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BACKGROUND REPORT ON OUTDOOR-INDOOR NOISE REDUCTION CALCULATION PROCEDURES EMPLOYING THE EXTERIOR WALL NOISE RATING (EWNR) METHOD

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NOTICE

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BACKGROUND REPORT ON OUTDOOR-INDOOR NOISE REDUCTION CALCULATION PROCEDURES EMPLOYING THE EXTERIOR WALL NOISE RATING (EWNR) METHOD

For

U.S. DEPARTMENT OF TRANSPORTATION
Federal Highway Administration
Office of Development
Washington, D.C. 20590

By

Gary E. Mange
Steven R. Skale
Louis C. Sutherland
WYLE RESEARCH
El Segundo, California 90245

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ABSTRACT

This background report on the procedure for evaluating outdoor-indoor noise reduction of structure in terms of the single number metric Exterior Wall Noise Rating (EWNR) first reviews the basis of previous single number ratings emphasizing the Sound Transmission Class (STC). It is shown that the latter was initially designed to try to account for the relative loudness of interior noises in typical residences as heard by adjoining neighbors on the other side of a common party wall.

In a similar, but quite independent manner, the EWNR metric was developed so that the A-weighted indoor noise level, due to highway noise sources outdoors, could be roughly estimated directly from the value of EWNR and the A-weighted outdoor noise level. The basis for this is defined, first in terms of the basic theory for noise reduction from outdoors to indoors at one frequency. The result is then summed over all frequencies to give the overall effective noise reduction. The EWNR single number rating replaces this complex summation and, as shown by recently conducted field tests, provides a valid method with an accuracy of about $\pm$ 3 dB for predicting levels inside buildings due to outdoor transportation noise sources.

This background report also briefly reviews the basis for the tables of EWNR values and tables of various EWNR adjustment factors used to evaluate the composite noise reduction of A-weighted noise levels for a wide range of practical residential structural assemblies which may include walls, windows, doors, roofs, and ceilings.

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CHAPTER 1

INTRODUCTION AND HISTORICAL BACKGROUND

The procedures for estimating outdoor-indoor noise reduction of A-weighted noise levels specified in a recently completed manual for FHWA are based on application of a single number index for sound transmission through exterior building structures called Exterior Wall Noise Rating (EWNR).[1] This single number rating concept was originally developed by Wyle in a study for the U.S. Department of Housing and Urban Development.[2] This report summarizes the basis for development of EWNR as it was applied in the FHWA manual.

Chapter 2 of this report summarizes the basic theory for noise reduction between a free sound field outdoors impinging on a structure and the sound field inside a room of that structure. Chapter 3 develops the specific analytical background behind the single number rating EWNR and summarizes the basis for an additional term necessary to account for interior absorption of residential rooms. Chapter 4 summarizes the evaluation of EWNR and other possible single number rating methods.

Appendix A summarizes recently acquired experimental data which demonstrates the general validity of the EWNR method. Appendix B lists the same EWNR values for residential structures that were presented in the FHWA manual.[1]

An Historical Perspective

Before developing the analytical background for EWNR, it is desirable to briefly review the historical basis for the development of this single number rating and other similar ratings. The sound transmission loss of a structure varies substantially with frequency so that a formal calculation of the overall (wide-band) sound level transmitted through a structure from a wide-band noise source must include the summation of the sound energy transmitted over all frequency bands considered, such as the 16 one-third octave bands from 125 to 4000 Hz. In lieu of always carrying out this straightforward but inconvenient calculation, some single number index of the sound attenuating effectiveness of a structure has often been utilized as a rough qualitative, or, in some cases, quantitative guide.

The first such index was developed in about 1950 for the air-borne sound transmission loss (STL) through a structure and consisted simply of the arithmetic average value in decibels of STL for a specimen at the test frequencies employed – nominally 125, 190, 250, 375, 500, 750, 1000, 2000, and 4000 Hz.[3] This index was simply called the average transmission loss and clearly provided only a rough qualitative measure of the sound attenuating effectiveness with emphasis on the low frequencies. A similar method was also being considered in England.[4] Subsequently, other attempts to develop improved single number indices were made.[5, 6] In all cases, these indices were being applied to the rating of interior walls between multifamily dwelling spaces, offices, school rooms, hospital rooms, etc. They did not include any consideration of the spectral content of the noise source nor did they account for a subjective measure of the received noise.

In 1962, a new approach was taken towards rating of sound transmission effectiveness of interior walls.[7] The noise sources to be isolated consisted of peak noise levels from human voices, and home appliances such as radios, room air conditioners and vacuum cleaners. Furthermore, it was assumed that the subjective reaction to the received sound would be related to its loudness. Thus, an index dependent upon the interior noise source spectrum and the received loudness, which are both frequency-dependent quantities, was developed and identified as the Sound Transmission Class (STC).[7] The average interior noise source spectrum assumed for STC was approximated by the generalized shape illustrated in Figure 1; it was characterized by a constant band level from 250 to 1000 Hz decreasing above and below this frequency range at the rate of 4 dB/octave. The frequency weighting curve used to define the subjective loudness of the transmitted sound inside the receiver space was the 0.5 sone loudness contour corresponding to a loudness level of 46 phons.[7] Thus, the STC index value for a particular construction would be derived by fitting the actual transmission loss curve of the construction as closely as possible to a standard reference transmission loss curve. This reference curve was designed so that the transmitted noise from the assumed generalized interior noise source would generate a received noise spectrum where each band would contribute approximately equally to the subjective loudness.* The final curve selected in 1963 for the STC concept was adjusted slightly to be consistent with a similar approach that had been adopted earlier in Germany.[8] The STC single number rating, developed on the basis of the preceding concepts, has now been finalized in nearly identical form in international and national standards.[9, 10]

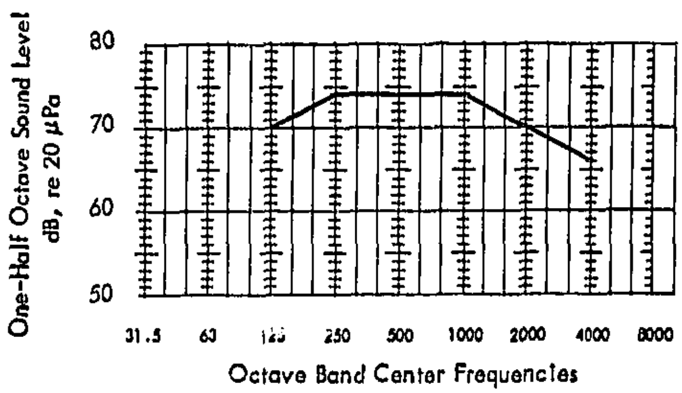

Figure 1. Generalized Half-Octave Band Levels of Typical Interior (Household) Noises Used for the Development of the Sound Transmission Class (STC) Index (from Reference 7)

The resulting reference transmission loss curve shape for the U.S. standard on STC shown in Figure 2, increases from 125 Hz to 400 Hz at a rate of +9 dB per octave, increases further from 400 to 1250 Hz at a rate of +3 dB per octave and remains constant to 4000 Hz. (The ISO curve starts at 100 Hz and ends at 3150 Hz but otherwise has the same shape.)

*The initial choice of the reference transmission loss curve for STC also considered frequency weightings for the received signal represented by the 0.5 noy equal noisiness contour and the NC-25 noise criterion curve for rooms.[7]

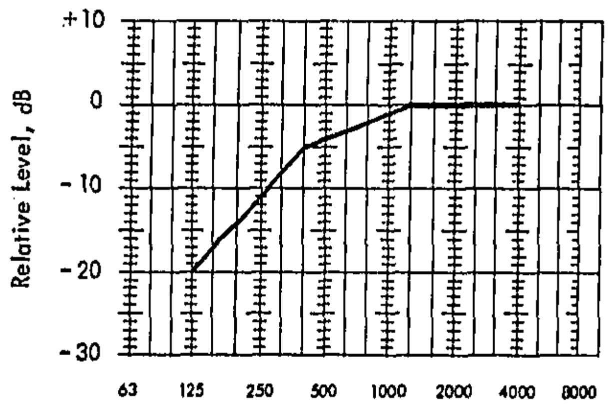

Figure 2. Reference Transmission Loss Curve Shape Adopted for Evaluating Sound Transmission Class[10]

Again, it must be emphasized that STC was developed entirely for application to rating transmission loss of interior walls. At least one attempt to apply the STC rating to estimation of outdoor-indoor noise reduction is reported;[11] however, unless the outdoor noise spectrum shape were similar to that illustrated in Figure 1 for internal noise sources, the STC index would not be expected to provide the degree of accuracy desired for predicting a subjective measure of noise transmission from the outdoors to interior spaces. Thus, a new index was developed with the following objectives:

- Designed to be suitable for evaluating outdoor-indoor noise reduction of major outdoor noise sources (i.e., ground and air transportation).
- Utilize the A-weighting curve for evaluation of the magnitude of both the exterior and interior noise levels.
- Provide an approximate method for estimating the overall composite noise reduction in A-weighted noise levels for a structure consisting of several structural elements, each with its own single number rating of sound transmission loss in terms of EWNR. This had apparently not been attempted with the STC rating method.

The remainder of this report outlines the basis for the development of this new single number rating method.

CHAPTER 2
THEORY OF NOISE REDUCTION

2.1 Introduction

The degree of acoustical isolation between two fully enclosed spaces is termed Noise Reduction (NR). Quite simply, it is the difference between the mean square sound pressure levels existing in a source room and a receiving room — the two enclosed spaces of interest. Normally Noise Reduction is measured in 16 one-third octave bands and the resulting frequency dependent data is used to evaluate the acoustical environment in the receiving space.

The theory for calculating noise reduction between two spaces is well-defined and is briefly summarized in the next section. It shows that the noise reduction is dependent on two parameters; the sound transmission loss of the intervening wall and the acoustic absorption of the receiving space. A similar, but not identical, formulation is required to define the noise reduction between a free outdoor sound field and the interior of a building immersed in this sound field. This second case is treated at the end of this chapter.

2.2 Noise Reduction Between Two Rooms

When a sound wave impinges on an interface between air and a solid, as it does in the case of a structural wall, some of the acoustic power is transmitted through the structure and the rest is reflected. The fraction of acoustic power that is transmitted is called the transmission coefficient, τ. Since τ is always less than 1, it is convenient to use its reciprocal in logarithmic notation as follows to define the transmission loss (TL)

$$TL = 10 \log_{10}(\tau)^{-1} \quad , \text{dB} \qquad (1)$$

Transmission loss is commonly measured in a laboratory environment in which the panel under test is placed between two reverberant (enclosed) rooms. It may be shown that in a reverberant sound field, the acoustic intensity I, which is the acoustic power transmitted through a unit area, is given by:[12]

$$I = \frac{E\,c}{4} \tag{2}$$

where E is the energy density in the reverberant sound field (energy per unit volume) and c is the sound speed.

Following standard methods, the acoustic power transmitted through the test panel of area S is simply τ times the incident intensity I, times S:[12]

$$W = \tau I_1 S = \frac{\tau E_1 c S}{4} \tag{3}$$

Now, the same power flowing into the receiving space (designated by the subscript 2) will result in an intensity in that space equal to the power divided by the total receiving room absorption, A, as follows:[12]

$$I_2 = \frac{W}{A} = \frac{\tau E_1 c S}{4A} \tag{4}$$

Hence, as the receiving room intensity is also equal to one-fourth of the energy density times the sound speed

$$I_2 = \frac{E_2 c}{4} = \frac{\tau E_1 c S}{4A} \tag{5}$$

or, solving for $1/\tau$,

$$\frac{1}{\tau} = \frac{E_1}{E_2}\,\frac{S}{A} \tag{6}$$

Now since the energy density is proportional to the mean square pressure, we may write:

$$\frac{1}{\tau} = \frac{p_1^2}{p_2^2} \frac{S}{A} \qquad (7)$$

which in the familiar logarithmic notation becomes:

$$TL = L_1 - L_2 + 10 \log \frac{S}{A} \quad , \text{dB} \qquad (8)$$

where L_1 and L_2 are the sound pressure levels (averaged over space and time) existing, respectively, in the source and receiver rooms separated by the panel under test.

For two fully enclosed rooms in which the sound fields are diffuse, the difference between the mean sound pressure levels $(L_1 - L_2)$ is recognized as the term we have called noise reduction, so that:

$$NR = TL - 10 \log_{10} \frac{S}{A}, \text{ dB} \qquad (9)$$

It is important to clearly differentiate between transmission loss and noise reduction even when the term 10 log S/A is small. Transmission loss is a property of the structure and is independent of noise source and receiving space characteristics - that is, the TL value of a material does not vary with its environment (ignoring second-order effects of temperature or humidity on dynamic properties of the wall material). On the other hand, noise reduction is a function of transmission loss, the area of the transmitting wall and the acoustic absorption in the receiving space.

It is common practice for architects and building designers and even acoustical engineers to specify transmission loss values for a structure in an attempt to design a building with a satisfactory acoustic environment. Of course, specifying transmission loss is important so long as the designer is able to make some accurate prediction of noise reduction of which transmission loss is only a part. The occupants of a completed structure certainly do not care about the transmission loss of their building; what is important is the interior noise level or noise reduction. In a recent paper, T. Schultz points out that not only is noise reduction (or acoustical isolation) of primary importance but building codes should contain acoustical criteria in terms of noise reduction instead of transmission loss.[13]

2.3 Outdoor-Indoor Noise Reduction

We have been dealing up to now with isolation between two interior spaces. If the source space is taken to be the area exterior to a structure – as it is for highway noise analysis – then the concept of noise reduction is not strictly defined because of the difficulty in establishing an average sound pressure level in the outside "space." If, however, our goal is to predict and rate the acoustical environment inside a building to be built or modified, the concepts developed above are still valid.

Consider the situation where the source is exterior to a fully enclosed space – as would be the case for a residential living area in a structure near a highway. Since the source no longer is a diffuse field, the relation between energy density and intensity is slightly different. For a progressive wave incident on the exterior wall of a structure, the incident sound intensity, I, is given by:[12]

$$I_1 = E_1 c \tag{10}$$

where E_1 is the energy density in the incident progressive wave. The acoustic power transmitted through the exterior wall is still given by:

$$W = \tau I_1 S = \tau E_1 c S \tag{11}$$

The acoustic intensity existing in the interior space is the same as that given earlier by Equation (2) for a reverberant sound field, so that, from Equation (11):

$$I_2 = \frac{W}{A} = \tau E_1 c \frac{S}{A} \tag{12}$$

and, from Equation (2):

$$I_2 = \frac{E_2 c}{4} \tag{13}$$

Therefore, combining Equations (12) and (13) and again employing the relationship that the energy density (E) in a sound field is proportional to the mean square pressure (P^2)

$$\frac{1}{T} = 4 \frac{E_1}{E_2} \frac{S}{A} = 4 \frac{P_1^2}{P_2^2} \frac{S}{A} \tag{14}$$

The only difference between this case and the first one is the multiplying factor of 4 due to the differing energy density in a progressive wave field and a reverberant acoustic field. Utilizing our logarithmic notation again, we may write an equation for the effective transmission loss (TL) for this case as:

$$TL = L_1 - L_2 + 10 \log_{10} \frac{S}{A} + 6 \quad , \text{db} \tag{15}$$

Or, since L_2 is the interior noise level, we obtain the desired result for outdoor-indoor noise reduction

$$NR = L_1 - L_2 = TL - 10 \log \frac{S}{A} - 6 \quad , \text{dB} \tag{16}$$

It is assumed that the effective transmission loss will include the effects of random angles of incidence of highway noise. As pointed out by Sabine, the transmission loss values corresponding to random incidence conditions are suitable for exterior wall design purposes.[14]

Now consider the quantity L_1 which is the sound pressure level corresponding to the incident acoustic intensity. Analytical techniques may be used to theoretically predict L_1. However, if L_1 is measured with a microphone near the building wall, reflections from the building will affect the measurement. If the measurement is made in contact with the wall of the building, boundary conditions at the wall cause approximate pressure doubling. Hence, in logarithmic notation, the sound pressure level measured at the wall would ideally exceed the actual pressure level by 6 dB. (This assumes that the wall is not absorptive, as is the case with most residential structure exterior walls. The actual value will be about 5 dB in most field situations.) Therefore, the measured noise reduction (NR_m) can be defined as

$$NR_m = L_1 - L_2 \simeq L_{ex} - L_2 - 5 \quad , \text{dB} \tag{17}$$

where L_{ex} is the average sound pressure level on the face of the exterior wall of the structure equal to about $L_1 + 5$ dB.* This is in agreement with the relationship by Sabine in a recent evaluation of the acoustical performance of exterior walls.[14]

First, however, it is necessary to recognize that we have not considered how the quantities TL and 10 log S/A vary with frequency. Thus, in order to determine, rigorously, say, the A-weighted noise level inside a room L_{A_2} due to external sources, Equation (16) can be modified to the form of Equation (18) for the interior A-weighted band level $L_{A_2}(f)$. (The A-weighted noise metric was chosen for this study to express both exterior and interior noise levels since this noise metric is widely used and recognized as suitable for assessment of noises – in terms of human response.)

$$L_{A_2}(f) = L_1(f) + a(f) - TL(f) + 10 \log\left(\frac{S}{A}\right) + 6 \quad , \text{dB} \tag{18}$$

where the term $a(f)$ represents the A-weighting at frequency f and the external band level and transmission loss for this frequency band are designated by $L_1(f)$ and $TL(f)$ respectively. Although the room absorption A should also be a function of frequency, it will be shown later on that for all practical purposes it can be considered independent of frequency.

*Procedures for measuring the external sound level L_{ex} at the surface of a building are defined in Chapter 3 of the FHWA Manual.[1]

Now, summing over all bands, the A-weighted inside level L_{A_2} is formally determined by:

$$L_{A_2} = 10 \log \left[\sum_f 10^{[L_1(f) + a(f) - TL(f)]/10} \right] + 10 \log \frac{S}{A} + 6 \ , \text{dB} \qquad (19)$$

The next chapter outlines the approach employing the EWNR single number rating to eliminate the need to carry out the complex summation suggested by Equation (19).

CHAPTER 3

DEVELOPMENT OF EWNR RATING SCHEME

3.1 EWNR Concept

In developing a single number EWNR rating, two basic principles were employed: (1) restrict the outdoor noise spectrum to a constant shape varying only in level, and (2) approximate the actual transmission curve for a structure in terms of an ideal TL curve which would filter the outdoor spectrum such that the resulting interior spectrum has the inverse shape of the A-weighting curve. Then when the resulting interior spectrum is A-weighted, each one-third octave band would contain equal energy and therefore be equally important in determining the interior A-weighted noise level. This facilitates the prediction of interior A-weighted noise levels and noise reduction.

The problem is conceptualized in Figure 3. Consider, for the moment, that the exterior noise spectrum exhibits a shape similar to that shown in the figure. As will be discussed, this, in fact, is the nominal average spectrum for the typical source noise. It is desired, then, that the transmission characteristic of the wall act as a shaping "filter" to the prescribed exterior noise spectrum so as to produce an interior noise spectrum similar in shape to the inverse of the A-weighted response curve. Interior absorption, which will be shown to be nearly independent of frequency, will not affect the shape of the interior noise spectrum.

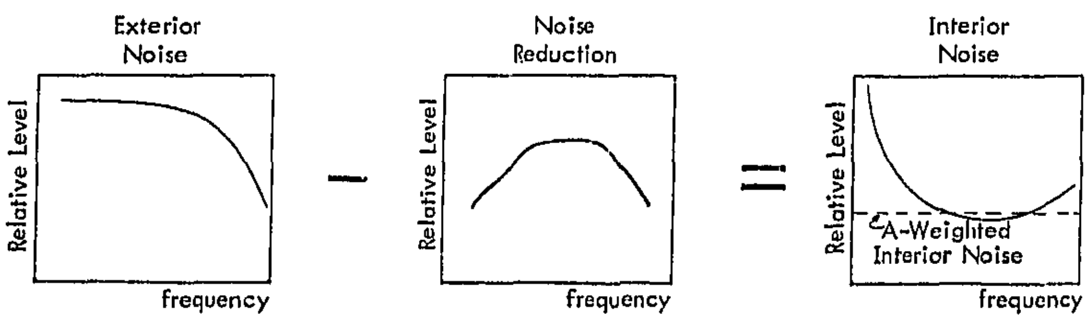

Figure 3. Conceptual Illustration of Basis for Standard TL Curve for EWNR Concept

3.2 Outdoor Source Spectrum

To identify the precise shape of this standard transmission loss curve, an assumption must be made as to the frequency characteristics of the incident exterior noise. For the initial development of EWNR, the characteristics chosen were those of highway traffic noise. Figure 4 presents the range of highway noise spectra measured at a single location near a heavily travelled freeway, and averaged over a 24-hour period. Consequently, these averaged data include sound spectra from vehicles at various distances as they approached and departed the measurement location. Individual vehicle spectra fall generally within this range of freeway spectra. However, since the absorption of sound by air is greatest for high frequencies (over 1000 Hz), the time averaged spectra of Figure 4, which result principally from propagation over distances of several hundred feet, show less high frequency content than much of the published spectral data for individual vehicles, which are usually measured at a distance of 50 feet. Figure 5 shows the nominal average octave band spectrum for highway noise based on the measured range, where the octave band levels are normalized to the continuous equivalent A-weighted noise level, L_{eq}, in dB.[16]

3.3 Interior Absorption Correction

It was implied earlier for Equation (19) that the acoustic absorption (A) inside the receiver room was not frequency dependent. The next step, then, is to actually evaluate the term 10 log S/A where A is, theoretically, a function of frequency. In a study of the noise attenuation properties of residential buildings impacted by aircraft noise, the absorption in over 100 typical rooms in 20 separate houses in the Los Angeles area was measured.[17] These data were used along with dimensions taken from plans for the houses to calculate the 10 log S/A term in each case. The results are given in Figure 6 for living rooms, kitchens, and bedrooms. As can be seen in Figure 6, average values for each type of room are reasonably independent of frequency and differ from each other by a small but significant amount.

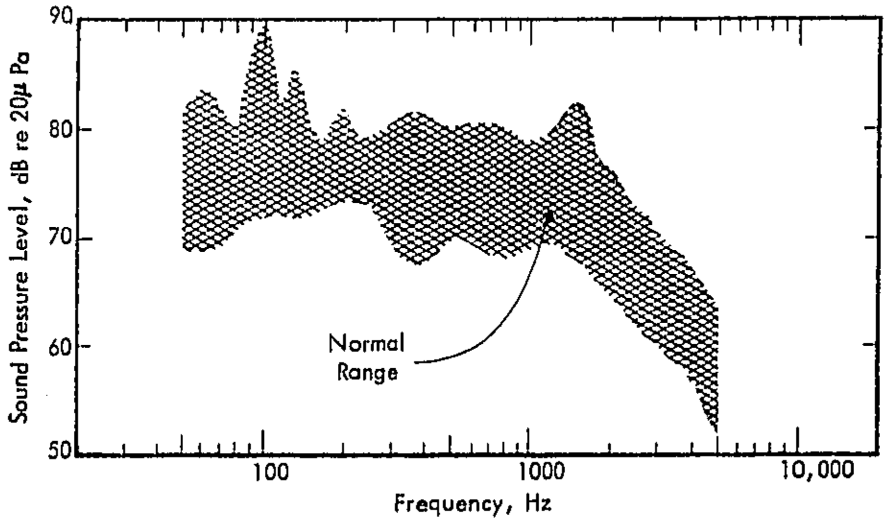

Figure 4. Typical Highway Noise Spectra[15]

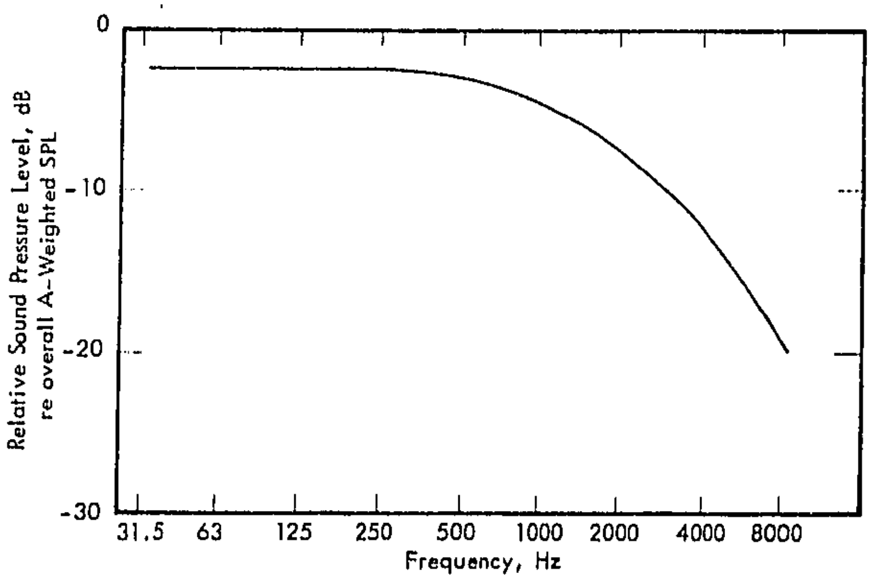

Figure 5. Standard Highway Noise Spectrum Used for Development of EWNR[2]

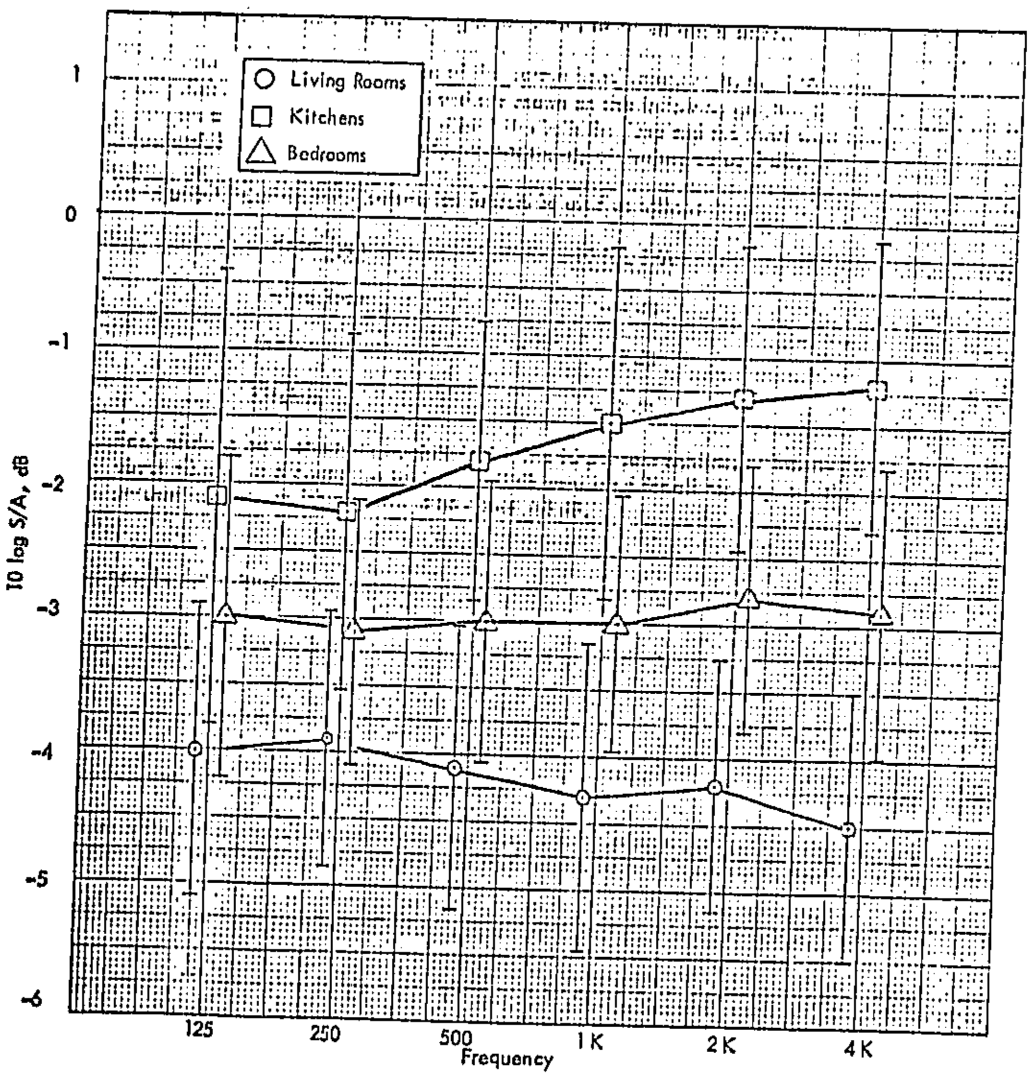

Figure 6. 10 log S/A Term for Living Rooms, Kitchens and Bedrooms in Residential Buildings with One Wall Exposed to Noise Source (based on data from Reference 17)

Additional analysis for typical room dimensions indicated that with two walls exposed (as in the case with a corner room) to the noise source, the 10 log S/A term will increase by 3 dB. The 10 log S/A corrections resulting from this analysis are tabulated below in Table 1.

Table 1

Values of 10 log S/A in dB for Residential Building Rooms with One and Two Walls Exposed

Interior Space	One Wall Exposed	Two Walls Exposed
Living Rooms	-4	-1
Bedrooms	-3	0
Kitchens	-2	+1

3.4 EWNR Design Curve

Knowing the characteristics of the exterior noise spectrum, the shape of the special transmission loss curve shown in Figure 7 was computed according to the concepts of Figure 3. Several straight-line approximations to the curve were investigated and the curve shown in Figure 8 was finally chosen as the EWNR standard contour. This contour is used in a manner similar to an STC contour to determine the EWNR rating for a given wall or construction element based on its transmission loss as a function of frequency. To do this, the standard contour is adjusted vertically to the highest position relative to the TL curve until, over the frequency range of 125 to 4000 Hz, the sum of the deficiencies in the 16 one-third octave bands (that is, deviations of the TL curve below the contour) is 32 dB or less. The initial EWNR is then arbitrarily taken as the value of the standard curve level at 500 Hz.

The fact that the initial EWNR value is arbitrarily taken as the level of the standard EWNR contour at 500 Hz implies that an EWNR value obtained using the above procedures will require final adjustment by a constant to better approximate the actual

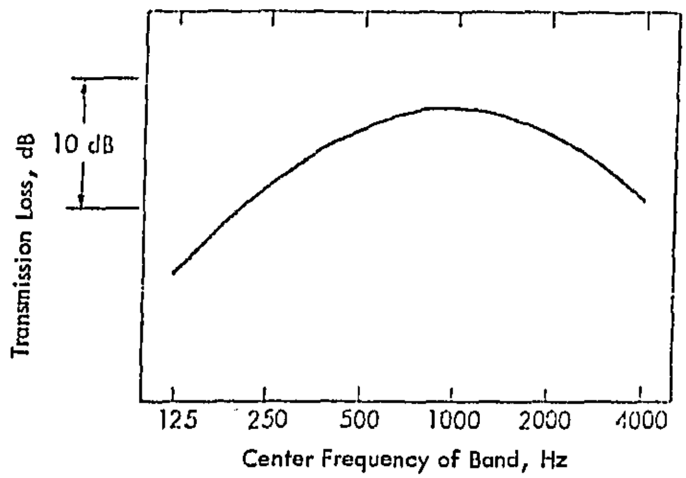

Figure 7. Calculated Shape for Ideal Standard Transmission Loss Curve to Give Equal Emphasis to Each Band for A-Weighted Interior Levels for the Outdoor Source Spectrum Shown in Figure 5.

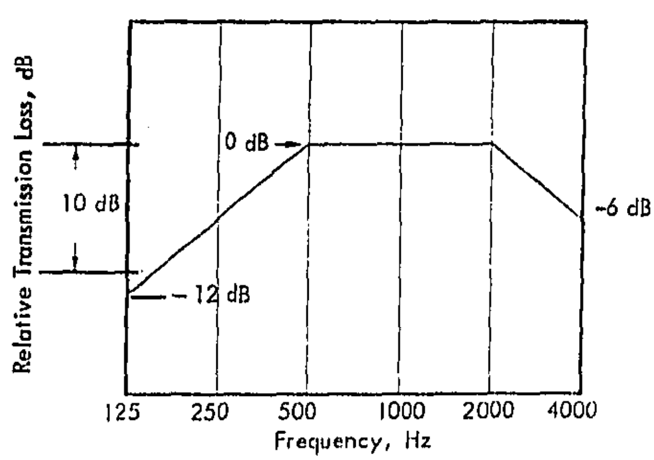

Figure 8. Practical Standard Contour for the Exterior Wall Noise Rating

reduction in A-weighted noise levels for the structure. The adjustment constant obtained for the highway noise spectrum will be incorporated into the final values of EWNR given in Appendix B to simplify the noise reduction calculation for highway noise sources. To use EWNR values for predicting building attenuation of noise from other sources such as aircraft, a different constant would be applicable and so an adjustment to the noise reduction equation would be required. The numerical values of the adjustment constants for different source spectra are developed in Section 4.4 of the next chapter.

Thus, a rating which approximates the broad band transmission characteristics of structures, called Exterior Wall Noise Rating (EWNR), is developed to calculate outdoor-indoor noise reduction of incident A-weighted sound levels. This allows application of the following equation in place of the complex summation of Equation (9).

$$NR = L_{A_1} - L_{A_2} = EWNR - 10 \log S/A - 6 \quad , dB \qquad (20)$$

where

NR = Difference between (1) the free-field A-weighted sound level which would exist, in the absence of the structure, at the structure exterior surface (L_{A_1}), and (2) the average interior A-weighted sound level (L_{A_2})

EWNR = Exterior Wall Noise Rating (including the adjustment constant).

S = Transmitting surface area

A = Room absorption

Note that Equation (20) applies only to a single homogeneous structure. Also, it is assumed, for now, that the adjustment constant required to adjust the initial, graphically determined value, is included in the final EWNR value utilized in Equation (20).

3.5 EWNR for Composite Structures

When a structure is composed of several different transmitting elements, the transmission loss of the composite structure must be determined. Standard procedure first entails calculating the composite transmission loss in each one-third octave band. Then a single number rating such as EWNR may be determined from this composite transmission loss curve. However, several hundred sample calculations indicated that a composite EWNR value may be determined with little error by obtaining the EWNR of each structure element and combining these values independently of frequency as shown below in the same fashion as is normally used to compute composite transmission loss:

$$EWNR_{composite} = 10 \log_{10} \frac{\sum_i S_i}{\sum_i \tau_i' S_i} \quad , \text{dB} \qquad (21)$$

where

i = Index for the transmitting structure elements

S_i = Surface area of the i^{th} element

τ_i' = Transmission coefficient of the i^{th} element corresponding to the EWNR of that element ($EWNR_i$), or:

$$\tau_i' = 10^{-EWNR_i/10} \qquad (22)$$

Now, if Equations (21) and (22) are substituted into Equation (20), the following general expression may be defined to predict the noise reduction of A-weighted sound levels of a composite structure.

$$NR = L_{A_1} - L_{A_2} = -10 \log_{10}\left\{\sum_i \left[S_i \; 10^{-EWNR_i/10}\right]\right\} + 10 \log_{10} A - 6 \quad , \text{dB} \qquad (23)$$

3.6 Calculation of the Tabulated EWNR Values

The EWNR values given in Tables 13, 15, 19, 20, and 21 of Appendix B were calculated using a computer algorithm which simulates the standard EWNR contour-fitting technique described earlier. The transmission loss curves used for the contour-fitting exercise were obtained in one of two ways.

Transmission loss data used for determining wall and roof-ceiling EWNR values were calculated using a second computer algorithm based on the transmission loss theory presented in a recent U.S. Department of Housing and Urban Development Report.[18] This theory allows calculation of TL values assuming the existence of significant acoustical absorption in studwork walls, in furred walls, and in single-joist roof-ceilings. Since EWNR values for building elements without absorption were desired, negative EWNR adjustments to account for the effects of the insulation were required. These adjustments were obtained from an extensive literature search for transmission loss values of all types of building constructions, as discussed in Section 3.7. Comparative EWNR analyses using numerous TL data for walls and roof-ceilings with and without absorption resulted in absorption corrections of minus 4 dB for studwork walls, minus 3 dB for furred walls and minus 5 dB for single-joist roof-ceilings. These corrections were applied to the calculated EWNR values.

Transmission loss values used for calculating the EWNR of windows, doors, and air conditioners consisted of published measurement data collected during the literature search. No adjustments for absorption were required for these items.

It should be noted that the EWNR values tabulated for walls and roof-ceiling constructions were calculated ideal values which would not be completely achieved by standard construction techniques due to the usual presence of gaps, leaks and flanking paths. The literature search data indicated that the average reduction of these ideal values due to the imperfections of actual standard exterior construction is about 4 dB. Thus, an additional 4 dB was subtracted from calculated EWNR values for walls and roof-ceilings to make the tabulated values representative of field construction. EWNR values for the other construction elements are based on measured performance and, hence, no adjustment was necessary.

A final correction was applied to all EWNR values before placement in the tables. This was a constant value of minus 4 dB, which is related to the noise source spectrum as is described in Chapter 4.

3.7 Development of Tabulated EWNR Adjustments

The tabulated EWNR values discussed above are for extremely basic wall or roof-ceiling configurations. Hence, these values alone are not sufficient to predict the EWNR of most actual construction which contains additional detail features. To account for the effects of details which modify the basic construction types given, approximate EWNR adjustments have been developed. These are given in Tables 14, 16, 17 and 18 in Appendix B.

Table 14 contains adjustments to be added to the EWNR of basic wall construction which account for the tabulated modifications to the basic constructions. These EWNR adjustments are based on an analysis of three types of data obtained from the literature. These are:

1. Transmission loss values in one-third octave bands for 104 different wall constructions.

2. STC values published for various wall constructions.

3. STC adjustments published for several wall modifications.

These data were analyzed in the following ways. The transmission loss data were used to compute the EWNR value for each of the 104 wall constructions using the computer method described in Section 3.6. Then, to determine the EWNR change of a wall due to addition of any particular modification, EWNR values for walls without the modification were compared with values for walls identical but including the modification. This gave rise to a set of EWNR adjustment factors which could be compared to the second type of data - published STC adjustments for specific construction features. For each feature or modification, the average EWNR and STC adjustments were identical. This appeared to be a reasonable outcome based on the similarities between the EWNR and STC concepts, and allowed the use of the third data type, published STC values, to develop EWNR adjustments for additional modifications in the way that the calculated EWNR values had been used. These procedures yielded 77 independent determinations of EWNR adjustment factors for the eight modifications listed in Table 14 . The table contains the average EWNR change for each modification.

In a similar fashion, 61 comparisons were made for walls with multiple modifications. These gave rise to the following rationale regarding interactions between multiple modifications. In general, the wall modifications belong to three categories. These are: modifications which increase the mass of the wall surfaces, modifications which add acoustically absorptive material to the stud space, and those which resiliently mount the wall panels to the studwork. The first category helps prevent sound from entering the wall, the second limits the buildup of the reverberant sound within the wall, and the third increases the limpness of the wall structure. The noise reducing mechanism of each category operates independently from those of the other two. Thus, when modifications from different categories are made, the full benefit of each modification will be realized. However, once a modification in a given category has been made, a second modification in that category will contribute less than its full independent effect. The data assembled for multiple modifications indicate that one-half of the benefit of the second modification in a category will be realized. Notes indicating how to apply these principles in determining the total EWNR of a wall are given at the bottom of Table 2.

Tables 16 and 17 in Appendix B contain EWNR adjustments which account for variations to basic roof constructions. These values can be applied to a basic roof-ceiling EWNR to adjust for the presence of acoustical absorption in the structure or for venting of an attic space. The value given in Table 16 for addition of absorption in single joist construction is based on the above analysis of wall data which yielded a 4 dB EWNR adjustment for addition of absorption in double panel walls. The 4 dB adjustment for walls was increased to 5 dB for double panel roof-ceiling construction to account for the larger amount of acoustical absorption provided by typically thick joist space thermal insulation. All other EWNR adjustments contained in Tables 16 and 17 are the results of direct calculations of transmission loss through the listed structures, based on transmission loss and absorption properties of the individual structural panels or components. The transmission loss properties for panels used in these calculations were averaged values from available literature, or, if not published, were calculated using the panel physical properties. The calculational procedures followed were those given in Reference 18.

The EWNR adjustments given in Table 18 of Appendix B can be applied to roof EWNR values to account for the effect of self-shielding of traffic noise. These values were developed using typical roof geometry and classical acoustical barrier considerations. The self-shielding adjustments in Table 18 would of course <u>not</u> be used for aircraft noise sources.

CHAPTER 4

EVALUATION OF SINGLE NUMBER RATING SCHEMES

4.1 Introduction

During the course of developing the single number rating scheme, EWNR, several other rating methods were also considered for evaluating the transmission loss characteristics of exterior walls, including the STC method discussed in Chapter 1. These alternate methods are described as follows:

1. Speech Interference Level Transmission Loss (SILTL). The SILTL is the arithmetic average of the one-third octave band transmission loss values in the speech interference frequency range (400 Hz to 2500 Hz).

2. Average Transmission Loss (AVETL). The AVETL is the arithmetic average of the 16 one-third octave band transmission loss values.

3. Modified STC Ratings. These ratings are similar to STC, but the standard STC curve is replaced with a curve with positive slope rising at a rate of 0, 1, 2, 3, 4, 5, and 6 dB per octave and designated as Mod 0 through Mod 6. These standard curves are adjusted vertically to the highest position where the sum of the one-third octave band deficiencies is 32 dB or less. The rating is then the value of the standard curve at 500 Hz.

4. Exterior Wall Noise Rating (EWNR) for Highway Noise. The rationale for the selection of this rating has already been discussed in the last chapter. It was shown that a special transmission loss characteristic of external walls could be defined which "filtered" the appropriate exterior noise spectrum such that the acoustic energy contained in each third-octave band of this filtered internal noise spectrum would be equally important in determining the resulting interior A-weighted noise level.

4.2 Evaluation Method

Each of these rating methods was evaluated by comparing the noise reduction for a very wide variety of structural assemblies computed by the single number rating method and by the classical method as follow.

1. Single Number Rating Methods

   For these methods, the noise reduction for each structural assembly was computed with the following equation, which is equivalent to Equation (23) except that the single number rating X_i does not include an adjustment constant.

$$NR_u = -10 \log_{10}\left\{\frac{1}{S}\sum_i \left[S_i \, 10^{-X_i/10}\right]\right\} - 10 \log_{10}\frac{S}{A} - 6 \quad , \text{dB} \qquad (24)$$

   where X_i is one of the single noise ratings defined above (but without an adjustment constant) applied to the i^{th} element of a composite structural assembly, and thus NR_u is an unadjusted noise reduction.

2. Formal Noise Reduction Calculation Method

   For this classical method, the following equation was applied to each structural assembly to determine the true noise reduction NR' in A-weighted levels.

$$NR' = L_{A_1} - 10 \log\left[\sum_f 10^{[L_1(f) - \overline{TL}(f) + a(f)]/10}\right] - 10 \log\frac{S}{A} - 6 \quad , \text{dB} \qquad (25)$$

   where

   L_{A_1} = A-weighted exterior noise level

   $L_1(f)$ = octave band exterior noise level at frequency f

   $a(f)$ = A-weighting at frequency f

   $\overline{TL}(f)$ = composite TL of assembly at frequency f which is

$$\overline{TL}(f) = -10 \log \left\{ \left[\sum_i S_i \, 10^{-TL_i(f)/10} \right] \Big/ \sum_i S_i \right\} \qquad (26)$$

and $TL_i(f)$ = the TL of i^{th} element with area S_i at frequency f.

For this classical method, the noise reduction in A-weighted levels involves computing the interior octave band level over the full spectrum using the actual composite transmission loss curve at each frequency. The resulting interior band levels are A-weighted, summed, and subtracted from the exterior A-weighted level to define the outdoor-indoor noise reduction.

Noise reduction values were computed by each of these methods for combinations of 225 wall constructions and 33 window constructions in area ratios of 0, 10, 15, and 20 percent of total wall area for a total of 22,500 separate cases. In each case, composite transmission loss values in one-third octave bands and single number composite transmission loss values were determined by the preceding expressions using published and computed data for the actual transmission loss of each element as a function of frequency.

For each noise rating method, the statistical correlation between the approximate (Equation (24)) and true (Equation (25)) noise reduction values was computed utilizing all 22,500 pairs of values obtained from the combinations of structural assemblies considered. An initial linear regression analysis was carried out using each of these pairs of noise reduction values. Since the slope of this regression line was usually very close to unity, an additional regression forcing the slope to be unity was performed. A conceptual illustration of this process is shown in Figure 9. The dashed lines indicate the nominal bounds of the 90 percent confidence limits about the regression line constructed to have a unit slope.

As illustrated in the figure, for each single number rating method, the estimated noise reduction NR_u could be related to the classical value (NR') by a simple linear equation based on the use of a unit slope for the regression line

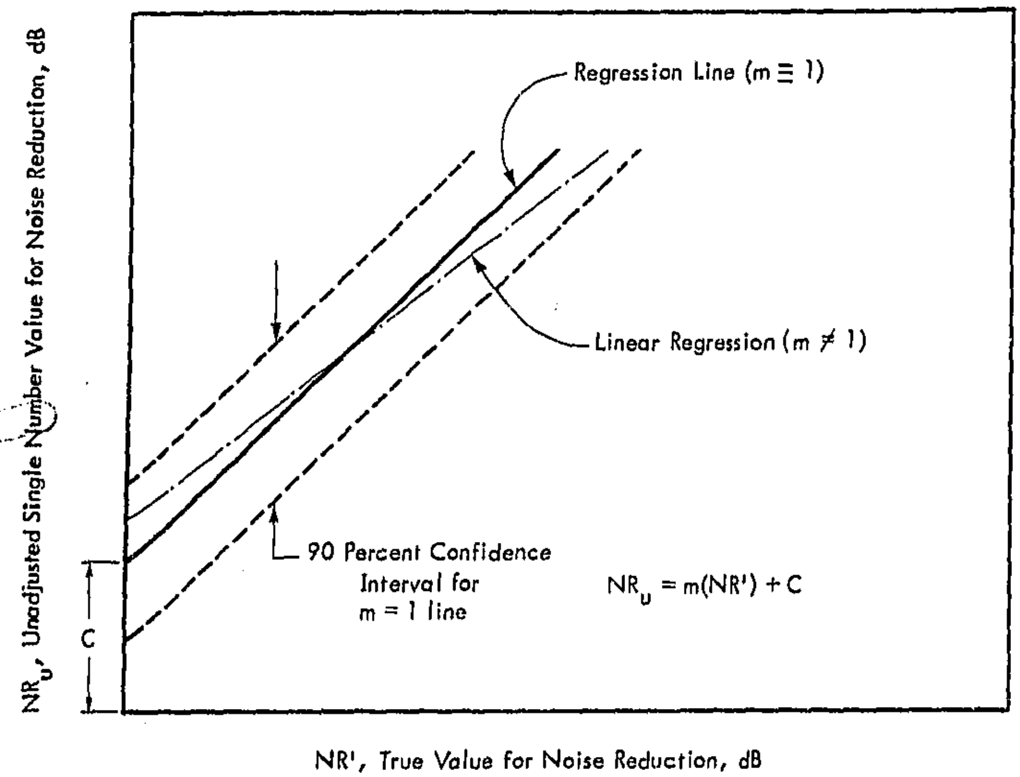

Figure 9. Conceptual Illustration of Regression Analysis Results Comparing Unadjusted Noise Reduction of A-Weighted Noise Levels Computed by the Single Number Method (NR_u) with Values (NR') Computed by the Classical Method

$$NR_u = NR' + C \tag{27}$$

where C was the intercept of the regression line on the vertical axis. The value of C is the adjustment constant defined in Section 3-4. This constant is dependent on:

- The particular single number noise metric including the specific details of the graphical computation methods
- The spectrum assumed for the exterior noise source

The accuracy of any one of the single number ratings, assuming it is adjusted by the adjustment constant C (intercept of the regression line identified above), is conveniently represented by the width of the 90 percent confidence limits about the mean regression line. These confidence limits also varied with the same three elements identified above which influenced the adjustment constant C. Thus, each of these elements was evaluated in turn.

4.3 Relative Accuracy of the Single Number Ratings

Due to the large number of cases to be evaluated, the entire evaluation process was computerized. For each single number rating method, the program computed: (1) the approximate noise reduction value based on the single number rating, (2) the true noise reduction value based on the actual TL data versus frequency, and (3) the regression lines between these two data pairs for all the 22,500 wall-window combinations.

The results of this analysis are shown in Table 2 in terms of the correlation coefficient and 90 percent confidence intervals for each of the 11 single number ratings; the latter are based on the highway noise spectrum in Figure 5 of Chapter 3. With a correlation coefficient of 0.998 and a 90 percent confidence interval of $\pm$ 0.6 dB, the EWNR method is apparently more accurate than any of the others investigated.

Table 2

Correlation Coefficients and 90 Percent Confidence Intervals for Prediction of Interior A-Weighted Noise Levels for 11 Single Number Transmission Loss Rating Schemes

Single Number Rating	Correlation Coefficients	90% Confidence Intervals, dB
STC	0.962	±2.7
SILTL	0.960	±2.8
AVETL	0.981	±1.9
Mod 0	0.978	±2.1
Mod 1	0.987	±1.7
Mod 2	0.988	±1.5
Mod 3	0.985	±1.8
Mod 4	0.975	±2.2
Mod 5	0.956	±2.9
Mod 6	0.927	±3.8
EWNR	0.998	±0.6

The adjustment constant C from the regression analysis of the EWNR method had a value of approximately + 4 dB for the highway noise spectrum. (Values for other spectra are given in Table 4.) This represented the constant difference between the A-weighted structure attenuation predicted by the EWNR method (Equation 24) and the true attenuation calculated with Equation (25). This constant value of 4 dB has been incorporated into all data tabulated in the FHWA manual[1] and in Appendix B so that the tabulated EWNR values may be applied directly to predict the attenuation of highway noise. However, 4 dB must be subtracted from the value of the EWNR contour at 500 Hz when determining EWNR values by graphical means from TL data.

4.4 Comparison of Rating Methods for Other Exterior Noise Spectra

Additional analyses of single number rating schemes were conducted utilizing noise spectra for various other sources. Based on the preceding evaluation, the five most feasible rating schemes were selected for further analysis: EWNR, STC, Mod 0, Mod 3, and SILTL. The extended evaluation of these rating schemes centered on the utilization of two additional highway noise spectra based upon octave band data identified as TSC[19] and NCHRP 78[20] data. Each of these spectra were considered in light of both a one and five percent truck mix, thereby resulting in four highway noise spectra test cases.

Commonly-used wall constructions were again combined with various window types in area ratios of 20, 15, 10 and 0 percent. A total of 192 different wall constructions and 16 windows were used in this analysis. Linear regression analyses again were conducted for each case to compare the accuracy of the single number rating schemes against the true values calculated from the frequency-dependent TL data. The tabulated 90 percent confidence intervals are shown here in Table 3. For all four highway noise spectra, the EWNR method provided the most accurate single number rating of transmission loss values.

Table 3

Ninety Percent Confidence Intervals in dB for Comparison of Alternate Single Number Rating Methods for Different Highway Noise Spectra

Single Number Rating	TSC		NCHRP 78	
	1 Percent Trucks	5 Percent Trucks	1 Percent Trucks	5 Percent Trucks
EWNR	±0.9	±0.9	±1.1	±1.1
Mod 0	±2.3	±2.3	±1.6	±1.5
Mod 3	±1.2	±1.2	±1.4	±1.4
STC	±2.1	±2.0	±2.6	±2.6
SILTL	±4.2	±4.1	±4.8	±4.8

Other Noise Sources

In addition to analyzing the sensitivity of EWNR to variations in the source spectra for highway noise, several other source spectra were also considered. In this case, generalized spectra for highway, railroad, aircraft, and combinations of these sources were generated from data in Wyle's files.[16] Again, the same type of regression analysis was made for the 22,500 wall-window combinations. In this case, the results were computed with the slope of the regression line forced to unity. For comparison, the same analysis was also made of the STC single number rating method. The results are shown in Table 4 in terms of the 90 percent confidence limits and the adjustment constant C for the various sources and for both the EWNR and STC methods.

Table 4

Comparative Accuracy of EWNR and STC Rating Methods for Several Source Spectra

	Rating Method*			
	EWNR		STC	
Source Spectrum[16]	90% Confidence Limits dB	Adjustment Constant** C dB	90% Confidence Limits dB	Adjustment Constant** C dB
1. Highway	±0.64	3.5	±2.74	1.8
2. Railroad	±0.82	3.9	±2.84	2.2
3. Aircraft	±1.94	5.8	±3.85	4.1
4. 1 and 2 Combined	±0.81	3.7	±2.81	2.0
5. 1, 2, and 3 Combined	±2.10	4.4	±3.59	2.7

* Based on unity slope for regression line as in Figure 9.

**Constant to be subtracted from value of standard EWNR curve at 500 Hz when the latter is adjusted to fit actual TL curve as defined in Chapter 3.

A limited analysis was also made using both the linear regression line without forcing the slope to unity and a unit slope regression line. The results are shown in Table 5 comparing the EWNR and STC methods with aircraft and highway source spectra.[16]

Table 5

Comparison of Correlation Coefficients and 90 Percent Confidence Intervals for Two Alternate Single Number Rating Methods for Predicting Outdoor-Indoor Noise Reduction of A-Weighted Noise Levels

Rating Method	Aircraft Source			Highway Source		
	Regression Line		Unit Slope	Regression Line		Unit Slope
	r	90% Confidence Limits		r	90% Confidence Limits	
EWR	0.984	±1.7	±1.9	0.998	±0.6	±0.6
STC	0.926	±3.5	±3.9	0.962	±2.7	±2.8

The 90 percent confidence limits for the STC method are approximately three times (about ±3 instead of ±0.6 dB) that for the EWNR method for highway source. The EWNR method should therefore be somewhat more reliable for application to FHWA programs. Actual measurements of outdoor-indoor noise reductions for A-weighted noise levels carried out in another program involving aircraft noise as a source were also shown to agree satisfactorily (within about ±2.5 dB) with predicted values based on the use of EWNR (see Appendix A). Even better agreement between predicted and measured noise reduction would be expected for highway noise since the EWNR method was based on the latter as the exterior source.

Finally, it should be pointed out that the STC method was not expected to show higher accuracy for predicting outdoor-indoor noise reduction of A-weighted noise levels than the EWNR method since, as outlined in Chapter 1, it was based on the use of an average interior noise source spectra.

Thus, the EWNR method appears well suited for convenient application to evaluating outdoor-indoor noise reduction. In summary, three points are reemphasized.

1. To evaluate the EWNR of a structure or building component from transmission loss data, the following procedure is employed. The standard EWNR contour is adjusted vertically to the highest position relative to the TL curve until, over the frequency range of 125 to 4000 Hz, the sum of the deficiencies in the 16 one-third octave bands is no greater than 32 dB. The value of the standard contour at 500 Hz is then reduced by the adjustment constant of 4 dB to obtain the final EWNR value.

2. To calculate the reduction of noise from ground transportation sources (highways and railroads), equation (23) should be utilized.

3. To calculate building noise reduction for aircraft noise sources, apply equation (23) and subtract 2 dB from the result. The 2 dB subtraction accounts for the difference between the "adjustment constants" for ground transportation and aircraft noise sources (see Section 4.2 and Table 4).

Appendix A presents a comparison between measured noise reduction values and values predicted using these methods.

Appendix B summarizes the specific values of EWNR used in the FHWA manual.[1]

Appendix C summarizes the results of an analysis carried out to evaluate the sensitivity of the graphical technique for computing EWNR. The specific procedures for summing the allowed deficiences between the EWNR standard contour and the actual TL contour for any specimen, as defined in Chapter 3, are shown to be optimum.

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APPENDIX A

COMPARISON OF MEASURED AND PREDICTED NOISE REDUCTION

During the course of a recent FAA-sponsored feasibility study of noise insulation for public buildings around airports, the EWNR rating method was used to estimate noise reduction into such buildings and experimental data were taken to validate these predictions in 42 rooms inside 22 schools and hospitals near three airports (Los Angeles International, Boston-Logan International, and Denver). The noise reduction measurements were carried out essentially in accordance with the procedures outlined in the FHWA manual.[1] This appendix summarizes the comparison between these measured and predicted values of noise reduction. Although the EWNR method was designed around the use of surface transportation as the noise source, it was also possible to make reasonably accurate predictions of outdoor-indoor reduction in A-weighted levels of aircraft noise. As illustrated in the following data, the average predicted noise reduction was within ±2.5 dB of the measured value 90 percent of the time.

A.1 Measured Noise Reduction

Tables 6 through 8 show the measured exterior noise levels (corrected to free-field), interior noise levels, and noise reduction for the 42 rooms tested. Except where noted otherwise, each value shown is the average of measurements from 12 aircraft noise events. The standard deviation for each set is shown. In addition to measurement variations, the standard deviation of the levels represents the variation of levels between aircraft. The standard deviation of the noise reductions is due to variations in NR associated with aircraft spectrum variations, plus spatial variations in noise within the room. These variations are normally expected, and are the reason why NR is taken as the average of a number of events and a number of interior positions.

A.2 Comparison with Predicted Noise Reduction

Tables 9 through 11 show the measured and predicted NR for each room, together with the difference (Δ). The difference is the predicted value minus the measured value in decibels.

A statistical analysis of the differences has been performed for the buildings around each airport, and is summarized in Table 12. Shown are the mean difference, standard deviation of differences, and 90 percent confidence limits.

The confidence limits are illustrated in Figure 10. Shown are the 90 percent confidence limits for the three airport groups, relative to Δ = 0. Also shown for comparison is the expected confidence limit of ±1.9 dB for the difference between noise reductions for aircraft noise computed with EWNR and by the classical method using transmission loss data at each frequency band. While the confidence limits about the mean for each airport fall well within this expected EWNR confidence interval, the extremes of the confidence limits for the measured data for all three airports extends to ±2.5 dB. However, considering inherent field measurement accuracy of typically ±1-2 dB, these confidence limits for the difference between measured and predicted noise reduction are quite reasonable. Thus, the use of the EWNR method appears to be well validated.

Table 6

Measured Levels and Noise Reduction – LAX[1]

Building	Room	Exterior		Interior		NR	
		Av.	σ	Av.	σ	Av.	σ
Imperial School	2	85.7	4.1	56.8	3.2	28.9	1.8
	11	85.0	5.2	57.5	3.1	27.5	2.6
	6	82.6	5.1	50.8	3.4	31.8	2.5
Lennox H.S.	4 Bldg 3	71.3	3.3	50.9	4.2	20.4	2.3
	3 Bldg 6	75.6	5.6	53.7	5.7	21.9	2.0
	3 Bldg 4	71.3	3.7	57.9	3.3	13.4	1.5
Felton Ave. School	9	89.1	5.0	70.8	5.6	18.3	2.4
	5	83.8	6.5	65.7	8.7	18.1	2.7
	11	86.1	6.0	66.9	7.3	19.2	2.4
Clyde Woodworth School	4	78.4	5.1	57.0	4.1	21.4	1.5
Morningside H.S.	J2	86.0	3.4	63.2	3.9	22.8	1.1
	V2	76.0	8.4	54.5	6.3	21.5	3.5
Centinella Hospital	5114	68.3	3.5	40.8[2]	1.9	30.0[2]	1.7
	8128	68.9	3.2	42.6[3]	1.5	29.9[3]	1.0
Westchester H.S.	F9	67.2	5.4	51.3	4.9	16.0	1.3
Imperial Hospital	227	69.4	2.3	46.0	2.0	23.3	2.3
	224	69.2	2.3	47.4	1.9	21.3	2.7

[1]Arithmetic Average (Av) A-weighted aircraft noise levels outside (corrected to free-field) and inside rooms and corresponding noise reduction (NR) in decibels. σ is standard deviation of results from several overflights.

[2]Counting only 5 interior measurements above background.

[3]Counting only 4 interior measurements above background.

Table 7

Measured Levels and Noise Reduction - BOS[1]

Building	Room	Exterior Av.	Exterior σ	Interior Av.	Interior σ	NR Av.	NR σ
Winthrop Community Hospital	319	82.8	7.7	60.3	9.0	22.5	3.6
	271	78.1	6.1	49.4	5.7	28.8	1.6
Winthrop JHS	206	76.3	4.9	56.3	3.1	20.0	3.4
	220	68.8	6.9	45.0	7.3	23.8	6.5
Julia Ward Howe School	Left Front	84.7	2.4	63.1	2.0	21.6	1.0
	Right Front	85.7	3.5	60.7	3.3	25.0	1.0
Cherverus School	8	77.2	4.9	58.8	4.0	18.4	2.4
	2	78.9	2.4	61.0	1.4	18.0	1.9
Chapman School	Left	79.0	4.8	70.0	5.5	9.0	1.6
	Right	78.3	4.2	64.7	4.3	13.4	2.3
Chelsea Memorial Hospital	201	74.3	2.9	50.3	2.0	24.1	3.0
	210	78.9	5.3	55.0	4.3	24.0	3.8
Williams School	15	75.7	4.9	57.2	4.8	18.5	1.5
	20	77.2	3.9	58.1	3.6	19.0	0.6

[1] Arithmetic Average (Av) A-weighted aircraft noise levels outside (corrected to free-field) and inside rooms and corresponding noise reduction (NR) in decibels. σ is standard deviation of results from several overflights.

Table 8

Measured Levels and Noise Reduction - DEN[1]

Building	Room	Exterior Av.	Exterior σ	Interior Av.	Interior σ	NR Av.	NR σ
Clyde Miller Elem. School	5	72.9	4.5	57.7	3.9	16.9	1.0
Park Lane Elem. School	20	91.5	6.3	57.4	5.3	34.1	2.9[2]
	6	87.9	3.9	53.1	3.3	34.8	2.6[2]
Sable School	Faculty DiningRoom	85.7	6.0	70.3	4.3	15.5	2.7
	4	79.6	5.1	50.6	5.1	28.7	1.5
North JHS	13	84.5	6.2	59.4	3.2	25.0	5.2
	12	87.6	3.4	63.5	3.3	24.1	0.7
Fitzsimons Hospital	4133	81.9	2.9	56.4	3.6	25.5	1.0
	4062	81.7	3.7	56.3	4.0	25.3	1.5
Boston Elem. School	1	87.6	2.6	61.8	2.8	25.8	1.8
Paris Elem. School	1	61.5	3.3	41.6	1.9	19.9	2.0

[1] Arithmetic Average (Av) A-weighted aircraft noise levels outside (corrected to free-field) and inside rooms and corresponding noise reduction (NR) in decibels. σ is standard deviation of results from several overflights.

[2] Wall with windows facing away from aircraft. Microphone on wall facing aircraft approximately 10 dB self-shielding.

Table 9

Predicted and Measured Noise Reduction - LAX, in dB

Building	Room	Predicted	Meas'd	Δ
Imperial School	2	25.8	28.9	-3.1
	11	25.8	27.5	-1.7
	6	31.8	31.8	0
Lennox H.S.	4 Bldg 3	21.4	20.4	1.0
	3 Bldg 6	21.4	21.6	-0.2
	3 Bldg 4	21.4	18.0	3.4
Felton Ave. School	9	19.2	18.3	0.9
	5	19.2	18.1	1.1
	11	19.2	19.2	0.0
Clyde Woodworth School	4	18.0	21.4	-3.4
Morningside H.S.	J2	18.3	22.8	-4.5
	V2	20.1	21.5	-1.4
Centinella Hospital	5114	25.7	30.0	-4.3
	8128	25.7	29.9	-4.2
Westchester H.S.	F9	19.0	16.0	3.0
Imperial Hospital	227	24.0	23.3	0.7
	224	24.0	21.9	2.1

Algebraic Mean	Absolute Mean	Standard Deviation
$\overline{\Delta} = -0.4$,	$\overline{\lvert\Delta\rvert} = 2.2$,	$(\overline{\Delta^2})^{\frac{1}{2}} = 2.6$

Table 10

Predicted and Measured Noise Reduction - BOS, in dB

Building	Room	Predicted	Meas'd	Δ
Winthrop Hospital	319	22.0	21.7	0.3
	271	28.0	28.8	-0.8
Cherverus School	8	20.0	18.4	1.6
	2	20.0	18.0	2.0
Winthrop J.H.S.	206	28.0	23.0	5.0
	220	25.0	27.0	-2.0
Chapman School	3rd Fl., left	14.2	9.0	5.2
	3rd Fl., rt.	14.2	13.4	0.8
Julia Ward Howe School	Left	22.0	21.6	0.4
	Right	22.0	25.0	-3.0
Williams School	15	21.6	18.5	3.1
	20	20.6	19.0	1.6
Chelsea Memorial Hospital	201	26.9	24.1	2.8
	210	26.9	25.0	1.9

$\overline{\Delta} = 1.3$, $\overline{|\Delta|} = 2.2$, $(\overline{\Delta^2})^{\frac{1}{2}} = 2.6$

Table 11

Predicted and Measured Noise Reduction - DEN, in dB

Building	Room	Predicted	Meas'd	Δ
Clyde Miller Elem. School	Classroom	18.0	16.9	1.1
Park Lane Elem. School	20*	33.0	34.3	-1.3
	6*	33.0	34.8	-1.8
Sable School	Faculty DiningRoom	16.5	15.5	1.0
	4	22.9	28.7	-6.0
North J.H.S.	13	21.0	25.0	-4.0
	12	23.9	24.1	-0.2
Fitzsimons Hosp.	4133	26.5	25.5	1.0
	4062	26.5	25.3	1.2
Boston Elem.School	1	21.5	25.8	-4.3
Paris Elem.School	1	21.5	19.9	1.6

$$\overline{\Delta} = -1.2 , \qquad \overline{|\Delta|} = 2.1 , \qquad \left(\overline{\Delta^2}\right)^{\frac{1}{2}} = 2.7$$

*Includes 10 dB shielding due to windows facing away from aircraft.

Table 12

Summary of Statistical Analysis of Differences
Between Predicted and Measured Noise Reduction, in dB

				90% Confidence Limit		
Airport	N*	Mean	σ	Lower	Upper	About Mean
LAX	17	-0.6	2.5	-1.7	0.5	±1.1
BOS	14	1.3	2.3	0.2	2.5	±1.1
DEN	11	-1.1	2.6	-2.5	0.4	±1.4

*Number of rooms measured for each airport.

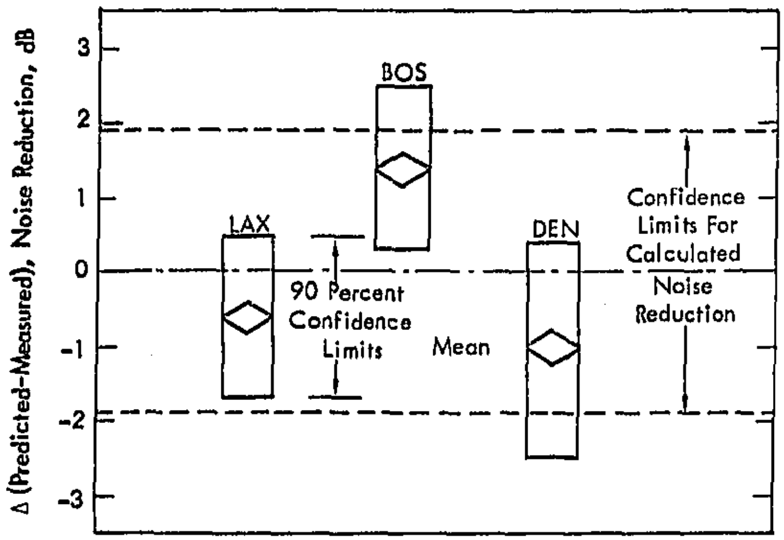


Figure 10 Comparison of 90 Percent Confidence Limits for Predicted Minus Measured Values of Noise Reduction for Three Airports. (The Mean Difference for Each Airport is Designated by the Diamond.) For Comparison, the Anticipated 90 Percent Confidence Limits According to Calculated Values of Noise Reduction Are Shown (See Chapter 4).

Table 13

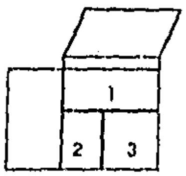
Exterior Wall Noise Rating (EWNR) Values in dB for Standard Exterior Construction (For Use with Highway Noise)

Note: Approximate Metric thicknesses in centimeters may be obtained by multiplying the nominal English-inch units by 2.54

EXTERIORS	INTERIORS	Gypsumboard - 1/2" to 5/8"	1/8" to 1/2" Plaster on 3/8" Gypsum Lath	1/2" Soundboard on Gypsumboard - 3/8" to 1/2"	Plaster - 1/2" to 7/8"	Plywood - 1/2"	Plywood Paneling - 1/4"	Hardboard Paneling - 1/4"	Exposed Solid Wall
		1	2	3	4	5	6*	7*	8
Alum. Siding on 1/2" Wood	A	28	31	29	32	25	29	31	--
7/8" Stucco	B	36	34	37	30	33	37	38	--
7/8" Stucco on 1/2" Wood	C	37	36	37	32	34	38	39	--
Wood Siding - 1/2" to 3/4"	D	27	29	27	31	24	28	30	--
4-1/2" Brick Veneer	E	44	42	44	39	42	45	46	--
9" Brick	F	47	50	50	45	45	45	45	45
4" Concrete	G	46	47	47	41	40	40	40	40
6" Concrete	H	46	48	48	42	42	42	42	42
6" Hollow Concrete Block	I	38	40	40	34	33	33	33	33
8" Hollow Concrete Block	J	40	42	42	36	35	35	35	35
6" Block w/1/2" Stucco	K	39	41	41	35	34	34	34	34
8" Block w/1/2" Stucco	L	41	43	43	37	36	36	36	36

*Both 1/4" Paneling Interiors (columns 6 and 7) are mounted on 1/2" Gypsumboard only for Exteriors A through E.

LEGEND



Area 1: Stud-work Constructions — All conventional 2x4 wood studs on 16-inch centers with no insulation in stud spaces.

Area 2: Solid Wall with Furred Interior Surfaces — All interior surfaces mounted on 3/4-inch furring strips on 16-inch centers.

Area 3: Solid Wall with Glued Interior Surfaces — All interior surfaces glued directly to the solid wall.

APPENDIX B
TABLES OF EWNR VALUES AND ADJUSTMENTS

Table 14

Adjustments to Basic EWNR Values Due to Modifications[1]

Modification Category 1: Mass Increases	Δ EWNR, dB	Modification Category 2: Stud Space Absorption	Δ EWNR, dB	Modification Category 3: Limpness Increases	Δ EWNR, dB
Double Mass One Side	3	Absorption in Stud Space (2)	4	Fiberboard Under Both Panels	8
				Resilient Mounting of One or Both Panels	8
Double Mass Both Sides	4			Staggered Studs	6
				24-inch Stud Spacing	2
				Metal Channel Studs	5

Table Instructions

(1) To obtain the Total EWNR adjustment for multiple modifications: add the adjustments for each of the three categories. If more than one Category 3 modification is used, count the value of the largest adjustment plus one-half of the value of the next largest.

(2) If fiberboard is used for a Category 3 modification, count Category 2 stud space absorption as only 2 dB.

Table 15

EWNR Values in dB for Basic Roof-Ceiling Constructions 1
(For Use With Highway Noise)

ROOF CONSTRUCTION	CEILING CONSTRUCTION	1/2" Gypsumboard	3/8" Gypsum Lath on 1/8" Plaster	1/2" Fiberboard	Exposed Framing
		1	2	3	4
Wood Shingles	A	28	28	24	21
Composition Shingles	B	31	34	26	25
Clay or Concrete Tiles	C	39	40	33	32
Built-Up Roofing	D	31	31	26	24
1/2" Wood and Sheet Metal	E	–	–	–	23
Wood Shingles	F	36	39	48	–
Composition Shingles	G	40	43	53	–
Clay or Concrete Tiles	H	45	48	58	–
Built-Up Roofing	I	38	41	50	–
1/2" Wood and Sheet Metal	J	36	39	49	–

LEGEND

Area 1	Area 1: Single Joist Constructions
Area 2	Area 2: Attic Space Constructions

1/8" = .32 cm
3/8" = .95 cm
1/2" = 1.27 cm

Table 16

Adjustment to Basic EWNR for Addition of Absorption* in Nonvented Ceiling/Joist Spaces

Description	Adjustment Factor, dB (To be Added)
Single Joist Constructions -	
All Cases	5
Attic Space Constructions -	
Fiberboard Ceiling	2
Plaster or Gyp Ceiling	6

*A minimum of 4 inches (10.16 cm) is required to count this adjustment.

Table 17

Effects of Venting Attic Space Constructions* on EWNR Values with and without Absorption

Basic Construction EWNR, dB		Vented Attic EWNR, dB (Without Absorption)	Vented Attic EWNR, dB (With Absorption)
Plaster or Gypboard Ceiling	36 to 39	24	31
	40 to 42	25	32
	43 to 45	26	33
	46 to 48	27	34
Fiberboard Ceiling	48 to 58	35	38

*Based on minimum venting requirements of the Uniform Building Code.

Table 18

Adjustment to Basic EWNR to Account for Building Self-Shielding

Roof Line Description	Adjustment Factor, dB (to be added)
Flat Roof	6
Sloped Roof	3

Table 19

EWNR Values for Common Window Assemblies*[1]
(For Use with Highway Noise)

	DESCRIPTION	EWNR, dB
Single Glazed Windows	1/16" glass (.16 cm)	24
	1/8" glass (.32 cm)	24
	1/4" plate glass (.64 cm)	24
	5/16" glass (.79 cm)	28
	3/8" glass (.95 cm)	30
	2-ply glass, 0.53" total (1.35 cm)	38
	3-ply glass, 0.82" total (2.1 cm)	41
Jalousie Window	4-1/2" wide, 1/4" thick louvers with 1/2" overlap - cranked shut	18
Double Glazed Windows**	3/32" glass, 4" airspace, 3/32" glass	30
	1/8" glass, 2-1/4" airspace, 1/8" glass	32
	1/8" glass, 2-1/4" airspace, 1/4" glass	36
	1/4" glass, 2-1/4" airspace, 1/4" glass	38
	3/16" glass, 2" airspace, 1/4" glass	39
	1/4" glass, 2" airspace, 3/8" glass	40
	3/16" glass, 2" airspace, 3/8" glass	41
	3/16" glass, 4-3/4" airspace, 1/4" glass	44

3/32" = .24 cm; 3/16 = .48 cm; 1/2" = 1.3 cm; 2" = 5.08 cm; 4" = 10.16 cm

Note: The addition of a storm window to an existing single glazed or jalousie window will increase the EWNR by 5 dB.

*If the window is fully open (such as a fully open Jalousie or crank type window), its EWNR value is 4 dB. If the window is not completely open (usually the case for sliding windows), use 4 dB for the open area, the given value for the closed or unopenable area, and combine the two values using the procedures explained in Section 2.6 of Reference 1.

**The approximate EWNR value for "thermopane" type windows with two panes of plate glass separated by an air space of less than 1 inch is 28 dB.

Table 20

EWNR Values for Commonly-Used Doors[1]

(For Use with Highway Noise)

	DESCRIPTION	EWNR, dB
Hollow Core Doors	1-3/4" wood, 1/16" undercut	16
	1-3/4" wood, Weather-Stripped	17
	Steel (3.22 lbs/ft^2, 15.72 kgs/m^2) Magnetic weather-strip	28
Solid Core Doors	1-3/4" wood, 1/16" undercut	18
	1-3/4" wood, Weather-Stripped	26
	1-3/4" wood, Drop seal threshold	35
	1-3/4" wood, weather-strip, and Aluminum storm door, glazed 1/16" glass	31
Sliding Door	Glazed 3/16" (.48 cm) safety glass	26

1-3/4" = 4.45 cm

1/16" = .16 cm

Note: The addition of a weather-stripped single glazed storm door to an existing door will increase the EWNR by 5 dB.

Table 21

EWNR Values for Through-the-Wall Air Conditioners for Vents Open and Closed[1]

(For Use With Highway Noise)

	Vent Open	Vent Closed
EWNR, dB	21	24

APPENDIX C

Evaluation of Maximum Allowable Sum of Deficiencies in Graphical Computation of EWNR

In its initial development, the ideal EWNR contour was calculated to the nearest one-tenth of a dB in each of the 1/3-octave bands. The values were normalized to 0 dB at 500 Hz as shown in Table 22.

Table 22

Relative EWNR Curve Values, dB

Freq., Hz	125	160	200	250	318	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
Relative EWNR	-11.2	-8.7	-6.5	-4.5	-2.8	-1.2	0	0.9	1.5	1.5	1.3	0.6	-0.4	-1.7	-3.4	-5.4

The EWNR contour is adjusted vertically relative to the test transmission loss curve to the highest position possible such that some of the transmission loss values for the test specimen fall below those of the EWNR contour but that the sum of the deficiencies is not greater than some maximum integer value. In the method for determining the STC of a given transmission loss curve, the sum of the deficiencies may not be greater than 32 dB.[10] A regression analysis using 22,500 combinations (as described in Chapter 4) was carried out using a variety of values for the allowable maximum sum of the deficiencies to determine the optimum value for use with EWNR. The results are shown in Table 23.

Table 23

Sensitivity of 90% Confidence Limits in EWNR To Allowable Sum of Deficiencies Used For Graphical Computation of EWNR

Maximum Allowable Sum of Deficiencies, dB	90% Confidence Limits, dB	Correlation Coefficient
0	± 2.80	.96114
8	1.37	.99128
16	0.89	.99626
26	0.69	.99770
28	0.67	.99775
30	0.66	.99786
31	0.64	.99793
32	0.63	.99802
33	0.63	.99807
34	0.63	.99804
36	0.64	.99790
38	0.66	.99783
64	0.99	.99551

It can be seen from Table 23 that the highest correlation and lowest 90% confidence limit occurs for the maximum allowable sum of deficiencies equal to 33 dB. However, since 32 is already in use for STC and since the correlation and standard error for 32 is almost the same as for 33, it was decided that the maximum allowable sum of deficiencies would be 32 dB for determining EWNR.

Another regression analysis was done with the additional restriction that the deficiency in any one 1/3-octave band could not be greater than 8 dB. The results are shown in Table 24.

Table 24

Effect on Accuracy of Changing Maximum Allowable Deficiency
In Any One Band When Fitting EWNR Contour to TL Curve
(For Case Where Sum of Deficiencies Equal to 32 dB)

	90% Confidence Limits, dB	Correlation Coefficient
with 8 dB restriction	± 2.81	.96070
without 8 dB restriction	.63	.99802

It can be seen from Table 24 that the 8 dB limitation reduces the correlation coefficient and increases the standard error. Therefore, no such limitation was included in the EWNR evaluation.

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