≥ 35 degrees (Pre-Test)	< 35 degrees (Pre-Test)	≥ 35 degrees (Post-Test)	< 35 degrees (Post-Test)
NLR (dB)	25.5	25.3	33.4	32.0
Difference (dB)	-	0.2	-	1.4
Number of Rooms in Sample	-	45	-	40

IBANA has an option to apply a correction to account for the horizontal angle to the horizon, atmospheric absorption, and ground reflections. Room No. 1 and 8 from this study were selected for applying these corrections in IBANA where the roof exposure has been included so that the modeling is comparable to the Inglewood

measurements. For category 1, 790 feet average distance to the flight track and 58 degrees angle to the horizon was used. For category 2, 1,690 feet average distance to the flight track and 21 degrees angle to the horizon was used. For both rooms, the NLR of category 1 was five (5) dB lower than category 2. When the same room is modeled using 1/8”-glass-1/2”-air-1/8”glass windows and wood doors with magnetic seals, the NLR of category 1 was four (4) and six (6) dB lower than category 2 for rooms 1 and 8; respectively.

The differences of the trends may be related to the way that IBANA handles roof exposure. Using real aircraft NLR measurements of rooms that have skylights may provide additional insight. The reason for the differences between the IBANA calculations and measurements are uncertain at this time, as number of factors may contribute to differences. Additional measurements of rooms with sky lights and NLR measurements as a function of time during an overflight may provide additional insight.

SECTION 5 INCORPORATION OF ACRP STUDY FINDINGS

The information presented in the previous sections shows that the acoustical consulting industry uses various acoustical models that are based on varying assumptions and input parameters. In almost all cases, adjustment or correction factors are required to calibrate the model to match the measurement results.

A review of *Task 3 – Acoustical Test Plan* of the Detailed Work Plan for ACRP 02-51 shows one of the measurement plans for the study will be *"Architectural Survey and Noise Reduction Calculations"*. The purpose of this test is to obtain enough information to model the NLR of each of the rooms by collecting data on the physical dimensions of the test rooms and elements, obtain enough information to determine TL data for the building elements and obtain information on the room absorption. All information will be input into the IBANA model to determine a modeled NLR for each residence and room.

In the statement of work it was stated that a modeling task will be undertaken in the study for each of the estimated 20 rooms at 10 residences that are part of the planned acoustical testing at San Diego International Airport (SAN). A similar amount of testing and modeling was to be undertaken at Boston's Logan International Airport (BOS). The acoustical testing that was undertaken at SAN and BOS includes the following:

- Outdoor Sound Source (Loudspeaker) Measurement Plan
- Indoor Sound Source (Loudspeaker) Measurement Plan
- Fixed Microphone Flyover Measurement
- Moving Microphone Flyover Measurement
- Acoustic Intensity Measurements, Interior Loudspeaker + Exterior Intensity
- Acoustic Intensity Measurement, Exterior Loudspeaker + Exterior Intensity
- Acoustic Intensity Measurement, Exterior Loudspeaker + Interior Intensity

The ACRP 02-51 study evaluated various measurement methods for determining the NLR. The study included the "ground loudspeaker" measurement method and that is what the modeled results are compared to in this report. On average, the "ground loudspeaker" measurement method produces NLRs that are 1.4 dB lower than the average of a number of different NLR measurement methods that were evaluated. The "ground loudspeaker" measurement method is currently an accepted measurement method, and has been used in this study without any applied corrections.

The resulting findings from the ACRP 02-51 study were released to the public as ACRP Report 152 in early 2016[14]. This study helps explain the differences between the measurement methods and, ultimately, this information may be useful to help understand the limitations to the acoustical modeling. This study may help set precedence to an accepted measurement method that will be consistent among all consultants who perform NLR measurements. For evaluating the modeling process the modeling results will be compared to an industry wide accepted measurement method using the loudspeaker on a tripod.

The ACRP study does consider modeling in conjunction with on-site home inspections as an option for determining the NLR. IBANA was used to perform the calculations in that study. The study found the calculated NLR to be 0.7 to 1.3 dB higher than the average measured NLR through various methods. The report also mentions the possibility of missing "noise leaks" that may result in an overstatement of NLR. Although the study did not find a significant correlation to whole building leakage and NLR, the study did indicate a chance of overstatement of the NLR when leaks around critical elements are not accounted for. This observation has been supported in this study.

The ACRP study did evaluate modeling using IBANA as well as a spreadsheet calculation. As part of the evaluation of modeling, they used information from an on-site inspection for the IBANA modeling process, and measured reverberation times for the spreadsheet calculation process. This study evaluates the option to model rooms.

[14] Airport Cooperative Research Program (ACRP) Report 152, "Evaluating Methods for Determining Interior Noise Levels Used in Airport Sound Insulation Programs", 2016.

SECTION 6 RECOMMENDATIONS FOR SHORT-TERM BEST PRACTICES

This study evaluated the NLR modeling process, used by a number of acoustical consulting firms. The study outlined the models used and the various input assumptions that play a role in how the results vary. Ideally, the results obtained through modeling should be in agreement with the various measurement methods. However, due to differences in models, and the various input assumptions, the modeling results differ between consultants. Also, to evaluate the modeling usefulness, the results are compared to measurements. As different measurement methods result in different results, the question arises which measurement method is the best to compare modeling results to.

Sections 6.1 to 6.10 summarizes the variations that result from the model, the TL data used, the room and element dimensions data used, the room acoustics assumptions and the conditions of the elements. Following the summary, Section 6.11 provides recommendations for short-term implementable best practices to minimize the variation amongst different consultants, in an effort to focus on industry-wide modeling consistency.

6.1 NLR Models (General)

Consultant's proprietary room models, and the commercially available IBANA model, are used for determining the NLR based on composite TL data, room absorption data and aircraft noise exposure data.

The basic inputs that the models require are defined below:

- *Exterior Noise Source Input* - Spectrum of the exterior noise source.
- *Transmission Loss Data Input* - TL data for all exposed transmitting surfaces.
- *Dimensional Data Input* **-** Room size and element sizes for all exposed surfaces.
- *Interior Room Acoustics Input* - Amount of absorption in the room.

Differences in assumptions and approaches may lead to differences in the resulting calculated NLR. The influence of variations of these inputs on the final NLR is further discussed in the following sections.

6.2 Diffuse Sound Field Assumptions of the NLR Model

The equation Consultant "A" and IBANA uses for determining the NLR is based on composite TL data and room absorption data and assumes a diffuse sound field. It is expected that the models of other consultants also use this assumption, as it is a well-established equation. A diffuse sound field is an appropriate assumption for modeling the NLR based on aircraft noise exposure.

When modeling rooms, the way interior openings in rooms are handled may differ among consultants and that may ultimately affect the interior absorption of the rooms. Large openings between rooms are a typical scenario that may affect the interior absorption.

Key Finding: Using one model in the industry reduces differences in the modeling results amongst consultants due to differences in the modeling process that the model assumes.

6.3 Exterior Noise Source Input

For this study an average measured aircraft noise spectrum was provided to all consultants to minimize the impact of this input variable. While consultants generally develop an exterior noise source spectrum in a variety of ways, this data is generally not a major factor in the development of accurate modeling results. It should be noted that a separate study to determine the impact of exterior noise source spectrum is on-going.

Key Finding: Consistency in the exterior spectrum that is used will reduce differences in the modeling results amongst consultants.

6.4 TL Data Input - Exposed & Critical Elements

Given the correlation between the measured NLR and SIE, the results of the critical elements are one of the main factors driving the accurate modeling of NLR. Critical elements are typically the weaker links in the exterior exposed elements and are typically defined as windows, doors and thru-wall air conditioning units. Roof structures and walls have typically a higher TL and are usually less critical. This correlation is evident from the different regions and different room types that were measured and modeled. Given the magnitude of the variations of the TL data of critical elements compared to the variation from differences in assumptions regarding room absorption, the TL data of the windows and doors is the primary focus in this study.

This study revealed that the consulting industry used a variety of sources for TL data in modeling. Many times measured TL data can be used if measurements are undertaken in the field. Measured TL data was provided for windows and doors in this study but walls and roof data was still provided from other sources. Laboratory TL data is used in some instances, as is modeled TL data from a variety of sources. Consistent application of TL data would help in reduce differences in modeling results amongst consultants.

Importance of Leakage on TL Data

The TL of critical elements is significantly influenced by the seals and gaps around the perimeter. This was measured on a previous project as well as modeled using laboratory data. This difference was shown to be as high as (five) 5 dB. The influence of gaps and cracks around element can be modeled, providing that

detailed dimensions of the gaps and cracks are provided. As much as development of accurate TL data is important to the NLR modeling process, assessing the condition of the elements is even more important. A detailed assessment of the elements would be required to determine the condition of the elements and to detail gaps and cracks. Without an on-site inspection of the condition of the critical elements, the uncertainty of the results of the modeling process increases significantly.

Key Finding: A consistent approach amongst consultants to address the condition of the elements as well as taking the conditions into account in the modeling process would reduce differences in modeling results amongst consultants and is expected to improve correlation with measured results.

6.5 Dimensional Data Input

For this study exact room and element dimensions were provided to all consultants to minimize the impact of this input variable. Consultants generally measure these dimensions in the field or get the data off of building plans. This study has not included NLR variation due to differences in modeling dimensions as they are obtained by consultants through means of various methods. The dimensional data primarily affects the second term (10log(S/A)) in the diffuse sound field equation for determining NLR. Due to the logarithmic component of this term, small linear variations have significantly smaller variations on that term, thus also on the NLR.

Key Finding: A consistent approach input dimension of the rooms and elements, including determining the average ceiling heights of rooms with vaulted ceilings would reduce differences in the modeling results amongst consultants. To obtain reliable dimensions, an on-site inspection is almost always required, unless detailed plans are available.

6.6 Interior Room Acoustics Input - Assumptions Regarding Absorption

For this study photographs were provided to all consultants and they determined the interior acoustics based on their own observations. The assumptions consultants used for openings are not known and may differ and may impact the overall absorption. Previous studies have shown that NLR differences of up to three (3) dB can occur by significantly changing the absorption in a room. It is expected that differences of the assumptions regarding the absorption amongst consultants will result in NLR differences less than three (3) dB. The absorption assumptions used by all the consultants has not been thoroughly documented.

Key Finding: A consistent approach for estimating absorption of rooms, including addressing how openings are treated would reduce differences in the modeling results amongst consultants.

6.7 Modeling Consistency

When the TL data of critical elements and exterior noise exposure are consistent, modeled NLR results differed among the consultants. In addition, the spread of the differences of the modeled and measured results differed as well. Due to a number of both known and unknown factors that may have contributed to these differences, the cause is not evident. The median difference of the modeled and measured NLR results amongst all consultants ranges by approximately seven (7) dB.

Key Finding: It is expected that applying the best practices mentioned in earlier paragraphs would significantly reduce the variation in the modeling results amongst consultants.

6.8 Comparison to NLR Measurements

The modeled results were compared to measured results. The measured results were obtained using the loudspeaker measurement method. In an effort to reduce the differences between modeled and measured results, all but one consultant based their modeling on having only facades exposed. Since the roof structure was not considered a critical element, it is expected that this influence would be minimal. The ACRP study of various NLR measurement methods may facilitate a measurement method selection to which modeling processes can be compared to.

Key Finding: Modeling consistency combined with an assessment of element conditions obtained during an on-site inspection are expected to aid a consistent approach to modeling the critical elements and may reduce the variation between modeled results and measured results.

6.9 Building Self-Shielding Considerations

Both NLR measurements and IBANA calculations show an NLR increase when the facades of a room are partially exposed to the flight tracks.

Key Finding: If mandatory adjustment factors are to be applied to measured NLR data, corresponding adjustments factors may be justified.

6.10 Angle above the Horizon Considerations

Measured NLR data may initially suggest that the NLR increases as the angle above the horizon decreases. However, a number of factors affect the NLR that way depending on the airport. When taking into account the angle above the horizon, the change in atmospheric absorption as the slant distance changes and the effects from ground reflection interference, IBANA projects an increasing NLR as the angle above the horizon increases. The cause for this discrepancy may be related to the way the roof exposure is handled in IBANA.

Key Finding: Until the exposure and additional factors are well understood, adjustment factors for the angle above the horizon applied to measured or modeled NLR data is not recommended.

6.11 Recommendations for Short-Term Best Practices

The NLR model that is used should not have much impact on the overall modeling process and the ultimate results. However, the input entered is what ultimately influences the calculations and the final results. The goal is to have as much consistency as possible in the modeling process amongst consultants. If diffuse sound field equation is used in all models for determining the NR, then the variables for that equation are determined by the input of the software, and the assumptions that are made when acoustically modeling a physical space.

Key Recommendations of short-term implementable approaches for the modeling process that may be standardized for consistency are discussed below:

6.11.1 Use of One Model

As stated earlier, differences in assumptions and approaches may lead to differences in the resulting calculated NLR. Therefore, to improve the consistency of the modeling process amongst consultants, it is recommended to use one model. This has the benefit that one set of procedures can be applied for all consultants to follow.

6.11.2 Noise Exposure and Exposed Surfaces

The number of facades including walls and roof exposure can impact the modeling results. Differences such as the number of facades to include in the room exposure, and the inclusion of roof exposure, are examples of areas where modeling consistency can be increased. The number of exposed facades and roof exposure can be chosen to be consistent to the actual aircraft exposure and a consistent aircraft noise spectrum at a 45-degree angle of incidence.

6.11.3 Critical Elements and Leakage

The TL data for elements is a very important factor that can impact the modeling results. A detailed understanding of the condition of critical elements is important to determine the leakage around critical elements, which may be determined during an inspection of the home. During on-site inspections, the condition of the critical elements can be rated into three levels; average, poor and very poor, thereby applying the leakage modeling accordingly to adjust the TL.

6.11.4 Absorption

Absorption data can also impact the modeling results. Using a standard amount of absorption for different types of rooms may reduce issues due to conditions of unusual furnishing, and thereby basing the modeling process on average home furnishings. In IBANA this can been done using the absorption slider control for

fine tuning the amount of absorption, yet IBANA also has available a preset for living rooms and bedrooms. These presets may be expanded to also include dining rooms and kitchens. During on-site inspections to determine the condition of critical elements and obtain dimensional data, optionally reverberation time measurements may be performed to determine the room absorption.

SECTION 7 RECOMMENDATIONS FOR FUTURE LONG-TERM RESEARCH

If modeling is to be considered a viable and accurate method to predict NLR for eligibility, a detailed understanding of the error margin needs to be determined. The error margin consists of two aspects; the modeling process itself and the difference between modeled and measured results. This section discusses areas where additional long-term research may improve modeling consistency amongst consultants, and improve agreement between measured and modeled results using the knowledge and findings in this and other studies.

7.1 Recommendations for Future Long-Term Research

Key recommendations for long term research are broken down in the following paragraphs below.

7.1.1 Variation in Modeling Consistency

Modeling consistency amongst consultants can be studied to determine the modeling variation despite best efforts of consultants using one model and a prescribed procedure. Currently the reduction of variation amongst consultants using a single modeling process is unknown. Although variation amongst consultants is expected to reduce, it is useful to gain insight as to how much the reduction would be.

7.1.2 Influence of the Condition of Critical Elements

The modeling variation between consultants can be reduced through standardizing the model to be used and modeling procedures that are to be applied. In order for the modeling process to be in more in agreement with measurements, the influence resulting from the condition of critical elements (such as doors and windows) would need to be measured, assessed and well understood.

In an effort to improve the agreement between modeled and measured results, the influence of the condition of critical elements on the TL and NLR may be studied. Once the influence is well understood, adjustment factors may be applied to account for the condition of critical elements. The modeling process can then be compared to measured results. A consistent measurement method must be agreed upon where the modeled results are compared to.

7.1.3 Determining Room Absorption

Instead of calculating room absorption from laboratory data, the modeling process may be improved by measuring the reverberation times of the room that can be used to determine the room absorption. When inspections are done to measure the dimensions of the rooms/elements and to assess the condition of critical elements, then measuring the reverberation times of the rooms may be an option to reliably determine the room absorption. Further study may show how the comparison

between measured and modeled results is affected depending on what room absorption data is used.

7.1.4 Measurement Method Selection and Future Research

Another limitation for modeling as well as measuring NLRs is the noted difference between using real aircraft and a loudspeaker as the noise source. The difference between the two methods is approximately two (2) dB. The ACRP study recommends that four (4) angles of incidence should be averaged. Using data from the "Study of Noise Level Reduction (NLR) Variation" report, and additional measurements may provide insight on how the ground loudspeaker measurement method averaged at various angles compares to the overflight measurement method. In addition, the flyover measurement method was used for many years for the Inglewood Residential Sound Insulation Program. The outdoor and indoor time histories were recorded for each aircraft event. To gain insight to the differences between the ground loudspeaker measurement method and flyover measurement method, the NLR can be plotted as a function of time. This information combined with the angle of incidence analysis may provide insight to this difference. The usefulness of modeling process can be evaluated against measurements of which the results are better understood. This provides a better understanding of how well modeled results are in agreement with measured results. Measuring a pulse response with a source and microphone at various locations would provide insight how reflections and interference at certain frequencies occur and thereby help explain the differences of the measurement methods.

SECTION 8 CONCLUSIONS

NLR is typically determined through measurements using various methods and techniques. However, NLR can also be calculated through acoustical modeling and the modeling the NLR of rooms is useful in various context including modeling for design recommendations and eligibility determination.

8.1 Modeling for Design

As part of the design process for sound insulation programs, consultants will determine the influence of changing products by modeling. The installation of acoustical products and the estimated relative change in NLR can be projected. These modeling efforts are usually validated using measured data and are useful for the purpose of projecting changes. The consultant survey included in this study (Section 3) confirms that most consultants will validate the modeling efforts thru measurements.

For example, consultant will typically model existing conditions of a room, validate the modeled results with measured data, then change the room conditions by entering data for acoustical windows and have confidence that the new windows will result in the decibel increase as modeled.

Modeling the NLR to aid in design is recommended and should continue, especially when done in conjunction with measurements to validate the results. While each consultant has their own acoustical model and their own techniques, implementation of the short-term best practices should be encouraged to improve the overall results.

8.2 Modeling for Eligibility

Noise reduction of buildings determines the interior noise exposure from an exterior noise source. The NLR and the interior DNL is now a definitive factor in the determination of the eligibility for mitigation treatments in sound insulation programs. FAA policy seems to be focused on the determination of eligibility based on a single interior DNL number. As a result, the consistent determination of NLR is important. Since eligibility is based on an interior DNL equal to or greater than 45 dB, the existing conditions are even more important in determining the NLR of a room. In addition, differences in assumptions and how consultants model various aspects will result in different NLR results. These differences between consultants may be reduced by using one model and a consistent modeling approach.

8.2.1 Modeling (without On-Site Inspection)

Without the ability to validate the modeling process thru measurements or on-site inspection, the uncertainty of the NLR is significantly increased due to various factors that are unknown and influence the final result. For example, the interior furnishings and the condition of the critical elements may affect the NLR significantly. Without an on-site inspection, the seals around critical elements and the interior furnishings are unknown which increases the uncertainty of TL and

absorption; respectively. Without an on-site inspection, there is greater uncertainty, and a significantly increased risk that homes that may have been eligible through measurements may not be eligible though a modeling process.

Modeling NLR without an on-site inspection for eligibility purposes is not recommended even if a consistent modeling approach has been established within the industry.

8.2.2 Modeling (with On-Site Inspection)

During an on-site inspection for preparation of modeling rooms, the dimensions of the rooms and elements are measured, the conditions of critical elements are categorized, and optional reverberation times are measured. With this additional information available and an industry wide consistent modeling process, modeling may present an option for determining eligibility. This has the advantage that roof exposure can be included in the modeling process where the roof structure may be of greater importance, such as flat or vaulted roof structures. In instances where measurements of rooms with flat or vaulted roof structures cannot be performed due to access limitations, modeling in conjunction with an on-site visit may be preferred.

However, one has to evaluate the effort and cost of an on-site inspection and modeling of every room in every house versus just measuring the NLR directly. The cost to send a team in to perform the on-site inspection, plus modeling could equal the cost to send a person or two in to perform measurements. In addition, homeowners would more easily believe the results of actual measurements versus the results from a computer model, especially if their property does not become eligible.

Modeling NLR in conjunction with an on-site inspection for eligibility purposes will provide more accurate results if room and element dimensions are logged, condition of critical elements are noted, and room reverberation times are collected. When further research is completed and a consistent modeling approach has been established within the industry even more accurate results are expected.

APPENDIX A
CONSULTANT NLR MODELING SURVEY

Acoustical Consultant Survey Regarding Noise Level Reduction (NLR) Modeling Methodology

February 12, 2015

The FAA has funded a new research project to address technical issues in estimating Noise Level Reduction (NLR) and has contracted with Landrum & Brown Inc. (L&B) to undertake this work. This project will focus on the prediction of NLR. The process will consist of two objectives that are intended to gather data from various acoustical consultants that are involved in providing acoustical input to airport sound insulation programs. The first objective is to fill out a short survey regarding your modeling methodology. The second objective is a request to undertake some modeling based on a standard set of room data.

Completion of this survey will fulfill the first objective. We appreciate your assistance and support in responding to the survey. Your participation is voluntary and all information you provide will remain confidential. If you feel the need for more anonymity with the survey, you are welcome to provide the information to Bill He at the FAA and he will ensure it gets to L&B without your company information being included. You may contact Dr. Hua (Bill) He at the FAA Office of Environment and Energy (AEE) (202-267-3565) who is copied on this email.

* * * * * *

1. ***Model***

- What model do you use?
  - Proprietary?
  - Commercially Available?
    - Name & Version
- Please describe the model you use in your own words
- Describe the model limitations
- Do you have any other details or assumptions regarding your model that you consider relevant that has not been discussed in the previous questions?

2. ***Modeling Process***

- What are your assumptions for exterior noise source spectrum to base your NLR on?
  - Single aircraft?
  - Airport specific?
  - General fleet mix based on INM mix?
  - Pink noise?
- How do you typically get room dimensions?
  - Architects plans?
  - Measured in field?

- What assumptions do you make?
  - Large openings?
  - Irregular rooms?

- What data do you typically use for the transmission loss of the elements on exposed facades?
  - Laboratory data?
  - Field measured data?
  - Calculated using programs such as Insul?

- Do you apply any corrections to the transmission loss data?
  - Angle of incidence?
  - Leaky products?

- How do you determine the total interior absorption of the room?
  - Laboratory data?
  - Measured data?

- What assumptions do you make for typical rooms?

- Do you apply any corrections to account for the exposure in relation to the flight path?
  - Room location?
  - Angle?
  - Shielding from nearby buildings?

- Do you have any other details or assumptions regarding your modeling process that you consider relevant that has not been discussed in the previous questions?

3. ***Verification of Results***

- Do you have a process to validate or verify the accuracy of your modeled results?
  - National averages?
  - Actual measurements?

APPENDIX B
NLR ROOM MODELING DATA

Room # 1	**Airport** FLL		
Room Type Living Room	**Length (ft)** 12	**Width (ft)** 12	**Height (ft)** 7.8
Exterior Windows Aluminum SH-SH-SH	**Width (ft)** 9.3	**Height (ft)** 4.3	**Glazing (inch)** 1/8
Exterior Doors Metal door/not solid core/poor seals	**Width (ft)** 3	**Height (ft)** 6.7	
Roof Style Pitched asphalt shingles -Attic	**Ceiling** Plaster		
Walls Exposed CMU stucco exterior	**# walls exposed** 1		
Walls Interior painted wallboard	**Floors** Pergo		
Interior Doors One door in kitchen, three in hallway			
Openings to Adjacent Spaces Kitchen Hallway	**Width (ft)** 7.5 3	**Height (ft)** 7.8 7.8	**Depth (ft)** 13 13
Main Furniture 2 chairs 1 couch multimedia stand table			

Room # 2	**Airport** FLL		
Room Type Bedroom	**Length (ft)** 10	**Width (ft)** 11	**Height (ft)** 7.8
Exterior Windows Aluminum SH Aluminum SH	**Width (ft)** 3 3	**Height (ft)** 4 4	**Glazing (inch)** 1/8 1/8
Exterior Doors	**Width (ft)**	**Height (ft)**	
Roof Style Pitched asphalt shingles -Attic	**Ceiling** Plaster		
Walls Exposed CMU Stucco exterior	**# walls exposed** 2		
Walls Interior Painted Wallboard	**Floors** Tile		
Interior Doors door and closet door			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Main Furniture Twin bed 2 Dressers			

Room # 3	**Airport** FLL		
Room Type Bedroom	**Length (ft)** 10	**Width (ft)** 12	**Height (ft)** 8.2
Exterior Windows Aluminum awning window	**Width (ft)** 6	**Height (ft)** 3.25	**Glazing (inch)** 3/32
Exterior Doors	**Width (ft)**	**Height (ft)**	
Roof Style Pitched asphalt shingles -Attic	**Ceiling** plaster		
Walls Exposed CMU stucco exterior	**# walls exposed** 1 (12-ft wall)		
Walls Interior Painted Wallboard	**Floors** Carpet		
Interior Doors sliders for closet and door			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Main Furniture Twin bed Desk + Chair Dresser			

Room #	**Airport**		
4	FLL		
Room Type	**Length (ft)**	**Width (ft)**	**Height (ft)**
Living Room	13.8	14.8	8.3
Exterior Windows	**Width (ft)**	**Height (ft)**	**Glazing**
Aluminum awning window	6	3	3/32
Aluminum awning window	6	4	3/32
Exterior Doors	**Width (ft)**	**Height (ft)**	
Wood Door	3	6.7	
Roof Style	**Ceiling**		
Pitched asphalt shingles -Attic	Plaster		
Walls Exposed	**# walls exposed**		
CMU stucco exterior	2		
Walls Interior	**Floors**		
Painted wallboard	Carpet		
Interior Doors			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Opening	3.2	8.3	-
Main Furniture			
Couch			
4 tables			
TV table			

Room # 5	**Airport** ONT		
Room Type Bedroom	**Length (ft)** 10	**Width (ft)** 9.5	**Height (ft)** 7.6
Exterior Windows Vinyl DH	**Width (ft)** 2.8	**Height (ft)** 4.8	**Glazing** 1/8-1/2air-1/8
Exterior Doors	**Width (ft)**	**Height (ft)**	
Roof Style Pitched asphalt shingles - Vented Attic	**Ceiling** Plaster		
Walls Exposed Wood frame stucco exterior	**# walls exposed** 1 (10 ft wall)		
Walls Interior Painted wallboard	**Floors** Tile		
Interior Doors Door and Closet Door			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Main Furniture Double bed Armoir			

Room # 6	**Airport** ONT		
Room Type Living Room	**Length (ft)** 13.3	**Width (ft)** 12.3	**Height (ft)** 8.2
Exterior Windows Vinyl DH Vinyl DH	**Width (ft)** 3.8 3.8	**Height (ft)** 4.7 4.7	**Glazing** 3/16-1/2air-3/16 3/16-1/2air-3/16
Exterior Doors Solid Wood Door	**Width (ft)** 3	**Height (ft)** 6.7	
Roof Style Pitched asphalt shingles - Vented Attic	**Ceiling** Plaster		
Walls Exposed Wood frame stucco exterior	**# walls exposed** 2		
Walls Interior Painted wallboard	**Floors** Tile		
Interior Doors			
Openings to Adjacent Spaces Kitchen	**Width (ft)** 7.5	**Height (ft)** 8.2	**Depth (ft)** 11
Main Furniture 2 couches chair			

Room # 7	**Airport** ONT		
Room Type Bedroom	**Length (ft)** 10	**Width (ft)** 12	**Height (ft)** 8.2
Exterior Windows Vinyl DH	**Width (ft)** 6	**Height (ft)** 2.7	**Glazing** 3/16-1/2air-3/16
Exterior Doors Solid Wood Door	**Width (ft)** 3	**Height (ft)** 6.7	
Roof Style Pitched asphalt shingles - Vented Attic	**Ceiling** Plaster		
Walls Exposed Wood frame stucco exterior	**# walls exposed** 2		
Walls Interior Painted wallboard	**Floors** Carpet		
Interior Doors Door and closet door			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Main Furniture Double bed			

Room #	**Airport**		
8	ONT		
Room Type	**Length (ft)**	**Width (ft)**	**Height (ft)**
Living Room	17.4	18	7.8
Exterior Windows	**Width (ft)**	**Height (ft)**	**Glazing**
Vinyl DH Windows	2	4.7	3/16-1/2air-3/16
Vinyl F Windows	4	4.7	3/16-1/2air-3/16
Vinyl DH Windows	2	4.7	3/16-1/2air-3/16
Exterior Doors	**Width (ft)**	**Height (ft)**	
Solid wood door	3	6.7	
Roof Style	**Ceiling**		
Pitched asphalt shingles	Plaster		
Walls Exposed	**# walls exposed**		
Wood frame stucco exterior	2		
Walls Interior	**Floors**		
Painted wallboard	Wood		
Interior Doors			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Dining Room	12.5	7.8	8
Main Furniture			
2 couches			
(Table + 6 chairs)in adjacent Dining Room			

Room # 9	**Airport** ONT		
Room Type Bedroom	**Length (ft)** 10.3	**Width (ft)** 10	**Height (ft)** 7.8
Exterior Windows Vinyl DH Windows Vinyl DH Windows	**Width (ft)** 2.5 2.5	**Height (ft)** 4.7 4.7	**Glazing** 3/16-1/2air-3/16 3/16-1/2air-3/16
Exterior Doors	**Width (ft)**	**Height (ft)**	
Roof Style Pitched asphalt shingles	**Ceiling** Plaster		
Walls Exposed Wood frame stucco exterior	**# walls exposed** 1 (10.3 ft wall)		
Walls Interior Painted wallboard	**Floors** Wood		
Interior Doors door and 2 closet doors			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Main Furniture Double bed Area rug Dresser			

Room # 10	**Airport** ONT		
Room Type Living Room	**Length (ft)** 11.2	**Width (ft)** 10	**Height (ft)** 7.8
Exterior Windows Vinyl DH Windows Vinyl DH Windows	**Width (ft)** 2.5 2.5	**Height (ft)** 4.7 4.7	**Glazing** 3/16-1/2air-3/16 3/16-1/2air-3/16
Exterior Doors	**Width (ft)**	**Height (ft)**	
Roof Style Pitched asphalt shingles	**Ceiling** Plaster		
Walls Exposed Wood frame stucco exterior	**# walls exposed** 2		
Walls Interior Painted wallboard	**Floors** Wood		
Interior Doors door and 2 closet doors			
Openings to Adjacent Spaces	**Width (ft)**	**Height (ft)**	**Depth (ft)**
Main Furniture Double bed			

A-Weighted Aircraft Spectra

Airport	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz	A-Weighted Total
FLL	63.2	74.1	80.4	84.1	84.0	82.4	75.0	58.2	89.3 dBA
ONT	66.6	78.3	85.3	88.9	88.8	87.1	79.0	61.2	94.0 dBA

FLL

Room #	Element	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
1	Window	12.3	14.5	12.9	19.2	17.7	21.7	24.5	23.3
1	Door	10.6	13.9	11.8	18.2	21.1	19.0	21.5	23.4
2	Window	13.8	11.3	14.9	14.2	17.5	18.3	22.9	22.8
3	Window	12.3	10.1	10.5	12.0	16.1	16.8	20.9	21.8
4	Window	13.4	11.4	15.5	18.9	22.4	26.7	26.0	21.1
4	Door	12.9	12.4	18.8	19.6	22.5	23.7	23.7	25.6

ONT

Room #	Element	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
5	Window	17.9	14.5	17.7	24.8	26.0	25.9	27.5	36.1
6	Window	16.0	15.0	15.9	20.2	28.8	27.5	32.6	35.7
6	Door	13.1	15.9	18.5	21.9	24.0	19.9	25.3	28.1
7	Window	22.0	17.2	20.7	18.7	31.7	33.8	38.5	43.2
8	Window	18.3	19.1	18.0	25.5	28.1	23.8	23.9	31.7
8	Door	13.7	19.3	18.2	21.4	23.7	19.1	21.4	24.2
9	Window	20.8	20.0	16.9	27.9	30.1	30.5	30.5	34.8
10	Window	18.3	19.1	18.0	25.5	28.1	23.8	23.9	31.7
10	Door	13.7	19.3	18.2	21.4	23.7	19.1	21.4	24.2