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Field Validation of the Indoor-Outdoor Method for Measurement of Noise Reduction

January 2025

Final Report

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16. Abstract

The Federal Aviation Administration's (FAA) Airport Improvement Program (AIP) handbook outlines guidance for the funding of noise mitigation projects and the accuracy of existing noise reduction measurements of a structure. Prior research by the FAA to develop best practices for measuring the aircraft noise reduction of building façades resulted in the development of a new SAE Aerospace Recommended Practice (ARP) 6973, that provides additional details for application to practical situations. Like its predecessor, ASTM E966, the method requires the use of an outdoor loudspeaker. However, there are situations encountered in the field, such as areas with limited exterior space, where it is difficult to position a loudspeaker or to generate a uniform distribution of sound energy over the test façade.

To overcome these limitations, an alternative method for measuring noise reduction has been developed, with a loudspeaker placed inside the house and the noise reduction measured from the inside to the outside. This approach removes restrictions on the placement of an external loudspeaker. A feasibility study of such an indoor-to-outdoor test procedure for measuring noise reduction in buildings demonstrated the equivalence of the results with those of the standard outdoor-to-indoor method.

The goal of this project was to further develop the alternative indoor loudspeaker procedure with additional measurements in houses with special conditions, such as those with limited outdoor free space or attached porches, and to incorporate the methods into a revised version of SAE ARP 6973.

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LIST OF ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
AIP	Airport Improvement Program
ARP	Aerospace Recommended Practice
ASTM	American Society for Testing and Materials
dBA	A-weighted decibel scale
dB	Decibel
DI	Directivity index
DNL	Day-night average sound level
FAA	Federal Aviation Administration
Hz	Hertz
I-O	Indoor-outdoor
mks	Meter (length), kilograms (mass), and seconds (time)
NLR	Noise level reduction
O-I	Outdoor-indoor
PWL	Sound power level
RSS	Reference sound source
SAE	SAE International, formerly the Society of Automotive Engineers

EXECUTIVE SUMMARY

In 2014, the Federal Aviation Administration (FAA) amended the Airport Improvement Program (AIP) Handbook to clarify guidance for the funding of noise mitigation projects. The clarification addressed requirements that structures eligible for sound insulation treatment not only be located within the day-night average sound level (DNL) 65-decibel (dB) noise contour but also experience existing interior noise levels that are 45 dB or greater with the windows closed. This restated guidance placed greater emphasis on the accuracy in measuring the existing noise reduction of a structure.

Subsequent research by the FAA to develop best practices for measuring the aircraft noise reduction of building façades has resulted in the development of a new SAE Aerospace Recommended Practice (ARP) 6973, that provides additional details for application to practical situations. Like its predecessor, ASTM E966, the method requires the use of an outdoor loudspeaker. However, there are situations encountered in the field, such as areas with limited exterior space, where it is difficult to position a loudspeaker or to generate a uniform distribution of sound energy over the test façade.

To overcome these limitations, an alternative method for measuring noise reduction was investigated, with a loudspeaker placed inside the house and the noise reduction measured from the inside to the outside. This approach removes restrictions on the placement of an external loudspeaker. A feasibility study of this indoor loudspeaker test procedure for measuring noise reduction was conducted in eight rooms of three houses and demonstrated the equivalence of the results with those of the standard outdoor loudspeaker method.

The goal of this current project was to further develop the indoor loudspeaker procedure with additional measurements in houses with special conditions, such as limited outdoor free space or attached porches, to identify conditions where it can be used as an alternative test method, and to incorporate them into a revised version of SAE ARP 6973.

Following a series of preliminary parameter tests designed to provide the necessary details to further define an indoor loudspeaker test procedure, field measurements were conducted in 22 rooms of six houses to demonstrate equivalence of the results with those of the standard outdoor loudspeaker method. When combined with the data from the previous feasibility study, the differences between the outdoor and indoor loudspeaker methods of measuring noise reduction for the total of 30 rooms tested were all well within ±1 dB, the average difference being 0.1 dB.

1. INTRODUCTION

The results presented in a previous study on the Indoor-Outdoor Method for Measurement of Noise Reduction (Sharp & Cox, 2023) demonstrated the feasibility of using an indoor-to-outdoor (I-O) method for measuring Noise Level Reduction (NLR) with good accuracy compared to the outdoor-to-indoor (O-I) method (SAE, 2021), recognizing the limited sample of rooms and houses tested. The I-O method potentially represents an alternative procedure to the standard O-I method where exterior loudspeaker placement could prove to be difficult.

The tests described in this report were designed to provide the necessary details to further validate the equivalence of an I-O acoustical testing method as a supplemental or alternative approach for conducting noise reduction measurements of residential building façades for airport sound insulation programs. For the I-O method, the loudspeaker is placed inside the test room and the difference in sound levels measured inside and outside the room provides a measure of noise reduction. The value of noise reduction might not be numerically equal to the value obtained using the exterior loudspeaker. Development of the I-O method is intended to provide a measurement of noise reduction using an interior loudspeaker that can be related (by a constant factor) to that measured by the O-I method.

However, while it is a relatively simple procedure, the I-O method requires a measurement of room absorption and a reference sound source. The absorption measurements are required to provide NLR data consistent with those measured using the O-I method.

An alternative method for measuring I-O noise reduction is to redefine the definition of noise reduction as the difference in sound power generated by the loudspeaker, W_s, in the test room, and the sound power, W_t, transmitted to the exterior via the test façade, namely:

$$NR_{IOAlt} = 10\log\left(\frac{W_s}{W_t}\right) \tag{1}$$

Since the sound power transmitted includes the effect of absorption, but the loudspeaker sound power measurement does not, the difference between the two quantities includes the influence of absorption and hence, is consistent with the standard O-I measurement. The numerical values of the two quantities will not necessarily be the same because they represent different definitions of noise reduction, but as they both measure the attenuation of noise by the test wall, they should be related to one another. The advantage of this alternative method is that it does not require a measurement of absorption.

For this method to be robust, the procedure for in-situ measurement of the sound power output level of the loudspeaker located in the test room has been examined and optimized. The results of this study are presented first in this report, followed by a presentation of the results obtained from a field validation of the I-O test method, and a summary of the findings as needed for the development of a test standard.

2. EVALUATION OF LOUDSPEAKER PARAMETERS

2.1 LOUDSPEAKER OUTPUT POWER MEASUREMENT DISTANCE

The sound power radiated by the loudspeaker can be calculated from the measured sound level at a distance d on the main axis. The sound power output of a loudspeaker in a room depends on its location with respect to the room surfaces. When situated far from these surfaces, an omni-directional source radiates sound equally in all directions and the sound power output is essentially the same as if it were outdoors in free space, namely:

$$W_S = 4\pi d^2 \left(\frac{p_d^2}{\rho c}\right) \tag{2}$$

where p_d is the root-mean-square sound pressure at a distance d from the source, and ρc is the characteristic impedance of air, equal to 407 meter-kilogram-second (mks) units at normal temperature and pressure (Beranek, 1986).

Except at very low frequencies, loudspeakers are not omni-directional sources radiating sound equally in all directions; they exhibit directivity patterns that vary with frequency. This characteristic can be included in Equation 2 by the addition of the Directivity Factor Q, defined as the ratio of the intensity measured at a stated distance on the main axis of the loudspeaker to the intensity that would be measured at that point by a point source radiating the same total power as the loudspeaker. Thus, Equation 2 becomes:

$$W_S = 4\pi d^2 \left(\frac{p_d^2}{\rho c}\right)\frac{1}{Q} \tag{3}$$

The value of Q is always equal to or greater than 1. Actual values of Q are provided by some loudspeaker manufacturers, but can be calculated using the procedure defined in Beranek (1986), and presented in the form of the Directivity Index, DI, defined as:

$$DI = 10 log Q$$

For the Mackie 350 used in this study, the values of DI as a function of frequency are shown in Table 1.

Table 1. Values of DI for Mackie 350 Loudspeaker

Frequency (Hz)	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**
DI (dB)	2	2	2	2	2	3	4	4	6	6	7	8	8	8	7

With this directivity information, the loudspeaker sound power output, W_s, can be calculated from a measurement of the sound pressure, p_x, at a distance d along the main axis.

The pressure measurement must be at a distance sufficiently far from the loudspeaker for the pressure and velocity to be in phase, such that the sound intensity is proportional to the square of the sound pressure, namely that $I_d = p_d^2/\rho c$ (Molloy, 1948). To determine the minimum distance that satisfies this requirement, a series of free-field measurements were conducted with a Mackie 350 loudspeaker on a hard ground surface, raised 3 ft, and raised 10 ft. At each loudspeaker height, sound levels were measured at distances of 1, 1.5, 2, 3, 4, and 8 ft along the axis of the low-frequency driver. The results are plotted in Figure 1, where the dashed line represents the inverse-square law relationship between sound level and distance.

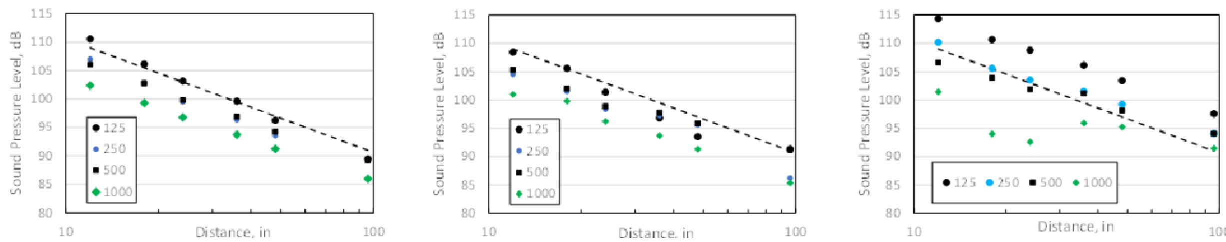


Figure 1. Free-Field Sound Level as Function of Distance from Mackie 350 Loudspeaker with Center of Low-Frequency Driver at (a) 130 inches, (b) 46 inches, and (c) 10 inches above Hard Ground Surface

Figure 1(a) shows the data for a loudspeaker 130 inches above the ground, essentially in free space away from reflecting surfaces. The inverse-square law relationship is obeyed at all distances down to 12 inches at all frequencies, indicating that the loudspeaker sound power level obtained from a measurement of the sound pressure at 12 inches is representative of the sound power level with the pressure measured at greater distances.

Figure 1(b) shows the same behavior with the loudspeaker height at 46 inches, as does Figure 1(c) with the loudspeaker base on the ground, except at the higher frequencies where ground reflection appears to dominate the relationship.

2.2 RATIONALE FOR LOUDSPEAKER PLACEMENT IN ROOM

An additional constraint on loudspeaker measurement distance when in a test room is that the pressure measurement must not be influenced by the room itself or by nearby reflecting surfaces. The results of analyses conducted as part of previous study (Sharp & Cox, 2023) showed that, for the I-O measurement procedure, the loudspeaker should be placed 5 ft from the corner of the test room farthest from the exterior wall(s) to be measured to minimize the variation of sound level over the wall surfaces. The height of the loudspeaker above the floor must be selected so that it is radiating into a free field, as described in Equation 3.

When a loudspeaker is placed near a wall, an edge, or a corner, the sound power level is modified as shown in Figure 2, which presents the sound power level as a function of $\frac{x}{\lambda}$ for a wall, or $\frac{r}{\lambda}$ for an edge or corner, relative to that measured in free-space, where x and r are distances from the floor/edge and corner, respectively, and λ is the wavelength of the sound. Figure 2 shows an increase of 3, 6, and 9 dB, respectively, for x or $r = 0$ at the surface of the wall in the edge, or in the corner.

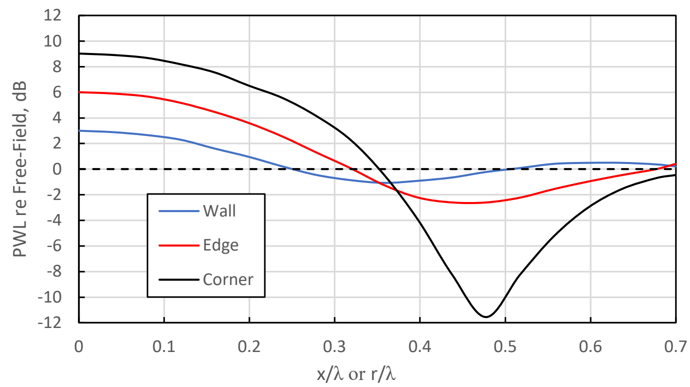


Figure 2. Increase in Sound Level Near Wall, Edge, and Corner of Room with Diffuse Sound Field (data from Waterhouse, 1955)

The increase in level close to a wall decreases with distance from the wall until it is zero at 0.25λ (blue line in Figure 2). For the level to be within 1 dB of the reverberant level in the room, the measurement distance must be no less than 0.2λ from the wall. At greater distances, the increase is generally less than 1 dB. The corresponding distances for edges and corners for the measurement to be within 1 dB are 0.6λ and 0.64λ, respectively. Figure 3 shows the measurement distances required for the 1 dB criterion to be met as a function of frequency.

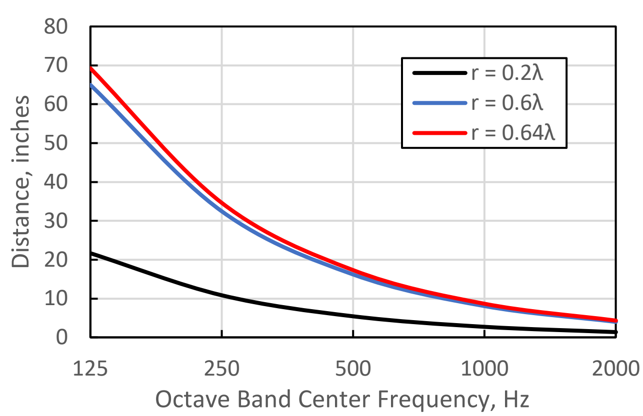


Figure 3. Minimum Distance from Room Surface to be Within 1 dB of Reverberant Sound Level

According to the data in Figure 3, assuming the low-frequency driver is a point source, the sound power output is unaffected by the presence of the floor, edge, or corner at the distances shown in Table 2.

Table 2. Distance from Room Floor, Wall, and Corner at which Free-Field Conditions are Applicable for Loudspeaker Radiation

Frequency (Hz)	Distance from Loudspeaker (ft)		
	Floor/Wall	Edge	Corner
100	2.3	6.8	7.2
125	1.8	5.4	5.8
160	1.4	4.2	4.5
200	1.1	3.4	3.6
250	0.9	2.7	2.9

With a horizontal distance to the edge/corner of 6 ft, and the center of the low-frequency driver 4 ft above the floor, the distance to the corner is 7.2 ft, which satisfies the free-field requirement stated in Table 2. Distance from Room Floor, Wall, and Corner at which Free-Field Conditions are Applicable for Loudspeaker Radiation at 100 Hz. It is also close to meeting the edge requirement of 6.8 ft.

Ideally, a frequency of 100 Hz would be used to define the spacing requirement. However, measuring in realistic situations where room sizes can be as small as 12 ft x 12 ft limits where a loudspeaker can be placed so that is not too close to the test walls. As a result, the validation tests described in the following section limited the distance to the corner to 5 ft and the maximum height to 3 ft.

2.3 VALIDATION OF LOUDSPEAKER PLACEMENT SELECTION

To validate Equation 3 and the selection of a measurement distance d, the calculated sound power output of the loudspeaker can be compared to a separate calculation based on the measurement of the reverberant room level generated in the room by the loudspeaker, together with the reverberant level produced by a reference sound source of known sound power. If PWL_{ref} is the sound power level of the reference sound source, and SPL_{ref} is the resulting reverberant sound level in the room from this source, then the sound power output of a loudspeaker in the same room, PWL_s , can be calculated from the expression:

$$PWL_s = PWL_{ref} + SPL_s - SPL_r \tag{4}$$

where SPL_s is the reverberant sound level produced by the loudspeaker in the room.

2.4 FIELD VALIDATION TESTS OF LOUDSPEAKER PLACEMENT

Field measurements were conducted in two rooms of a house in Marlborough, MA—a den and bedroom—with high and low absorption, respectively, that are typical of standard housing types. Floorplans of the two rooms are shown in Figure 4.

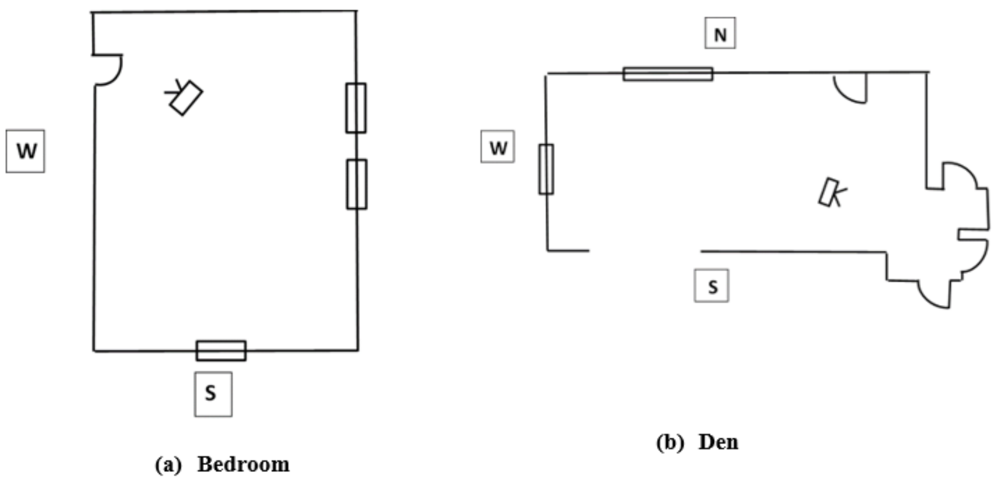


Figure 4. Floorplans of the Rooms for Loudspeaker Placement Tests

The objectives of the measurements are as follows:

- Measure the loudspeaker sound power output level as a function of:
  - Loudspeaker height
  - Measurement distance
  - Interior room absorption
- Measure room absorption by means of a standard procedure with reference sound source (RSS).
- Compare room sound levels calculated from the loudspeaker sound power output level and measured absorption with the measured room levels generated by the loudspeaker to determine the optimum loudspeaker measurement configuration.

Measurements for the Bedroom and Den:

- Open curtains and raise blinds.
- Leave furniture in place, as possible.

2.4.1.1 Loudspeaker Measurements

Interior loudspeaker measurements:

- Loudspeaker: Mackie SRM350
- Noise Spectrum: Pink noise
- Loudspeaker position:
  - Den: Facing towards, and 5 ft from, SE corner
  - Bedroom: Facing towards NW corner

- Loudspeaker height:
    - Floor level (center of low-frequency driver at 10 inches)
    - Raised 2 ft (center of low-frequency driver at 34 inches)
    - Raised 3 ft (center of low-frequency driver at 46 inches)

Loudspeaker sound level measurements for loudspeaker height (a):

- Measurement of sound level along the main loudspeaker axis at 1, 1.5, and 2 ft with a microphone height at center of low-frequency driver, approximately 10 inches

Loudspeaker sound level measurements for loudspeaker height (b):

- Measurement of sound level along the main loudspeaker axis at 1, 1.5, and 2 ft with a microphone height at center of low-frequency driver, approximately 34 inches

Loudspeaker sound level measurements for loudspeaker height (c):

- Measurement of sound level along the main loudspeaker axis at 1, 1.5, and 2 ft with a microphone height at center of low-frequency driver, approximately 46 inches

Interior sound level measurements for all loudspeaker heights:

- Two-dimensional (2D) scan over each window (separate measurements) at distance of 1 inch (flush) for 20 seconds

- Three-dimensional (3D) volume scan, maintaining distance of 2 ft from all room surfaces and 3 ft from the loudspeaker, for 20 seconds and repeat 3 times

2.4.1.2 Reference Sound Source Measurements

Interior room absorption measurements:

- RSS: Acculab RSS 101
- RSS position as per loudspeaker at:
    - Floor level
    - Raised 2 ft
    - Raised 3 ft

Interior sound level measurements for all RSS heights:

- 3D volume scan, maintaining a distance of 2 ft from all room surfaces and 3 ft from the RSS, for 20 seconds and repeat 3 times

2.5 LOUDSPEAKER PLACEMENT ANALYSIS AND RESULTS

A comparison of the A-weighted sound power levels calculated from Equations 3 and 4—calculated sound power level from Equation 3 minus sound power level from measurements and

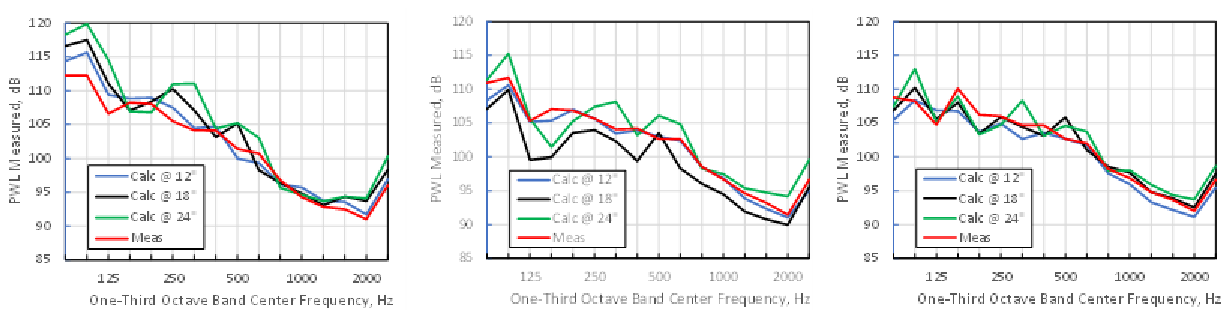
Equation 4—are presented in Table 3. The calculation of loudspeaker power based on the sound level measurement at 12 inches and Equation 3 agrees best with that calculated independently using Equation 4.

Table 3. Comparison of Loudspeaker Power Levels Calculated by Different Methods

Loudspeaker Height[1] (ft)	**Measurement Distance (in.)**	**Calc PWL – Meas PWL[2] (dB)**	
		Den	**Bedroom**
0	12	0.6	-0.4
	18	1.8	2.4
	24	3.4	4.3
2	12	-0.3	-0.5
	18	-2.2	-2.2
	24	1.8	2.3
3	12	-1.0	-0.5
	18	0.3	0.6
	24	1.0	2.4

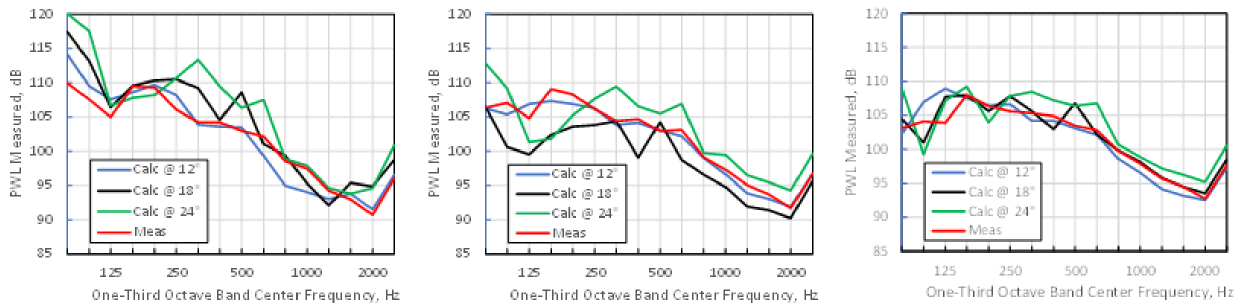
[1]Center of low-frequency driver at heights of 10, 34, and 46 inches.
[2]A-weighted PWL (sound power level) from 100 to 2,500 Hz

The comparisons shown in Table 3 are in terms of the A-weighted sound power level, where the summation is calculated over the frequency range 100 to 2,500 Hz. Comparison of the power spectra calculated using the two methods are shown in Figures 5 and 6, where the values calculated using the loudspeaker output method are labelled "Calc @ d" and those calculated using the reference sound source are labelled "Meas."



(a) (b) (c)

Figure 5. Calculated Sound Power Level from Measurements at Different Distances from Loudspeaker at (a) Floor Level, (b) Raised 2 ft, and (c) Raised 3 ft, in the Den, Compared to Values Based on Measurement of Room Reverberant Levels

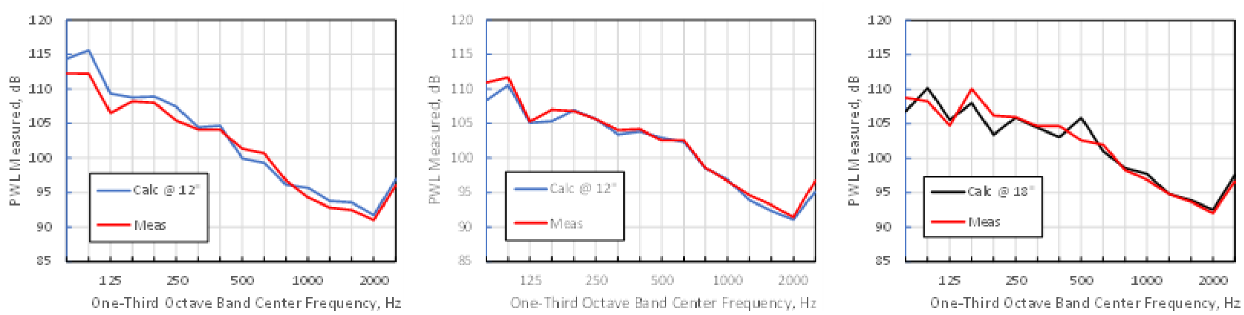


(a) (b) (c)

Figure 6. Calculated Sound Power Level from Measurements at Different Distances from Loudspeaker at (a) Floor Level, (b) Raised 2 ft, and (c) Raised 3 ft, in the Bedroom, Compared to Values Based on Measurement of Room Reverberant Levels

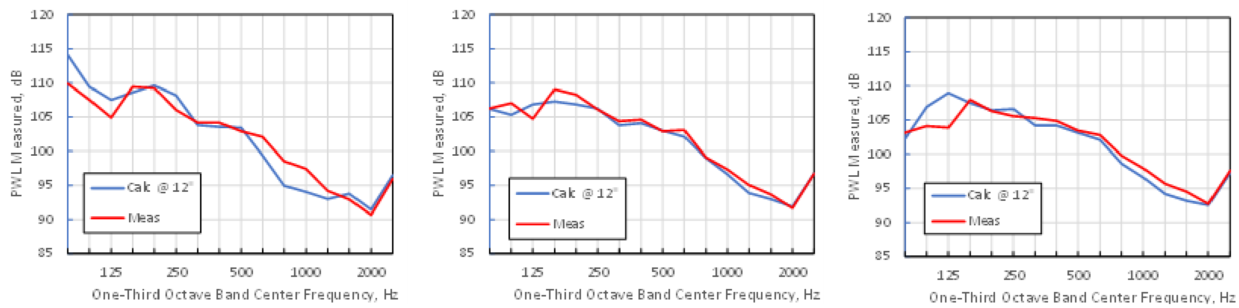
The den has greater spread in the data at all loudspeaker heights and measurement distances compared to the bedroom. This is possibly the result of the configuration of the room corner in the den, which forms part of the corridor to other rooms and could introduce unusual sound resonances. The den also has a large open connecting area to a kitchen which also could affect the sound field in the room and the measurement of the reverberant sound level. The bedroom, on the other hand, is an almost pure rectangle with no openings to other spaces.

The selection of the optimum measurement distance for the sound pressure in Equation 3 can be determined by viewing the best fit curves between calculated and measured sound power level in Figures 5 and 6. These are shown in Figures 7 and 8.



(a) (b) (c)

Figure 7. Best Fit of Sound Power Level from Measurements at Different Distances from Loudspeaker at (a) Floor Level, (b) Raised 2 ft, and (c) Raised 3 ft, in the Den, with Values Based on Measurement of Room Reverberant Levels



(a) (b) (c)

Figure 8. Best Fit of Sound Power Level from Measurements at Different Distances from Loudspeaker at (a) Floor Level, (b) Raised 2 ft, and (c) Raised 3 ft, in the Bedroom, with Values Based on Measurement of Room Reverberant Levels

The closest agreement between the two measurements of sound power level, in both Table 3 for overall A-weighted sound power levels and in Figures 7 and 8, is obtained at a microphone distance of 12 inches. Data presented in Section 2.1 show that measurements at this distance could be used to reliably calculate loudspeaker sound power.

The data show less deviation when the loudspeaker is raised from the floor, as might be expected because the loudspeaker is located away from a reflecting surface and is considered to be radiating into free space. The best agreement is obtained with a loudspeaker height of 2 ft. At this height (34 inches for the low-frequency driver), a loudspeaker 5 ft horizontal from a corner essentially satisfies the requirements in Table 2 at 125 Hz.

2.6 SUMMARY OF LOUDSPEAKER PLACEMETN ANALYSIS

The alternative method of measuring noise reduction using the I-O procedure requires the in-situ measurement of the sound power output level of the loudspeaker. As a result of the measurements and analysis described in Section 2, the optimum procedure for conducting such a measurement is as follows:

- Loudspeaker to be located 5 ft from, and facing, the corner opposite the wall(s) to be tested
- Loudspeaker height (the base of the Mackie 350) to be 2 ft above the floor

Sound level measurement along the main axis of the low-frequency driver at a distance of 12 inches.

3. I-O FIELD VALIDATION TEST PROCEDURE

Field measurements and analyses were conducted to develop best practices for conducting the I-O noise reduction measurements and to demonstrate equivalence with the O-I loudspeaker method, while adhering to the testing procedures and data analysis parameters developed in the previous research study (Sharp & Cox, 2023) and the results of the loudspeaker sound power output study described in Section 2.

Measurements were conducted in 32 rooms in nine houses to validate the concept of an I-O measurement methodology by comparing the results with simultaneous measurements obtained using the ARP 6973 O-I procedure (SAE, 2021).

3.1 TEST ROOM CONDITIONS

- Open curtains and raise blinds.
- Close all doors; close and lock prime and storm windows.
- Leave furniture in place where possible, except when required to position loudspeaker and conduct area and volume scans.
- Remove all occupants.
- Document overall room dimensions (length, width, and height).

3.1.1 O-I Loudspeaker Tests

- Loudspeaker: Mackie SRM350 (Houses #2 through #6)/SRM450 (Houses #7 through #10)
- Noise Spectrum: Pink noise (with limited bandwidth for Houses #7 through #10)
- Follow ARP 6973 guidelines for loudspeaker distance, height, and angle of incidence. Where possible, conduct measurements on corner rooms with a loudspeaker positioned diagonally to the corner, with separate 2D scans over each wall.
- For rooms with an attached open porch, conduct the exterior sound level measurement at 1 inch from the wall surface and at the porch opening, as specified in ARP 6973.

3.1.2 I-O Loudspeaker Tests

- Loudspeaker (LS: Mackie SRM350 (Houses #2 through #6)/SRM450 (Houses #7 through #10)
- Noise Spectrum: Pink noise (with limited bandwidth for Houses #7 through #10)
- Loudspeaker base raised 24 inches above floor on a firm support
- Loudspeaker positions for rooms with one or two exterior façades—see Figure 9(a) and (b)
- Along room diagonal, facing far corner from exterior walls, at a horizontal distance of 5 ft ±1 ft from the corner

- Loudspeaker position for rooms with three exterior façades—see Figure 9(c)
- In central part of room away from the three exterior façades, angled at 45° to the interior wall, and 3 to 4 ft from the wall

Interior Measurements for All Loudspeaker Positions:

- Measurement of sound level along the main loudspeaker axis at 12 inches with a microphone height at the center of the low-frequency driver, approximately 34 inches above the floor.
- 2D scans over each interior window/door area (separate scans for each element) at a distance of 1 inch for 30 seconds each. Small items of furniture can be moved as necessary to conduct the scan.
- 2D scans over each interior wall area at 1 inch for 30 seconds each, not including areas within 2 ft of the horizontal and vertical edges of the room. Small items of wall decoration can be moved as necessary to conduct the scan.
- For houses with single-joist roofs, perform 2D scans at 1 inch over the central area of the ceiling. For houses with beam ceilings, perform 2D scans at 1 inch over the central area of the ceiling in between the beams.
- 3D scan, maintaining a distance of 2 ft from all room surfaces and 3 ft from the loudspeaker, for 30 seconds.

Exterior measurements for all loudspeaker positions:

- 2D scan over each wall/window area (separate scans for each wall) at a distance of 24 inches from the exterior surface for 30 seconds, not including areas within 2 ft of the horizontal and vertical edges of the room. Scans should follow the contour of the exterior building façade and include areas within verandas and porches.
- For houses with single-joist roofs or beam ceilings, perform 2D scans at a distance of 24 inches over the central area of the roof covering the test room.
- Measurement of exterior background noise level in the absence of loudspeaker output for 30 seconds at a single position 24 inches from the center of each exterior wall.

<u>3.1.3 Reference Sound Source</u>

- RSS: Acculab RSS 101
- RSS raised 24 inches above floor level at the same position and height as the loudspeaker in 3.1.2, with sufficient space to conduct a measurement of the reverberant sound level in the room.
- 3D scan, maintaining a distance of 2 ft from all room surfaces and 3 ft from the RSS, for 30 seconds. This measurement will be used to calculate the sound absorption in the room.

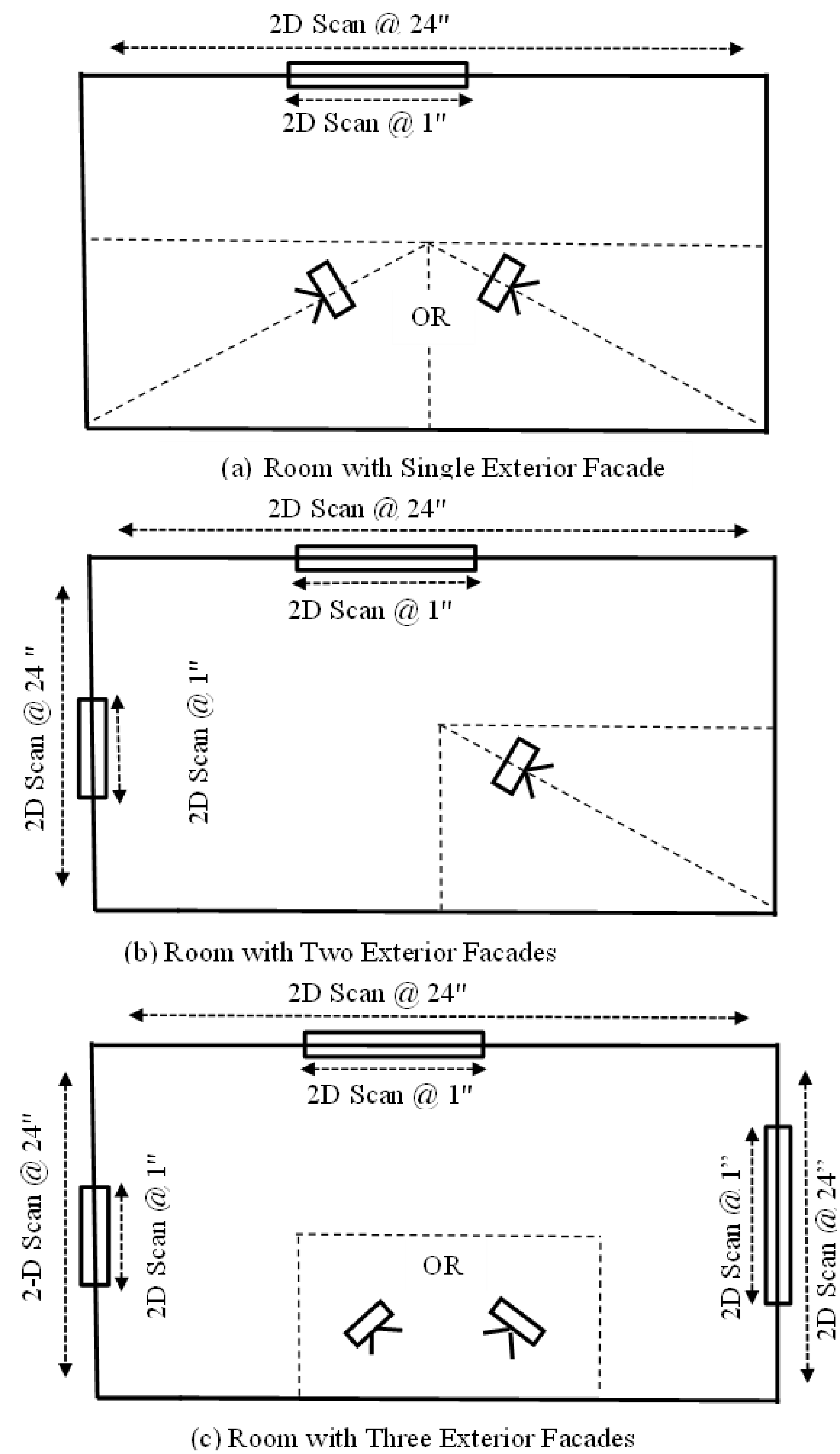


Figure 9. Loudspeaker Positions for I-O Tests

3.2 MEASUREMENT DATA ANALYSIS

The O-I noise reduction, NR_{OI}, was calculated in one-third octave bands as follows:

$$NR_{OI} = L_1 - L_r - 6, \text{ dB}$$

where L_1 is the energy average of the sound levels measured 1 inch from the exterior façades, and L_r is sound level of the interior reverberant sound field obtained from a 3D scan. The factor of 6 dB corrects the sound level measured at 1 inch from the surface to obtain the incident sound level.

The I-O noise reduction, NR_{IO}, was calculated in one-third octave bands as follows:

$$NR_{IO} = L_1 - 3 - L_{24} - 10\log\left(\frac{S}{A}\right) - K, \text{ dB}$$

where L_1 is the energy average of the sound levels measured 1 inch from the interior of the window surfaces, L_{24} is the energy average of the levels measured 24 inches from the exterior walls of the façade, S is the combined area of the façades in sq ft, and K is a constant equal to 11.5 determined empirically (refer to Sharp & Cox, 2023). The factor of 3 dB relates the sound level at 1 inch from the surface to the reverberant sound level in the room.

The room absorption, A, was calculated in one-third octave bands from the results of measurements using the RSS by the following expression:

$$A = 43.1 \; x \; 10^{\frac{PWL-SPL}{10}} \quad \text{sq ft}$$

where PWL is the sound power level of the RSS re 1 pW, and SPL is the average sound pressure level re 2 x 10^{-5} N/m^2 produced in the room by the RSS.

The alternative I-O noise reduction, NR_{IOAlt}, based on the alternative definition of noise reduction, was calculated in one-third octave bands from the following expression:

$$NR_{IOAlt} = L_{12} - DI - L_{24} - 10logS + C, \text{ dB}$$

where L_{12} is the sound level measured by a monitoring microphone 12 inches from the loudspeaker, L_{24} is the energy average of the levels measured 24 inches from the exterior walls of the façade, S is the surface area in sq ft of the transmitting surfaces, C is an empirical constant equal to 6.5 (Sharp & Cox, 2023), and DI is the Directivity Index equal to $10logQ$. The quantity Q is defined as the ratio of the intensity on the main axis of the loudspeaker to the intensity that would be produced by an omnidirectional point source radiating the same total power as the loudspeaker. Actual values of Q can be calculated using the procedure defined in Beranek (1986), and presented in the form of the Directivity Index, DI, defined as:

$$DI = 10logQ$$

For the Mackie 350 used in this study, the values of DI as a function of frequency were calculated from the loudspeaker polar plots. The DI for the Mackie 450 weas taken from the manufacturer's specifications. These values are shown in Table 4.

Table 4. Values of DI for Mackie 350 and Mackie 450 Loudspeakers

Frequency, Hz	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**
Mackie 350, dB	2	2	2	2	2	3	4	4	6	6	7	8	8	8	7
Mackie 450, dB	2	2	3	4	4	5	5	5	5	6	8	9	10	10	9

With this directivity information, the loudspeaker sound power output, W_s, can be calculated from a measurement of the sound pressure, p_d, at a distance d along the main axis.

4. HOUSES FOR VALIDATION TESTS

The validation tests were conducted in 9 houses, identified as Houses #2 through #10[1], the floorplans of which are shown in Figures 10 through 15, respectively. The black arrows in the floorplans indicate the angle of sound incidence from the exterior loudspeaker positions (distances not to scale) used for the O-I tests of each room.

House #5 is a one-story building of wood-frame construction with vinyl siding on all exterior façades, and an open-sided porch area at the front. A second story addition at the rear of the house above the kitchen and office provides an additional two bedrooms. At the rear of the house, a door in the kitchen leads to an open wooden deck that is raised 4 ft above the surrounding ground surface. Bedroom #3 on the second story extends 5 ft beyond the rear kitchen wall and over the rear deck, exposing a portion of the floor to exterior noise.

The interior of House #5 is not an open-plan design, but there is a 4 ft opening between the living room and the kitchen. Tests were conducted in the living room and kitchen on the first floor, bedroom #3 on the second floor, and in the partially sunken basement. As a result of limited access to the area adjacent to the house, the loudspeaker for the O-I measurements could only be positioned at 0 degrees to the façades of the test rooms.

House #6 is a single-story house with a finished attic providing an additional bedroom that extends the full width of the house with a single window at each end. The house is of a wood-frame construction with brick veneer exterior on all façades, and an open-sided porch area at the front over the living room façade. Tests were conducted in the living room and dining room on the first floor, bedroom #2 on the second floor, and in the partially sunken basement. As with House #5, limited access to the area adjacent to the house required the loudspeaker for the O-I measurements to be positioned at 0 degrees to the façades of the test rooms.

House #7 is a single-story house of wood-frame construction with vinyl siding on all exterior façades. The house has a finished attic providing additional bedrooms, one with a dormer

[1] Houses #1 through #4 were tested previously, and the data were reported in Sharp & Cox (2023).

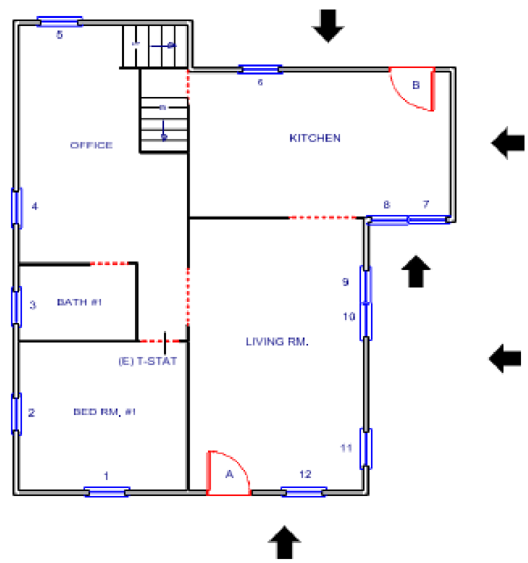
window. The interior layout is an open-plan design of the living room, dining room, and kitchen. Tests were conducted for the dining room/kitchen area and the living room separately, as well as in bedroom #3 on the second floor.

House #8 is a single-story house with a finished attic with a large bedroom that extends for the full length of the house with windows on the side. The house is of a wood-frame construction with brick veneer exterior on all façades, and an open-sided porch area at the front over a bedroom and the front door. The interior layout consists of a living room and dining room with a 4-ft opening connecting the two rooms. Tests were conducted on the living room, dining room, office, and bedroom #1. A fence on the property line to the left of the house in Figure 13 limited the loudspeaker distance to 4 ft for the O-I measurements.

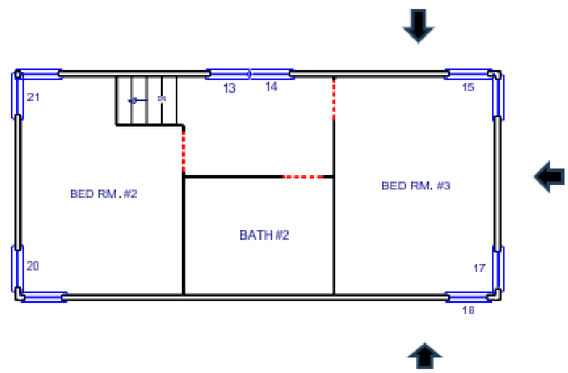
Houses #9 and #10 are single-story houses with stucco walls and beam ceilings. House #9 includes an open-plan living room/dining room/kitchen with a common wall 38 ft in length (on the left in Figure 14). Because of a neighboring house, the loudspeaker distance was limited to 12 ft. On the right, a wall of glass faces an internal courtyard. Measurements were conducted for all four walls (including the main door) and the roof, as well as for bedroom #3, which also faced into the courtyard.

House #10 has a connected living room and kitchen, so only the living room was measured along with the roof. Measurements were also taken for bedroom #1 at three different loudspeaker distances. Bedroom #3 has a large glass window extending the full width of the façade. A 6-ft concrete wall at a distance of 6 ft from the façade limited the loudspeaker distance to 5 ft.

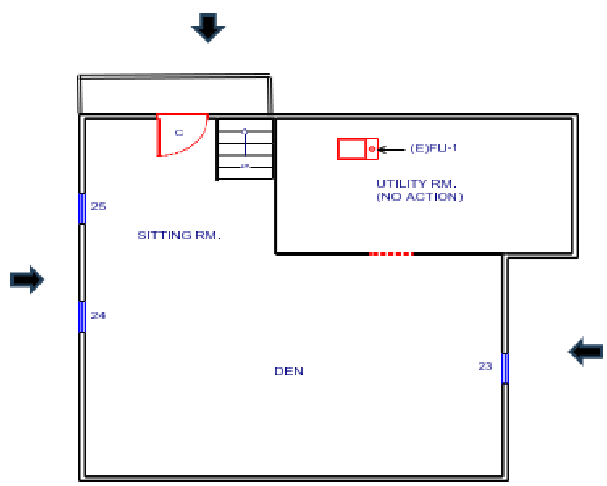
Figures 10 through 15 show floorplans of the test houses.



(a) 1st Floor Plan

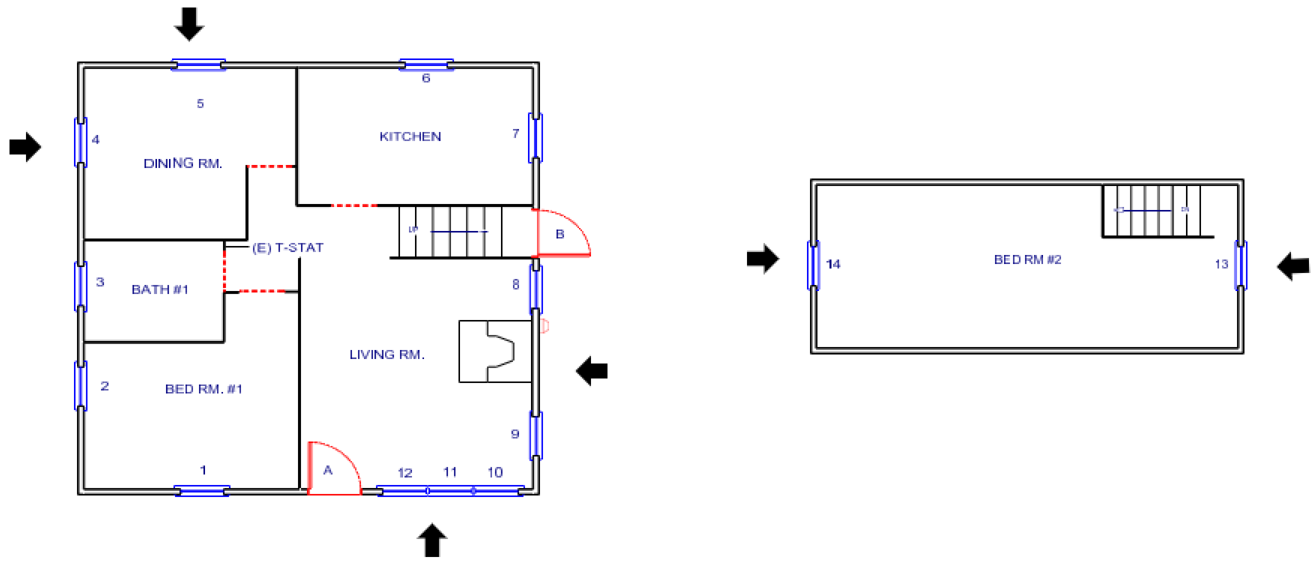


(b) 2nd Floor Plan



(c) Basement Floor Plan

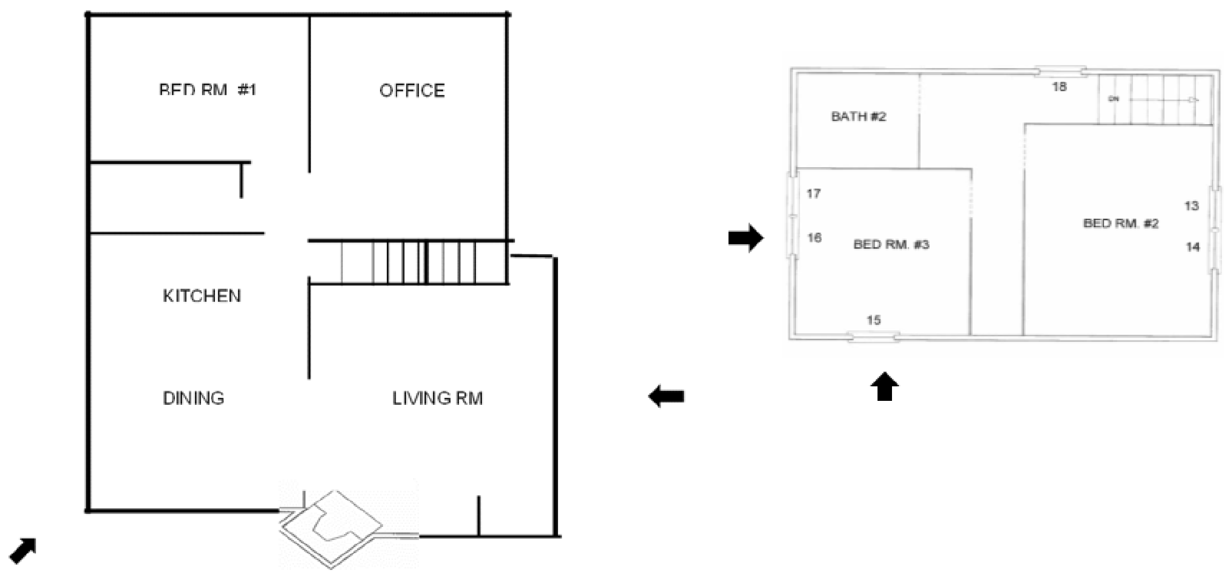
Figure 10. Floorplans for House #5



(a) 1st Floor Plan

(b) 2nd Floor Plan

Figure 11. Floorplans for House #6



(a) 1st Floor Plan

(b) 2nd Floor Plan

Figure 12. House Plans for House #7

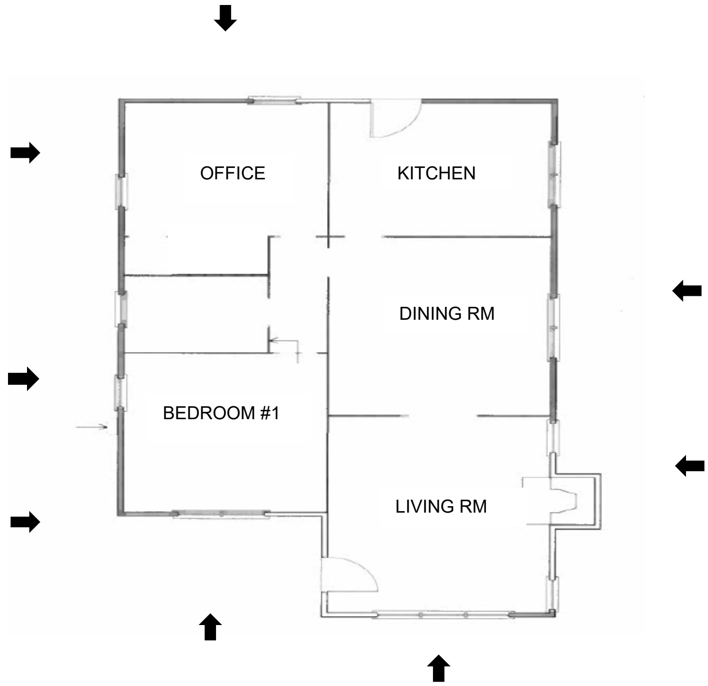


Figure 13. House Plans for House #8

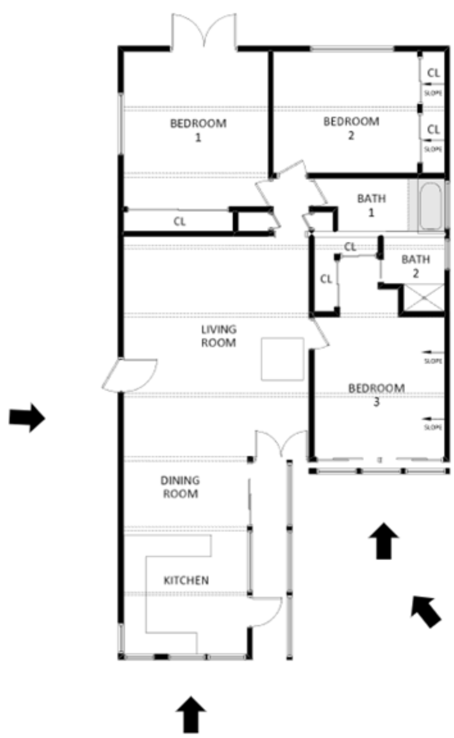


Figure 14. House Plans for House #9

Figure 15. House Plans for House #10

5. I-O FIELD VALIDATION TEST RESULTS

5.1 EVALUATION OF MEASUREMENT PROCEDURES

As part of the test series conducted in the houses, specific tests were performed to evaluate the alternative I-O measurement procedures.

5.1.1 O-I Exterior Tests for Rooms with Porches

The current ARP 6973 (O-I) test procedure (SAE, 2021) specifies that the exterior sound level for rooms with an attached porch should be measured by a 2D scan over the porch opening. Previous measurements on rooms with a closed balcony, i.e., with side walls (Sharp, 2019), demonstrated that the sound level incident onto the room surface (in that case, a sliding-glass door) was influenced by the presence of the balcony. As a closed balcony is an integral part of the room, the incident sound level should, therefore, be measured at its opening. This presents no problem with measurements at normal (0 degree) incidence, but it does lead to interpretation when measuring with sound incidence at other angles (45 degrees is the recommended angle of incidence). Moreover, it was not certain that the same reasoning would apply to an open balcony or porch, i.e., with a roof but open sides. As a result, measurements of the exterior sound level for rooms with an attached open porch were conducted at 1 inch (flush) from the wall surface and at the porch opening, as specified in ARP 6973, in an attempt to simplify the test procedure.

For the three houses tested in this series, Table 5 shows the results of four examples of rooms with open porches and the difference between the sound levels measured 1-inch flush with the main wall of the room and those measured at the porch opening. The difference in sound levels is shown for the individual wall with an attached porch and for the entire room (with a second wall without a porch).

Table 5. The Effect of an Open Porch on Measured NLR

House/Room	ΔNLR (Flush – Porch Opening), dB	
	Wall	**Room**
House #5, LR	0.3	0.1
House #5, K	0.6	0.2
House #6, LR	0.8	0.4
House #8, BR1	0.3	0.2
Average	0.5	0.2

For this small sample, the average increase in NLR of a single wall with an open porch, where the exterior sound level is measured at 1 inch (flush) rather than at the porch opening, is 0.5 dB. The average increase in NLR for the room (one wall with a porch, and one without) is 0.2 dB. The conclusion is that for a room with one wall with an attached open porch and one without, the effect of the porch on the incident sound level is minimal. The effect on NLR for the individual wall with a porch is small at 0.5 dB and can be considered insignificant. However, the incident sound level should be measured at the opening of closed porches or balconies with one or more side walls.

5.1.2 I-O Interior Tests for Windows and Walls

The method for measuring NLR using the difference between interior and exterior sound levels and measuring the room absorption (the absorption method) requires a 2D scan of the sound level at 1 inch over the interior surface of the windows. In a previous report (Sharp & Cox, 2023) it was determined that the sound levels provided by this scan were within 0.5 dB above the entire frequency range of those from a 2D scan over the test wall. This is a convenient alternative when a scan over the entire wall is not always possible due to artifacts on the wall surface.

This was the approach included in the test plan for the NLR measurements in this series of validation tests. However, in one of the test houses (House #5), the windows in rooms on the second floor were at the extreme edges of the walls near the room corners, which raised the concern that a scan over their surfaces might not represent the average over the entire wall. Accordingly, measurements of the interior sound level were conducted both over the windows and over the walls to verify their equivalence. Figure 16 presents a bar chart that shows the difference between scans over the windows and over the entire walls. The red bars in the figure are from measurements in the current tests; the blue bars represent data from the previous research (Sharp & Cox, 2023).

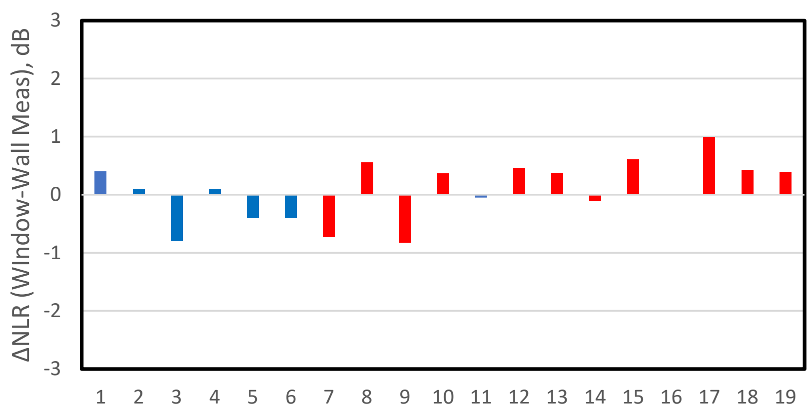


Figure 16. Comparison of Interior Sound Levels Measured by Scans over the Window and Walls

The average difference between the two methods for a sample size of 19 is 0.1 dB. The average difference for the three rooms in House #5 with windows at the room corners was -0.3 dB, indicating that the window scan was marginally lower than the wall scan, but within limits of measurement accuracy. The conclusion is that the window average is representative of the wall average.

5.2 VALIDATION OF I-O MEASUREMENT PROCEDURE

The test plan described in Section 3 was implemented in four rooms (three main rooms and one basement room) in both Houses #5 and #6, in four rooms in both Houses #7 and #8, two rooms (one large open-plan) in House #9, and three rooms in House #10. The values of the NLR measured in each room by the I-O and O-I procedures were compared to validate the I-O test procedure.

Table 6 shows the results obtained from the field measurements using the room absorption method for calculating NLR_{IO} (Sharp & Cox, 2023) for each of the 21 rooms tested in Houses #5 through #10. In addition, the data for the 10 rooms in Houses #2, #3, and #4 from previous measurements (Sharp & Cox, 2023) are included for comparison, for a total of 31 rooms in nine houses. The measured values of NLR_{OI} are shown in the third column of the table. The remaining columns show the values of NLR_{IO} for calculated values of the constant K from 11 to 12, and the difference between NLR_{OI} and NLR_{IO} also for values of K from 11 to 12.

Table 6. Comparison of O-I NLR with I-O NLR Using the Room Absorption Method

House	Room	O-I NLR	I-O NLR, dB			ΔNLR (O-I – I-O), dB		
			K=11	K=11.5	K=12	K=11	K=11.5	K=12
2	Den	24.9	25.1	24.6	24.1	-0.2	0.3	0.8
	BR	23.8	23.3	22.8	22.3	0.5	1.0	1.5
3	LR	26.9	27.1	26.6	26.1	-0.2	0.3	0.8
	DR/K	22.2	23.3	22.8	22.3	-1.1	-0.6	-0.1
	BR1	25.3	25.2	24.7	24.2	0.1	0.6	1.1

House	Room	O-I NLR	I-O NLR, dB			ΔNLR (O-I – I-O), dB		
			K=11	K=11.5	K=12	K=11	K=11.5	K=12
	BR2	23.0	24.3	23.8	23.3	-1.3	-0.8	-0.3
4	LR	22.9	23.1	22.6	22.1	-0.2	0.3	0.8
	DR	22.3	23.5	23.0	22.5	-1.2	-0.7	-0.2
	BR1	26.0	27.5	27.0	26.5	-1.5	-1.0	-0.5
	BR2	24.8	25.9	25.4	24.9	-1.1	-0.6	-0.1
5	LR	21.4	20.8	20.3	19.8	0.7	1.2	1.7
	K	20.8	20.8	20.3	19.8	0.0	0.5	1.0
	BR3	20.3	22.0	21.5	21.0	-1.6	-1.1	-0.6
	BMT	27.6	33.1	32.6	32.3	-5.5	-5.0	-4.5
6	LR	25.0	26.3	25.8	25.3	-1.4	-0.9	-0.4
	DR	26.4	28.1	27.6	27.1	-1.8	-1.3	-0.8
	BR2	26.3	26.0	25.5	25.0	0.2	0.7	1.2
	BMT	32.2	35.9	35.4	34.9	-3.7	-3.2	-2.7
7	LR/DR/K	20.1	19.4	18.9	18.4	0.7	1.2	1.7
	LR	24.0	24.0	23.5	23.0	0.1	0.6	1.1
	DR/K	22.4	21.3	20.8	20.3	1.1	1.6	2.1
	BR3	25.3	25.6	25.1	24.6	-0.3	0.2	0.7
8	LR/DR	25.7	26.5	26.0	25.5	-0.8	-0.3	0.2
	LR	24.4	25.8	25.3	24.8	-1.4	-0.9	-0.4
	DR	27.5	29.1	28.6	28.1	-1.7	-1.2	-0.7
	BR1[1]	30.2	29.3	28.8	28.3	0.9	1.4	1.9
	Office	27.6	27.8	27.3	26.8	-0.2	0.3	0.8
9	LR/DR/K	17.0	15.9	15.4	14.9	1.1	1.6	2.1
	BR3	23.6	23.7	23.2	22.7	-0.1	0.4	0.9
10	LR	23.9	24.7	24.2	23.7	-0.8	-0.3	0.2
	BR1	26.0	25.6	25.1	24.6	0.4	0.9	1.4
	BR3	22.8	22.3	21.8	21.3	0.5	1.0	1.5
Overall Average (excluding basement data)						-0.4	0.1	0.6

[1]Exterior Wall 1 only.

The data for House #7 in Table 6 include NLR values for the open plan area, living room/dining room/kitchen, within the house, and the values for the individual rooms (living room and dining room/kitchen). Similarly for House #8, the NLR values are shown for the connecting rooms (living room/dining room) and the individual rooms (living room and dining room).

Examination of the data in Table 6, except for the results of measurements in the two basement rooms (which will be discussed in Section 5.4), shows that the value of 11.5 for the kitchen provided the lowest average difference between the two methods. Figure 17 shows a comparison of the accuracy of the I-O test method to the standard O-I method, excluding the basement data, and including the data for Houses #2 through #4 from the previous Measurements (Sharp &Cox, 2023).

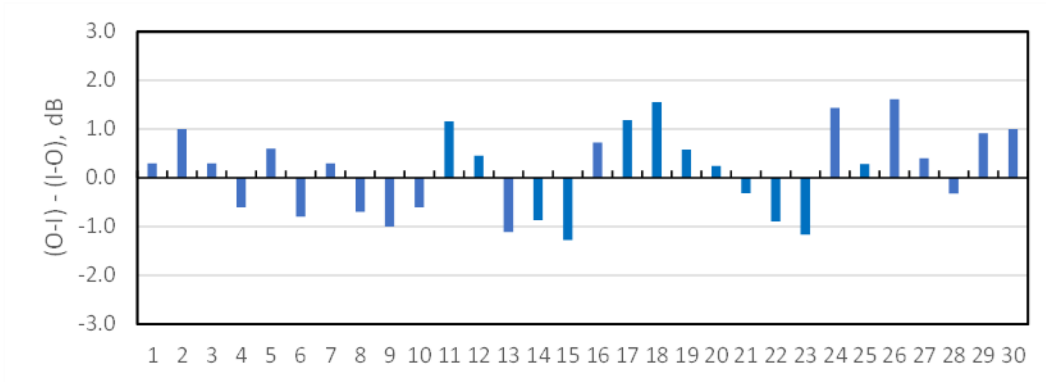


Figure 17. Comparison of O-I NLR with I-O NLR Using the Room Absorption Method for K = 11.5

The differences between the O-I and I-O measurements for the 30 rooms tested (excluding the basements) are generally within ±1 dB, the average difference being -0.2 dB.

Table 7 presents the results obtained from the field measurements using the sound power level method for calculating NLR_{OI} for each of the 21 rooms tested in Houses #5 through #10, including values for the open plan and connecting areas and the individual rooms. In addition, the data for Houses #2, #3, and #4 from the previous tests (Sharp & Cox, 2023) are included for comparison. The measured values of NLR_{OI} are shown in the third column of the table. The remaining columns show the values of NLR_{IO} for calculated values of the constant C from 6 to 7, and the difference between NLR_{OI} and NLR_{IO} also for values of C from 6 to 7.

Table 7. Comparison of O-I NLR with I-O NLR Using the Sound Power Level Method

House	Room	O-I NLR	I-O NLR, dB			ΔNLR (O-I – I-O) dB		
			C=6	C=6.5	C=7	C=6	C=6.5	C=7
2	Den	24.9	24.7	25.2	25.7	0.2	-0.3	-0.8
	BR	26.6	25.3	25.8	26.3	1.3	0.8	0.3
3	LR	26.9	26.3	26.8	27.3	0.6	0.1	-0.4
	DR/K	22.2	22.0	22.5	23.0	0.2	-0.3	-0.8
	BR1	25.3	23.7	24.2	24.7	1.6	1.1	0.6
	BR2	23.0	22.6	23.1	23.6	0.4	-0.1	-0.6
4	LR	22.9	21.9	22.4	22.9	1.0	0.5	0.0
	DR	22.3	22.3	22.8	23.3	0.0	-0.5	-1.0
	BR1	26.0	25.9	26.4	26.9	0.1	-0.4	-0.9
	BR2	24.8	24.6	25.1	25.6	0.2	-0.3	-0.8
5	LR	21.4	19.6	20.1	20.6	1.8	1.3	0.8
	K	20.8	20.9	21.4	21.9	-0.1	-0.8	-1.1
	BR3	20.3	20.4	20.9	21.4	-0.1	-0.6	-1.1
	BMT	27.6	30.7	31.2	31.7	-3.0	-3.5	-4.0
6	LR	25.0	25.5	26.0	26.5	-0.5	-1.0	-1.5
	DR	26.4	26.7	27.2	27.7	-0.3	-0.8	-1.3
	BR2	26.3	25.6	26.1	26.6	0.7	0.2	-0.3
	BMT	32.2	36.1	36.6	37.1	-3.9	-4.4	.4.9
7	LR/DR/K	20.1	19.9	20.4	20.9	0.2	-0.3	-0.8
	LR	24.0	24.2	24.7	25.2	-0.2	-0.7	-1.2
	DR/K	22.4	21.8	22.3	22.8	0.5	0.0	-0.5
	BR3	25.3	24.1	24.6	25.1	1.2	0.7	0.2
8	LR/DR	25.7	24.4	24.9	25.4	1.3	0.8	0.3
	LR	24.4	25.1	25.6	26.1	-0.7	-1.2	-1.7
	DR	27.5	27.7	28.2	28.7	-0.2	-0.7	-1.2
	BR1[1]	30.2	28.9	29.4	29.9	1.3	0.8	0.3
	Office	27.6	26.4	26.9	27.4	1.2	0.7	1.2
9	LR/DR/K	17.0	15.7	16.2	16.7	1.3	0.8	0.3
	BR3	23.6	22.4	22.9	23.4	1.3	0.8	0.3
10	LR	23.9	24.0	24.5	25.0	-0.1	-0.6	-1.1
	BR1	26.0	24.8	25.3	25.8	1.2	0.7	0.2
	BR3	24.0	22.5	23.0	23.5	1.5	1.0	0.5
Overall Average (excluding basement data)						0.5	0.0	-0.5

[1]Exterior Wall 1 only.

Examination of the data in Table 7, except for the results of measurements in the two basement rooms (which will be discussed in Section 5.4), shows that the value of 6.5 for the constant C provided the lowest average difference between the two methods. Figure 17 shows a comparison of the accuracy of the I-O test method to the standard O-I method, except for the basement data, and includes the data for Houses #2 through #4 from the previous measurements (Sharp & Cox, 2023).

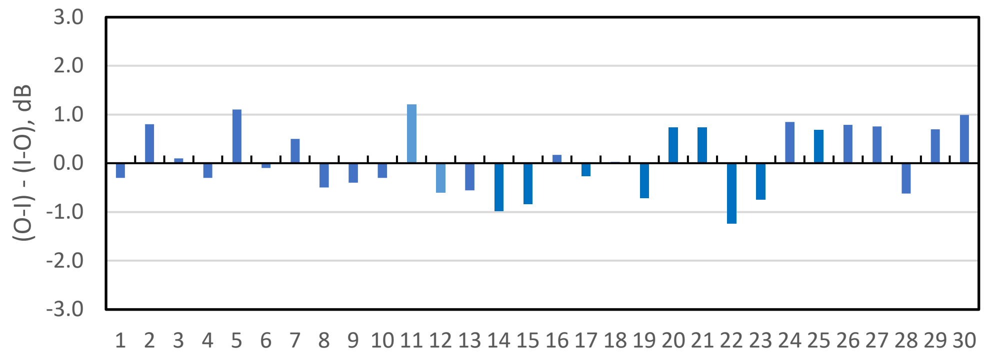


Figure 18. Comparison of O-I NLR with I-O NLR Using the Sound Power Level Method for C = 6.5

The differences between the O-I and I-O measurements for the 30 rooms tested (excluding the basements) are generally within ±1 dB, the average difference being 0.1 dB.

A comparison of the results for the room absorption and sound power level methods in Figures 16 and 17 shows that the latter method generally provides a lower spread in the data. One of the advantages of the sound power level method is that it does not require a measurement of the interior room sound level, thus eliminating one source of potential variation.

5.3 COMPARISONS OF O-I AND I-O NOISE REDUCTION SPECTRA FOR HOUSES #5 AND #6

In addition to the results shown in Tables 6 and 7, an additional validation of the I-O test methodology can be assessed by reviewing the spectral comparisons with the O-I method, as shown in Figure 19.

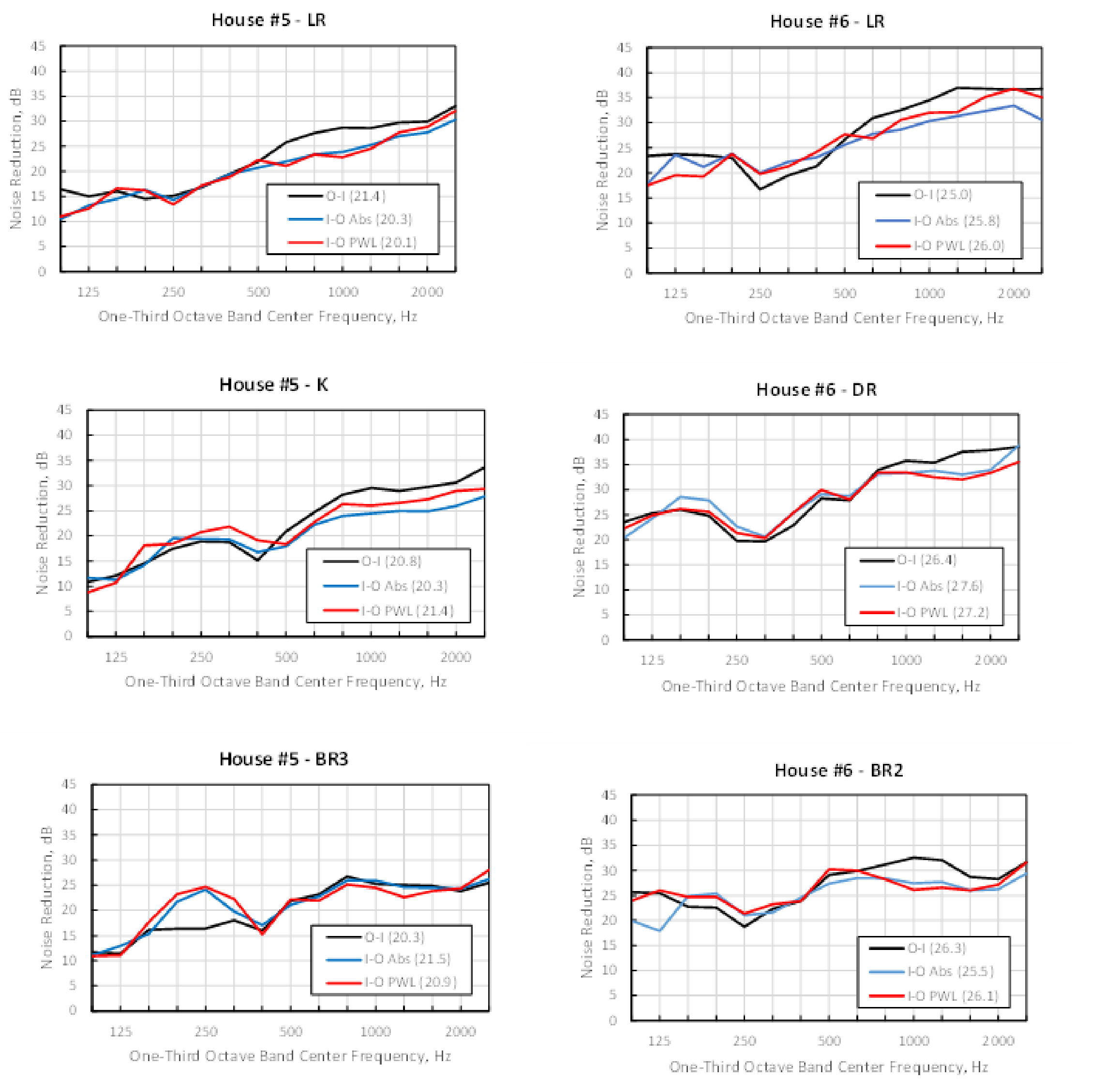


Figure 19. Spectral Comparison of O-I NLR and I-O NLR for Rooms in Houses #5 and #6

The agreement in spectra is reasonably good, with the one notable exception of bedroom #3 of House #5, which shows a significant deviation at low frequencies, but excellent agreement at higher frequencies. As noted in Section 4, bedroom #3 is a room on the second story that extends beyond the rear kitchen wall and over the rear deck, exposing a 5-ft portion of the floor to exterior noise, which provides a flanking path of sound transmission into the room. This flanking transmission is accounted for in the O-I test, but sound radiation through this floor section was not measured in the I-O test, thus leading to the difference in calculated noise reduction. The structure of the floor is such that the sound transmission loss would be lower at low frequencies. Future I-O tests should include exterior measurements over potential flanking paths where possible.

Comparisons of the spectra for the other rooms tested are generally good for both the room absorption and sound power level methods over the main frequency range of interest, 125 to 500 Hz, where the values of noise reduction generally determine the NLR. At higher frequencies there are deviations between the two methods that are likely the result of interference from background noise.

5.4 MEASUREMENT RESULTS FOR BASEMENT ROOMS

The test results for measurements on the two basement rooms did not follow the generally good trend of the other rooms tested. As shown in Figure 20, the I-O tests using both procedures provided NLR that were considerably higher than the values from the O-I tests.

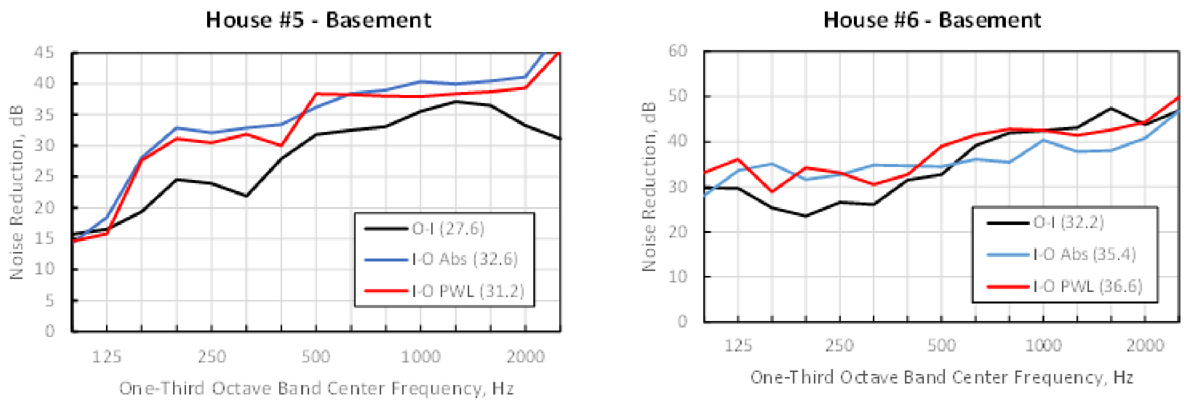


Figure 20. Spectral Comparison of O-I NLR and I-O NLR for Basement Rooms in Houses #5 and #6

The basic construction of the basement walls in both houses is 4- to 5-inch concrete, with the exterior height 4 ft above the ground.

The NLR value of 27.6 dB for House #5 as measured using the O-I test procedure is certainly lower at low frequencies for a concrete construction. The values at low frequencies, and the dip at 315 Hz in the noise reduction frequency curve, are features normally associated with wood-frame structures—see the curves in Figure 6. As a result, it is probable that flanking noise through the walls of the main house above the basement reduces the NLR as measured by the O-I procedure.

A similar characteristic at low frequencies is shown for the data in Figure 19 for the basement in House #6, although the flanking is less severe at low frequencies. The noise reduction data at high frequencies at this house for both the O-I and I-O tests were limited by background noise.

5.5 COMPARISONS OF O-I AND I-O NOISE REDUCTION SPECTRA FOR HOUSES #7 AND #8

In addition to the results shown in Tables 6 and 7, an additional validation of the I-O test methodology can be assessed by reviewing the spectral comparisons with the O-I method, as shown in Figure 21.

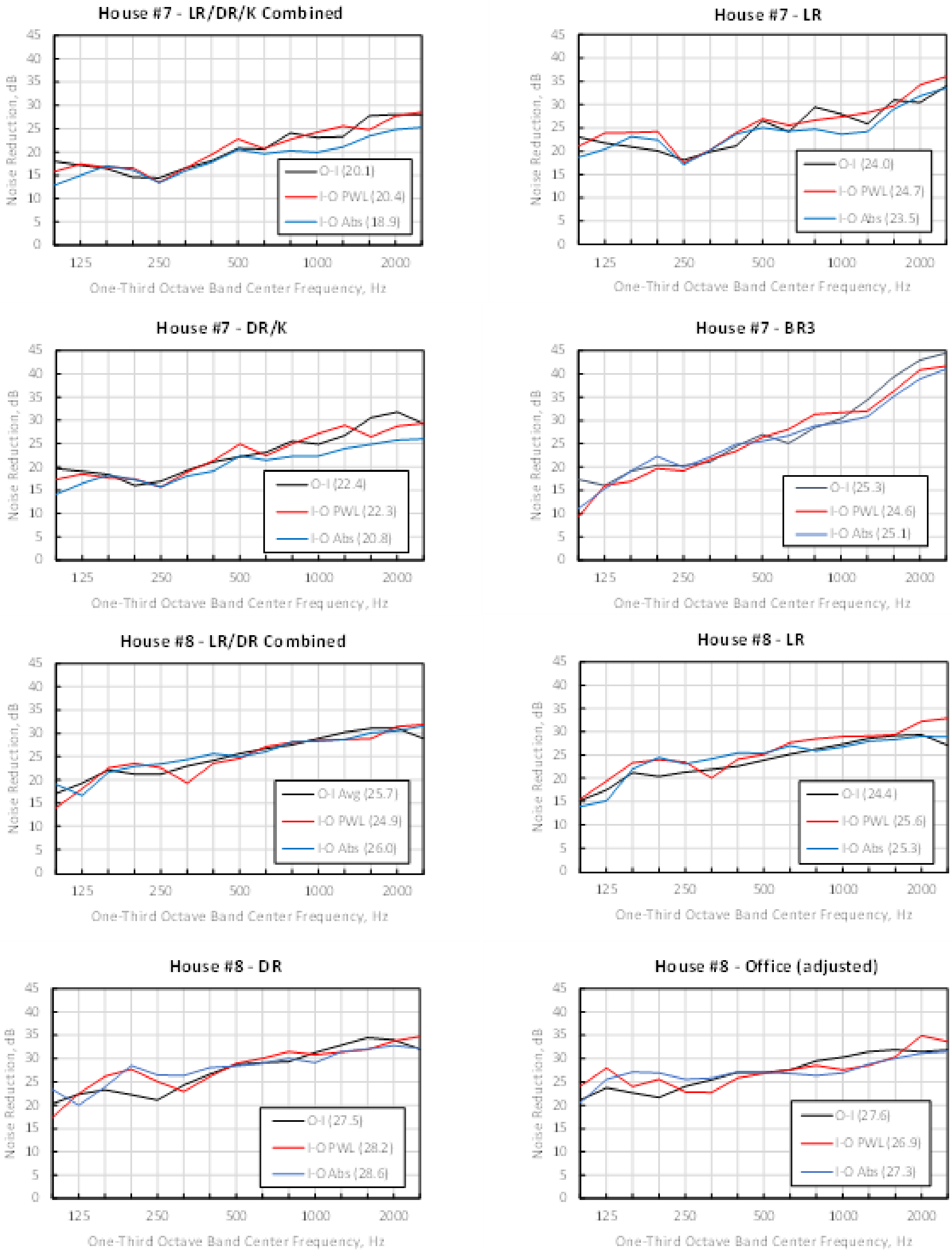


Figure 21. Spectral Comparison of O-I NLR and I-O NLR for Rooms in Houses #7 and #8

5.6 MEASUREMENTS OF NLR IN OPEN PLAN ROOMS

The measurements for House #7 were conducted so that the O-I and I-O noise reduction could be calculated both for the for the open plan living room/dining room/kitchen combination, as well as the living room and dining room/kitchen individually. In all three cases, the I-O sound power level method agreed very well with the O-I data, both in NLR values and spectra. The I-O absorption method provided slightly lower values.

In conducting the O-I measurements for the open plan rooms in House #7, the NLR of the combined areas was calculated from the NLR values of the two individual areas, considering them as part of the one large open plan area. The latter, in turn, are calculated based on the interior sound level that is determined by 3D scans of the individual areas. This approach provided a good agreement between the O-I and I-O NLR values for the combined and individual areas in House #7. In this house, there was a large opening between the individual rooms, with no intervening wall-to-floor partitions, thus forming a truly open plan area.

The O-I and I-O measurements for House #8 were similarly conducted so that noise reduction could be calculated both for the connected dining room and living room and the individual rooms. In conducting the O-I tests on the living room, it was noted that the interior levels in this room were much higher than those in the adjoining dining room, indicating that little sound energy was passing through the opening between the rooms. Combining the NLRs of the two rooms as if they were, in fact, part of an open plan area, as in House #7, resulted in a combined NLR that was 3 dB less than the I-O value. Because the opening between the individual rooms in House #8 was only 4 ft wide, the two rooms should be considered as separate, but connected, rather than forming an open plan area. If the combined NLR of the two rooms is required, it should be calculated as the average of the NLRs of the individual rooms, and this value showed good agreement between the O-I and I-O values and spectra, as can be seen in Figure 21. The agreement between O-I and I-O NLR was also good for the individual rooms.

These O-I measurements show that a distinction must be made between rooms that form an open plan, and rooms that are just connected by an opening, as the combined NLRs are calculated differently. In the latter case, the concept of a combined NLR loses its meaning, and so the O-I NLR of the two rooms should be measured separately. In a true open plan area, either the combined O-I NLR or the individual O-I NLRs of the constituent spaces can be measured. In this context, an open-plan area can be defined as follows:

> *An open-plan area in a home is where barriers such as walls and doors that traditionally separate distinct functional areas are eliminated, such as combining a living room, dining room, and kitchen into a single great room. It is a room which has few or no walls inside, so it is not divided into smaller rooms. Connected floor plans designate each area of the house as their own separate spaces, such as a living room, dining room, and kitchen, separated by walls, though there may be openings in the walls between the rooms.*

These conclusions refer to the O-I measurement of NLR. Because the I-O tests measure the sound energy passing through the external walls (and roofs), and do not require a knowledge of the interior sound field, the NLR can be calculated for either combined or separate room layouts.

5.7 O-I TEST RESULTS FOR HOUSE #8 WITH RESTRICTED MEASUREMENT SPACE

The property line to the left side of House #8 in Figure 13 was 5 ft from the side wall of the house, and was marked with a fence, thus restricting the space to locate the loudspeaker for the O-I measurements. According to ARP 6973 (SAE, 2021), measurements at distances less than 10 ft are not recommended. When space is limited, an exception is allowed but must be noted in the appendix to the test report. In such situations the loudspeaker should be as far as possible from the test façade within the space limitations imposed, with the main axis at an angle of incidence of 0 degrees (perpendicular) to the center of the façade, or to the center of the acoustically weakest element on the façade.

To conduct the O-I test for the side walls of the office and bedroom #1 of House #8, the loudspeaker distance was limited by the presence of the fence to 4 ft from the test wall, well below the recommended minimum. At these distances, the sound level at the extreme edges of the façade can be 6 dB or more lower than that at the center of the façade, and the 2D scan used to measure the average sound level over the façade for the O-I measurement should include the entire width and height of the façade, rather than limiting the scan to areas 2 ft from the edges of the façade as recommended in ARP 6973 (SAE, 2021). Alternatively, the adjustments shown in Table 8 (see Appendix A) should be subtracted from the values measured by the current O-I procedure.

Table 8. Adjustments to Exterior Sound Level for Loudspeaker Distances Less than 10 ft

Loudspeaker Distance, ft	**Façade Width, ft**							
	10	**12**	**14**	**16**	**18**	**20**	**22**	**24**
4	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.3
5	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1
6	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9
8	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7
10	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5

These adjustments take account of the decrease in sound level towards the extreme edges of the façade with small loudspeaker distances that are not measured by the current procedure. They should not be applied in situations where reflections from nearby surfaces could negate the assumption of a free-field incident sound distribution and provide a more equal distribution of the incident sound. These adjustments have been applied to the data shown in Tables 6 and 7 and in Figure 21, in the measurement of noise reduction for the office in House #8, and in the measurement for wall 1 in bedroom #1 of House #8 shown in Figure 22.

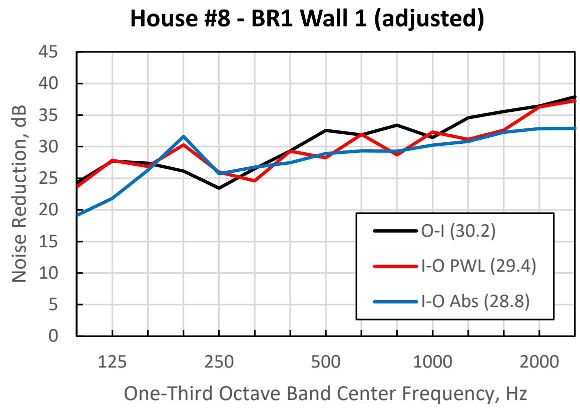


Figure 22. Adjusted Noise Reduction Spectra for Exterior Wall 1 in Bedroom 1 of House #8

The conclusion from this limited set of data is that O-I noise reduction measurements at distances less than the recommended minimum of 10 ft can overestimate the NLR by up to 1.5 dB by excluding the measurement of exterior sound level in areas within 2 ft from the edges of the façade. This restriction is imposed in ARP 6973 (SAE, 2021) to avoid measuring the sound level near the façade edges where the sound field might be influenced by diffraction effects. If it is assumed that these effects are minimal, then a more accurate measure of the exterior sound level in the O-I test method can be obtained by scanning the exterior façade over the entire width and height. Alternatively, the corrections of Table 8 can be applied to the current measurement procedure. It should be noted that the I-O test method does not have these limitations and might be more appropriate for use in situations where space is limited.

5.8 COMPARISONS OF O-I AND I-O NOISE REDUCTION SPECTRA FOR HOUSES #9 AND #10

In addition to the results shown in Tables 6 and 7, an additional validation of the I-O test methodology can be assessed by reviewing the spectral comparisons with the O-I method, as shown in Figure 23.

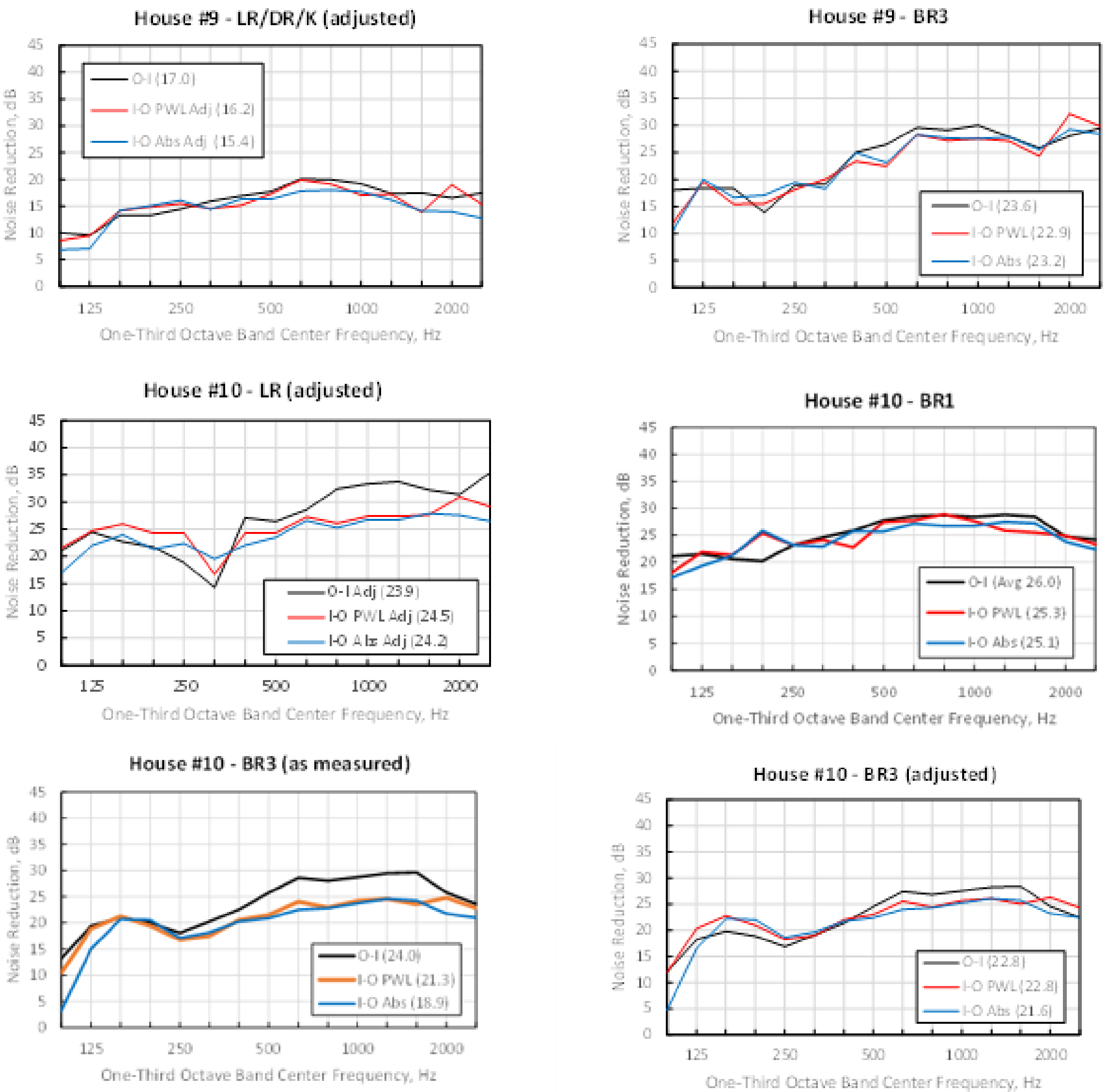


Figure 23. Spectral Comparison of O-I NLR and I-O NLR for Rooms in Houses #9 and #10

The living room/dining room/kitchen in House #9 consisted of a large 38 ft x 17 ft open-plan area with a glass wall on one side opening onto a courtyard. Including the door area, there were four external façades to measure, in addition to the beam ceiling with a 10-degree sloping roof. As it was not possible to measure the noise reduction of the roof independently from the walls, the noise reduction of the entire room was measured in conjunction with measurements of one of the walls. It was important to measure the roof sound transmission as part of only one of the wall measurements to avoid duplicating its influence in measurements of the other walls.

Accordingly, the roof measurement was combined with the measurement of wall 1 (to the left of the house shown in Figure 14) by elevating the loudspeaker to a height of 10 ft as recommended in ARP 6973 (SAE, 2021). The noise reductions of the other three walls were measured using a

ground-level loudspeaker with minimal roof sound exposure. The noise reduction for the living room of House #10 was also measured using a 10-ft-high loudspeaker.
However, despite the elevated loudspeakers, the incident sound levels on the roof were significantly lower than those to the wall for both houses, as shown in Figure 24.

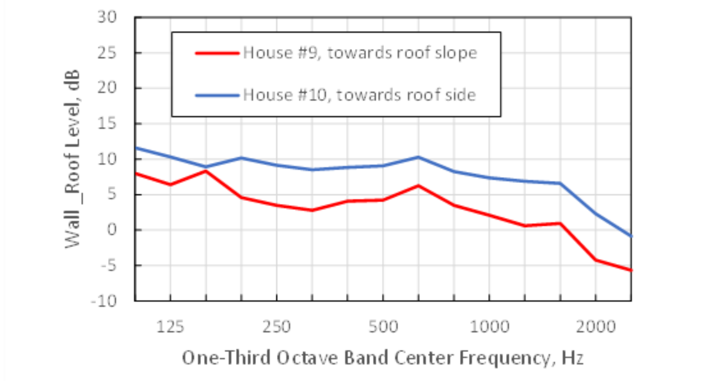


Figure 24. Wall to Roof Differences in Incident Sound Level for a Loudspeaker Elevated to 10 ft

As a result, the noise reduction measured for the wall/roof combination using the O-I method was not equivalent to, and was, in fact, numerically greater than, that which would have been measured with equal exposure to both wall and roof. The I-O test method, on the other hand, measures the noise reduction of the wall/roof façade for an equal sound exposure to each element. As it was not possible to account for the difference in exposure in the O-I analysis, to provide a realistic comparison of the O-I and I-O methods, the difference between the roof and wall exposure was applied to the I-O analysis, resulting in the adjusted data shown in Figure 22. The measured data for each of the individual walls of the living room/dining room/kitchen in House #10 are shown in Figure 25.

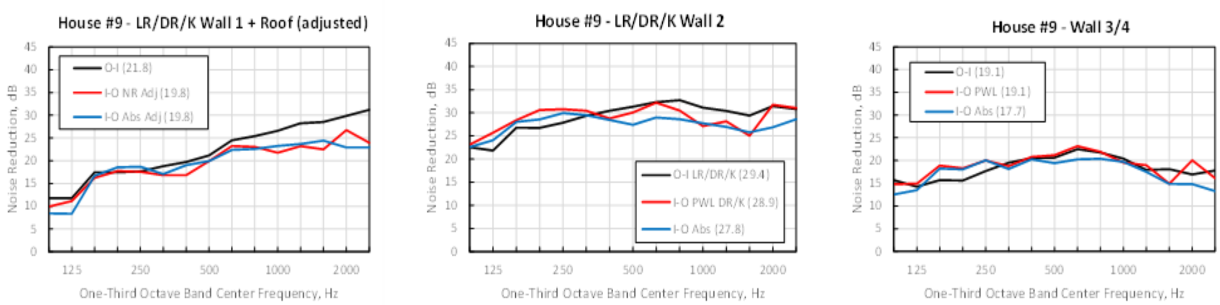


Figure 25. Spectral Comparison of O-I NLR and I-O NLR for Each Facade in Living Room/Dining Room/Kitchen Area of House #9

It should be noted that the adjustments applied to the I-O measurement data for roof transmission were solely for the purpose of comparing the results between the I-O and O-I test methods. The correct value of noise reduction for the room, when all façades are equally exposed to incident sound, is provided by the I-O method.

Measurements of the noise reduction for bedroom #1 in House #10 were conducted using three loudspeaker locations to examine the effect of reducing the loudspeaker-to-façade distance to less than the recommended 10 ft (SAE, 2021). The loudspeaker configurations are shown in Table 9, and the spectral noise reduction data are shown in Figure 26.

Table 9. The Effect of Loudspeaker Location on Measured O-I Noise Reduction

LS Distance, ft	LS Height, ft	LS Position	O-I NR, dB
15	0	Aimed at Façade Center	25.9
5	6	Aimed at Façade Center	26.0
5	6	Aimed at French Door	25.7

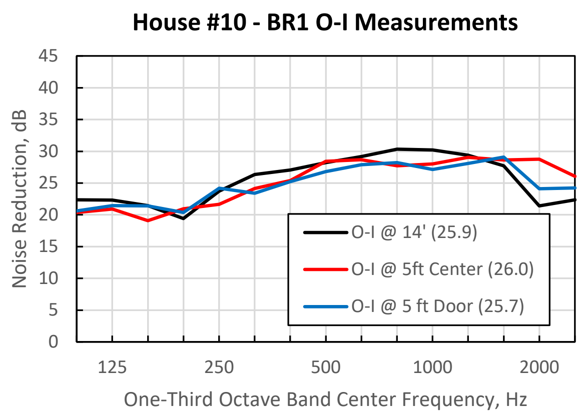


Figure 26. The Effect of Loudspeaker-to-Facade Distance on Measured Noise Reduction

In this case, no adjustments for loudspeaker distance were applied because reflections from the adjacent living room wall negated the assumption of a free-field incident sound distribution.

The measurements for bedroom #3 in House #10 required adjustments for the loudspeaker distance as placement was limited by the presence of a solid wall 5.5 ft from, and parallel to, the test façade. This wall also provided reflections that increased the sound levels measured at 24 inches from the façade in the I-O test. An estimate of the magnitude of this increase in sound level due to a reflecting wall is outlined in Appendix B and presented in Table 10 for a range of distances from the façade and various façade dimensions. The values in this table should be added to the values of the noise reduction measured using the I-O test method.

Table 10. The Increase in Measured Sound Level Due to the Presence of a Reflecting Wall

Distance to Reflecting Wall, ft	**Façade Width, ft**										
	10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
4	2.1	2.3	2.4	2.5	2.7	2.7	2.8	2.9	3.0	3.0	3.1
5	1.5	1.6	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.4	2.4
6	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.8	1.9	1.9
8	0.7	0.7	0.8	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.3
10	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.9	0.9
12	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.7
14	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5

The adjustment for loudspeaker distance and wall reflections have been applied to the measured values of noise reduction for bedroom #3 in House #10, shown in Figure 23.

6. LOUDSPEAKER DIRECTIVITY INDEX

The measurement of I-O noise reduction using the sound power level (PWL) method is based on the calculation of loudspeaker power output. The output, PWL_s , is calculated based on a measurement of the sound level, SPL_1, at 1 ft from the loudspeaker, combined with the loudspeaker DI according to the equation (Sharp & Cox, 2023),

$$PWL_s = SPL_1 - DI + 1.4 \quad (5)$$

The DI of a loudspeaker is available from the specifications provided by some manufacturers, or can be calculated from the loudspeaker polars, where these are available. The published (or calculated from published data) values of DI as a function of frequency for three commercial loudspeakers in common use (Mackie 450, Mackie 350, and JBL AC96, with 12-inch, 10-inch, and 8-inch low-frequency drivers, respectively) are very similar, as shown in Figure 27.

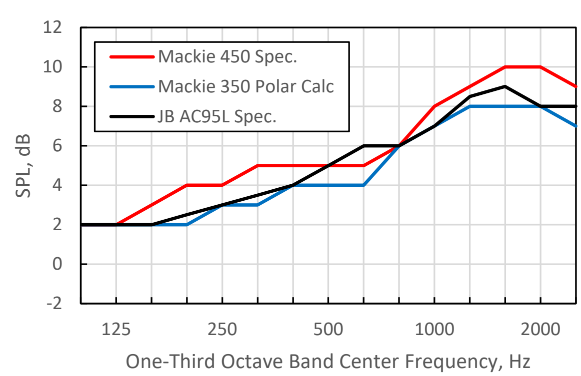


Figure 27. Comparison of DI for Three Loudspeakers from Manufacturer's Specifications

These values of DI are applicable to loudspeakers situated in free space. It is possible, however, that the directional characteristics are modified when the loudspeakers are placed near reflecting surfaces. Fortunately, data were collected in the field measurements described in Section 4 that can be used to calculate the in-situ, and, hence, *effective* values of DI for the loudspeakers as used in the field measurements.

The sound power output of the loudspeaker can be calculated by a completely different method that is based on the measurement of reverberant room sound level, SPL_s , generated in the room by the loudspeaker during the I-O test, together with measurement of room absorption using a reference sound source of known sound power output, PWL_{ref}, according to Equation 6,

$$PWL_s = PWL_{ref} + SPL_s - SPL_r \tag{6}$$

where SPL_r is the reverberant sound level produced in the test room by the reference sound source (Sharp & Cox, 2023). Combining Equations 5 and 6 provides a method for calculating the effective values of DI for the Mackie 350 and Mackie 450 loudspeakers used in the field measurements. The results are shown in Figure 28.

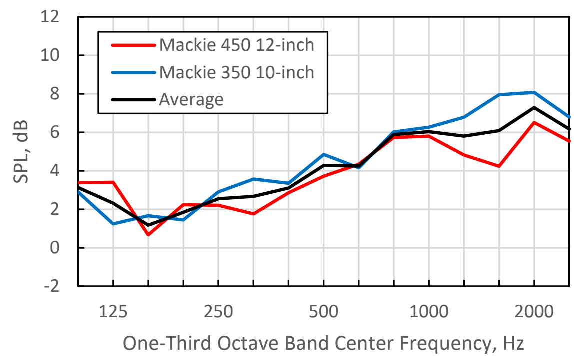


Figure 28. Effective Measured Values of DI for Mackie 350 and Mackie 450 Loudspeakers

The values of DI for the loudspeakers are similar, except at frequencies greater than 1000 Hz. The difference is due to the different crossover frequencies[2] for the two loudspeakers—1600 Hz for the Mackie 450 and 2400 Hz for the Mackie 350. The average values rounded to the nearest decibel are shown in Table 11.

Table 11. Effective Measured Values of DI for Mackie 350/450 Loudspeakers

Frequency, Hz	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**
DI, dB	1	1	2	2	3	3	4	4	4	6	6	6	6	6	6

The values in Table 11 were applied retroactively to the calculation of I-O noise reduction presented in Section 4. The average values for 100 and 125 Hz were selected at 1 dB as the best values for comparison to the O-I noise reduction.

[2] The frequency at which the major source of sound generation changes from the low- to high-frequency driver.

7. THE INFLUENCE OF BACKGROUND NOISE

The I-O test method relies on a measurement of the exterior sound level at 24 inches from the surface of the façade. Even though the interior sound level is high, transmission through the façade reduces the level significantly. As a result, the influence of exterior background noise on the measured exterior sound levels needs to be addressed to ensure that I-O measurements of NLR are accurate.

The loudspeaker used for both the O-I and I-O testing for Houses #2 through #6 was the Mackie 350, and the test signal was broadband pink noise. To minimize the influence of exterior background noise, the tests for Houses #7 through #10 were conducted using a more powerful loudspeaker, the Mackie 450, together with a reduced pink noise bandwidth of 80 to 2500 Hz to maximize sound power output in the frequency range of interest. A comparison of the sound levels measured at 1 ft from the loudspeaker for the two Mackie models, with a reduced bandwidth for the test signal for the Mackie 450, is shown in Figure 29.

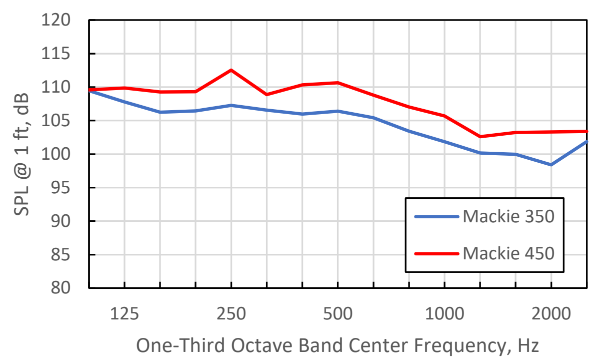


Figure 29. Comparison of Sound Levels at 1 ft from Mackie 350 and Mackie 450 Loudspeakers

The data in Figure 29 are the average of measurements conducted in Houses #5 and #6 for the Mackie 350, and Houses #7 through #10 for the more powerful Mackie 450, showing an increase in sound power output of 4 to 5 dB over much of the frequency range. For the tests in these houses, with typical suburban background noise levels in the range 45 to 55 dBA (A-weighted scale of decibel levels), this increase translated into an improved signal-to-noise ratio for the exterior sound level, as shown in Figure 30.

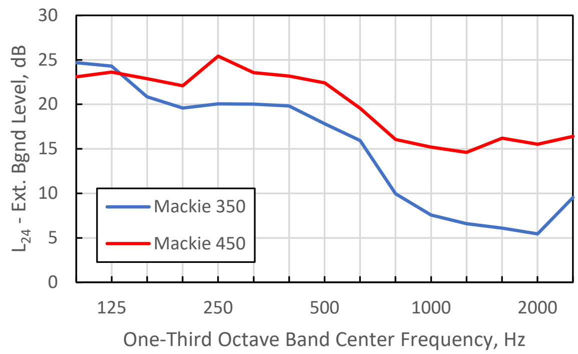


Figure 30. Exterior Sound Levels Relative to Background Levels for Mackie Loudspeakers

Figure 30 shows a signal-to-noise ratio of at least 20 dB over the most important frequency range of 100 to 630 Hz, and about 15 dB at higher frequencies, which are less important in determining NLR. The Mackie 450 with the limited signal spectrum was used for the subsequent testing of Houses #7 through #10.

The influence of external background noise must be considered prior to conducting I-O measurements to ensure that the results will be accurate. If the steady background levels are too high, the apparent measured NLR will be too low. Ideally, the steady background levels should be at least 10 dB lower than the test levels so that their influence is minimized. If additional post-modification measurements are planned, then the difference should preferably be 15 dB. Field conditions often require some compromise so that adjustments can be made to the measured values of L_{24} if the steady background levels are within 10 dB of the exterior test levels but are limited when the difference is less than 6 dB (SAE, 2021). Measurements should always be paused in the presence of intermittent noise sources, such as passing trucks or aircraft overflights.

Guidelines for defining acceptable levels of background noise can be developed based on the data from the tests described in Section 4. Clearly, with a fixed source sound output, the exterior noise level, L_{24}, is dependent on the noise reduction of the test façade, as shown by the black circles and the dashed linear trendline in Figure 31.

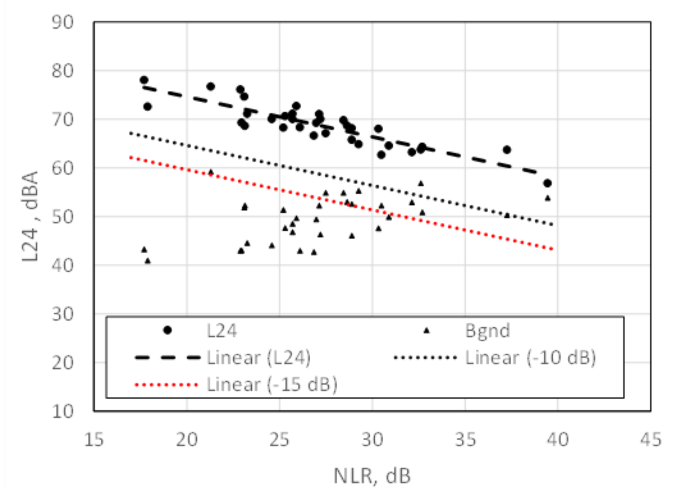


Figure 31. Measured Exterior Sound Levels and Background Levels Using Mackie Loudspeakers

Figure 31 also contains the background noise levels (shown as black triangles) associated with each of the measured data points. The data represent a range of NLR from 18 to 40 dB, and a range of A-weighted background levels from 41 to 59 dB and can be considered to cover most field conditions. As noted above, the background noise levels should preferably be 10 dB below the test levels, and, in some cases, 15 dB, as indicated by the dotted black and red lines, respectively, in Figure 31. This graph can then be used to establish guidelines for acceptable background noise levels. For example, to measure the I-O noise reduction of a façade with a NLR of 30 dB, with a 10 dB signal-to-noise ratio, the background noise level should not exceed 57 dBA. For a façade with an NLR of 40 dB, the background noise level should not exceed 49 dB. If the signal-to-noise ratio is increased to 15 dB, the background noise level for a façade with a NLR of 25 dB should not exceed 55 dB.

Three considerations should be noted. First, the data shown in Figure 31 were obtained using Mackie 350 and Mackie 450 loudspeakers, with the latter producing values of L_{24} about 3 to 4 dB higher than the former. These loudspeakers are typical of those used in airport sound insulation program measurements. Second, corrections were required to the data from two façade tests shown in Figure 30 where the background levels were within 10 dB of the measured L_{24} levels.

Third, the guidelines based on the data in Figure 30 are conservative, because the values of L_{24} are A-weighted sound levels calculated over the range 100 to 2500 Hz (and differ by less than 0.5 dB from levels calculated over a full frequency range of 50 to 4000 Hz), whereas the most important frequency range for data that determine the NLR value for most structures is 100 to 800 Hz. Figure 32 shows the signal-to-noise ratio, which is the difference between the value of L_{24} and the background noise level, averaged over the frequency range 100 to 800 Hz plotted against NLR, for the Mackie 350 and Mackie 450 loudspeakers.

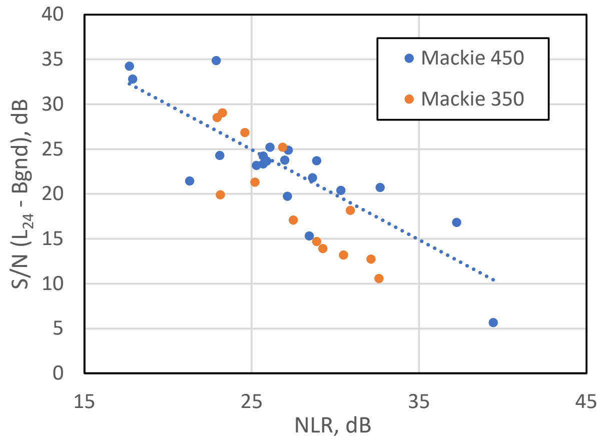


Figure 32. Signal-to-Noise Ratio for L_{24} Averaged over Frequency Range 100 to 800 Hz

Figure 32 shows that the signal-to-noise ratio for the test data in Figure 30 is greater than 10 dB for all façades, with the exception of one data point at 8 dB for an NLR of 39.5.

8. CORRECTIONS FOR ROOF TRANSMISSION

In measuring the O-I noise reduction of a façade using an external loudspeaker at ground level or at 10 ft, the contribution to the interior sound level from transmission through the roof is not completely measured because the sound exposure on the roof is less than that on the walls. The result is that the measured noise reduction is greater than if the sound exposure was distributed equally over all the elements as it would be by an elevated loudspeaker. Experience shows that measurements using an elevated loudspeaker are cumbersome and difficult to set up and are limited to easily accessible areas around the house. The issue is addressed in ARP 6973 (SAE, 2021) by providing a set of correction factors to be applied to O-I measurements with a ground level or 10-ft loudspeaker to simulate equal sound exposure to the walls and roof.

Similarly, when measuring noise reduction using the I-O method, only the sound transmission through the walls is considered, as it is difficult to perform measurement of the sound level over the roof surfaces of many houses. As a result, the measured noise reduction will be equivalent to that measured by the O-I method, but with no roof exposure to incident sound. The corrections to the I-O measured noise reduction to account for roof transmission will be similar but greater than those for the O-I method. An estimation of the correction factors for the I-O method to account for roof transmission is obtained using the same procedure as for the O-I method described in Sharp et al. (2019).

The calculations to estimate the contribution of roof transmission to overall I-O noise reduction have been performed for a typical corner room with two exterior perpendicular walls, two windows, and a roof, for several different combinations of elements with differing acoustic performance as shown in Table 12. The term "Single" refers to a single pane window of 3/32″ or 1/8″ glazing, and the term "Storm" refers to an additional pane of 3/32″ or 1/8″ glazing. Detailed spectral information for the elements included in Table 12 can be found in Sharp et al. (2019).

Table 12. Specifications of Room Elements in the Calculation of the Influence of Roof Sound Transmission

Element	Area (sq ft)	Type	STC	OITC
Window	27.5	Single	26	24
		Single + Storm	32	24
		Acoustic	44	33
Wall	165	Siding	38	27
		Stucco	43	33
		Brick	55	42
Roof	144	Beam Ceiling	29	25
		Single Joist	43	30
		Attic w/o Ins.	41	33
		Attic w/ Ins.	50	37

The baseline case is a calculation of I-O noise reduction where all the elements (walls and roof) of the corner room are exposed to the sound from an indoor loudspeaker. The calculated difference in noise reduction between the baseline case and that calculated for transmission through the walls alone is a correction factor to be applied to measured values of noise reduction to account for roof transmission. The correction factors for different construction types to be subtracted from the I-O measured value of noise reduction are presented in Table 13.

Table 13. Corrections to be Subtracted from Measured Values of I-O NLR to Account for Roof Transmission

		Roof/Ceiling Type			
		Single Joist		Attic	
Window	Wall	Beam Ceiling	Gypsum Ceiling + Insulation	Without Insulation	With Insulation
Single	Siding	2.8 (1.9)	0.3 (0.2)	0.5 (0.3)	0.1 (0.1)
	Stucco	3.6 (2.4)	0.4 (0.3)	0.6 (0.5)	0.1 (0.1)
	Brick	4.9 (3.1)	0.6 (0.5)	1.0 (0.7)	0.2 (0.1)
Single + Storm	Siding	3.1 (2.1)	0.3 (0.2)	0.5 (0.4)	0.1 (0.1)
	Stucco	4.1 (2.6)	0.5 (0.4)	0.8 (0.6)	0.1 (0.1)
	Brick	5.9 (3.5)	0.8 (0.6)	1.3 (1.0)	0.2 (0.2)
Acoustic	Siding	4.0 (2.6)	0.5 (0.4)	0.7 (0.6)	0.1 (0.1)
	Stucco	6.1 (3.6)	0.9 (0.7)	1.4 (1.0)	0.3 (0.2)
	Brick	15.0 (5.6)	5.1 (3.4)	6.8 (4.0)	2.1 (1.5)

Values in parentheses represent NLR corrections for O-I tests with ground level loudspeaker.

The corrections are small except for structures with beam ceilings, and brick and stucco structures with attics without insulation. The differences between the I-O and O-I NLR values are minor, except for houses with beam ceilings or with brick walls combined with acoustic windows, as shown in Table 14.

Measurements on Houses #9 and #10 provide a comparison of the calculated correction factors with field measurements conducted on one-story houses with stucco walls and beam ceilings, as shown in Figure 32.

Table 14. Comparison of Calculated and Measured Correction Factors for Rooms with Beam Ceilings

<table>
<tr><th>House</th><th>Element(s)</th><th>O-I NR (dB)</th><th>ΔO-I NR (dB)</th><th>Calc ΔO-I NR (dB)</th><th>I-O NR (dB)</th><th>ΔI-O NR (dB)</th><th>Calc ΔO-I NR (dB)</th></tr>
<tr><td rowspan="2">#9</td><td>Wall only</td><td>24.2</td><td rowspan="2">2.4</td><td rowspan="4">2.4</td><td>21.5</td><td rowspan="2">3.6</td><td rowspan="4">3.6</td></tr>
<tr><td>Wall + Roof</td><td>21.8</td><td>17.9</td></tr>
<tr><td rowspan="2">#10</td><td>Wall only</td><td>25.1</td><td rowspan="2">3.4</td><td>26.1</td><td rowspan="2">4.8</td></tr>
<tr><td>Wall + Roof</td><td>21.7</td><td>21.3</td></tr>
</table>

There is good agreement between calculated and measured correction factors for both the O-I and I-O test methods for House #9 with values of 2.4 dB and 3.6 dB, respectively. The measured correction factors at House #10 are slightly larger than, but consistent with, the calculated values.

The calculated corrections for houses with brick walls are large, particularly for those with beam ceilings, and exceed what could be considered appropriate for determining NLR without measurement of the roof transmission. It might be possible to overcome this limitation by measuring sound levels 24 inches from the roof surface as part of the I-O test method, at least for one-story houses.

9. SUMMARY AND CONCLUSIONS

This report describes the measurements conducted to examine the feasibility of using an I-O testing method, in which a loudspeaker is placed inside the house and the noise reduction is measured from inside to outside, as a supplemental or alternative measurement procedure to the (O-I method of ARP 6973 (SAE, 2021). This approach eliminates the need for any adjustments to the measurement levels and removes restrictions on the placement of an external loudspeaker. A summary of the results shows that:

- The measurements conducted in 30 rooms of 9 houses have validated the I-O procedure for the measurement of noise reduction.
- Both of the methods for I-O measurement, namely the absorption and sound power level methods, provide similar results that are in good agreement with the standard O-I procedure as described in ARP 6973 (SAE, 2021).
- The data provided by the sound power level method show a lower spread than those measured by the absorption method as it requires fewer sound level measurements.

- The value of the constants K = 11.5, for the room absorption method, and C = 6.5, for the sound power level method, are consistent with findings of the previous research (Sharp & Cox, 2023).

- In restricted areas where the exterior loudspeaker distance to the façade is less than the recommended minimum of 10 ft, the O-I test method tends to provide higher values of NLR than the I-O method due to the limitation on the area of the exterior sound level scan for the O-I test method in ARP 6973. Corrections can be applied to account for this increase (see Appendix A.1), or the façade scan procedure can be modified. In such situations, the I-O test method provides more realistic values of noise reduction than the O-I method.

O-I measurements of the noise reduction for open plan areas within a house can consider the area as a single room, or as a series of individual areas, as both methods provide NLR values that agree well with results using the I-O method.

O-I measurements of the noise reduction of connected rooms within a house must consider the rooms as individual and should be measured separately.

Comparisons of the two I-O methods (sound power level and absorption) with the O-I method averaged over the rooms in each house are shown in Tables 15 and 16 and indicate good agreement.

Table 15. Noise Level Reduction Comparison of Average O-I and I-O Room Absorption Methods

House	**No. Rooms**	**Average NLR**			**Median NLR**		
		O-I	**I-O**	**Δ**	**O-I**	**I-O**	**Δ**
2	2	24.4	23.7	0.6	24.4	23.7	0.6
3	4	24.4	24.5	-0.1	24.2	24.3	-0.1
4	4	24.0	24.5	-0.5	23.9	24.2	-0.3
5	3[1]	20.8	20.7	0.2	20.8	20.3	0.5
	4[2]	22.5	23.7	-1.1	21.1	20.9	0.2
6	3[1]	25.9	26.3	-0.5	26.3	25.8	0.4
	4[2]	27.4	28.6	-1.2	26.3	26.7	-0.4
7	3	23.0	23.1	-0.1	24.0	24.6	-0.6
8	4	27.4	27.5	-0.1	27.5	28.0	-0.5
9	2	20.3	19.3	1.0	20.3	19.3	1.0
10	3	24.2	23.6	0.6	23.9	24.2	-0.3
Average (excluding basement data)				0.2			0.2
Average (including basement data)				0.0			0.1

[1] Excludes basement data; [2] Includes basement data

Table 16. Noise Level Reduction Comparison of Average O-I and I-O Sound Power Level Methods

House	No. Rooms	Average NLR			Median NLR		
		O-I	I-O	Δ	O-I	I-O	Δ
2	2	25.8	25.5	0.3	25.8	25.2	0.6
3	4	24.4	24.2	0.2	24.2	23.7	0.5
4	4	24.0	24.2	-0.2	23.9	24.0	-0.1
5	3[1]	20.8	20.8	0.1	20.8	20.9	-0.1
	4[2]	22.5	23.4	-0.8	21.1	21.1	0.0
6	3[1]	25.9	26.4	-0.6	26.3	26.1	0.2
	4[2]	27.4	29.0	-1.5	26.3	26.6	-0.3
7	3	23.9	23.9	0.0	24.0	24.6	-0.6
8	4	27.4	27.5	-0.1	27.5	27.6	-0.1
9	2	20.3	19.5	0.8	20.3	19.5	0.8
10	3	24.2	24.1	0.1	23.9	24.5	-0.6
Average (excluding basement data)				0.0			0.0
Average (including basement data)				-0.2			0.0

[1] Excludes basement data; [2] Includes basement data

The data provided by the I-O test methods applied to basements did not agree well with the O-I data due to flanking transmission through the walls of the main building. Future I-O testing of basements should take this flanking into account by also performing the exterior measurements over adjoining walls and including these data in the calculations.

Exterior background noise can interfere with the I-O measurements at high frequencies. The loudspeaker initially used in this series of tests on Houses #2 through #6 was a Mackie 350 model. Subsequent tests on Houses #7 through #10 used a more powerful loudspeaker, the Mackie 450, together with a restricted noise bandwidth to generate higher exterior sound levels at medium and high frequencies in the I-O measurements.

The results of the measurements provide a method to establish guidelines for defining acceptable conditions where the I-O method can be implemented.

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APPENDIX A—THE EFFECT OF LIMITED TWO-DIMENSIONAL FAÇADE SCANS

The procedure for measuring the exterior sound level produced by an exterior loudspeaker with the O-I measurement of noise reduction is to conduct a two-dimensional (2D) scan over the surface of the façade, excluding areas within 2 ft of the horizontal and vertical edges of the façade. This limitation is designed to avoid measuring the effects of diffraction at the edges of the façade. When the loudspeaker is located at large distances from the façade, the difference in the average measured sound level from that which would be measured using a full scan over the façade is minimal. However, at distances where the loudspeaker distance is comparable to, or less than, the dimensions of the façade, the difference could be significant. An estimate of this difference is provided by the analysis that follows.

Consider a rectangular façade of width $2w$, and height $2h$, exposed to sound from a loudspeaker with a sound power output W located at a distance d, as shown in the diagram of Figure A-1.

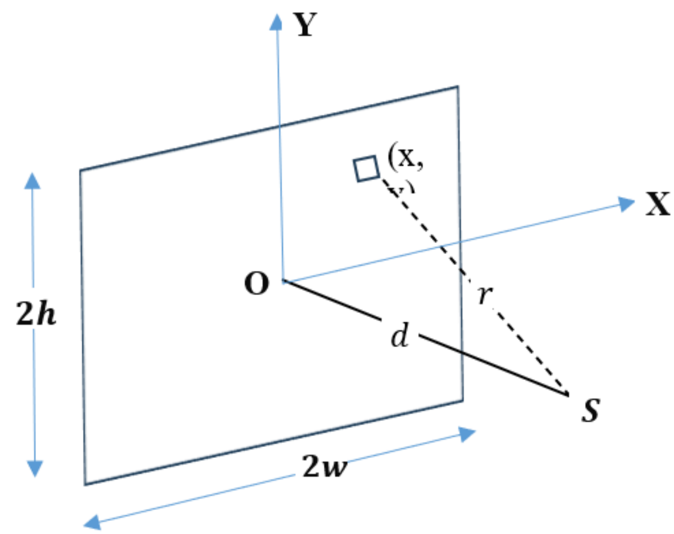

Figure A-1. Rectangular Façade Configuration

At the position (x, y), at a distance r from the source, the expression of the mean square sound pressure produced by the sound source is given by reorganizing Equation 2 from Section 2,

$$p_r^2 = \frac{W_S \rho c}{4\pi r^2} \tag{A-1}$$

The average mean-square pressure over the entire façade area, that is equivalent to a 2D scan over the area, is given by integrating Equation A-1 over the façade area and dividing by the area, as follows:

$$p_{av}^2 = \frac{W\rho c}{4\pi lw} \int_{-l}^{l} \int_{-w}^{w} \frac{dxdy}{r^2}$$

Substituting $x = dtan\theta, y = dtan\vartheta, and\ r = \frac{d}{cos\theta}$ where 2θ and 2ϑ are the angular widths and heights of the point (x, y) from the source, the average sound level over the façade is given by

$$p_{av}^2 = \frac{W\rho c}{4\pi lw}\int_{-\theta}^{\theta}\int_{-\vartheta}^{\vartheta} d\theta d\vartheta$$

And the solution is

$$p_{av}^2 = \frac{W\rho c}{\pi lw} tan^{-1}\left(\frac{l}{d}\right) tan^{-1}\left(\frac{w}{d}\right) \tag{A-2}$$

If the average sound pressure is calculated according to the measurement procedure in ARP 6973 (SAE, 2021), then Equation A-2 becomes

$$p_{av,lim}^2 = \frac{W\rho c}{\pi(l-2)(w-2)} tan^{-1}\left(\frac{l-2}{d}\right) tan^{-1}\left(\frac{w-2}{d}\right)$$

The difference, ΔL, between a measurement scan over the entire façade to that not including areas within 2 ft of the edges of the façade, is, therefore,

$$\Delta L = 20 \log\left(\frac{p_{av}}{p_{av,lim}}\right)$$

The value of ΔL for a range of loudspeaker differences and façade widths, for a typical façade height between 8 and 10 ft, is shown in Table A-1.

Table A-1. Adjustments to Exterior Sound Level as a Function of Loudspeaker Distance

Loudspeaker Distance (ft)	**Façade Width (ft)**							
	10	**12**	**14**	**16**	**18**	**20**	**22**	**24**
4	1.5	1.5	1.5	1.5	1.5	1.4	1.4	1.3
5	1.2	1.2	1.2	1.2	1.2	1.1	1.1	1.1
6	1.0	1.0	1.0	1.0	1.0	0.9	0.9	0.9
8	0.6	0.6	0.6	0.7	0.7	0.7	0.7	0.7
10	0.4	0.4	0.4	0.5	0.5	0.5	0.5	0.5

These adjustments are to be subtracted from NLR values measured using the O-I test method. They are small but significant for loudspeaker distances less than 6 ft, and minimal for distances greater than 10 ft.

REFERENCE

SAE. (2021). *Aircraft noise level reduction measurement of building facades* (SAE Aerospace Recommended Practice ARP 6973).

APPENDIX B—INDOOR-OUTDOOR MEASUREMENTS IN RESTRICTED SPACES

In many field situations, when using the indoor-outdoor (I-O) test procedure, it is necessary to measure the exterior sound level, L_{24}, in restricted spaces where reflections from nearby buildings or walls and fences could influence the result. The magnitude of this effect can be estimated using the same approach as in Appendix A.

The sound radiation from a façade exposed to sound from inside the test room can be approximated from the configuration in Figure A-1 in reverse, where the façade is now considered to consist of an infinite number of incoherent sound sources, each with sound power output W, and the resulting sound pressure at point S is given by Equation A-2. If there is a reflecting wall at a distance d from the façade, there will be a series of reflections between the wall and the façade which will add to the sound level, L_{24} measured at 2 ft. The magnitude of the effect of these reflections can be estimated using Equation A-2 to calculate the sound pressure at the appropriate distances 2(d-2), 2(d-2)+4, 4(d-2)+4, etc., and add each contribution to the value at 2 ft. The increase in sound level due to the presence of wall reflections is shown in Table B-1.

Table B-1-2. The Increase in Measured Sound Level Due to the Presence of a Reflecting Wall

Distance to Reflecting Wall (ft)	**Façade Width (ft)**										
	10	**12**	**14**	**16**	**18**	**20**	**22**	**24**	**26**	**28**	**30**
4	2.1	2.3	2.4	2.5	2.7	2.7	2.8	2.9	3.0	3.0	3.1
5	1.5	1.6	1.8	1.9	2.0	2.1	2.2	2.2	2.3	2.4	2.4
6	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.8	1.9	1.9
8	0.7	0.7	0.8	0.9	1.0	1.0	1.1	1.1	1.2	1.3	1.3
10	0.4	0.5	0.6	0.6	0.7	0.7	0.8	0.8	0.8	0.9	0.9
12	0.3	0.4	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.6	0.7
14	0.2	0.3	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5	0.5

These increases in sound level are to be subtracted from the sound level measured at 2 ft from the test room surface in the I-O measurement method.