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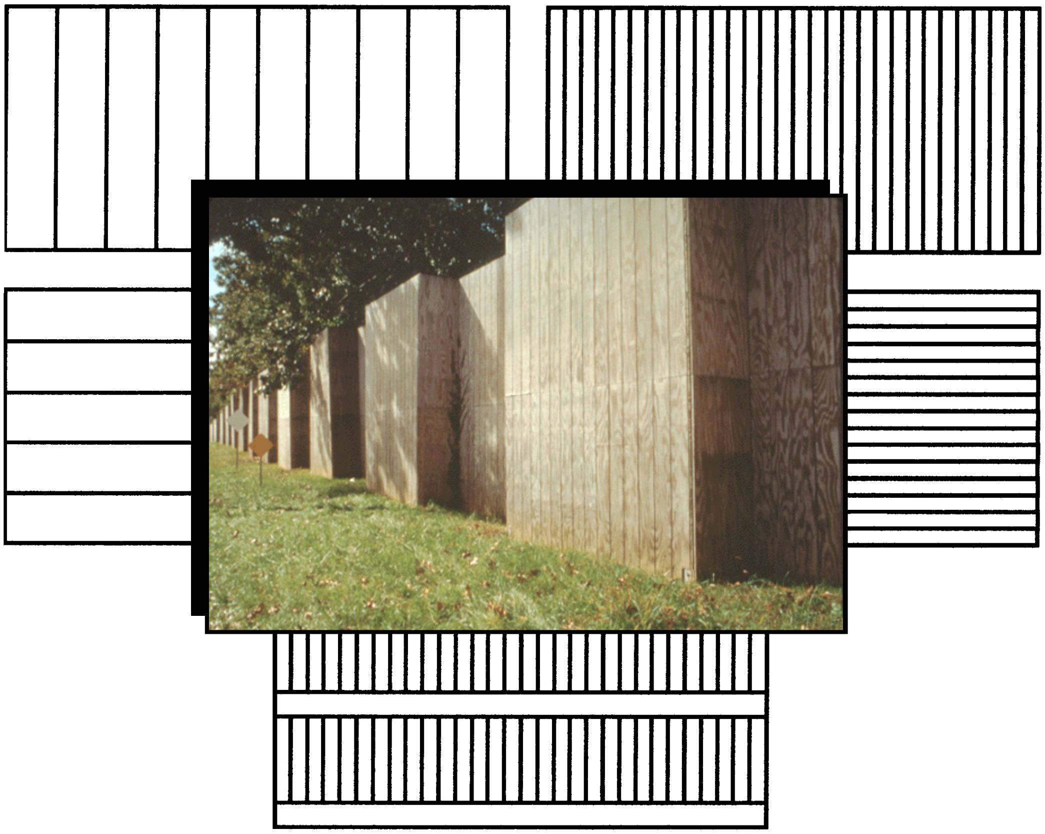
Design of Wood Highway Sound Barriers

Thomas E. Boothby
Courtney B. Burroughs
Craig A. Bernecker
Harvey B. Manbeck
Michael A. Ritter
Stefan Grgurevich
Stephen Cegelka
Paula D. Hillbrich Lee



Abstract

As new and existing U.S. residential areas and high volume highways continue to intermingle, traffic noise abatement procedures continue to be important. This study investigated the acoustic effectiveness, public acceptance, and structural requirements of various designs and types of sound barriers. In addition, the acoustic effectiveness of a prototype sound barrier is reported. Results are presented on the acoustic effectiveness from in situ measurements of one cement-bonded composite panel barrier and four precast concrete, two plywood, two glued-laminated, and three post and panel barriers. The research on public acceptance of sound barriers focused on the perception of visual compatibility. Based on results from semantic-differential and individual ratings, wood and concrete barrier designs were perceived to have favored “rural” qualities. Data collected during the research on acoustic effectiveness and public acceptance were used to develop structural requirements and construction details for a prototype wood sound barrier. The prototype wood sound barrier provided insertion losses of 15 dB or greater, exceeding the 10-dB acceptable performance for a highway sound barrier.

Keywords: Wood barrier, sound barrier, barrier effectiveness, acoustics

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Units of Measurement

Measurements included in the text, tables, and some figures are expressed in SI units. In other figures, notably those of design details used to develop the test sound barrier, measurements are expressed in inch–pound units. The conversion factors for these units are shown in the following table.

Inch–pound unit	Conversion factor	SI unit
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
pound force/square inch (lb/in^2)	6.894	kilopascal (kPa)
pound force/square foot (lb/ft^2)	47.88	pascal (Pa)

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Thomas E. Boothby, Associate Professor
Courtney B. Burroughs, Senior Research Associate
Craig A. Bernecker, Associate Professor
Harvey B. Manbeck, Distinguished Professor
The Pennsylvania State University, University Park, Pennsylvania

Michael A. Ritter, Assistant Director
Forest Products Laboratory, Madison, Wisconsin

Stefan Grgurevich, former Graduate Student
Stephen Cegelka, former Graduate Student
The Pennsylvania State University, University Park, Pennsylvania

Paula Hillbrich Lee, former General Engineer
Forest Products Laboratory, Madison, Wisconsin

Introduction

Project Overview

As new and existing U.S. residential areas and high volume highways continue to intermingle, traffic noise abatement procedures will always be of importance. Since the mid-1960s, traffic noise analysis and control procedures, primarily by State and Federal governments, have increased. Agencies such as individual State Departments of Transportation, the Federal Highway Administration (FHWA), the U.S. Environmental Protection Agency (EPA), and the Transportation Research Board (TRB) have provided funding and research of traffic noise control.

The three primary ways to control traffic noise are by source, receiver, and path (FHWA 1994c). Source control imposes regulations on emissions of trucks, motorcycles, and buses. Receiver control includes carefully planned zoning, building codes, land ownership control, and site planning. Path control attempts blocking or lengthening the path traveled by traffic noise. Path control consists of either shifting the vertical alignment of the road surface, which may shield traffic noise, or using a sound barrier, which attempts to reduce sound levels on the residential side of the barrier by altering the direct path that traffic noise follows from the highway (source) to the resident (receiver). Government agencies concentrate much of their research on the implementation of sound barriers (FHWA1994c).

Highway sound barriers placed near residential neighborhoods provide an effective tool to control traffic noise. Barriers can be constructed of earth, precast concrete panels, concrete block, brick, wood, metal, or a combination of these (FHWA 1994a). In 1992, total length of highway sound barriers in the United States exceeded 1,486 km (FHWA 1994b). Cohn and Harris (1990) reported that wood and the combination of wood and earth berm account for approximately 17% of all sound barriers on U.S. highways.

From 1991 to 1996, annual expenditures for sound barriers in most States exceeded $2 million per year (FHWA 1994c). This spending included type 1 and type 2 projects. Type 1 projects involve the simultaneous construction of the highway and sound barrier; type 2 projects involve construction of the sound barrier after the highway has been built and traffic noise has become a problem. Most States design barriers to attain an insertion loss of 5 to 10 dB; any barrier providing less than this may be considered cost inefficient. The FHWA (1994c) reported that a barrier attaining this acoustic effectiveness level would cost approximately $\$12/\text{ft}^2$, regardless of material. Cost per residence is another way to measure cost effectiveness. Costs ranging from $8,000 per residence in Washington to $40,000 in Maryland have been reported (FHWA 1994c). Cost can also be measured by dollars per residence per A-weighted sound level (dBA) loss. Costs reported in this manner are preferred because dBA values provide a better indication of the effectiveness of the barrier. The average initial costs of a wood barrier are much less than those of a concrete barrier. However, the effects of weathering cause maintenance costs for wood barriers to exceed those of concrete barriers. The annual cost for both wood and concrete barriers compared with their respective design lives are very competitive (FHWA 1994c). A computer program is available for designing cost-effective barriers (Anderson and others 1997).

Literature Review

Acoustic Effectiveness

The acoustic effectiveness of sound barriers can be measured in terms of insertion loss and transmission loss. Insertion loss is the noise reduction that a barrier causes if it is built between the source and receiver. Transmission loss is a measure of how much sound travels through a barrier. Together, these two measures give the designer a sense of the acoustic effectiveness of a proposed barrier.

Insertion loss is a measurement that includes the diffraction of sound waves over the top of a sound barrier. Because most barriers block sound transmission, most sound that reaches receivers behind the barrier diffracts over the top of the barrier. The importance of sound waves diffracting over the top of the barriers is reinforced by research on the special treatment of barrier tops. Absorption and a T-profile on top of a barrier increase barrier insertion loss 1 to 1.5 dB (May and Osman 1980). Absorptive cylinder tops increase insertion loss 2 to 3 dB (Fujiwara and Furuta 1991), and a phase-delay device produces increases of 3 to 5 dB (Amram and others 1987). Another variable that influences insertion loss is the height of a barrier. Increasing the height, however, has a limit when the increased benefit is no longer cost effective. The height limitations reported by researchers vary from 4.0 m (May and Osman 1980) to 4.9 m (Lambert 1978). If a parallel barrier in installed on the opposite side of the highway, the insertion loss is further reduced by approximately 2 dB, because sound waves are reflected by one barrier towards and over the opposite barrier (Bowlby and others 1987). Although absorptive material does not significantly affect the insertion loss of a single barrier (May and Osman 1980), surface absorption reduces reflection from the barriers and improves the insertion loss of parallel barriers by 3.5 to 4.5 dB (Bowlby and others 1987).

In contrast, transmission loss and its influence on insertion loss is a concern to many designers of highway sound barriers. Because the mass density of wood is lower than that of concrete or steel, designers are concerned that when wood barriers are not sufficiently thick, the low transmission loss will counteract the insertion loss. In other words, sound waves will travel through the barrier and reduce the shielding effect of the barrier between the receiver and sound source. However, according to Kurze and Anderson (1971), transmission through barriers can be ignored if the surface mass of the barrier is greater than 20 kg/m^2. This assumes that there are no resonance or coincidence effects to reduce transmission losses. If such effects existed, damping would be necessary for the barrier. Resonance and coincidence effects do exist in steel sound barriers. Behar and May (1980) reported that the damping of steel barriers resulted in a 4-dB increase in insertion loss.

Public Acceptance

The need for highway sound barriers comes from the desire of a community to reduce public annoyance caused by traffic noise. Therefore, public acceptance is a critical evaluation criterion for sound barrier designs. According to Cohn and Bowlby (1984), community acceptance has two components: the perception of noise mitigation and the perception of visual compatibility. Even though both components are subjective, it is necessary to address them for a barrier to satisfy the desires of the community.

Quantification of the perception of noise mitigation has been attempted by several methods. One method widely used by professionals is equating an average sound level with a percentage of the population that would be annoyed by the highway noise (Schultz 1982). By correlating average day and night sound levels with the percentage of population describing themselves as “highly annoyed” by transportation noise, designers only need to reduce noise levels that cause annoyance in a specified percentage of the population. However, because it is unrealistic to expect an insertion loss of much more than 15 dB from a sound barrier (May and Osman 1980) and additional insertion loss might be needed to satisfy this sound criterion, other strategies might have to be used to gain public acceptance. Consequently, the perception of visual compatibility must be considered.

The public perception of visual compatibility is considered to be more important than the acoustic performance in studies of perceived effectiveness (Cohn 1981). Many people perceive landscaping to reduce noise levels, even though the measured loss due to landscaping is negligible. Although it is impossible to objectively quantify public perception concerning the aesthetics of a highway sound barrier, characteristics of barriers have been identified that influence a community’s acceptance of a barrier.

Cohn and Bowlby (1984) identified these characteristics to be size and mass, material selection and color, landscaping, and public involvement. The public does not favor the use of tall or massive sound barriers. The public also believes that materials should be perceived as compatible with the surrounding environment. Consequently, earthen berms are usually the most easily accepted material for a barrier and metallic structures the most poorly received. Next, the public usually considers landscaping to soften the visual impact of sound barriers. Landscaping on both sides of the barrier can naturally camouflage the barrier so that it blends into the natural surroundings. Finally, public involvement in the design of the barriers increases the level of acceptance. Involvement in the design makes the barrier more visually compatible to the community. Taking all identified characteristics into account in the evaluation of barrier design will help the community view the barrier as both effective and less intrusive.

Structural Requirements and Durability

Sound barrier designs follow the *Guide Specifications for Structural Design of Sound Barriers* (AASHTO 1989a), the 1994 Uniform Building Code (UBC 1994) or the *BOCA National Building Code* (BOCA 1987), regulations from individual State Departments of Transportation, and design manuals related to material type such as the ACI 318–95 (ACI 1995) and the *National Design Specification for Wood Construction* (AF&PA 1991).

Wood sound barriers are typically designed with a panel section attached to posts. The panels can be made of timber planks or glued-laminated panels. The posts are normally large solid-sawn timbers or glued-laminated timbers, but they may be steel or concrete. The primary live loads are wind loads. In most cases, no vertical loads are applied, and the self-weight of the sound barrier and its foundation are used in determining the soil-bearing capacity. Other loads may include earth loads, for which the barrier functions as a retaining wall, and traffic or impact loads. Traffic impact loads are not necessary to apply unless the sound barrier is combined with a traffic barrier (AASHTO 1989b). In addition, sound barriers on structures, such as bridges and retaining walls, as well as traffic barriers require certain specifications beyond those for ground-mounted barriers.

Durability is a measure of the length of time a sound barrier remains aesthetically acceptable and structurally and acoustically effective. Weathering and decay are the main concerns for a wood sound barrier. Weathering, which causes dimensional changes in wood, results in cracking, checking, and warping, which causes gaps to develop in the barrier, decreasing transmission loss, structural integrity, and aesthetics. Decay results in wood decomposition, which affects the structural and acoustic performance of the barrier.

Preservative treatments and water repellents are commonly used to resist decay and dimensional changes, respectively, in exterior wood applications. Oilborne preservatives provide resistance to weathering and decay; waterborne preservatives provide only decay resistance (FPL 1999). Preservatives are widely used on wood transportation structures such as bridges, guardrails, and retaining walls. Oilborne preservatives used in timber bridge applications are creosote, pentachlorophenol, and copper naphthenate. These preservatives cause skin irritations and should not be used in applications that involve human contact (FPL 1999). Some preservatives may also darken the surface of the barrier somewhat, lead to bleeding when the barrier is in direct sunlight, and produce a slightly oily surface that makes additional surface preparation difficult. Waterborne preservatives primarily used in softwood bridge applications include chromated copper arsenate (CCA), ammoniacal copper arsenate (ACA), and copper zinc arsenate (ACZA). Waterborne preservatives will accommodate the variety of wood species that are typically used in wood sound barriers. These preservatives leave the surface clean and can be used where human contact is expected. With the use of preservative treatment and water repellent, wood sound barriers have an expected service life of 15 to 25 years (FHWA 1994c). Although the chemicals used for treating wood are regulated under EPA pesticide regulations, the treated wood is not subject to additional regulation, that is, not considered a pesticide (Webb and Gjovik 1988). The research results on leaching rates of preservatives from treated wood are few and inconclusive, but research to date indicates that leached copper, chromium, and arsenic have little mobility in soil (Lebow 1996).

Acoustic Effectiveness

The acoustic effectiveness of concrete and wood sound barriers was determined by *in situ* testing of existing sound barriers. The in situ testing of different design types and materials was necessary because of the lack of extensive data on insertion and transmission losses of various barrier types. The goal of this testing was to determine the insertion and transmission losses of various wood and concrete barriers. Data were normalized to allow for direct comparison between different barrier design types. The objective was to determine if wood and concrete barriers are equivalent in terms of acoustic effectiveness.

Barrier Selection

The wood barrier designs investigated in the *in situ* testing are listed in the *Guide Specification for Highway Noise Barriers* (NFPA 1985). The following three design types of barriers are listed:

1. Timber plank (also called post and panel) barriers, made of heavy timber posts and dimension lumber panels
2. Plywood barriers, made of plywood panels, usually supported by dimension lumber
3. Glued-laminated barriers, made of glued-laminated wood members

The barriers selected for testing were located on flat land and were easily accessible from both sides. Eight wood barriers were selected for in situ testing: three glued-laminated, three post and panel, and two plywood. The glued-laminated barriers were located outside Washington, DC, on I-495; near Troy, New York, on Route 7; and in Erie, Pennsylvania, on I-79. Two post and panel barriers were located on the Hutchinson River Parkway outside New York and one on the Long Island Expressway. In situ tests were also performed on a cement-bonded composite post and panel barrier in Madison, Wisconsin. This barrier was made of cement-bonded composite wood fiber panels and precast concrete posts. The two plywood barriers were located at a truck weigh station across the Pennsylvania/Maryland border on I-83 and outside Baltimore on I-95. In addition to the wood barriers and composite barrier, four precast concrete panel barriers were identified for in situ testing. The concrete barriers were located on I-695 outside Baltimore, on I-95 outside New York City, on Route 24 outside Whippany, New Jersey, and on I-78 in New Jersey. Photographs of the barriers are in Appendix A.

In Situ Testing

Insertion losses of the selected barriers were determined using the indirect predicted method of the *American National Standard—Methods for Determination of Insertion Loss of Outdoor Noise Barriers* (ANSI 1987). Even though this standard does not prescribe the use of a particular prediction method, it does specify the following:

1. The type of ground and topography between the source and receiver should be included in the predictions.
2. The prediction model should be validated over the relevant range of source/receiver distances and for the relevant topography and type of ground.
3. If wind velocity and temperature gradients are not considered in the prediction method, then the indirect predicted method should only be used for calm wind conditions, which are defined as 1.2 m/s (2.7 m/h).

The prediction model used is outlined in the FHWA Highway Traffic Noise Prediction Model (FHWA 1978b). This method was used to determine insertion losses at distances of 3.1, 7.6, and 15.3 m behind the barriers used for the in situ measurements. A measured free-field sound level was adjusted to predict sound levels that would occur at the receiver positions in the absence of the barrier. Only four microphones were available for in situ testing; therefore, two different microphone setups were used to obtain sufficient measurements to determine transmission and insertion losses at 3.1, 7.6, and 15.3 m. The two microphone setups were used for two separate recordings or cuts (Figs. 1 and 2). Figure 1 illustrates the locations of the microphones for cut 1. Microphone 1 was located next to the road, allowing for sound level to be corrected for differences in traffic noise levels between the two cuts. Microphones 3 and 4 helped determine the transmission losses of different barriers. Microphone 3 recorded the free-field sound levels used to predict sound levels in front of the barrier and at 3.1, 7.6, and 15.3 m from the barrier in the absence of the barrier. Figure 2 illustrates the locations of the microphones for cut 2. Microphone 1 was located next to the road as in cut 1 to allow for sound level adjustment between cuts. Microphones 2, 3, and 4 were located 3.1, 7.6, and 15.3 m, respectively, behind the barrier to help determine insertion losses of the barriers.

Using these two setups with a multi-channel tape recorder, sound levels were measured simultaneously at each set of four locations. Simultaneous recordings eliminated the need to adjust all sound levels for changes in traffic noise levels. The only adjustments required were between cuts because the free-field sound level was measured in cut 1 by microphone 3 and the sound levels behind the barrier were measured in cut 2. Thus, two adjustments were necessary to determine insertion loss: (1) the free-field sound level measured in cut 1 by microphone 3 was adjusted to predict the pre-barrier sound level at the receiver position, and (2) the sound levels measured in different cuts were adjusted for changes in the traffic noise levels that occurred between cuts. Both adjustments were made after the recordings were reduced to determine the sound levels. In contrast, transmission loss did not require a sound level correction between cuts because all the recordings necessary to determine transmission loss were taken in cut 1.

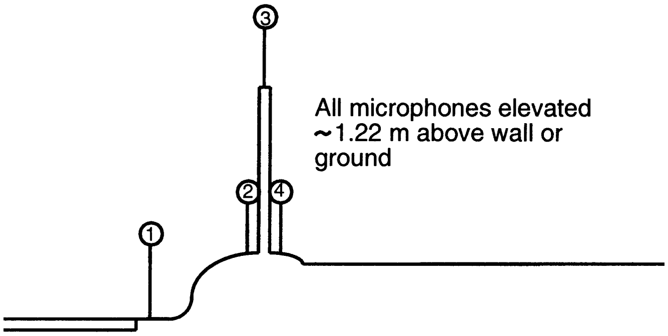


Figure 1—Microphone locations for cut 1.

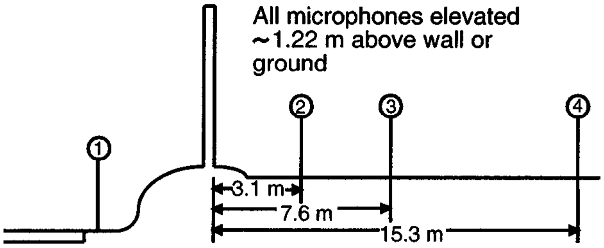


Figure 2—Microphone locations for cut 2.

For the measurements made on the side of the barrier opposite the traffic, amplification was required prior to recording to increase levels of the recorded signal above the electronic background noise levels, although when amplification was used, the effect of electronic noise was reduced. Amplifiers had no effect on nontraffic background noise present at the measurement sites.

Determination of Normalized Insertion Loss

Analysis of Recordings

Readings on a standard sound level meter using the A-scale incorporate a frequency-weighting network approximating the variation of ear sensitivity with frequency to tones of a 40-dB sound pressure level. The multi-channel recordings of the two cuts were analyzed to determine average sound pressure levels in the third-octave bands from 200 Hz to 5 kHz. Below 200 Hz, A-weightings are greater than 10 dB, and above 5 kHz, the level of traffic noise decreases. Thus, it is in the 200-Hz to 5-kHz range where the contribution of traffic noise to A-weighted noise levels is dominant and therefore of primary concern for reduction by a sound barrier. Because traffic varied during recordings, different averages were taken from continuous recordings for approximately 15 min. At sites where traffic was heavy and the source noise levels were high and constant, averages were taken when the traffic was heavy and continuous. Corrections for background noise were unnecessary. At sites where traffic was not heavy or continuous, averages during quiet and noisy periods were taken. These two averages were then used to remove the effect of background noise. Even with the correction for background noise, insertion loss predictions were based on data taken when traffic noise levels were at a maximum, thereby reducing the effects of background noise on the measured levels.

Reduction of the recorded signals was performed by a multichannel analyzer. Corrections were applied for differences in sensitivity of each measurement channel. The determination of absolute sound pressure levels was not required because results reported here are differences in sound pressure levels; absolute levels are not presented. Output from the analyzer resulted from the following:

$$L_\mathrm{v} = 20 \log(V_\mathrm{rms} / 1\,\mathrm{volt}) \tag{1}$$

where L_v is recorded sound level referenced to 1 volt, and V_rms is the root mean square of the measured voltage.

The units of this formula are decibels referenced to 1 volt (dB re 1volt). All recordings were less than 1 volt; therefore, the resulting levels are negative. Repeat measurements were used to establish means and variations for purposes of estimating random measurement errors and identifying invalid data points.

The corrections for differences in traffic noise levels between the two cuts were made because the measurement of the free-field sound levels was made in cut 1 and the measurements of sound levels behind the barrier were made in cut 2. These corrections involved taking the difference between measurements taken in the two cuts of microphone 1, which remained in the same location. These corrections were added to the sound levels for microphone 3 during cut 1 so that these levels, after correction for differences in distance, could be compared directly with levels measured during cut 2.

Pre-barrier sound levels occurring at reference positions behind the barrier were predicted using the corrected sound levels for microphone 3 in cut 1. This required two steps: (1) predicting the spreading loss and accounting for ground effects that occurred between microphone 3 and the reference location and (2) correcting for the sensitivity differences between the microphones.

Sound Level Predictions

The prediction model used to account for the spreading loss and ground effects occurring between the reference free-field location (microphone 3 in cut 1) and the reference locations behind the barrier is described in the FHWA Highway Traffic Noise Prediction Model (FHWA 1978b). This model calculated the spreading loss and ground effects as

$$\Delta L_\mathrm{s} = 10 \log(D_0 / D)^{1+\alpha} \tag{2}$$

where

ΔL_s is change in sound level between recorded free-field sound level and receiver location,

D perpendicular distance between roadway and receiver location on nontraffic side of barrier,

D_0 distance between roadway and location of microphone 3 in cut 1 where free-field sound level was measured, and

α site parameter whose value depends upon site conditions, $\alpha = 0$ for acoustically hard (paved) surfaces and $\alpha = 1/2$ for absorptive (landscaped) surfaces.

Preliminary pre-barrier sound levels at sites on the nontraffic side of the barrier were predicted. When ground conditions, such as a soft surface in front of and a paved surface behind the barrier, changed between the source and receiver, this formula was used twice, once for the first ground condition, then for the second ground condition.

The prediction model satisfied the three requirements outlined in ANSI S12.8 (ANSI 1987). First, the model accounts for ground and topography between the source and receiver. Second, Highway Noise Measurements for Verification of Prediction Models (FHWA 1978b) provide extensive results concerning the field validation of the prediction model over the relevant range of source/receiver distances and for the relevant topography and type of ground. This reference provides statistical data showing that the noise prediction model presents theoretical values close to measured values. Third, recorded wind velocity and temperature data during tests showed that wind velocities less than 7 km/s did not affect the results of the prediction model for the receiver distances used in this project. Because wind conditions during the in situ testing were calm (<7 km/s), wind velocity and temperature gradients should not have affected the predictions of insertion and transmission losses.

Table 1—Microphone calibration results

	Calibrated sound pressure for test microphones 1 to 4 (dB re 1 V)			
	1	2	3	4
Calibration 1	3.6	1.7	5.2	3.1
Calibration 2	4.0	0.1	0.9	0.3

Because the four microphones used in the in situ testing had slightly different sensitivities, they were calibrated with the associated recording instrumentation. The in situ testing was conducted twice: in the fall of 1994 (calibration 1) and the spring of 1995 (calibration 2). Microphones and recording equipment were calibrated for both sets of tests. The calibration was done by placing a pistophone, which produces a sound level of 124 dB at a frequency of 250 Hz, over each microphone to produce a sound recording. The recordings from each microphone were then reduced with the same equipment used to reduce all the measurement data to obtain the voltage levels that corresponded to the 124-dB calibration sound pressure level. Calibration 1 was used for all the in situ testing except the two tests in New Jersey and the test on the plywood barrier outside Baltimore. Calibration 2 was used for these tests. The calibration results are given in Table 1. Because of problems in availability of microphones, different microphones were used for each calibration, which could account for the differences in the calibration values listed in Table 1.

The correction for the prediction of pre-barrier sound levels was simply the difference between the free-field reference microphone, which in all cases was microphone 3, and the receiver microphone, which was either microphone 2, 3, or 4. The preliminary prediction was corrected for differences in microphone sensitivity by taking this difference and adding it to the preliminary prediction.

Background Noise Adjustment

The final correction necessary to estimate the insertion loss for barriers was to compensate for the effects of background noise. Background noise in a recording increases recorded sound levels, causing a decrease in the estimated insertion or transmission loss. The cause of background noise was either electronic noise produced by the recording equipment or by sources of nontraffic noise on the nontraffic side of the barrier. If traffic noise is constant and loud enough and an amplifier is used to increase the signal of the microphone recorded on the nontraffic side of the barrier, background noise has no effect on the recorded sound levels. However, when traffic noise is not loud enough, even an amplifier does not allow for compensation for background noise.

Compensation for the background noise from the recordings involved manipulating sound levels recorded during noisy and quiet periods. First, ratios of measured increase in sound pressure at roadside and on the nontraffic side of the barrier were found. The two ratios are expressed in terms of source pressures as follows:

$$x_1 = \left(\frac{P_\mathrm{s}^\mathrm{n}}{P_\mathrm{s}^\mathrm{Q}} \right)^2 \tag{3}$$

$$x_2 = \frac{\left(P_\mathrm{n}^\mathrm{Q}\right)^2 + \left(P_\mathrm{n}\right)^2}{\left(P_\mathrm{n}^\mathrm{n}\right)^2 + \left(P_\mathrm{n}\right)^2} \qquad x_1 > x_2 > 1 \tag{4}$$

where

x_1 is	measured increase at roadside,
x_2	measured increase behind barrier,
P_s^n	source pressure under noisy conditions,
P_s^Q	source pressure under quiet conditions,
P_n^n	nontraffic side pressure under noisy conditions,
P_n^Q	nontraffic side pressure under quiet conditions, and
P_n	background pressure.

By assuming that $(P_\mathrm{n}^\mathrm{n}/P_\mathrm{n}^\mathrm{Q})^2 = (P_\mathrm{s}^\mathrm{n}/P_\mathrm{s}^\mathrm{Q})^2 = x_1$, the ratio $(P_\mathrm{n}/P_\mathrm{n}^\mathrm{Q})^2$ in terms of x_1 and x_2 is

$$(P_\mathrm{n} / P_\mathrm{n}^\mathrm{Q})^2 = y = (x_1 - x_2) / (x_2 - 1) \tag{5}$$

Equation (5) requires that the sound levels acquired from the recordings be converted to sound pressures x_1 and x_2. By taking the difference between “noisy” and “quiet” periods, Δ_i, the sound levels can be converted to a ratio of sound pressure with

$$x_i = 10^{\Delta_i/10} \tag{6}$$

The variable y for each pair of noisy and quiet recordings can be determined for every frequency. The difference between quiet recordings of the microphone of interest and the background noise level is

$$A = -10 \log(1 + 1/y) \tag{7}$$

The background noise level is determined by logarithmically subtracting the value A from the sound level of the microphone of interest.

According to ANSI S12.8 (ANSI 1987), if the difference between the recorded noisy sound level and background noise is less than 4 dB, the sound level is reported as being masked by the background noise. All recorded noisy sound levels that were within 4 dB of the background noise were deleted from the data sets.

Estimated Insertion Loss

Test results are absent or incomplete for some barriers. Results for the three barriers tested in Erie, Pennsylvania, were not used because traffic was light and amplifiers were not available; thus, the recorded levels were contaminated by electronic noise. In addition, background noise was a problem for recordings for the precast concrete barrier on I-695 outside Baltimore and the post and panel barrier on the Hutchinson River Parkway. The insertion losses at the frequencies masked by background noise were deleted from the data set. Consequently, data were truncated for these barriers. Background noise also masked a few frequencies of recordings for the I-83 Maryland plywood barrier, the Route 7 New York glued-laminated barrier, and the Long Island Expressway post and panel barrier. Recordings from cut 2 for the post and panel barrier on the Long Island Expressway were lost.

The estimated insertion losses presented in Table 2 range from 10 to 20 dB. However, insertion loss did not increase with frequency as expected. Also, there appears to be no correlation between the height of the barrier and insertion loss. For example, the 2.5-m-high barrier on I-78 New Jersey had a greater insertion loss than did the 6.7-m-high barrier on I-95 Baltimore. The insertion losses were normalized to a common distance between the barrier and roadway and for a common height to remove the effect of these parameters. However, other parameters were not included in the normalization, such as the acoustic impedance of the ground and the topography around the barrier.

For most barriers, insertion loss decreased as the distance behind the barrier increased (Table 2). The exceptions were the barriers on I-78 New Jersey, on Route 24 New Jersey, on I-83 Maryland, on the Hutchinson River Parkway New York, and outside Madison, Wisconsin. The barriers on I-78 New Jersey, I-83 Maryland, and outside Madison were either situated on a berm or the ground rolled off behind the barrier. The barriers on the Hutchinson River Parkway were located far from the roadway (about 14 m). There were no unusual characteristics for the barrier on Route 24 New Jersey.

Normalization of Estimated Insertion Loss

Variation was observed in the insertion losses within groups of barriers of similar design type. Much of the variation was due to differences in barrier height, topography, and distance of the barrier from the roadway. Barrier heights and distances from the roadway are listed in Table 3 for each barrier.

In this study, the distance from the roadway to the barrier was assumed to be the distance from the edge of the road to the barrier, except for the I-95 Baltimore and I-495 Washington DC barriers, where the traffic noise was assumed to be centered in the first lane and the distance was adjusted accordingly. This adjustment was necessary because of the proximity of these barriers to the driving lanes.

The normalization of the insertion losses for the three different receiver locations involved the use of the prediction model presented in FHWA–RD–77–108 (FHWA 1978b). The normalization factor for a barrier was the difference between the predicted insertion loss and the predicted value at a given height and distance from the road on a flat site. The estimated insertion losses were normalized by subtracting the normalization factor from the estimated insertion loss. The insertion losses for all the barriers were normalized to a height of 4.3 m, a distance of 9.2 m from the roadway, and a flat site. The 4.3-m height was chosen because greater heights rarely produce a cost-effective benefit (May and Osman 1980, Lambert 1978). The 9.2-m distance was chosen because it was the mean of the source-to-barrier distances for barriers used in this research project. Normalization of estimated insertion losses allowed direct comparisons of all test barrier types and locations.

The FHWA prediction model used for the normalization uses two equations. These equations vary slightly because the insertion loss of an earth berm is greater than that of a wall barrier. The equation for barrier insertion loss is

$$\mathrm{IL} = 20\log\frac{(2\pi N)^{1/2}}{\tanh(2\pi N)^{1/2}} + 5 \leq 20\mathrm{dB} \qquad (8)$$

where IL is predicted insertion loss, $N = 2(r_{\mathrm{SB}} + r_{\mathrm{BR}} - d_{\mathrm{SB}} - d_{\mathrm{BR}})/\lambda$ (distances defined in Fig. 3), and $\lambda = (343/f)$.

The variable N is the Fresnel number, λ is acoustic wavelength in meters, and f is the frequency in hertz. Equation (8) was used for most of the barriers tested.

The earth berm equation used in the normalization is

$$\mathrm{IL} = 20\log\frac{(2\pi N)^{1/2}}{\tanh(2\pi N)^{1/2}} + 8 \leq 23\mathrm{dB} \qquad (9)$$

The only differences between Equations (8) and (9) are the constant added in Equation (9) and the maximum allowable value. Equation (9) was only used for the precast concrete barrier on I-78 New Jersey. This was the only barrier that was built on a berm, which is approximately 1.7 m high. Equation (8) was used for the remainder of the barriers.

Normalized Insertion Loss

Data on normalized insertion losses are presented in Table 4. Incomplete data were the consequence of recordings masked by background noise. The same frequencies were masked for both the normalized and the estimated insertion losses, because normalized data were an adjusted version of estimated data.

Table 2—Estimated insertion loss at various distances behind the barrier[a]

Octave band center fre-quency (Hz)	Insertion loss (dB) for various barrier types[b]																													
	Precast concrete												Plywood						Post and Panel									Cement-bonded composite		
	I-695 Baltimore (6.7 m)			I-95 NY (4.9 m)			I-78 NJ (2.5 m)			Rt.24 NJ (5.3 m)			I-95 Baltimore (3.3 m)			I-83 MD (4.3 m)			Long Island Expressway, NY (6.7 m)			Hutchinson River Parkway, NY 1 (1.9 m)			Hutchinson River Parkway, NY 2 (3.3 m)			Madison, WI (3.1m)		
	Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)		
	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3
200	12	10	9	13	—[a]	15	15	13	10	16	13	9	12	8	7	8	10	7	10	—[a]	—[a]	—[a]	—[a]	—[a]	7	2	10	2	0	4
250	12	11	8	11	—[a]	12	16	15	10	16	12	10	15	10	9	8	8	7	19	6	9	—[a]	—[a]	—[a]	8	10	9	5	4	3
315	11	10	7	15	—[a]	13	19	20	16	18	13	13	15	8	7	8	8	8	19	15	10	—[a]	—[a]	—[a]	11	11	12	12	8	17
400	12	11	9	16	—[a]	12	18	20	17	18	13	13	15	9	6	8	8	9	17	11	9	—[a]	—[a]	—[a]	10	12	11	8	8	12
500	13	12	10	18	19	13	16	18	16	19	15	17	16	9	5	8	8	10	13	12	9	—[a]	—[a]	—[a]	12	13	9	11	9	14
630	13	12	10	19	20	16	18	17	17	20	15	17	15	8	5	8	9	9	17	14	10	—[a]	8	6	11	12	9	12	11	16
800	13	12	11	18	20	15	18	18	17	20	16	18	14	7	5	9	10	9	18	13	11	—[a]	8	6	10	12	10	8	8	16
1,000	13	12	11	20	—[a]	—[a]	18	18	18	20	16	18	14	7	5	8	8	8	19	14	12	—[a]	8	6	9	10	8	12	12	17
1,250	12	11	10	—[a]	—[a]	—[a]	19	18	17	20	16	17	15	8	6	7	8	8	20	13	11	—	8	5	8	10	7	12	14	17
1,600	11	11	9	—[a]	—[a]	—[a]	19	19	18	19	15	17	16	8	6	7	7	8	18	10	9	17	8	5	8	10	7	11	15	16
2,000	11	10	9	—[a]	—[a]	—[a]	19	18	17	18	14	15	16	10	7	8	9	9	19	13	10	14	7	5	8	9	6	10	15	14
2,500	10	9	8	—[a]	—[a]	—[a]	19	18	18	18	14	15	15	9	6	5	6	7	18	13	10	13	6	—[a]	8	9	7	9	15	16
3,150	9	8	7	—[a]	—[a]	—[a]	18	18	18	16	13	14	15	9	6	4	5	6	19	13	11	12	—[a]	—[a]	9	10	7	8	16	18
4,000	10	8	8	—[a]	—[a]	—[a]	18	17	18	17	12	14	16	10	7	3	4	4	18	12	9	—[a]	—[a]	—[a]	10	11	8	10	16	16
5,000	—[a]	8	7	—[a]	—[a]	—[a]	18	17	19	18	12	17	17	11	9	3	—[a]	6	19	—[a]	11	—[a]	—[a]	—[a]	11	—[a]	10	7	14	17

[a] Missing values indicate that data were masked by background noise and removed from data set.

[b] Values in parentheses indicate barrier height.

Table 3—Description of barriers

Barrier type	Barrier location	Barrier height (m)	Distance from roadway (m)
Precast concrete	I-695, Baltimore, MD	6.7	9.0
Precast concrete	I-95, New York City	4.9	6.6
Precast concrete	I-78, New Jersey	2.5	10.9
Precast concrete	Rt. 24, Whippany, NJ	5.3	9.8
Plywood	I-95, Baltimore, MD	3.3	2.4[a]
Plywood	I-83, Maryland Weigh Station	4.3	24.4
Glued-laminated	I-495, Washington, DC	5.1	1.5[a]
Glued-laminated	Route 7, Troy, NY	2.5	4.9
Post and panel	Madison, WI	3.1	12.2
Post and panel	Long Island Expressway, NY	6.7	12.2
Post and panel	Hutchinson River Parkway, NY 1	1.9	7.6
Post and panel	Hutchinson River Parkway, NY 2	3.3	14.0

[a] These barriers were 6.1 m from centerline of outside driving lane.

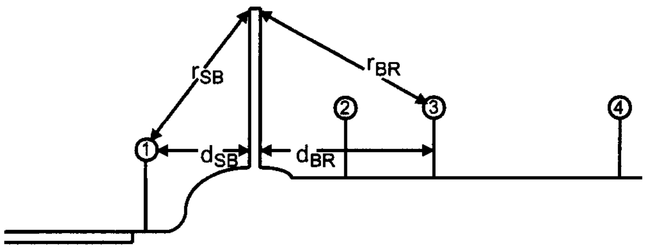


Figure 3—Distances used in FHWA insertion loss prediction model (FHWA 1978b).

Comparison of the normalized results in Table 4 with the unaltered results in Table 2 indicates that normalization did not reduce the spread in data. However, some factors that could have contributed to data variability were not included in normalization, such as topography and ground impedance on each side of the barrier. Note that in spite of the spread in the insertion losses, there appears to be no correlation of the losses with the materials used for the barriers.

Determination of Transmission Loss

The method used to determine transmission loss was similar to the method used to determine insertion loss. At first, transmission loss was determined by the recordings in the first cut, for which microphone locations are shown in Figure 1. Transmission loss was the difference in the sound levels between microphones 2 and 4. However, any sound reflecting off the barrier increased the sound level recorded by microphone 2. This pressure doubling artificially inflated the sound level recorded by microphone 2 and, consequently, increased the estimated transmission loss for the barrier. To compensate for this pressure doubling, the sound level in front of the barrier (pre-barrier sound level) was predicted the same way as predicted for the insertion loss calculations. The pre-barrier sound level was predicted by taking the free-field sound level occurring at microphone 3 and adjusting for spreading loss and ground effects, as well as sensitivity differences between microphones. Having adjusted the predicted pre-barrier sound level and the sound levels measured by microphone 4 for background noise, the transmission loss was found to be the difference between the two adjusted sound levels. Because transmission loss was not affected by barrier height, barrier distance from the road, or topography, normalization was not necessary for the direct comparison of transmission loss values.

Transmission losses are presented in Table 5. Transmission losses could not be computed for the Madison barrier because of the failure of microphone 4. All transmission losses in Table 5 are greater than 10 dB; most range from 15 to 25 dB. These values are greater than the values for the insertion losses, indicating that insertion losses are controlled primarily by diffraction over the top of the barriers. The transmission losses for the plywood and post and panel barriers were lower than those for the two glued-laminated barriers. These results do not take into account the transmission loss data for the Madison barrier.

Analysis of Normalized Insertion Loss and Transmission Loss

Comparison of Normalized Insertion Loss With Estimated Transmission Loss

To assist in the explanation of why the insertion loss did not increase with frequency, the normalized insertion losses were compared with estimates of the transmission losses for barriers where a complete set of data were available. In general, the slope of the transmission loss followed that of the insertion loss. When the insertion loss remained nearly constant with increasing frequency, so did the transmission loss. In one case where the insertion loss increased with frequency, the transmission loss also increased with frequency. This implies that leaks (gaps) in the barriers hold down the insertion loss at higher frequencies. Since the transmission loss for leaks in the barrier is insensitive to frequency, leaks would tend to bound the transmission loss and thereby the insertion loss at all frequencies. The average transmission loss was between 13 and 21 dB, indicating that the insertion loss would be limited to about 20 dB as frequency increases. The transmission losses were based on single-point measurements in the nearfield of the barriers and were therefore subject to variations. However, these losses do imply that the cause of the flattening of the insertion losses may be leaks in the barriers. Additional measurements are needed to substantiate this hypothesis.

Table 4—Normalized insertion loss at various distances behind the barrier[a]

	Insertion loss (dB) for various barrier types[b]																													
	Precast concrete												Plywood						Post and Panel									Cement-bonded composite		
	I-695 Baltimore (6.7 m)			I-95 NY (4.9 m)			I-78 NJ (2.5 m)			Rt.24 NJ (5.3 m)			I-95 Baltimore (3.3 m)			I-83 MD (4.3 m)			Long Island Expressway, NY (6.7 m)			Hutchinson River Parkway, NY 1 (1.9 m)			Hutchinson River Parkway, NY 2 (3.3 m)			Madison, WI (3.1m)		
	Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)			Distance behind barrier (m)		
Octave band center fre-quency (Hz)	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3	3.1	7.6	15.3
200	8	6	6	12	—[a]	13	16	11	8	13	8	4	14	12	9	14	9	7	7	—[a]		—[a]	—[a]	—	11	5	13	2	2	4
250	9	7	5	9	—[a]	10	17	13	8	13	7	5	18	13	12	18	6	7	17	2	5	—[a]	—[a]	—	11	13	13	5	6	3
315	9	6	4	13	—[a]	10	20	18	14	16	9	8	18	12	10	18	6	8	17	11	6	—[a]	—[a]	—	15	15	16	12	10	17
400	11	8	6	15	—[a]	10	19	17	15	17	10	11	18	13	9	18	7	9	16	8	5	—[a]	—[a]	—	14	15	15	8	10	12
500	13	10	7	18	17	10	18	16	15	19	13	13	19	12	8	19	6	10	13	10	6	—[a]	—[a]	—	15	16	13	11	11	14
630	13	11	8	19	19	13	18	15	15	20	14	15	16	12	7	16	8	9	17	13	8	—[a]	18	16	13	16	13	12	13	16
800	13	12	9	18	20	14	17	15	16	20	16	17	14	10	8	14	10	9	18	13	9	—[a]	19	16	11	16	14	8	10	16
1,000	13	12	10	20	—[a]	—	17	15	16	20	16	18	14	10	8	14	8	8	19	14	11	—[a]	18	17	10	13	12	13	14	17
1,250	12	11	10	—[a]	—[a]	—	16	15	15	20	16	17	15	10	8	15	8	8	20	13	11	—[a]	18	16	8	11	10	14	16	17
1,600	11	11	9	—[a]	—[a]	—	16	16	15	19	15	17	16	9	7	16	7	8	18	10	9	20	17	15	8	10	10	14	17	17
2000	11	10	9	—[a]	—[a]	—	16	15	14	18	14	15	16	10	7	16	9	9	19	13	10	17	15	14	8	9	8	14	18	14
2500	10	9	8	—[a]	—[a]	—	16	15	15	18	14	15	15	9	6	15	6	7	18	13	10	15	13	—	8	9	7	14	19	17
3,150	9	8	7	—[a]	—[a]	—	15	15	15	16	13	14	15	9	6	15	5	6	19	13	11	13	—[a]	—	9	10	7	14	21	20
4,000	10	8	8	—[a]	—[a]	—	15	14	15	17	12	14	16	10	7	16	4	4	18	12	9	—[a]	—[a]	—	10	11	8	17	22	19
5,000	10	8	7	—[a]	—[a]	—	15	14	16	18	12	17	17	11	9	17	—[a]	6	19	—[a]	11	—[a]	—[a]	—	11	—[a]	10	15	21	21

[a] Missing values indicate that data were masked by background noise and removed from data set.

[b] Values in parentheses indicate barrier height.

Table 5—Transmission loss of barriers[a]

Octave band center frequency (Hz)	Transmission loss (dB)										
	Precast concrete barrier				Plywood barrier		Glulam barrier		Post and panel barrier		
	I-695 Baltimore	I-95 NY	I-78 NJ	Rt. 24 NJ	I-95 Baltimore	I-83 MD	I-495 DC	Rt.7 NY	Long Island Express, NY	Hutchinson River Parkway, NY 1	Hutchinson River Parkway, NY 2
200	17	17	11	14	11	—[a]	14	14	15	—[a]	—[a]
250	16	19	13	15	13	10	20	16	—[a]	—[a]	12
315	19	20	16	18	15	13	19	17	—[a]	16	14
400	19	20	16	21	14	13	21	15	—[a]	—[a]	14
500	20	21	15	22	14	13	21	14	—[a]	15	14
630	20	21	16	23	14	16	21	17	—[a]	15	15
800	19	22	17	23	15	16	21	18	—[a]	14	15
1,000	19	24	16	23	16	16	22	18	—[a]	15	14
1,250	19	24	17	21	17	14	22	19	—[a]	16	15
1,600	18	24	17	22	17	14	22	22	—[a]	16	15
2,000	18	24	18	24	18	14	21	22	—[a]	15	15
2,500	17	23	17	24	18	13	20	25	—[a]	14	13
3,150	17	22	17	22	18	12	19	27	—[a]	13	15
4,000	17	—[a]	15	20	18	11	18	26	—[a]	—[a]	15
5,000	18	—[a]	16	18	20	12	19	28	—[a]	15	17

[a] Missing values indicate that data were masked by background noise and removed from data set.

A-Weighting of Insertion and Transmission Losses

To approximate the sound heard by the normal human ear, A-weighting was applied to the normalized insertion and transmission losses. The A-weighted sound level, in dBA units, is the sound pressure level in decibels measured with a frequency-weighting network corresponding to the A-scale specified by ANSI S1.4–1971 (ANSI 1987). The A-scale tends to suppress lower frequencies, that is, <1,000 Hz. A-weighting relative responses by frequency are listed in Table 6.

The A-weighting factors are applied to the third-octave band levels predicted in the absence of the barrier and to the levels corrected with the barrier. The A-weighted levels are logarithmically summed to produce overall A-weighted levels with and without the barrier. After converting the sound levels (L_p) into sound pressure using

$$p^2 / p_{\mathrm{ref}}^2 = 10^{L_p/10} \qquad (10)$$

sound pressures (p) were added together, then converted back to sound pressure level (SPL) using

$$\mathrm{SPL} = 10\log(p^2 / p_{\mathrm{ref}}^2) \qquad (11)$$

to obtain the overall A-weighted sound pressure level. The A-weighted level predicted without the barrier was subtracted from the A-weighted level corrected with the barrier to determine a single value for the transmission loss and insertion loss at each distance. The A-weighted insertion losses were normalized in a similar fashion used in each band except that the correction factor was calculated at 550 Hz and added to the A-weighted insertion loss. Predictions at 550 Hz best approximate A-weighted sound levels (FHWA 1978a).

Table 6—A-weighting relative response by frequency

Frequency (Hz)	A-weighting response	Frequency (Hz)	A-weighting response
200	–100	1,250	0.6
250	–8.6	1,600	1.0
315	–6.6	2,000	1.2
400	–4.8	2,500	1.3
500	–3.2	3,150	1.2
630	–1.9	4,000	1.0
800	–0.8	5,000	0.5
1,000	0.0		

The A-weighted normalized insertion and transmission losses are presented in Table 7. These are the final results of the acoustic effectiveness study of this research project. The tabulated values are the A-weighted normalized insertion

Table 7—A-weighted normalized[a] insertion and transmission losses

Barrier type	Barrier location	Barrier height (m)	Distance from road to barrier (m)	Insertion loss (dBA) at distance behind barrier			Transmission loss (dBA) at 3.1 m behind barrier
				3.1 m	7.6 m	15.3 m	
Precast concrete	1-695, Baltimore, MD	6.7	9.0	12	10	7	19
Precast concrete	1-95, New York City	4.9	6.6	18	17	12	22
Precast concrete	1-78, New Jersey	2.5	10.9	19	16	16	17
Precast concrete	Rt. 24, Whippany, NJ	5.3	9.8	19	14	14	22
Plywood	1-95, Baltimore, MD	3.3	2.4[b]	17	12	8	15
Plywood	1-83, Maryland Weigh Station	4.3	24.4	7	6	7	14
Glued-laminated	1-495, Washington, DC	5.1	1.5[b]	15	11	7	21
Glued-laminated	Route 7, Troy, NY	2.5	4.9	16	14	10	20
Wood post and panel	Long Island Expressway, NY	6.7	12.2	18	11	7	15
Wood post and panel	Hutchinson River Parkway, NY 1	1.9	7.6	21	18	15[c]	15
Wood post and panel	Hutchinson River Parkway, NY 2	3.3	14.0	12	14	12[c]	15
Cement-bonded composite panel	Madison, WI	3.1	12.2	13	10	15	—[d]

[a] Normalized to a height of 4.3 m, a distance 9.2 m from the roadway, and a flat site.
[b] These barriers were 6.1 m from centerline of outside driving lane.
[c] Over-normalized.
[d] Transmission loss data not collected.

losses for the three receiver locations and the A-weighted transmission losses for each barrier.

Experimental Error Calculations

The experimental error calculation used in this project follows the guidelines established in the standard ANSI S12.8 (ANSI 1987). The method calculates experimental error by summing the variances produced by background noise, differences in the sound levels with and without barriers, errors in the prediction model, and measurement errors. Experimental error is defined as the standard deviation.

The variances of pre-barrier background noise at reference and receiver locations as well as the variance of the difference between the sound levels at the reference and receiver locations were zero, because the receiver sound levels were calculated from the reference sound levels and no background noise influenced the recordings of the reference microphone. For post-barrier conditions, there was no background noise for the reference microphone, but background noise sometimes affected the receiver microphone. The variance of the calculated background noise level was included if background noise influenced the recordings. Because reference and receiver recordings for the post-barrier conditions were in the two separate cuts for each barrier, the variance of the difference between these two values were included in the error calculations. Bias errors caused by the prediction model and microphone calibration were calculated, assuming a confidence level of 95%. Conservatively, the calibrator had a bias error of 0.5 dB and the prediction model a bias of 1 dB. At the 95% confidence interval, the bias errors were reduced to variances of 0.06 and 0.25 dB.

The mean standard error values, as well as the range and coefficients of variation of the standard error values, are presented in Table 8. Tabulated values are for the three insertion loss calculations and the transmission loss calculations. Table 8 further breaks down the standard error by showing the errors in calculations affected by and those not affected by background noise.

The standard error calculations provided a measure of the reliability of the insertion and transmission loss data and calculated results. The maximum errors calculated indicate that the error can be ±2 dB even though all the means occurred around 1dB. The range of the standard error values did not vary much between calculations, with or without background noise.

Comparison of Normalized and Estimated Insertion Losses

A major concern was whether the normalization process for height, distance, and topography for the tested barriers had an overpowering effect on the estimated insertion losses; that is, whether the normalization correction factors had a

Table 8—Standard errors for insertion and transmission loss calculations

	Standard errors for data taken at various distances behind barriers, with and without background noise[a]							
	w/back (3.1 m)	no back (3.1 m)	w/back (7.6 m)	no back (7.6 m)	w/back (15.3 m)	no back (15.3 m)	w/back (TL)	no back (TL)
Receiver location								
Mean (dB)	1	1	1	1	1	1	1	1
Max. (dB)	2	2	2	2	2	2	2	2
Min. (dB)	1	1	1	1	1	1	1	1
COV (%)	7	7	9	8	10	9	6	5
Receiver location group means[b]								
Mean	1 dB		1 dB		1 dB		1 dB	
COV (%)	7		9		10		5	

[a] w/back designates data affected by background noise; no back, data not affected by background noise; TL, transmission loss.

[b] Standard error means and COVs for insertion losses at each receiver location and transmission losses. Means and COVs include data sets affected and unaffected by background noise.

significant impact on the estimated insertion losses, making the normalized insertion losses more of a prediction than a measurement. Visual comparison of the graphs of the estimated and normalized insertion losses suggested that, for the most part, normalization only slightly affected the insertion losses. The normalization process only had a significant effect on the results from barriers where the topography shortened their effective height or from the barrier situated on top of an earth berm.

The conditions that necessitated significant normalization occurred with the two Hutchinson River Parkway wood post and panel barriers and the I-78 New Jersey precast concrete barrier. One Hutchinson River Parkway barrier was only 1.9 m high and was situated 7.6 m from the road. At 15.3 m behind the barrier, the insertion loss was 6 to 15 dB across the 200- to 5,000-Hz range of frequencies. When compared with the predicted insertion loss of 13 to 20 dB at the same receiver location across the same range of frequencies for a 4.3-m-high barrier 9.2 m from the road, the normalization correction factor ranged from 5 to 11 dB. The site of the other Hutchinson River Parkway barrier slopes downward from the roadway, then upward beyond the barrier. This valley effectively reduces the height of the barrier. For the 3.3-m-high barrier situated 14.0 m from the road, the normalization correction factors ranged from 0 to 6 dB, with only the 4,000- and 5,000-Hz frequencies escaping a correction factor. The precast concrete barrier on I-78 New Jersey was the only barrier in this study for which an earth berm forms part of the barrier. Although the barrier is only 2.5 m high, it rests on an approximately 1.7-m-high earth berm, which increased its insertion loss. Comparing the performance of this barrier with that of the Route 24 New Jersey precast concrete barrier, it is clear that the insertion losses differed for the same design. By normalizing the results for the earth berm, the insertion loss of the I-78 barrier was reduced 2 to 3 dB across the entire range of frequencies. In doing so, the insertion losses of the two barriers converged (Table 7).

Aside from these three instances, normalization of the insertion losses had only a minimal effect. For the most part, the normalization correction factor only applied to frequencies less than 1,000 Hz. At the receiver position 15.3 m behind the barrier, the data for some barriers required normalization correction factors at frequencies slightly greater than 1,000 Hz, but these were usually about 1 or 2 dB. Thus, because A-weighting suppresses levels below 1,000 Hz, most normalizations did not affect the final A-weighted insertion losses. Except for the Hutchinson River Parkway barriers and the I-78 New Jersey barrier, the normalization correction factors for the A-weighted sound levels were less than 3 dB, a change in sound level that is barely perceptible to the normal human ear.

Trends Within Design Types

Acoustic trends occurred within the different design types. The A-weighted insertion losses in Table 7 allowed comparisons of the insertion losses for different barrier design types. The same data allowed comparison of the performance of each barrier to a target minimum insertion loss of 10 dBA at 3.1, 7.6, and 15.3 m behind the barrier. The results presented as the A-weighted transmission loss in Table 7 allowed comparison of the transmission losses produced by each barrier.

The precast concrete barriers generally had fairly high insertion losses (7 to 19 dBA) for the three receiver positions. A large portion of the data for the barrier on I-95 outside New York City was masked by background noise. These data, consequently, were not considered reliable. However, for the other precast concrete barriers, insertion loss was between 12 and 19 dBA at 3.1 m behind the barrier, between 10 and 16 dBA at 7.6 m, and between 7 and 16 dBA at 15.3 m. Even though the values range widely, they can be used as minimum and maximum values for the following reasons. At greater distances (7.6 and 15.3 m) from the barrier, an insertion loss of 15 dBA is difficult to achieve. A slight inflation of the values could be due to a slightly different ground effect than predicted. Moreover, the values of 7 and 10 dBA were low for the geometries of the I-95 New York barrier. Thus, the insertion losses of 7 and 10 dBA should also be considered extreme. An insertion loss falling between these two sets of values should be easily attainable. A precast concrete barrier, with a height of 4.3 m and constructed 9.2 m from the road, can attain insertion losses of 16 or 17 dBA at 3.1 m behind the barrier, 13 or 14 dBA at 7.6 dBA, and 11 or 12 dBA at 15.3 m. All these values suggest that the goal of 10-dBA insertion loss is easily attainable with precast concrete barriers.

The noise attenuation results for the two plywood barriers were extreme (7 to 17 dBA) near the barrier (3.1 m) and converged to 7 to 8 dBA at the furthest distance (15.3 m) (Table 7). The values at 3.1 and 7.6 m resulted because the I-95 barrier was located directly next to the road and the I-83 barrier was located at least 24.4 m from the road. The farther the barrier is situated from the road, the smaller the insertion loss. Transmission losses for plywood barriers were lower than those for the concrete barriers and may have reduced the insertion losses of the plywood barriers. The low transmission losses of the plywood barriers were caused by cracks that had developed between the panels or the panels and posts and by the low surface mass density of the 1.92-cm-thick plywood. Increasing the number of plywood layers or plywood thickness and paying careful attention to details to avoid cracks should raise the transmission loss such that transmission through the barriers should not affect the insertion loss. With these adjustments, the 10-dBA minimum insertion loss for plywood barriers can be achieved.

Insertion losses for glued-laminated barriers were 15 and 16 dBA at 3.1 m, 11 and 14 dBA at 7.6 m, and 7 and 10 dBA at 15.3 m behind the barriers (Table 7). These results suggest that the insertion loss goal of 10 dBA is attainable by glued-laminated barriers. The transmission losses for the glued-laminated barriers were in close agreement (20 and 21 dBA). These values are plausible because of the thick (6.67-cm) glued-laminated panels used in these barriers. The 10-dBA insertion loss can be obtained without an adverse effect from noise traveling through the barrier.

In contrast, the post and panel barriers offered the most divergent set of noise attenuation results (Table 7). Several reasons can account for the variable results. Background noise masked some data from the 1.9-m-high Hutchinson River Parkway barrier, providing incomplete results. In addition, both Hutchinson River Parkway barriers were influenced by high correction factors in the normalization process. Consequently, the attenuation results should not be used to make final decisions about post and panel barriers but imply that higher attenuation values are possible. The other post and panel barrier, on Long Island Expressway, had insertion loss values of 18 dBA at 3.1 m, 11 dBA at 7.6 m, and 7 dBA at 15.3 m, and a transmission loss of 15 dBA. By improving the detailing of the barrier, both the transmission and insertion losses can be improved. Thus, post and panel barriers have attainable insertion losses of 15 or 16 dBA at 3.1 m, 13 or 14 dBA at 7.6 m, and 10 dBA at 15.3 m. Therefore, the insertion loss goal of 10 dBA is also attainable by post and panel barriers.

The transmission loss values for post and panel barriers were also masked by background noise. Available data converged to a transmission loss of approximately 15 dBA. The low transmission loss caused an insertion loss of 10 dBA to decrease by about 2 dBA. This low value was a consequence of poor detailing of these barriers. The tongue and groove panels pulled apart or the panels were separated from the posts. In either case, gaps that allow sound to travel through the barrier are avoidable with proper detailing. Because dimension lumber contains enough mass to produce a sufficient transmission loss, careful detailing should increase the transmission loss of post and panel barriers to values greater than 15 dBA.

Comparison of Design Types

The insertion and transmission losses of the different design types allowed comparison of noise attenuation. Comparisons were made among wood barriers and between wood and concrete barriers.

Most of the A-weighted insertion losses reported in Table 7 satisfied the 10-dBA minimum insertion loss goal. The only barrier that did not satisfy this goal at 3.1 and 7.6 m behind the barrier was the I-83 plywood barrier. The insertion losses suffered from the lengthy distance between this barrier and the road/sound source. Because insertion loss at a constant receiver location behind the barrier decreases as the distance between the sound source and barrier increases, the insertion losses of the I-83 barrier at the three receiver locations were less than the 10-dBA insertion loss goal. The insertion losses at 15.3 m behind the barrier averaged 12 dBA for the precast concrete and post and panel barriers and 10 dBA for the plywood and glued-laminated barriers. One precast concrete barrier, the I-695 barrier, did not satisfy the 10-dBA insertion loss goal. The plywood barriers on I-83 and I-95 suffered from acoustic leaks and low surface mass density that can be corrected by careful detailing; that is, the poor performance should not be attributed to the material. Thus, all insertion losses of the I-83 plywood barrier and the insertion loss at 15.3 m behind the I-95 barrier did not satisfy the insertion loss goal of 10 dBA. The only glued-laminated barrier that did not satisfy the 10-dBA insertion loss goal was the I-495 barrier. The post and panel on the Long Island Expressway also suffered from acoustic leaks, causing an insertion loss of 7 dBA at 15.3 m behind the barrier, well below the insertion loss goal. The two Hutchinson River Parkway barriers, however, suffered from "over normalization" as a result of their geometries, causing insertion losses of 15 and 12 dBA, well above the insertion loss goal. Thus, the insertion losses, determined from the in situ measurements presented here for the Route 7 glued-laminated barrier and Hutchinson River Parkway post and panel barriers were similar to the losses for the I-95, I-78, and Route 24 concrete barriers. All these barriers satisfied the 10-dBA insertion loss goal at 3.1, 7.6, and 15.3 m behind the barrier. The I-695 concrete barrier, the I-95 and I-83 plywood barriers, the I-495 glued-laminated barrier, the Madison cement-bonded composite panel, and the Long Island Expressway post and panel barrier had similar insertion losses. These barriers that did not satisfy the 10-dBA insertion loss goal as a result of detailing, low surface mass, and large distances between sound source and barrier.

The average transmission loss for the four concrete barriers and two glued-laminated barriers was 20 dBA. For the two plywood barriers and three post and panel barriers, the average transmission loss was 15 dBA. The values for the concrete and glued-laminated barriers were high enough to have little impact on the insertion losses. The low values for the plywood barriers were caused by the low surface mass of plywood. Poor detailing also contributed to low transmission loss values for the plywood barriers as well as the post and panel barriers. The panels pulled apart to create gaps, which can be avoided through proper detailing.

Public Acceptance

Public acceptance of the various types and designs of sound barriers focused on the public perception of visual compatibility. This involved asking individuals to evaluate computer-edited images of sound barriers using a series of rating scales. This testing allowed for a wide variety of design choices to be narrowed down so that general design guidelines for barriers could be established.

Selection of Design Types

The computer-generated images, which were presented in 35-mm slides, were designed for evaluation of the general appearance of wood barriers rather than the appearance of specific barrier design types. This was done because the casual observer cannot distinguish between plywood, timber, and glued-laminated barriers, whether viewed from the residential or highway side. This is particularly the case when the highway side is viewed from a fast-moving car. Thus, the images varied in barrier layout and panel orientation rather than finish or detail.

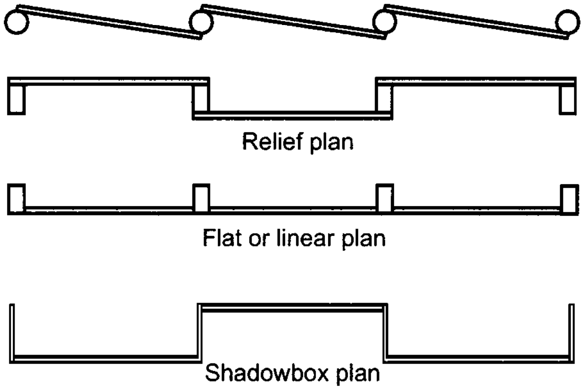


Figure 4—Barrier layout plans for public acceptance evaluation.

Variations of barrier layout were a flat or linear plan, relief plan, and shadowbox plan (Fig. 4). In the flat plan, the posts and panels were centered on a single line. In the relief plan, the posts were centered on a single line and the panels were connected in two ways: (1) alternately to the front and back of the posts or (2) alternately front-to-front and back-to-back of the posts. The shadowbox plan was similar to the relief plan except that additional panels were installed to deepen the relief. Panel orientation considered variations in the elevation of the barriers. Variations included wide and narrow strips, horizontal and vertical strips, and combinations of these strips (Fig. 5).

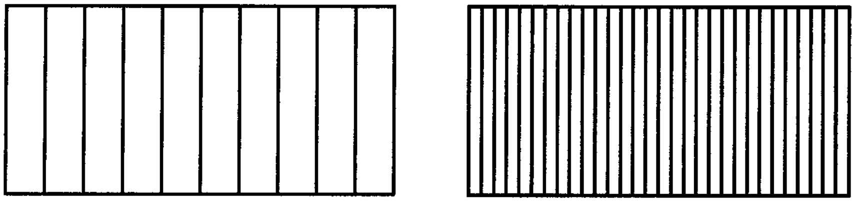
All variations in barrier layout and elevation were developed after reviewing designs of existing barriers. Given the wide variety of designs, the objective was to include most of the feasible barrier designs in the public acceptance evaluation.

To compare the public acceptance of various wood barriers as opposed to concrete barriers, slides of precast concrete barriers were created, using the three layout variations and standard wide horizontal panels. For example, slide F11 showed a barrier constructed of wide horizontal panels in the relief plan layout, viewed from the front or highway side. A matrix of the various barrier designs was developed for comparing the wood and concrete barriers (Table 9). A total of 36 slides was used for the evaluation; in half the slides, the barrier is viewed from the front and in the remainder, from the back.

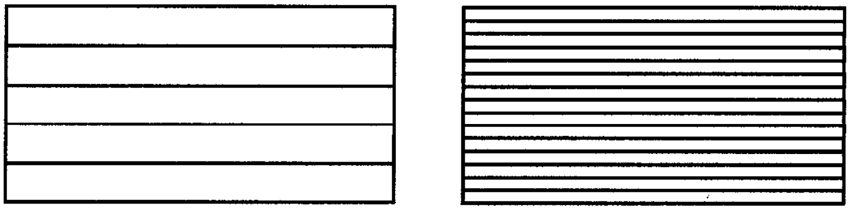
Slides

Modeling

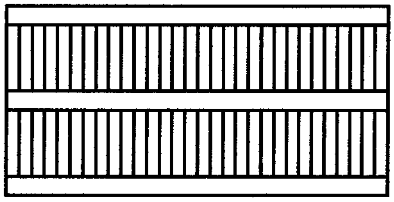
All slides for the public acceptance evaluation were created using an IBM compatible personal computer. Different types of barriers were modeled using AutoCAD Release 12 (Autodesk, Inc., San Rafael, California).



Elevations with vertical orientation of wide and narrow strips



Elevations with horizontal orientation of wide and narrow strips



Elevation with combination
(horizontal and vertical)
orientation of strips

Figure 5—Panel orientation variations for public acceptance evaluation.

The models were created as three-dimensional objects, which were then rendered by imposing texture, color, and lighting. Each model included three or four bays of the barrier. To ensure that panel orientation and width were distinguishable, strips were placed between panels, creating recesses that created shadows between panels when the model was rendered with a light source. The models were then placed in two views with perspectives similar to those of two background slides. At the same time, two general light sources were imposed on the model to simulate sunlight, illuminating the side facing the viewer.

Rendering

To render the models, the rendering menu in AutoCAD was replaced by the Autovision package by Autodesk (Autodesk, Inc., San Rafael, California). This package allowed for colors and textures to be scanned from slides of existing barriers and applied to the models. The scanned colors and textures were saved as a targa (.tga) file, which is acceptable as a texture file by Autovision. This texture file was manipulated within Autovision to adjust material properties such as reflectivity and roughness. The file was then applied to the AutoCAD model. Care was taken to ensure that the grain of the texture was parallel with the orientation of the panel or post. Finally, the barrier was rendered using the raytracing method and saved as a targa file.

Table 9—Matrix of barrier designs for public acceptance evaluation[a]

	Barrier type		
Panel orientation and size	Flat	Relief	Shadow box
Vertical, wide strips	F1 / B1	F2 / B2	F3 / B3
Horizontal, narrow strips	F4 / B4	F5 / B5	F6 / B6
Vertical, narrow strips	F7 / B7	F8 / B8	F9 / B9
Horizontal, wide strips	F10 / B10	F11 / B11	F12 / B12
Vertical and horizontal	F13 / B13	F14 / B14	F15 / B15
Concrete	F16 / B16	F17 / B17	F18 / B18

[a] Numbers are codes that identify the slides; F and B refer to front (highway) side and back (residential) side of the barrier, respectively. These letters were then applied to each box in the matrix, which had a number.

Creating

The goal was to create slides of barriers that appeared as realistic as possible. Each computer-rendered image was imported into the image-editing program PhotoStyler (Aldus Corp., Seattle, WA) and superimposed on a background slide. Using the barrier in the background slide, the brightness, contrast, perspective, and size of the rendering were adjusted to match the rest of the slide. The rendering was then copied, pasted, and enlarged or reduced to cover the barrier in the slide. The top edge of the barrier was sharpened and the bottom edge was blended with the landscape to create the appearance that the barrier actually belonged in the slide. The finished slide was saved for importing into a presentation program. The end result of the photography, modeling, rendering, image editing, and formatting was 36 slides of barriers, including views from both the highway and residential sides. Reproductions of these slides are presented in Appendix B and are labeled with the codes presented in Table 9.

Testing

Setup

The 36 computer-edited slides were used to evaluate the appearance of highway sound barriers. Twenty-four study participants rated the 36 slides using semantic-differential (SD) rating scales and individual rating scales. The participants were divided into three groups of eight each. Each group rated all 36 slides using the SD scales and a select group of slides using the individual rating scales. The SD and individual rating scales were used in separate sessions to limit the time of each session and so maximize the ability of the participants to concentrate on the scales. Within each session, the slides were divided into two sets: barriers viewed from the highway side and those viewed from the residential side. Each study group was first presented with the highway-side views and asked to rate the barriers from the perspective of a driver. After a 5-min break, each group was presented with the residential-side views and asked to rate the barriers from the perspective of a homeowner living next to the barrier. The goal was to determine if varying perspectives would result in different ratings.

The study participants included undergraduate students, graduate students, and staff members from Pennsylvania State University, as well as people employed elsewhere in State College, Pennsylvania. The students were from throughout the United States and the world, including Guatemala, France, Canada, Venezuela, Australia, and India. The participants ranged from 20 to 40 years of age; the majority were 25 to 30. All study groups were read the same set of instructions, given the same set of forms to read and sign, and presented with the same examples of sound barriers and the same set of slides.

(1)appropriate :____:____:____:____:____:____:____: inappropriate
(2)pleasant :____:____:____:____:____:____:____: foreboding
(3)confining :____:____:____:____:____:____:____: spacious
(4)attractive :____:____:____:____:____:____:____: unattractive
(5)acceptable :____:____:____:____:____:____:____: unacceptable
(6)intimidating :____:____:____:____:____:____:____: inviting
(7)imposing :____:____:____:____:____:____:____: unimposing
(8)satisfactory :____:____:____:____:____:____:____: unsatisfactory
(9)gloomy :____:____:____:____:____:____:____: cheerful
(10)darkening :____:____:____:____:____:____:____: lightening
(11)bright :____:____:____:____:____:____:____: dim
(12)dreary :____:____:____:____:____:____:____: cheerful
(13)distinctive :____:____:____:____:____:____:____: ordinary
(14)offensive :____:____:____:____:____:____:____: unoffensive
(15)distracting :____:____:____:____:____:____:____: focusing
(16)appealing :____:____:____:____:____:____:____: unappealing
(17)interesting :____:____:____:____:____:____:____: uninteresting
(18)safe :____:____:____:____:____:____:____: unsafe
(19)fortifying :____:____:____:____:____:____:____: weakening
(20)secluded :____:____:____:____:____:____:____: exposed
(21)private :____:____:____:____:____:____:____: public
(22)cluttered :____:____:____:____:____:____:____: uncluttered
(23)rural :____:____:____:____:____:____:____: urban
(24)harmonious :____:____:____:____:____:____:____: clashing
(25)environmentally friendly :____:____:____:____:____:____:____: environmentally hostile

Figure 6—Example of semantic-differential scales used for public acceptance evaluation.

Semantic-Differential Rating Scales

The SD scales were used for the first evaluation session. These scales have been used successfully in the evaluation of subjective responses to lighting systems (Flynn 1977) and for other aspects of the built environment (Rohles 1971). The SD scales consisted of a set of bipolar adjectives and a seven-point rating scale; example SD scales are presented in Figure 6. A response closest to the adjective on the left was given a rating of 1 and a response closest to the adjective on the right a rating of 7. If neither adjective described or was applicable to the barrier, a rating of 4 was recorded.

The SD scales were designed to elicit specific responses to attributes of various barrier designs. The scales were an attempt to identify all the factors involved in an opinion about a sound barrier design. The responses were statistically analyzed to determine how many factors influenced them and which barrier attributes caused these responses. The numbers on the scales were not included on the test instrument and were later incorporated as reference codes for analysis. For example, the acceptable/unacceptable rating scale was designated scale 5 (Fig. 6).

Table 10—Semantic-differential scale mean results of sound barriers viewed from highway side, group 1

	Mean rating for various barrier designs[a]																	
Scale	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18
1	3.63	4.38	3.63	3.13	3.25	5.38	4.00	3.75	4.38	3.00	3.25	4.25	3.75	3.63	4.88	4.13	3.25	3.75
2	4.13	3.88	4.13	3.13	4.00	5.25	3.50	3.25	4.75	3.00	3.25	4.25	3.38	3.38	4.75	4.00	3.38	4.00
3	3.25	3.75	3.13	3.88	4.13	3.63	4.00	4.13	3.88	4.38	4.25	3.25	4.13	3.50	3.75	3.88	4.13	4.38
4	3.63	3.88	3.75	3.25	3.25	5.38	4.13	3.75	4.00	3.25	2.88	4.13	3.88	3.38	5.00	4.63	3.75	4.13
5	3.00	3.50	3.75	3.00	2.75	5.50	3.38	3.00	3.88	2.75	2.75	4.00	3.25	3.25	4.38	3.63	3.00	3.63
6	4.25	4.13	3.63	4.00	3.13	1.88	3.63	4.00	2.75	3.88	4.50	3.00	4.25	4.00	3.38	3.88	4.13	3.13
7	4.13	4.13	3.50	4.38	2.63	1.63	3.63	4.00	2.88	3.25	4.25	3.00	4.25	3.38	3.38	4.25	3.75	3.13
8	2.88	3.38	3.63	3.13	3.38	5.38	3.38	3.13	4.13	3.00	2.63	4.00	3.50	3.50	5.00	3.63	3.25	3.63
9	3.75	3.75	3.00	3.88	4.00	3.00	4.13	4.00	3.25	3.63	4.88	3.38	3.88	4.00	3.13	3.50	4.38	3.75
10	3.00	2.88	2.88	4.00	2.75	2.50	4.63	3.13	2.75	3.25	4.00	3.50	3.75	2.88	2.75	5.00	5.00	4.88
11	5.00	4.63	4.88	4.38	4.75	5.38	3.88	4.63	5.00	4.38	3.75	4.50	4.25	4.50	5.38	2.75	2.75	2.75
12	3.50	3.25	3.63	3.63	3.75	2.88	4.00	3.38	2.88	3.50	4.00	3.38	3.63	3.75	2.88	4.00	4.13	3.88
13	3.38	4.50	2.25	3.25	2.63	2.38	3.38	3.25	1.75	3.38	3.88	2.88	3.38	2.75	2.75	5.38	3.75	3.13
14	4.88	4.50	4.25	4.63	4.50	2.50	4.75	4.50	3.63	4.63	5.00	3.88	4.50	4.25	3.38	4.50	4.50	3.88
15	3.50	3.75	3.38	4.00	3.75	2.13	3.13	3.50	2.13	4.00	3.63	3.13	3.75	3.00	2.63	4.88	5.00	3.75
16	3.50	4.13	3.63	3.50	3.50	5.25	3.88	3.25	3.75	3.25	2.88	4.00	3.63	2.88	5.00	3.75	3.50	3.88
17	3.38	4.13	2.88	3.13	3.25	3.38	3.50	3.63	3.13	3.50	3.00	3.25	4.00	2.50	4.13	5.13	3.63	3.13
18	3.50	3.13	3.38	2.50	2.50	4.13	3.13	3.13	3.13	2.88	3.38	2.63	3.25	3.00	3.63	2.63	2.13	2.50
19	3.50	3.38	2.38	3.13	2.75	2.13	3.25	3.25	2.38	3.13	2.88	2.38	3.38	2.63	2.88	2.88	1.75	1.63
20	3.88	3.13	3.13	3.38	4.50	3.25	3.63	3.38	3.50	3.25	3.38	3.38	3.63	3.25	3.25	4.25	3.75	3.75
21	3.75	4.00	3.63	3.75	3.25	3.38	3.50	3.88	3.25	3.50	3.38	3.38	3.63	3.13	3.63	4.88	4.00	4.63
22	4.63	4.38	4.38	4.38	5.25	2.63	4.13	4.25	2.50	5.38	4.50	3.13	3.75	4.25	3.25	5.50	4.13	3.88
23	4.13	4.25	4.13	4.38	4.63	3.38	4.13	4.13	4.25	3.13	3.63	4.63	3.63	4.50	3.75	5.25	6.25	5.38
24	4.63	4.13	4.00	3.50	4.25	5.50	4.00	4.38	4.38	3.38	3.63	4.00	4.25	3.25	5.00	4.38	4.25	4.38
25	4.25	3.63	3.63	3.75	3.13	5.25	4.00	3.75	3.88	3.38	3.25	4.13	3.75	3.25	4.5	4.13	4.75	4.50

[a] See Table 9 for description of barriers.

Principal component factor analysis and analysis of covariance (ANCOVA) were used to determine which scales were used in a consistent manner and what was the statistical significance of the results. (The statistical analyses and their results are explained in the section on analysis of rating scales.) The results of the SD scales were also used to select slides for evaluation by individual rating scales. The slides selected were those that drew favorable responses on the SD scales for both the highway and residential perspectives. For comparison purposes, the concrete barriers that received the most favorable responses and the most unfavorable responses were used for the individual ratings.

The ratings were converted into points (rating 1 = 1 point, rating 2 = two points, etc.), resulting in 20,700 responses. Group means were computed for each slide and response. The resulting values are listed in Tables 10–12 for the highway-side views and in Tables 13–15 for the residential-side views. These values were then analyzed using principal components factor analysis. This analysis determined the number of factors that caused the variance between slide ratings. Even though many factors may have been involved in causing the variance, it was usually possible to determine a few factors that explained a majority of the variances. When the factors and the scales that constitute these factors were identified, the scales that made up each factor for each subject were averaged. The averaged results for each factor and slide were then subjected to an ANCOVA to determine if variations between the averaged results were statistically significant.

Table 11—Semantic-differential scale mean results of sound barriers viewed from the highway side, group 2

	Mean rating for various barrier designs[a]																	
Scale	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18
1	3.75	3.13	4.00	4.25	4.88	5.00	4.13	4.00	4.25	3.75	3.50	4.38	3.75	3.88	4.88	4.00	4.13	4.88
2	4.13	3.00	4.25	4.13	4.88	5.38	3.98	3.63	4.63	3.88	3.88	4.88	3.88	4.25	5.25	3.88	4.13	4.88
3	4.13	4.50	3.50	4.13	3.63	3.13	4.50	4.88	3.63	4.00	4.25	3.13	3.50	3.63	3.25	4.75	4.25	4.00
4	4.50	3.38	4.38	4.63	5.38	4.75	3.88	4.25	5.00	4.00	3.63	4.75	4.25	4.38	4.88	3.88	4.00	5.25
5	4.13	3.00	4.25	4.13	4.88	5.00	4.13	3.88	4.00	3.88	3.50	4.75	4.50	4.00	4.75	3.75	3.88	4.63
6	4.00	4.38	3.50	4.00	3.63	3.50	4.00	4.50	3.75	4.00	3.88	3.13	4.00	4.00	3.13	3.50	3.75	3.63
7	4.00	4.63	3.25	3.75	4.00	3.38	4.00	3.88	3.50	3.88	3.88	3.13	3.75	4.00	3.38	3.63	3.63	2.75
8	4.25	3.25	4.38	4.00	4.88	4.88	3.88	3.75	4.13	3.88	3.25	4.88	4.25	4.00	5.13	3.88	4.13	4.63
9	4.25	3.63	4.25	4.00	3.13	2.50	4.25	4.63	3.13	3.88	3.88	3.25	3.25	3.38	2.75	4.38	4.63	3.25
10	4.25	3.13	3.88	3.88	2.25	1.88	4.50	4.88	2.75	3.00	3.75	3.25	3.13	3.38	2.50	5.63	5.75	5.63
11	4.50	4.63	4.00	4.38	5.25	5.63	3.63	3.63	4.88	4.75	4.00	4.50	4.88	4.50	5.25	3.00	3.13	3.13
12	4.25	4.13	3.88	3.63	3.00	2.75	4.38	4.25	3.25	4.25	4.00	3.13	3.25	3.75	3.00	4.25	4.25	3.63
13	4.88	3.75	3.13	4.00	3.13	2.50	4.13	4.13	3.13	3.75	4.13	3.13	4.63	4.00	3.38	5.25	4.75	4.25
14	4.88	4.88	4.25	4.13	3.75	2.50	4.25	4.50	3.63	4.63	5.00	3.38	3.88	4.13	4.50	4.25	4.38	3.38
15	4.38	3.75	3.75	3.88	4.00	3.38	3.88	3.75	3.75	4.13	4.13	4.00	4.25	3.88	3.75	4.00	4.13	4.00
16	4.38	3.50	4.13	4.25	4.50	4.63	4.13	3.88	4.63	3.88	4.00	4.75	4.88	4.25	4.75	4.25	4.38	5.00
17	4.75	3.50	4.00	4.38	3.88	4.00	4.00	4.38	3.50	4.50	4.13	3.88	4.50	4.38	3.88	3.88	4.25	3.88
18	4.00	3.38	4.00	2.88	3.13	4.00	3.50	2.88	3.00	3.13	2.75	2.88	4.00	3.50	3.88	2.75	2.50	2.75
19	4.13	3.13	3.63	2.75	3.00	2.63	3.13	3.00	3.00	3.25	3.00	2.38	3.75	3.25	3.13	2.38	2.00	2.25
20	4.13	3.88	3.50	3.88	3.63	3.50	3.88	3.63	3.38	3.75	4.25	3.75	3.88	3.13	3.63	4.00	3.88	4.13
21	4.38	3.63	3.38	4.38	3.38	3.25	4.38	4.13	3.00	3.50	3.63	3.63	3.75	3.88	3.63	4.38	4.50	3.75
22	4.63	3.88	3.63	4.00	3.50	3.25	4.50	4.25	3.75	4.75	4.75	3.63	3.75	3.38	3.38	4.88	4.63	3.88
23	4.38	4.13	4.25	4.88	4.63	5.25	5.25	5.13	4.00	3.38	4.38	4.75	3.25	3.50	3.88	6.13	5.88	5.88
24	3.75	3.25	5.00	4.00	4.13	4.63	4.25	4.25	4.13	3.88	3.50	4.50	4.00	3.75	4.50	4.38	4.00	4.63
25	3.88	3.00	4.50	4.38	4.25	4.63	4.13	4.00	3.50	3.75	3.25	4.25	3.88	4.00	4.00	4.38	4.13	4.63

[a] See Table 9 for description of barriers.

Individual Rating Scales

Fourteen of the 36 slides rated by the SD scales were selected for evaluation by individual rating scales. These slides were shown again to the study groups, who were asked to rate the barriers on the basis of their own personal criteria. The individual rating scales were aimed at obtaining an overall impression of the barriers and the SD scales at obtaining subjective impressions of specific areas.

The individual rating scales were quite simple. Participants were asked to rate each design on a scale from 1 to 10, with the rating relative to all the other designs shown. As for the SD scales, this procedure was repeated twice, once for the barriers viewed from the highway side and once for those viewed from the residential side.

Analysis of covariance was used to determine the statistical significance of differences between averaged ratings of groups. The individual ratings evaluated slides of wood barriers that had been rated favorable on the SD scales and, for comparison, slides of concrete barriers that had received the most and least favorable ratings. The ANCOVA determined whether the differences between favorable and unfavorable ratings, and between ratings for wood and concrete barriers, were statistically significant. Thus, the individual rating scales served as a check of the findings obtained by the SD scales. If the responses of the individual rating scales reinforced the findings of the SD scales, then the SD scales were given more validity. If the individual rating scales and SD scales did not show the same trend, it was inferred that the SD scales did not identify the correct responses or factors involved in personal evaluation of barrier designs.

Table 12—Semantic-differential scale mean results of sound barriers viewed from the highway side, group 3

	Mean rating for various barrier designs[a]																	
Scale	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18
1	4.29	3.43	4.86	4.43	4.71	5.00	5.29	5.14	4.29	4.29	4.29	4.57	4.14	4.57	4.71	4.71	5.29	5.00
2	4.57	3.14	4.86	4.29	5.00	5.00	4.86	5.29	4.14	4.57	4.43	4.57	4.57	4.57	4.86	5.57	5.57	5.29
3	3.43	3.57	2.86	3.43	2.86	2.57	3.14	3.57	3.43	3.00	3.14	3.43	3.29	3.14	3.29	2.71	2.71	3.00
4	4.86	3.43	4.57	4.57	4.86	5.14	5.14	5.57	4.29	4.86	4.57	4.29	4.57	4.57	5.00	5.86	5.57	6.00
5	4.14	3.14	3.86	4.14	4.43	4.71	4.86	5.00	3.71	4.00	4.00	4.00	3.86	4.14	4.29	4.57	4.29	5.43
6	3.43	4.00	3.43	3.71	3.00	2.43	3.43	3.29	4.00	3.29	3.4,3	3.14	3.57	3.57	2.86	2.57	2.71	2.29
7	3.57	4.57	3.00	3.43	2.86	2.14	2.71	2.71	3.57	3.29	3.86	3.29	3.43	3.29	3.14	2.43	2.43	2.14
8	4.29	3.14	4.29	4.14	4.43	5.00	4.57	5.14	3.86	4.29	4.29	3.43	4.29	4.71	4.29	4.57	4.57	4.71
9	3.57	4.14	3.29	3.14	2.71	2.57	3.86	3.71	3.00	3.14	3.43	3.29	3.00	3.00	2.57	3.14	3.29	3.14
10	3.57	3.71	3.57	3.00	2.14	2.14	3.86	3.86	2.86	3.00	3.29	3.00	3.00	2.57	2.29	4.71	4.86	4.86
11	3.86	4.14	4.29	4.86	5.29	5.00	4.00	4.14	5.00	4.86	4.43	4.29	4.71	5.29	5.14	3.29	3.00	3.00
12	3.29	4.29	3.14	3.29	3.00	2.43	3.71	3.29	3.29	3.00	3.29	3.57	3.14	2.86	2.71	3.29	3.29	3.00
13	3.71	3.43	3.29	4.29	3.29	2.86	3.86	3.57	2.86	4.71	4.00	3.29	4.14	4.14	3.14	5.43	5.43	3.86
14	3.57	4.71	3.57	3.14	2.86	3.14	2.71	3.00	4.00	3.14	3.43	3.86	3.14	3.57	3.57	2.86	3.29	2.43
15	3.29	4.14	2.86	3.43	2.86	2.57	2.43	2.14	3.14	3.00	3.14	3.14	3.14	.3.29	2.57	3.57	3.14	2.14
16	4.43	3.57	4.43	5.00	4.86	5.43	5.43	5.43	4.29	5.00	4.36	4.29	4.57	4.86	4.86	5.86	5.43	5.86
17	4.43	3.86	3.71	5.14	4.29	4.14	4.29	4.57	3.43	4.86	4.29	3.86	4.71	4.71	4.00	5.71	5.29	5.29
18	3.57	3.86	3.71	3.43	3.71	3.43	4.29	4.14	3.29	3.14	4.00	4.00	3.86	4.00	3.57	3.14	3.43	3.43
19	3.57	3.29	3.14	3.14	3.14	2.71	4.00	4.00	2.86	3.29	3.43	2.86	3.29	3.29	3.00	2.86	2.71	2.71
20	4.57	3.29	3.86	2.86	3.57	3.57	4.29	4.29	3.14	3.14	3.43	3.43	3.71	3.29	3.57	3.71	5.57	4.43
21	4.14	3.00	3.86	3.71	3.43	4.00	4.43	4.29	3.00	3.00	3.43	3.29	3.29	3.29	3.71	3.43	4.71	4.14
22	3.43	4.57	3.71	3.57	3.43	3.57	3.43	3.00	3.29	3.57	3.43	3.29	2.71	3.14	2.57	4.86	4.43	2.86
23	4.00	3.00	3.43	3.57	3.57	3.86	4.71	4.86	3.71	3.43	3.57	3.14	3.29	3.57	3.71	5.71	6.29	6.43
24	4.57	3.29	4.43	4.86	4.57	5.43	5.29	5.43	4.29	4.71	4.57	4.29	4.57	5.00	4.86	5.29	5.29	5.71
25	4.14	3.43	4.14	3.71	3.86	4.57	4.14	4.43	4.14	3.86	1 86	3.71	3.57	3.86	3.86	4.43	4.00	4.57

[a] See Table 9 for description of barriers.

The slides for individual rating included highway and residential views of seven barrier designs: F2/B2, F4/B4, F6/B6, F10/B10, F11/B11, F13/B13, and F17/B17. Slides F2/B2, F4/B4, F10/B10, F11/B11, and F13/B13 received favorable responses for both the highway and residential sides. Slides F6/B6 received the most negative responses, and slides F17/B17 of the concrete barrier design received the most favorable responses. Results of individual rating by slide and study participant are presented in Table 16. An analysis of variance (ANOVA) was performed on the means and individual values to determine the statistical significance of differences between the group responses and among the results.

Analysis of Rating Scales

Principal Components Factor Analysis of Semantic-Differential Ratings

The group averages of the SD scales for each slide were subjected to a principal components factor analysis (Flynn and others 1979). This analysis statistically determined the subsets of rating scales that were used in similar or consistent ways by the study participants. A group of scales evaluated in a consistent manner had high intercorrelation; that is, consistent rankings of alternatives resulted in high intercorrelation. Strong differences in individual ratings of factors were not required. When the mean values of the ratings were

Table 13—Semantic-differential scale mean results of sound barriers as viewed from the residential side, group 1

Scale	Mean rating for various barrier designs[a]																	
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18
1	3.63	3.63	4.75	3.25	3.63	4.13	2.88	4.13	4.63	3.00	3.13	4.50	3.13	3.75	5.00	4.50	4.75	5.23
2	3.50	3.00	4.75	3.13	4.38	4.38	2.88	3.50	4.63	3.13	3.63	4.63	3.25	3.63	5.00	4.50	4.50	5.38
3	3.75	4.13	3.63	4.00	4.00	3.13	2.88	3.63	3.25	3.00	3.50	3.00	3.38	3.63	3.25	2.50	2.25	3.75
4	3.50	3.63	4.50	3.75	4.50	4.50	3.50	3.50	4.38	3.25	3.25	4.50	3.75	4.00	5.13	4.63	5.00	5.75
5	3.50	3.38	4.50	3.25	3,63	4.00	2.88	3.50	4,38	3.00	2.88	4.13	3.13	3.13	4.88	4.25	4.63	5.38
6	3.38	4.50	3.25	4.38	3.88	3.00	4.25	3.88	3.00	4.25	3.88	2.88	4.38	4.25	2.88	3.25	3.25	2.25
7	3,63	4.63	2.50	4.13	4.13	4.00	4.13	4.13	3.38	3.88	4.00	3.00	4.38	3.75	3.63	3.38	3.00	2.38
8	3.25	3.25	5.00	3.13	3.75	4.00	3.13	3.00	4.25	2.88	3.13	4.13	3.13	3.38	5.13	4.50	4.63	5.13
9	4.00	3.88	3.13	4.00	2.63	3.00	4.63	4.25	3.25	4.00	3.88	3.25	3.88	4.25	3.13	3.63	3.75	3.25
10	4.25	4.00	3.38	4.13	2.50	2.88	4.75	4.50	3.00	3.38	3.88	2.88	4.25	3.88	3.00	5.38	5.25	5.00
11	3.50	4.25	4.50	3.88	5.13	5.00	3.50	3.63	5.00	3.88	4.13	4.75	3.75	4.63	5.00	2.63	2.50	2.88
12	4.00	3.88	3.25	4.13	3.13	3.00	4.50	4.00	3.50	3.75	3.88	3.25	4.25	4.25	3.13	3.75	3.75	3.63
13	4.00	4.25	3.13	3.50	3.88	2.88	2.88	3.63	2.75	3.75	3.00	2.88	3.38	3.38	2.50	3.75	3.50	3.50
14	4.38	5.13	3.25	4.38	3.75	2.88	4.38	4.13	3.88	4.88	4.75	2.88	4.50	4.38	2.88	3.75	3.88	3.50
15	3.50	4.50	3.13	3.88	4.00	3.25	4.00	3.50	3.38	4.25	3.88	3.25	4.00	3.88	2.63	3.63	3.38	3.25
16	3.88	3.25	4.75	3.50	4.50	4.50	3.13	3.63	4.38	3.38	3.63	4.50	3.13	3.00	5.13	4.50	4.88	5.50
17	4.50	4.00	3.75	3.38	4.25	2.75	3.25	3.63	3.50	3.75	3.00	3.38	3.50	3.50	3.50	4.88	4.13	4.38
18	3.75	3.38	2.88	2'.75	3.13	3.00	3.00	2.88	3.13	3.00	2.88	3.00	3.38	2.63	3.38	2.38	2.50	2.50
19	3.50	3.13	2.38	3.13	3.38	2.50	3.13	3.25	3.00	3.38	3.00	2.50	3.13	2.63	2.25	2.00	2.25	2.13
20	3.50	3.00	3.13	3.38	2.88	3.50	3.63	3.50	3.50	2.88	3.38	2.88	3.38	3.00	3.38	3.63	3.63	3.63
21	3.75	3.00	3.13	2.88	2.75	3.38	3.00	3.13	3.38	2.63	3.25	3.25	2.88	2.75	3.00	4.50	4.25	4.38
22	4.38	4.25	3.88	4.38	4.25	4.25	4.13	4.13	3.88	4.25	4.25	3.88	3.63	3.88	3.00	5.13	4.63	3.63
23	3.88	3.13	4.38	3.38	3.50	4.25	3.88	3.75	4.13	2.75	3.50	3.63	2.88	3.00	3.50	5.63	5.50	5.75
24	3.88	2.75	4.38	2.88	3.75	4.00	3.50	3.75	4.63	3.63	3.50	4.13	3.50	3.63	4.50	4.88	5.00	5.63
25	3.38	3.00	4.50	3.25	3.88	3.38	3.38	3.38	4.00	3.75	3.25	4.00	3.63	3.75	3.63	5.38	5.13	5.38

[a] See Table 9 for description of barriers.

calculated, these factor subsets were plotted so that alternatives being tested could be directly compared. Their validity was shown if scales that should have a high intercorrelation consistently ranked alternatives in a similar manner. Reasons for inconsistent rankings must be determined.

The results given in Tables 10 to 15 were analyzed using the principal components factor analysis in the statistical program Minitab. Seven components, or factors, were computed for both views (highway and residential sides) of the barriers. Although the analysis determined all the factors, only the seven factors that caused the most variance between barrier ratings were displayed. This analysis identified the three factors that caused most of the variations, thereby eliminating the need for identifying the remainder of the factors.

The results of the analysis included the loadings that each scale had on each factor. Loadings were values ranging between 1 and –1, with the absolute value of the loading being the measure of intercorrelation. Positive and negative loadings were due to the organization of the terms (adjectives) in each SD scale. In some scales, the positive adjective appeared on the left side and in others, on the right side. A negative loading indicated that ratings favored the adjective on the left and a positive loading that ratings favored the adjective on the right. Thus, 0.9 and –0.9 had a high loading of the same value. The loadings for seven factors for barriers viewed from the highway side and residential side are presented in Tables 17 and 18, respectively.

Table 14—Semantic-differential scale mean results of sound barriers as viewed from the residential side, group 2

	Mean rating for various barrier designs[a]																	
Scale	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18
1	3.75	3.13	4.00	4.25	4.88	5.00	4.13	4.00	4.25	3.75	3.50	4.38	3.75	3.88	4.88	4.00	4.13	4.88
2	4.13	3.00	4.25	4.13	4.88	5.38	3.88	3.63	4.63	3.88	3.88	4.88	3.88	4.25	5.25	3.88	4.13	4.88
3	4.13	4.50	3.50	4.13	3.63	3.13	4.50	4.88	3.63	4.00	4.25	3.13	3.50	3.63	3.25	4.75	4.25	4.00
4	4.50	3.38	4.38	4.63	5.38	4.75	3.88	4.25	5.00	4.00	3.63	4.75	4.25	4.38	4.88	3.88	4.00	5.25
5	4.13	3.00	4.25	4.13	4.88	5.00	4.13	3.88	4.00	3.88	3.50	4.75	4.50	4.00	4.75	3.75	3.88	4.63
6	4.00	4.38	3.50	4.00	3.63	3.50	4.00	4.50	3.75	4.00	3.88	3.13	4.00	4.00	3.13	3.50	3.75	3.63
7	4.00	4.63	3.25	3.75	4.00	3.38	4.00	3.88	3.50	3.88	3.88	3.13	3.75	4.00	3.38	3.63	3.63	2.75
8	4.25	3.25	4.38	4.00	4.88	4.88	3.88	3.75	4.13	3.88	3.25	4.88	4.25	4.00	5.13	3.88	4.13	4.63
9	4.25	3.63	4.25	4.00	3.13	2.50	4.25	4.63	3.13	3.88	3.88	3.25	3.25	3.38	2.75	4.38	4.63	3.25
10	4.25	3.13	3.88	3.88	2.25	1.88	4.50	4.88	2.75	3.00	3.75	3.25	3.13	3.38	2.50	5.63	5.75	5.63
11	4.50	4.63	4.00	4.38	5.25	5.63	3.63	3.63	4.88	4.75	4.00	4.50	4.88	4.50	5.25	3.00	3.13	3.13
12	4.25	4.13	3.88	3.63	3.00	2.75	4.38	4.25	3.25	4.25	4.00	3.13	3.25	3.75	3.00	4.25	4.25	3.63
13	4.88	3.75	3.13	4.00	3.13	2.50	4.13	4.13	3.13	3.75	4.13	3.13	4.63	4.00	3.38	5.25	4.75	4.25
14	4.88	4.88	4.25	4.13	3.75	2.50	4.25	4.50	3.63	4.63	5.00	3.38	3.88	4.13	4.50	4.25	4.38	3.38
15	4.38	3.75	3.75	3.88	4.00	3.38	3.88	3.75	3.75	4.13	4.13	4.00	4.25	3.88	3.75	4.00	4.13	4.00
16	4.38	3.50	4.13	4.25	4.50	4.63	4.13	3.88	4.63	3.88	4.00	4.75	4.88	4.25	4.75	4.25	4.38	5.00
17	4.75	3.50	4.00	4.38	3.88	4.00	4.00	4.38	3.50	4.50	4.13	3.88	4.50	4.38	3.88	3.88	4.25	3.88
18	4.00	3.38	4.00	2.88	3.13	4.00	3.50	2.88	3.00	3.13	2.75	2.88	4.00	3.50	3.88	2.75	2.50	2.75
19	4.13	3.13	3.63	2.75	3.00	2.63	3.13	3.00	3.00	3.25	3.00	2.38	3.75	3.25	3.13	2.38	2.00	2.25
20	4.13	3.88	3.50	3.88	3.63	3.50	3.88	3.63	3.38	3.75	4.25	3.75	3.88	3.13	3.63	4.00	3.88	4.13
21	4.38	3.63	3.38	4.38	3.38	3.25	4.38	4.13	3.00	3.50	3.63	3.63	3.75	3.88	3.63	4.38	4.50	3.75
22	4.63	3.88	3.63	4.00	3.50	3.25	4.50	4.25	3.75	4.75	4.75	3.63	3.75	3.38	3.38	4.88	4.63	3.88
23	4.38	4.13	4.25	4.88	4.63	5.25	5.25	5.13	4.00	3.38	4.38	4.75	3.25	3.50	3.88	6.13	5.88	5.88
24	3.75	3.25	5.00	4.00	4.13	4.63	4.25	4.25	4.13	3.88	3.50	4.50	4.00	3.75	4.50	4.38	4.00	4.63
25	3.88	3.00	4.50	4.38	4.25	4.63	4.13	4.00	3.50	3.75	3.25	4.25	3.88	4.00	4.00	4.38	4.13	4.63

[a] See Table 9 for description of barriers.

The three factors that caused most variance in the ratings were named for identification purposes as evaluative, environmental, and physical (Tables 17 and 18). The scales corresponding to emotional responses (such as appropriate/inappropriate, pleasant/foreboding, and attractive/unattractive) were named evaluative. The scales concerned with the effect of the barrier design on the surrounding (such as darkening/lightening, bright/dim, public/private, and rural/urban) were given the name environmental. Finally, the scales concerned with impressions of the personal state of being caused by the barrier design (fortifying/weakening and safe/unsafe) were named physical.

The evaluative, environmental, and physical factors caused 75.7% of the variance in the ratings of the highway-side views and 76.4% of the variance in those of the residential-side views. These factors were evaluated by the same SD scales from both sides, indicating that the factors were the same for the two sides. Because the remainder of the factors from both views only explained about 4% or less of the variances, the evaluative, environmental, and physical factors were used for the remainder of this analysis and the analysis of variance.

The loadings of the scales on the evaluative, environmental, and physical factors were examined more closely to determine which loadings were significant. Loadings of approximately ±0.7 and greater were considered high. Loadings close to the high limit were judged subjectively. If the loading of a scale was close to the limit and the scale

Table 15—Semantic-differential scale mean results of sound barriers as viewed from the residential side, group 3

	Mean rating for various barrier designs[a]																	
Scale	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18
1	4.29	3.43	4.86	4.43	4.71	5.00	5.29	5.14	4.29	4.29	4.29	4.57	4.14	4.57	4.71	4.71	5.29	5.00
2	4.57	3.14	4.86	4.29	5.00	5.00	4.86	5.29	4.14	4.57	4.43	4.57	4.57	4.57	4.86	5.57	5.57	5.29
3	3.43	3.57	2.86	3.43	2.86	2.57	3.14	3.57	3.43	3.00	3.14	3.43	3.29	3.14	3.29	2.71	2.71	3.00
4	4.86	3.43	4.57	4.57	4.86	5.14	5.14	5.57	4.29	4.86	4.57	4.29	4.57	4.57	5.00	5.86	5.57	6.00
5	4.14	3.14	3.86	4.14	4.43	4.71	4.86	5.00	3.71	4.00	4.00	4.00	3.86	4.14	4.29	4.57	4.29	5.43
6	3.43	4.00	3.43	3.71	3.00	2.43	3.43	3.29	4.00	3.29	3.43	3.14	3.57	3.57	2.86	2.57	2.71	2.29
7	3.57	4.57	3.00	3.43	2.86	2.14	2.71	2.71	3.57	3.29	3.86	3.29	3.43	3.29	3.14	2.43	2.43	2.14
8	4.29	3.14	4.29	4.14	4.43	5.00	4.57	5.14	3.86	4.29	4.29	3.43	4.29	4.71	4.29	4.57	4.57	4.71
9	3.57	4.14	3.29	3.14	2.71	2.57	3.86	3.71	3.00	3.14	3.43	3.29	3.00	3.00	2.57	3.14	3.29	3.14
10	3.57	3.71	3.57	3.00	2.14	2.14	3.86	3.86	2.86	3.00	3.29	3.00	3.00	2.57	2.29	4.71	4.86	4.86
11	3.86	4.14	4.29	4.86	5.29	5.00	4.00	4.14	5.00	4.86	4.43	4.29	4.71	5.29	5.14	3.29	3.00	3.00
12	3.29	4.29	3.14	3.29	3.00	2.43	3.71	3.29	3.29	3.00	3.29	3.57	3.14	2.86	2.71	3.29	3.29	3.00
13	3.71	3.43	3.29	4.29	3.29	2.86	3.86	3.57	2.86	4.71	4.00	3.29	4.14	4.14	3.14	5.43	5.43	3.86
14	3.57	4.71	3.57	3.14	2.86	3.14	2.71	3.00	4.00	3.14	3.43	3.86	3.14	3.57	3.57	2.86	3.29	2.43
15	3.29	4.14	2.86	3.43	2.86	2.57	2.43	2.14	3.14	3.00	3.14	3.14	3.14	3.29	2.57	3.57	3.14	2.14
16	4.43	3.57	4.43	5.00	4.86	5.43	5.43	5.43	4.29	5.00	4.86	4.29	4.57	4.86	4.86	5.86	5.43	5.86
17	4.43	3.86	3.71	5.14	4.29	4.14	4.29	4.57	3.43	4.86	4.29	3.86	4.71	4.71	4.00	5.71	5.29	5.29
18	3.57	3.86	3.71	3.43	3.71	3.43	4.29	4.14	3.29	3.14	4.00	4.00	3.86	4.00	3.57	3.14	3.43	3.43
19	3.57	3.29	3.14	3.14	3.14	2.71	4.00	4.00	2.86	3.29	3.43	2.86	3.29	3.29	3.00	2.86	2.71	2.71
20	4.57	3.29	3.86	2.86	3.57	3.57	4.29	4.29	3.14	3.14	3.43	3.43	3.71	3.29	3.57	3.71	5.57	4.43
21	4.14	3.00	3.86	3.71	3.43	4.00	4.43	4.29	3.00	3.00	3.43	3.29	3.29	3.29	3.71	3.43	4.71	4.14
22	3.43	4.57	3.71	3.57	3.43	3.57	3.43	3.00	3.29	3.57	3.43	3.29	2.71	3.14	2.57	4.86	4.43	2.86
23	4.00	3.00	3.43	3.57	3.57	3.86	4.71	4.86	3.71	3.43	3.57	3.14	3.29	3.57	3.71	5.71	6.29	6.43
24	4.57	3.29	4.43	4.86	4.57	5.43	5.29	5.43	4.29	4.71	4.57	4.29	4.57	5.00	4.86	5.29	5.29	5.71
25	4.14	3.43	4.14	3.71	3.86	4.57	4.14	4.43	4.14	3.86	3.86	3.71	3.57	3.86	3.86	4.43	4.00	4.57

[a]See Table 9 for description of barriers.

appeared similar to other scales evaluating a factor, the scale was considered as evaluating that factor. If the loading of a scale was close to the limit and the scale appeared dissimilar to other scales evaluating a factor, the scale was considered as not evaluating that factor and was eliminated. For barriers viewed from the highway side, the scales 13, 17, 18, 22, and 25 were eliminated. For barriers viewed from the residential side, the scales 3, 9, 13, 17, 20, 22, and 25 were eliminated. These scales were apparently interpreted in different ways. For example, a positive response to scale 17 (interesting/uninteresting) could mean that the barrier is interesting in itself or that it creates an interesting effect on the surroundings.

The mean values of scales contributing to the evaluative, environmental, and physical factors were calculated to determine whether there were any trends in the responses (Tables 17 and 18). The results are graphed in Figures 7 to 12. Overall, the results were more distinctive for the barriers that received negative ratings than for those that received positive ratings. The negative ratings were consistent for certain barriers, whereas the positive ratings were given to several types of barriers. The group means of the barriers favored by the majority were slightly lowered by unfavorable ratings from a few participants, causing the results to be less distinctive.

Table 16—Individual rating scale results and means

	Individual rating for various barrier designs[a]													
	Highway side[c]							Residential side[d]						
Code[b]	F2	F4	F6	Fl0	F11	F13	F17	B2	B4	B6	B10	B11	B13	B17
2A-1	5	4	3	5	6	4	6	7	2	4	6	6	4	3
2A-2	7	6	4	6	6	5	7	6	5	2	7	4	4	3
2A-3	8	10	1	9	8	3	5	8	8	1	10	9	9	1
2A-4	8	9	7	9	9	6	4	8	4	2	7	6	3	1
2A-5	5	8	1	6	4	2	9	4	8	3	9	7	6	1
2A-6	6	9	1	8	3	3	8	7	8	3	9	5	3	5
2A-7	8	9	3	10	5	6	1	9	7	3	7	6	6	1
2A-8	2	6	5	7	6	8	7	6	5	3	5	8	5	3
2B-1	5	8	9	8	7	4	1	8	7	9	10	7	4	2
2B-2	5	6	3	6	5	5	6	6	7	4	6	7	5	3
2B-3	6	4	3	4	5	7	2	7	4	3	4	5	6	2
2B-4	8	5	10	4	6	4	10	9	7	4	8	4	10	10
2B-5	7	1	1	1	2	2	7	9	2	1	2	2	1	1
2B-6	7	4	5	6	8	9	3	9	3	8	5	7	7	4
2B-7	7	4	4	4	6	8	5	5	5	3	6	7	8	7
2B-8	5	4	4	6	5	6	8	5	7	3	6	7	8	8
2C-1	4	6	1	7	3	5	9	6	5	1	8	3	7	2
2C-2	6	3	1	3	2	3	4	4	5	1	4	3	6	3
2C-3	6	8	5	9	9	7	2	6	5	7	6	6	2	1
2C-4	2	7	1	8	9	4	10	2	8	1	10	9	3	4
2C-5	7	8	4	8	9	6	2	9	5	1	4	6	3	3
2C-6	7	6	2	7	5	4	8	9	7	3	8	9	4	1
2C-7	8	9	4	6	7	5	6	10	5	8	8	6	3	7
2C-8	5	7	7	8	6	6	4	7	6	8	6	4	5	1
Mean	**6.00**	**6.29**	**3.71**	**6.46**	**5.88**	**5.08**	**5.58**	**6.92**	**5.63**	**3.58**	**6.71**	**5.906**	**5.08**	**3.21**

[a] See Table 9 for description of barriers.
[b] Subject identification code where first number is session number, letter is subject group, and second number is subject number.
[c] Slides of barriers viewed from highway side.
[d] Slides of barriers viewed from residential side.

One tendency was the dislike of the shadowbox plan layout. Except for slide F3, all slides of the shadowbox design received negative ratings. Both views of this barrier design (F3 and B3) needed to receive favorable ratings to consider the design as likely to be accepted by the public. Because B3 received negative ratings, F3 was also grouped with the rest of the shadowbox designs as unfavorable.

Another tendency was the less favorable response towards precast concrete barriers. Among the six slides of concrete barriers (F16 to 18, B16 to 18), only F17 received favorable evaluative responses. For comparison purposes, slides F17/B17 were included in the individual rating scales to check this assumption. Even though the concrete barriers were rated as "bright" and "lightening," these barriers did not receive more favorable evaluative responses. The concrete barriers were rated as more "fortifying" and "urban" than the wood barriers. They also received negative evaluative responses, which indicated that the color of a barrier can only help, but not cause, the barrier to be acceptable. Noting that the only wood barriers rated as "lightening" and "bright" were F7 and B7, this tendency was reinforced. This barrier design did not receive as many positive responses as did some other designs. This study suggests that a light finish on a wood barrier is more favorably received than a darker finish. Therefore, the value of the finish on a wood barrier is a factor that merits additional investigation.

Analysis of Variance of S–D Rating Scales

Results from the SD ratings and the principal components analysis were used to determine critical differences in value. The critical differences were determined in two steps. First, the mean of the scales contributing to a factor was determined. Second, these means were subjected to an ANCOVA with post hoc tests to determine which means have critical differences.

Table 17—Semantic-differential scale loadings, highway-side views

	Factors[a]						
Scale[b]	Evaluative	Environmental	Physical	4	5	6	7
Appropriate/inappropriate	–0.914	–0.153	–0.026	–0.094	0.080	0.058	–0.027
Pleasant/foreboding	–0.932	–0.142	0.008	0.096	–0.035	0.141	0.098
Confining/spacious	0.729	–0.224	0.141	–0.284	0.252	0.060	0.098
Attractive/unattractive	–0.892	–0.304	–0.131	0.068	0.111	0.018	0.027
Acceptable/unacceptable	–0.883	–0.183	–0.064	–0.093	0.273	0.109	0.197
Intimidating/inviting	0.801	0.073	–0.349	–0.058	0.282	0.065	–0.133
Imposing/unimposing	0.769	0.135	–0.381	0.023	0.325	0.101	–0.179
Satisfactory/unsatisfactory	–0.894	–0.109	–0.047	–0.028	0.244	0.154	0.191
Gloomy/cheerful	0.747	–0.379	–0.027	–0.399	–0.020	–0.140	0.130
Darkening/lightening	0.308	–0.873	0.078	–0.122	0.013	–0.245	0.042
Bright/dim	–0.281	0.861	–0.136	0.048	0.133	0.244	0.028
Dreary/cheerful	0.785	–0.412	0.084	–0.219	0.046	–0.076	0.281
Distinctive/ordinary	0.113	–0.685	–0.560	0.286	0.014	–0.200	–0.024
Offensive/unoffensive	0.910	0.045	–0.078	–0.036	0.009	0.174	0.021
Distracting/focusing	0.686	–0.297	–0.153	0.392	0.353	0.192	0.143
Appealing/unappealing	–0.889	–0.273	–0.220	0.091	0.048	–0.090	0.077
Interesting/uninteresting	–0.427	–0.490	–0.618	0.266	0.034	–0.159	–0.048
Safe/unsafe	–0.518	0.330	–0.550	–0.415	–0.027	–0.021	0.119
Fortifying/weakening	–0.013	0.215	–0.872	–0.263	–0.137	0.052	–0.013
Secluded/exposed	–0.113	–0.682	–0.119	–0.098	–0.466	0.444	0.072
Private/public	0.038	–0.781	–0.097	–0.218	0.014	0.269	–0.370
Cluttered/uncluttered	0.693	–0.368	–0.096	0.289	–0.191	0.107	0.142
Rural/urban	–0.032	–0.826	0.353	0.045	0.020	0.147	–0.026
Harmonious/clashing	–0.845	–0.226	0.015	–0.127	–0.086	–0.127	–0.176
Environmentally friendly/ environmentally unfriendly	–0.568	–0.414	0.303	–0.200	0.441	–0.009	–0.094
Variance	**11.274**	**5.237**	**2.430**	**1.098**	**1.027**	**0.684**	**0.491**
Percentage of variance[c]	**45.1**	**20.9**	**9.7**	**4.4**	**4.1**	**2.7**	**2.0**

[a] Factors identified by principal components factor analysis; highlighted items identify high loadings on a factor.

[b] See Figure 6 for example of scales.

[c] Percentage of the total variance accounted by this factor.

The means of six factors—three critical factors (evaluative, environmental, and physical) for each set of two slides (highway and residential views)—were determined solely to reduce the ANCOVA necessary to analyze the responses. Rather than conducting an ANCOVA for each of the 20,700 individual responses, pooling the results across the six factors reduced the responses to a much more manageable 138 mean values. Because of the high intercorrelation of these six factors, the 138 mean values were a good representation of the important SD scale responses. Therefore, performing an ANCOVA on each of these six factors was a satisfactory way to conduct an ANCOVA across the entire set of SD scale responses.

An ANCOVA was conducted to determine if any mean of a study group was significantly different from the other group means and if any mean of a slide was significantly different from that of the other slides. Because the ANCOVA is an omnibus test, it did not specify which group mean was significantly different from the others nor did it specify which slide mean was significantly different than the others. It only called attention to significant variations in the results. An *F*-test was conducted to determine if there was significant variation between the group and slide means at a significance level of 0.05. A Tukey HSD (honestly significant difference) post hoc test was used to determine significant differences between individual means (Stoline 1981).

Table 18—Semantic-differential scale loadings, residential-side views

	Factors[a]						
Scale[b]	Evaluative	Environmental	Physical	4	5	6	7
appropriate/inappropriate	–0.928	–0.028	0.050	–0.024	–0.157	0.005	–0.026
pleasant/foreboding	–0.955	0.041	0.019	–0.128	–0.016	–0.059	0.068
confining/spacious	0.520	–0.275	–0.196	–0.444	–0.456	–0.089	–0.378
attractive/unattractive	–0.928	–0.068	–0.035	–0.110	0.008	0.010	–0.054
acceptable/unacceptable	–0.905	–0.072	–0.006	–0.181	–0.214	0.157	0.023
intimidating/inviting	0.862	0.009	–0.182	–0.151	–0.121	0.160	–0.078
imposing/unimposing	0.878	0.147	–0.091	–0.180	–0.111	–0.019	0.051
satisfactory/unsatisfactory	–0.900	0.002	0.023	–0.226	–0.166	0.158	0.089
gloomy/cheerful	0.651	–0.585	–0.097	0.256	–0.177	0.178	–0.058
darkening/lightening	0.137	–0.917	0.094	0.225	0.031	0.046	–0.149
bright/dim	–0.037	0.880	–0.121	–0.358	–0.123	–0.040	0.066
dreary/cheerful	0.748	–0.542	–0.034	0.153	–0.144	0.145	–0.046
distinctive/ordinary	0.027	–0.612	–0.532	–0.275	0.410	–0.136	–0.164
offensive/unoffensive	0.847	–0.210	–0.076	–0.108	–0.098	0.111	0.180
distracting/focusing	0.733	–0.245	0.053	–0.482	0.090	0.128	0.241
appealing/unappealing	–0.942	–0.074	–0.131	–0.101	0.105	–0.062	–0.054
interesting/uninteresting	–0.469	–0.376	–0.540	–0.169	0.443	0.140	–0.104
safe/unsafe	–0.208	0.441	–0.748	0.180	–0.143	0.123	0.114
fortifying/weakening	0.231	0.295	–0.827	0.161	–0.014	0.186	0.089
secluded/exposed	–0.351	–0.551	–0.399	0.146	–0.269	–0.421	0.269
private/public	–0.425	–0.692	–0.266	–0.016	–0.279	–0.026	0.153
cluttered/uncluttered	0.466	–0.627	0.170	–0.161	0.276	–0.055	0.334
rural/urban	–0.490	–0.762	0.117	–0.126	–0.175	–0.119	–0.002
harmonious/clashing	–0.992	–0.154	–0.062	0.154	0.030	0.146	–0.058
environmentally friendly/ environmentally unfriendly	–0.676	–0.411	0.263	–0.080	–0.062	0.466	0.096
Variance	**11.576**	**5.219**	**2.308**	**1.143**	**1.076**	**0.698**	**0.572**
Percentage of variance[c]	**46.3**	**20.9**	**9.2**	**4.6**	**4.3**	**2.8**	**2.3**

[a] Factors identified by principal components factor analysis; highlighted items identify high loadings on a factor.
[b] See Figure 4 for example of scales.
[c] Percentage of the total variance accounted by this factor.

Results of the ANCOVA are presented in Tables 19 to 21 for barriers viewed from the highway side and Tables 22 to 24 for barriers viewed from the residential side. Each table presents an ANCOVA for one of the six factors identified by the SD scales. The ANCOVA determined the *F*-test values for the variations between slides and between participant groups for each slide. Using a significance level of 0.05, the critical *F*-values for the slides and groups were determined to be 1.65 and 1.45, respectively. Although all factors from both views had significant variations between slides, two factors (the environmental factor for the highway side and the evaluative factor for the residential side) had significant variations between groups. Significant variations between slides were an expected result of the scales. The scales were designed to help determine which barrier design types were preferred and why they were preferred. With the factors identified by the principal components factor analysis, the individual rating scales were established to test whether or not these factors determined the participant's overall impression of the barrier designs. At the same time, the individual rating scales were established to test the preliminary design guidelines, which embody the tendencies of the SD ratings. The significant variation between study groups, however slight, was not an expected result and necessitated closer investigation.

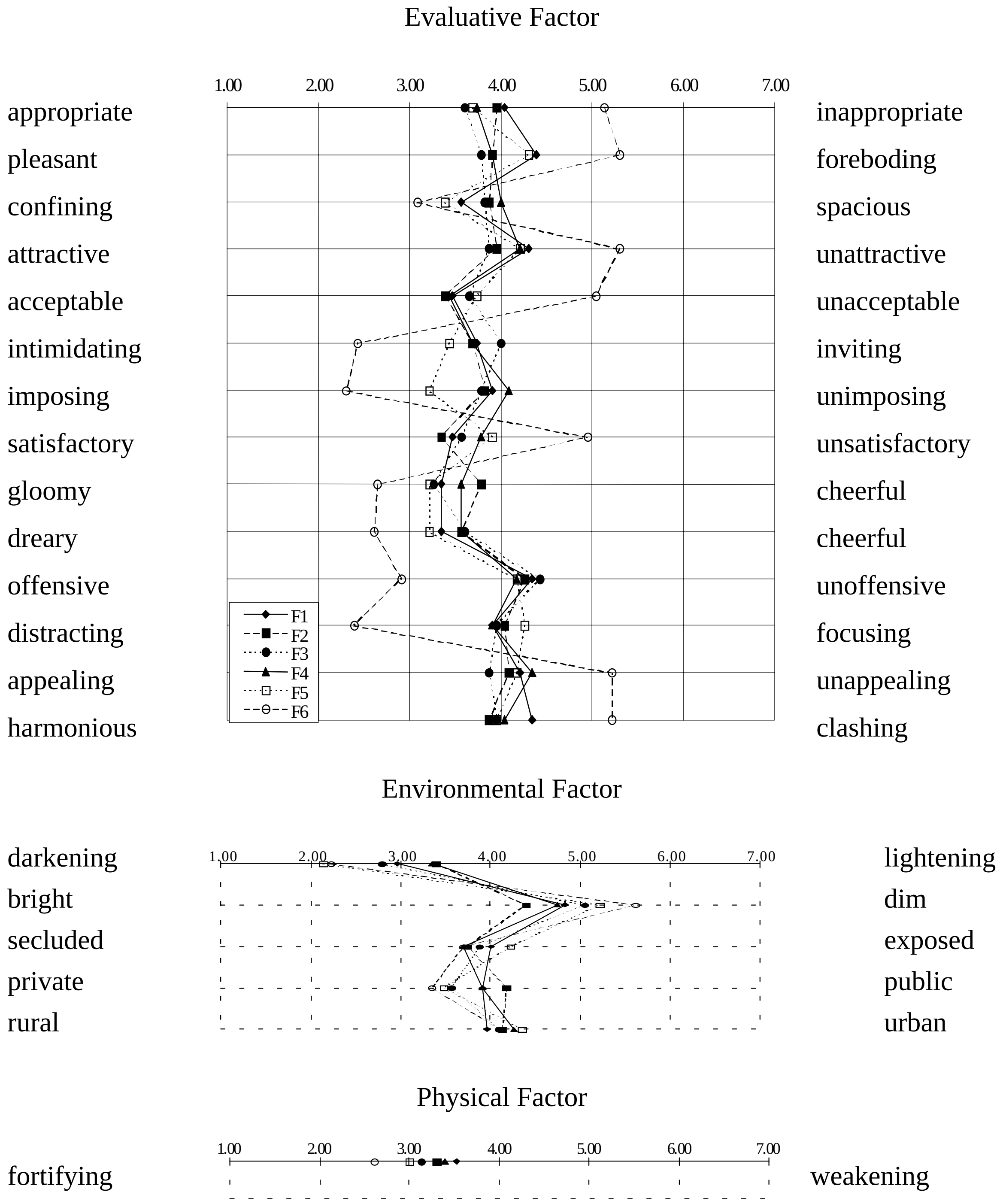
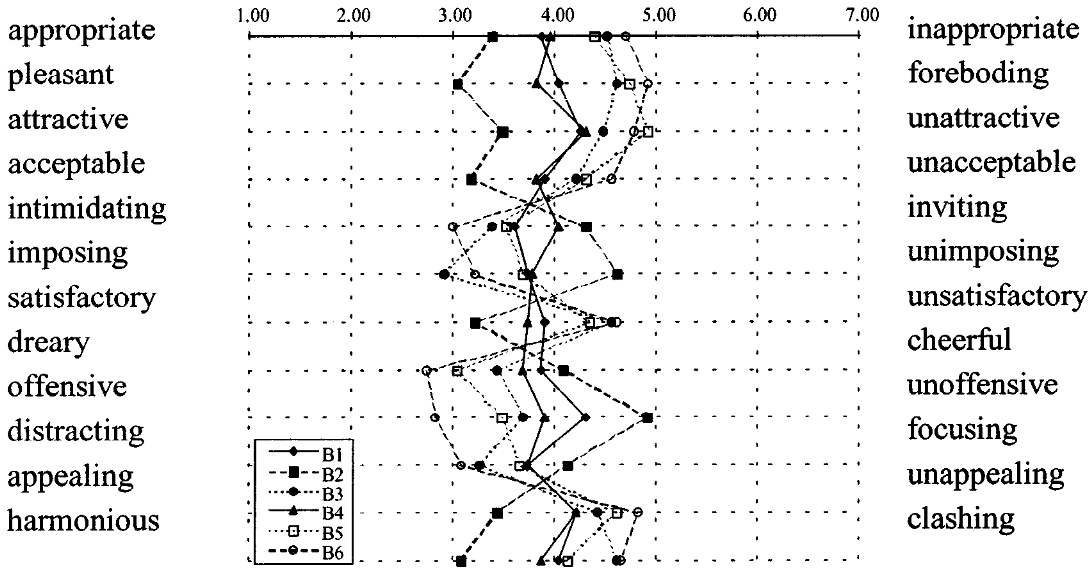
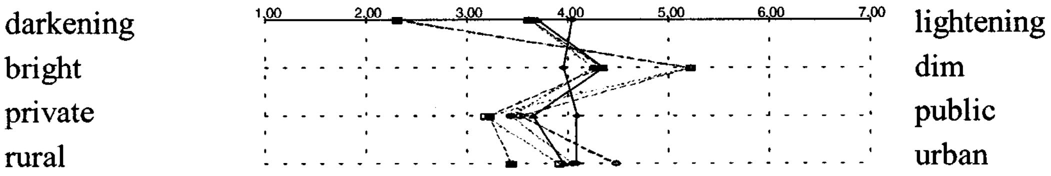


Figure 7—Results of semantic-differential scale evaluation of barriers F1 to F6 (highway-side view). Factors were identified by principal components factor analysis. Barriers are described in Table 9.

Evaluative Factor



Environmental Factor



Physical Factor

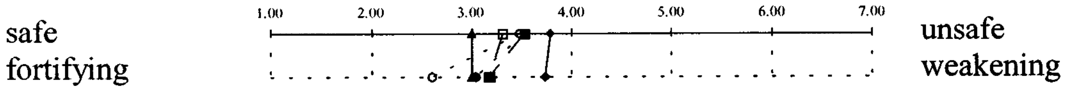


Figure 8—Results of semantic-differential scale evaluation of barriers B1 to B6 (residential-side view).

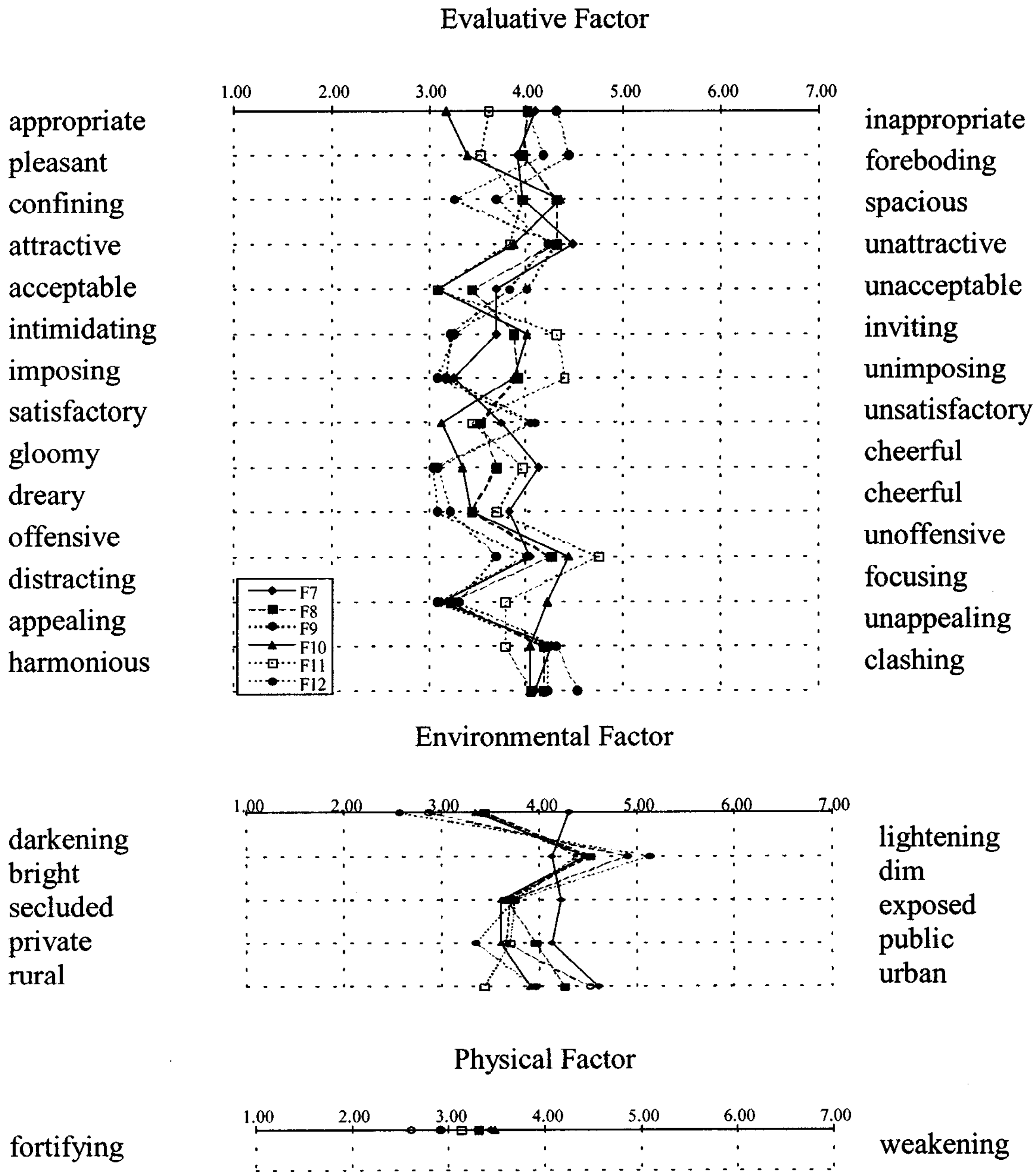


Figure 9—Results of semantic-differential scale evaluation of barriers F7 to F12 (highway-side view).

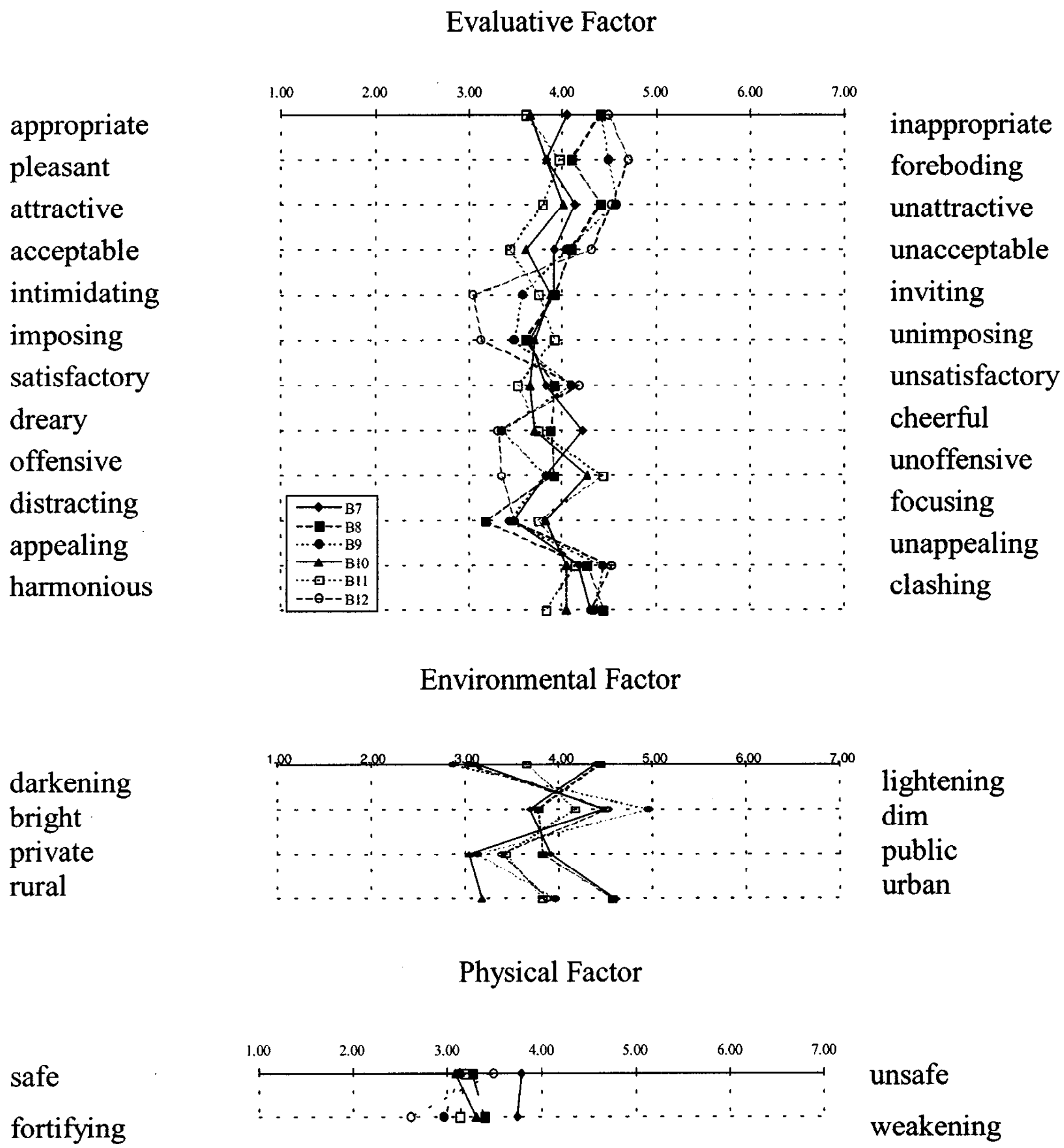
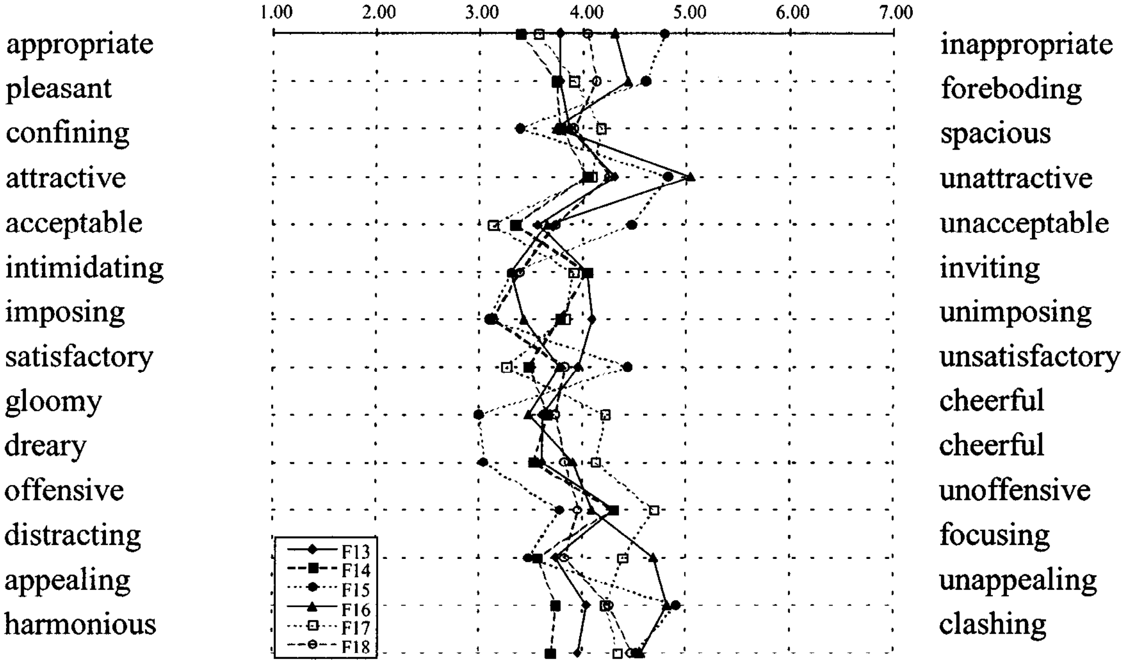
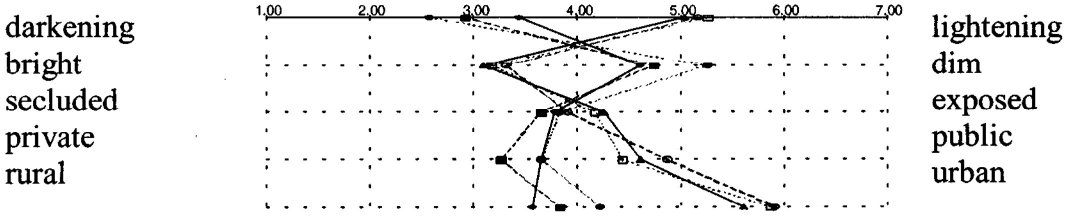


Figure 10—Results of semantic-differential scale evaluation of barriers B7 to B12 (residential-side view).

Evaluative Factor



Environmental Factor



Physical Factor

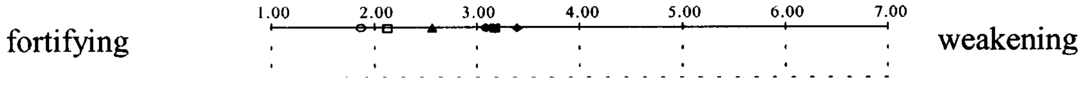
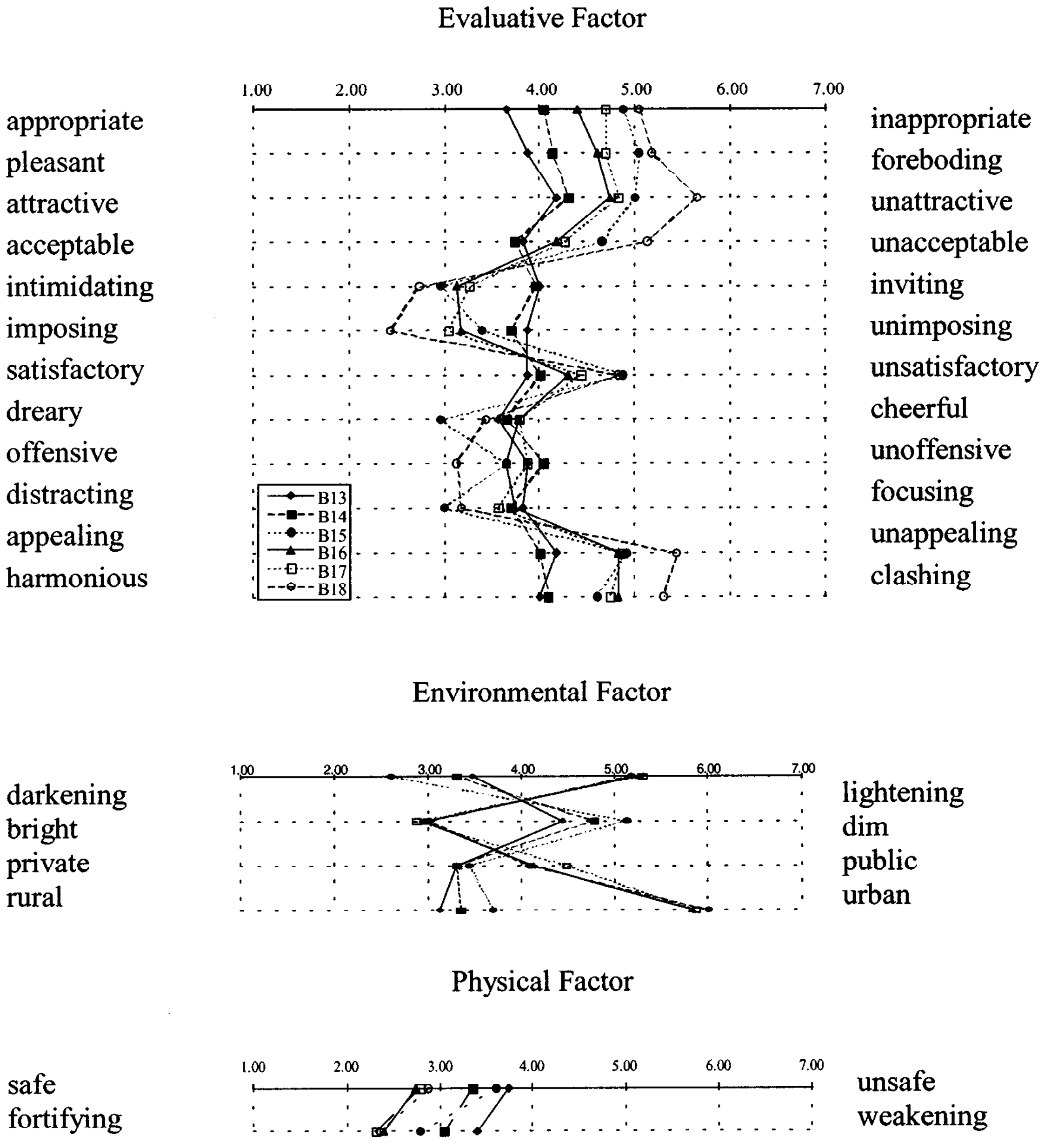


Figure 11—Results of semantic-differential scale evaluation of barriers F13 to F18 (highway-side view).



Evaluative Factor

Environmental Factor

Physical Factor

Figure 12—Results of semantic-differential scale evaluation of barriers B13 to B18 (residential-side view).

Table 19—ANCOVA of evaluative factor of SD scales, highway-side views[a]

	Result α = 0.05				
Source	DF	SS	MS	*F*	F_{cv}
Slide	17	52.958	3.1152	3.25	1.65
Group (Slide)	36	25.3688	0.7047	0.74	1.45
Error	360	344.7105	0.9575		
Total	413	423.0374			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, *F* = ANCOVA *F*-value, F_{cv} = critical *F*-value.

Table 20—ANCOVA of environmental factor of SD scales, highway-side views[a]

	Result α = 0.05				
Source	DF	SS	MS	*F*	F_{cv}
Slide	17	123.9796	7.2929	15.02	1.65
Group (Slide)	36	29.3493	0.8153	1.68	1.45
Error	360	174.8107	0.4856		
Total	413	328.1396			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, *F* = ANCOVA *F*-value, F_{cv} = critical *F*-value.

Table 21—ANCOVA of physical factor of SD scales highway-side views[a]

	Result ($\alpha = 0.05$)[a]				
Source	DF	SS	MS	F	F_{cv}
Slide	17	87.172	5.128	3.51	1.65
Group (Slide)	36	40.451	1.128	0.77	1.45
Error	360	525.375	1.459		
Total	413	652.998			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, F = ANCOVA F-value, F_{cv} = critical F-value.

Table 22—ANCOVA of evaluative factor of SD scales residential-side views[a]

	Result ($\alpha = 0.05$)[a]				
Source	DF	SS	MS	F	F_{cv}
Slide	17	67.991	3.999	3.51	1.65
Group (Slide)	36	60.967	1.694	1.49	1.45
Error	360	410.190	1.139		
Total	413	539.148			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, F = ANCOVA F-value, F_{cv} = critical F-value.

Table 23—ANCOVA of environmental factor of SD scales, residential-side views[a]

	Result $\alpha = 0.05$				
Source	DF	SS	MS	F	F_{cv}
Slide	17	190.7554	11.2209	19.21	1.65
Group (Slide)	36	13.3569	0.371	0.64	1.45
Error	360	210.317	0.5842		
Total	413	414.4294			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, F = ANCOVA F-value, F_{cv} = critical F-value.

Table 24—ANCOVA of physical factor of SD scales, residential-side views[a]

	Result $\alpha = 0.05$				
Source	DF	SS	MS	F	F_{cv}
Slide	17	42.691	2.511	1.92	1.65
Group (Slide)	36	41.875	1.163	0.89	1.45
Error	360	470.473	1.307		
Total	413	555.039			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, F = ANCOVA F-value, F_{cv} = critical F-value.

The variation between study groups was analyzed with one-way analyses of variance and Tukey post hoc tests to determine which slides had critical F-values and which groups had critical Q-values (also known as T-values). Using a significance level of 0.05, the critical values of F and Q were determined to be 3.49 and 3.58, respectively. With these values, only four values (one ANOVA F-value and three Q-values) showed significant differences. Slide F8, for the evaluative factor, had an F-value of 6.00. The reason for this critical value is the difference between groups 3 and 2, which had a Q-value of 4.93. The other two critical Q-values were for slide B4–environmental factor and slide B7–evaluative factor (Q-values of 3.58 and 3.65, respectively). For slide B4, the critical value appeared in the comparison between groups 1 and 2; for slide B7, the critical value appeared in the comparison between groups 1 and 3. Otherwise, the other F- and Q-values were not significant, indicating that the variance between group means was not significant.

The variations between slide ratings for each factor were analyzed with a Tukey post hoc test. Using a significance level of 0.05, the critical Q-value was determined to be 5.30. The graphs of the results reinforced the tendencies identified in the SD ratings. Barriers that were disliked, such as F6, had more distinctive ratings than barriers that were liked. At best, the positive response to barriers was lukewarm. Again, a simple plan layout and panel orientation for barriers were favored, and the concrete and shadowbox plans were disliked. Thus, we concluded that no significant difference in values was observed between the groups and the preliminary observations can be investigated further with the individual rating scales.

Analysis of Variance of Individual Rating Scales

The variation between individual rating scale group means was analyzed using ANCOVA with Tukey post hoc tests. The results of the ANCOVA showed no significant difference between the three study groups, but there was a significant difference between the slides. The results of the ANCOVA are presented in Table 25 for barriers viewed from the highway side and Table 26 for barriers viewed from the residential side. Each table presents an ANCOVA for individual ratings from one study group. The ANCOVA determined the F-values for the variations between slides and between study groups for each slide. Using a significance level of 0.05, the critical F-values for the slides and groups were determined to be 2.15 and 1.74, respectively. Although both the residential- and highway-side views showed significant differences between slides, neither view showed significant differences between groups.

A Tukey post hoc test was performed on the individual rating scales to determine which ratings were statistically

Table 25—ANCOVA of individual rating scales, highway-side views[a]

	Result $\alpha = 0.05$				
Source	DF	SS	MS	F	F_{cv}
Slide	6	98.917	16.486	3.08	2.15
Group (Slide)	14	85.667	6.119	1.14	1.74
Error	147	786.25	5.349		
Total	167	970.833			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, F = ANCOVA F-value, F_{cv} = critical F-value.

Table 26—ANCOVA of individual rating scales, residential-side views[a]

	Result $\alpha = 0.05$				
Source	DF	SS	MS	F	F_{cv}
Slide	6	254.952	42.492	8.54	2.15
Group (Slide)	14	56.083	4.006	0.81	1.74
Error	147	731.25	4.974		
Total	167	1,042.286			

[a] DF = degrees of freedom, SS = sum of the squares, MS = means squared, F = ANCOVA F-value, F_{cv} = critical F-value.

significant. This analysis simply determines which differences of means are statistically significant. Results are presented in Tables 27 and 28 for barriers viewed from the highway and residential sides, respectively. In these tables, the column boxhead indicates the mean of the slide being compared. A Q6 indicates the column in which the individual rating of slide F6 or B6, depending on the table, is being compared with the individual ratings of the other slides. The row where the *Q*-value is located indicates the mean of the other slide being compared.

Some differences in means were statistically significant. The mean response for slide F6 was different from that for slides F2, F4, F10, and F11 (Table 27). The mean responses for slides B6 and B17 were different from the responses for slides B2, B4, B10, and B11 (Table 28). The statistically significant ratings of slides F2/B2, F4/B4, F10/B10, and F11/B11 required that the design tendencies of the barriers illustrated in these slides be embodied in the final design guidelines. The mean responses for slides F13, F17, and B13 were not statistically different from either extreme. Because these means were close to the statistically significant ratings, these three slides helped clarify and reinforce the final design guidelines.

Table 27—Tukey post hoc test results for individual rating scales of barriers viewed from highway side ($\alpha = 0.05$)[a]

Slide[b]	Mean[c]	F6[d]	F13	F17	F11	F2	F4	Q_{CV}[e]
F6	3.71							
F13	5.08	2.98						
F17	5.58	4.06	1.09					
F11	5.88	**4.72**	1.74	0.65				
F2	6.00	**4.98**	2.00	0.91	0.26			
F4	6.29	**5.61**	2.63	1.54	0.89	0.63		
F10	6.46	**5.98**	3.00	1.91	1.26	1.00	0.37	4.22

[a] Boldface entries indicate significant difference between rating means.

[b] Barriers described in Table 9.

[c] Individual ratings scale means for slides calculated in Table 18.

[d] *Q*-value between slide ratings of column label and row label.

[e] Critical *Q*-value.

Table 28—Tukey post hoc test results for individual rating scales of barriers viewed from residential side ($\alpha = 0.05$)[a]

Slide[b]	Mean[c]	B17[d]	B6	B13	B4	B11	B10	Q_{CV}[e]
B17	3.21							
B6	3.58	0.83						
B13	5.08	4.19	3.36					
B4	5.63	**5.42**	**4.60**	1.23				
B11	5.96	**6.16**	**5.33**	1.97	0.74			
B10	6.71	**7.85**	**7.02**	3.65	2.42	1.68		
B2	6.92	**8.32**	**7.49**	4.13	2.89	2.15	0.47	4.22

[a] Boldface entries indicate significant difference between rating means.

[b] Slides defined in Table 9.

[c] Individual ratings scale means for slides calculated in Table 18.

[d] *Q*-value between slide ratings of column label and row label.

[e] Critical *Q*-value.

Comparison of Rating Scale Results

The results of the SD and individual rating evaluations were combined to observe tendencies that would aid in developing general design guidelines for wood sound barriers. The preliminary guidelines established by the SD scales were the unfavorable response towards concrete and shadowbox designs and the favorable response towards simple designs. By comparing the preliminary guidelines with the results of the individual rating scales, it was possible to determine if the individual rating scales reinforced these guidelines.

The first preliminary guideline was the dislike of the shadowbox design. This design type received negative responses on both rating scales; the barrier given the most negative ratings was depicted in slides F6/B6. Not only did the study participants dislike the appearance of the shadowbox-type barrier, they found it more “fortifying” than barriers with the same panel elements organized in the flat and relief plan layouts. Thus, shadowbox designs are not recommended for wood sound barriers from an aesthetic viewpoint.

The second preliminary guideline was the negative response towards precast concrete barriers. These barriers were rated as more “fortifying” and “urban” than the wood barriers. By including both views of the only favorably received concrete barrier (slides F17/B17) in the individual rating scales, it was possible to test this hypothesis. The residential-side view of this barrier received an unfavorable response, but the highway-side view received a favorable response. The mean rating for this slide was not statistically different from that of the slide receiving the worst rating nor was it different from that of the slide receiving the best rating. Its value, however, was closer to those of the slides given favorable responses than those given unfavorable responses. Thus, the reason for the somewhat favorable ratings of this concrete barrier needs to be investigated further.

Like the favorably rated designs of wood barriers, the design of the precast concrete barrier was simple. Its wide horizontal pattern and simple relief plan were similar to that of a wood barrier given favorable ratings. However, the material properties of concrete apparently led the study participants to give negative ratings to the same barrier viewed from the residential side. The rural background presented in the slides also could have influenced the ratings. The SD scales indicated that the concrete barriers were perceived as “urban” and wood barriers were perceived as “rural.” It was possible that the background could have biased the participants against the concrete barriers. Because wood barriers were perceived to have more “rural” qualities than concrete barriers, a rural background could have caused the participants to view wood barriers as more acceptable in the setting established. The fact that one view of a concrete barrier received a favorable rating suggests that there was not a bias against concrete per se. Nevertheless, the remainder of the responses indicated that wood barriers are more likely to be accepted by the public than are precast concrete barriers.

The final preliminary guideline from the SD scales was that the design type should be simple in plan layout and panel orientation. The four barriers given favorable responses in the individual rating scales shared this trait. These barriers were depicted in slides F2/B2, F4/B4, F10/B10, and F11/B11 (Table 9). Even though no one plan or panel layout was favored above the others, the barrier designs shown in slides F13/B13 and F17, which were given ratings close to those of the favored barriers, offered some insight into the preferred design traits. These designs used a simple flat or relief plan layout. Thus, the favorably rated barriers suggest that simplicity is important, not a specific plan layout or panel orientation. The simplicity guidelines, which lead to design guidelines for wood barriers most likely to be accepted by the public, are summarized as follows:

- Simple flat walls with either many or few elements in the elevation or relief walls with few elements in the elevation
- Barriers with many elements or a relief plan layout, but not both, to break up the monotony of long barriers
- Panels with either vertical or horizontal orientation in the elevations

Structural Requirements for Prototype Barrier

A systematic design procedure was developed to provide detailed information on the performance of wood barriers. A single prototype barrier was designed and fabricated so that a series of measurements could be conducted under more controlled conditions than was possible for the in situ measurements previously discussed. Data on acoustic effectiveness and public acceptance collected during the first phase of this project were applied to the structural requirements and construction details presented here.

Systematic Approach to Design

A system of eight wood sound barriers encompassing several design alternatives with similar details was developed. The designs included the details and plan layouts (discussed in the previous sections) that were determined to be acoustically effective and aesthetically acceptable. The fundamental design was solid-sawn timber or glued-laminated wood posts with dimensional lumber panels or manufactured glued-laminated panels. This system included three plan layouts and two panel orientations. Each sound barrier can be constructed according to one post design guideline and two different connection detail guidelines. Posts were selected from a chart that assigns a post size for a given bending and minimum shear stress. Panel materials required a minimum bending stress. Acoustic performance criteria and aesthetically acceptable formats obtained from the public acceptance evaluation were incorporated into the design details. The basic system of wood sound barriers was structurally analyzed based on the expected loading and designed accordingly.

An initial sound barrier design matrix was developed from several design styles, plan layout, and material options. This matrix, based on wood materials used for sound barriers outlined in the *Guide Specification for Wood Highway Noise Barriers* (NFPA 1985), consisted of all possible design options, plan layouts, and panel orientations that were under consideration (Table 29).

The matrix was developed to determine the sound barrier designs that could be incorporated into a systematic design approach where one standard set of design details encompassing acoustic performance and public acceptance could

Table 29—Original sound barrier design matrix

		Flush		Relief		Shadow-box
		Center-line	Flat	Flat	Skewed	
Timber plank	Vertical					
	Horizontal					
Glued-laminated	Vertical					
	Horizontal					
Plywood	Vertical					
	Horizontal					

be applied to each design option. No additional aesthetic evaluations were conducted. Individual design options were then ruled out on the basis of (1) the standards set from the acoustic effectiveness and public acceptance evaluations and (2) design details incompatible with a systematic design approach.

In the public acceptance evaluation, the following characteristics were described as aesthetically acceptable for wood sound barriers: simple flat or relief plan layout, many elements with horizontal or vertical alignment in flat format or few elements in relief format, and light in color. Specifically, a sound barrier design option was eliminated by public acceptance evaluation if it had many elements combined with the relief format and was dark in color. As a result, the shadowbox layout, which consisted of vertically and horizontally aligned elements and was typically dark in color, was eliminated from further consideration. An incompatible design option was the vertical orientation of panel elements in the relief format. Vertical panel elements required a means of attachment other than the posts, which consisted of purlins strung between the posts. Purlins on the front and back of a barrier were required in the relief format and presented awkward construction and incompatible design details. Thus, relief format options with vertically oriented panel elements were also eliminated from further consideration. Plywood had shown poor durability in field inspections and was not selected for additional investigation. The remaining design options are shown in Table 30 and the corresponding plan layouts in Figure 13.

The final design matrix (Table 30) consisted of all the design options that have common details, allowing for a systematic design approach. Specifically, the posts are the same for any design under equivalent conditions of height, spacing, and geography. The panels do not significantly differ from one configuration to another, and the system requires only two different connection details, one for timber plank and the other for a glued-laminated panel.

Table 30—Final sound barrier design matrix

		Flush	Relief	
		Flat	Flat	Skewed
Timber plank	Vertical		X	X
	Horizontal			
Glued-laminated	Vertical		X	X
	Horizontal			

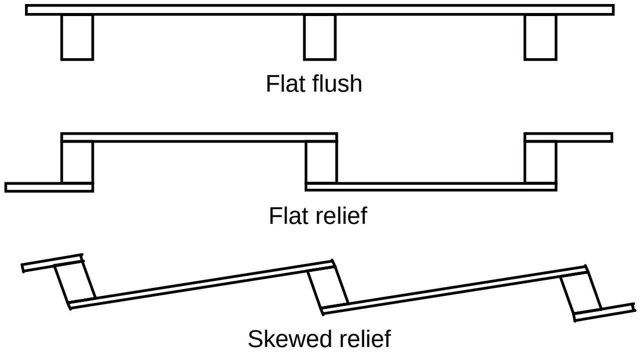


Figure 13—Plan layout options.

Considerations

The systematic design included detailing to prevent sight lines through the barrier to maintain acoustic performance and those attributes of aesthetic details reported from the public acceptance evaluation. To resist development of sight lines, tongue and groove construction, wood moisture content of less than 12% to 15%, and a light-colored preservative treatment were specified for the panel material. A cross section of a typical tongue and groove dimensional lumber plank is shown in Figure 14a. It is important to ensure a tight fit between planks when attaching them to the posts. Manufactured glued-laminated panels can also be developed with tongue and groove construction or a similar joinery arrangement such as shiplap and rabbetted to prevent sight lines from developing. The individual elements of the panels can be oriented vertically or horizontally. The elements of vertically oriented panels are edge glued and glued flatwise by layer (Fig. 14b). Horizontally oriented panels are made by sawing a wide glued-laminated beam vertically along the longitudinal axis to form two narrower beams of the same depth (Fig. 14c).

Options

Post and Panel—Posts were the same under equivalent conditions for each design option, and panels were dimensional lumber planks or manufactured glued-laminated panels. The three plan layouts shown in Figure 13 constituted the final design options. The flat flush format was used for four of the eight design options. Panels were attached to the

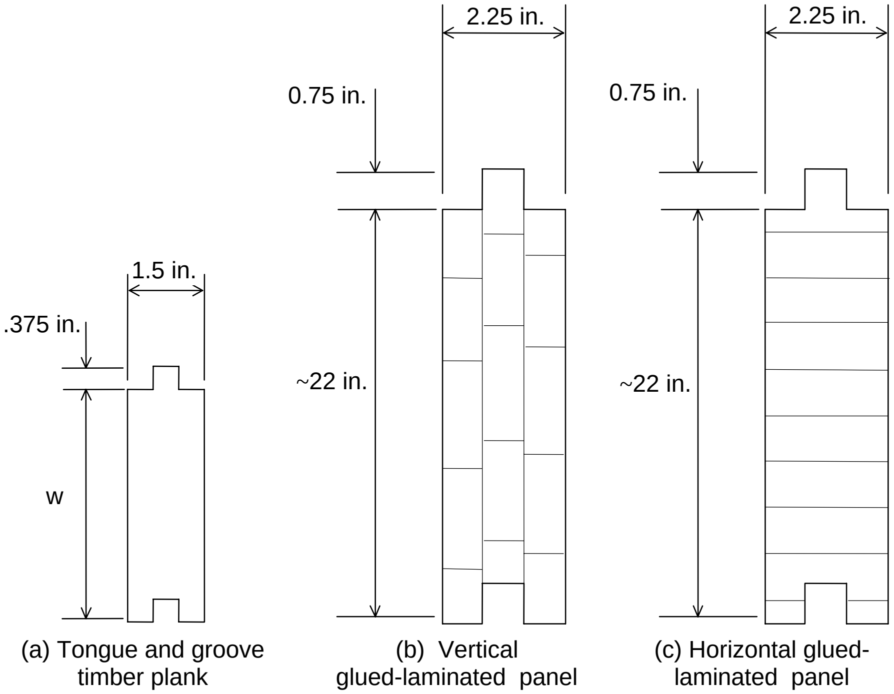


Figure 14—Options for panel elements.

highway side of the posts and parallel to the highway in horizontal or vertical alignment. In the flat relief format, the panels were aligned parallel to the highway but were alternated on the highway and residential sides of the posts. In the skewed relief option, the posts were slightly rotated with respect to the highway and the panels were alternately attached to the highway and residential sides of the posts.

From the final design option matrix, the flat flush plan with horizontally aligned timber planks combined with glued-laminated posts was selected as the test barrier. This sound barrier was structurally analyzed and designed according to the *Guide Specifications for Structural Design of Sound Barriers* (AASHTO 1989a), the *Guide Specification for Wood Highway Noise Barriers* (NFPA 1985), and the *National Design Specification for Wood Construction* (AF&PA 1991).

Connections—The connections were galvanized annularly threaded nails, wood screws, or lag bolts, as shown in Figures 15 to 18. Timber plank panels required either two 20d nails or two 76.2-mm-long wood screws on the end of each plank. Pre-boring the pilot holes made driving the nails and screws easier and helped prevent splitting of the wood. Glued-laminated panels required four 50d or 60d nails or two 127-mm-long, 15.875-mm-diameter lag bolts with washers on each panel end. Edge distances and spacing were at least 19 mm for nails and screws and 38 mm for lag bolts.

Procedure

Posts—The *Guide Specifications for Structural Design of Sound Barriers* (AASHTO 1989a) recommends the use of the *Standard Specification for Highway Bridges* (AASHTO 1989b), Section 13, Timber Structures, or the use of an industry-recognized design specification for wood sound barriers. The *National Design Specification for Wood Construction* (AF&PA 1991) was used to design the posts and panels. The posts were designed for flexure as a vertically aligned cantilever beam rigidly fixed at ground level. An alternative method was also considered—a cantilever beam having a maximum moment at a point one-third the depth of embedment below ground level. Even though a larger moment occurred below ground level, as shown in Figure 19, this method was not pursued, because the additional cross section of the concrete foundation was assumed to sufficiently increase the moment capacity of the post–pier foundation system.

Loading was based on a unit tributary area symmetrically aligned on the centerline of the post. The wind load was distributed over an equivalent single panel section according to the height and width of a panel section. The end posts were also designed in this manner so they could be compatible with the interior posts even though they had only half the tributary area. Serviceability criteria for wood structures were based on considerations of creep resulting from sustained load and limiting deflections to reasonable values.

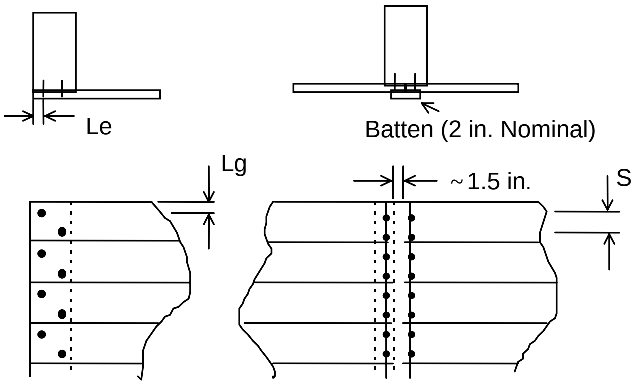


Figure 15—Timber plank horizontal nailed or screwed connection.

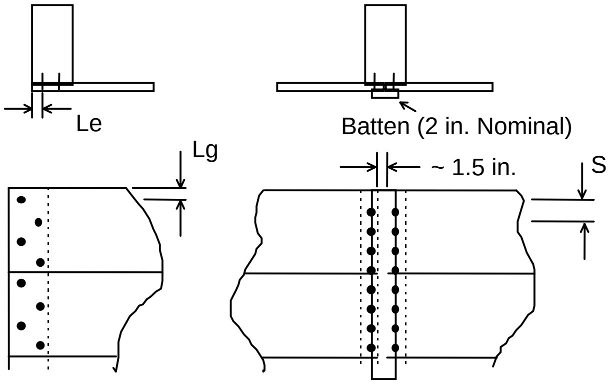


Figure 16—Glued-laminated horizontal nailed connection. Nominal 2 in. = standard 38 mm.

The deflection limitations for unoccupied vertical structures, such as sound barriers, do not need to be as strict as those for horizontal structures subject to human occupancy. Thus, the AASHTO (1989a) *Guide Specifications for the Design of Sound Barriers* does not include deflection limitations. In this study, a limitation of l/120 on horizontal deflections was adopted for the design of the posts. This helped keep the posts in the system to a size that could be easily manufactured by industry. Figures 20 and 21 display simplified post design charts for solid-sawn timbers with bending stresses of 5.2 MPa and 9.3 MPa, respectively. Figures 22 and 23 display the same type of charts for glued-laminated timbers with bending stresses of 11 MPa and 16.55 MPa, respectively. The design charts were developed according to the procedure presented in Appendix C, using the allowable stresses shown in Figures 20 to 23. Post dimensions were readily determined from these charts for a given wind pressure and sound barrier height. For most applications, sizes in the range of 172 by 279 mm to 172 by 349 mm were suitable for a glued-laminated post. Solid-sawn posts were typically larger and ranged from 203 by 305 mm to 254 by 356 mm.

Panels—Panels were designed by the action of the wind load on one panel element (plank or glued-laminated panel). The design method consisted of comparing the stress caused by the wind load with the allowable stress of the panel element. Calculations showed that the allowable stress for bending was much greater than the actual stress caused by the design wind load. In other words, the design wind load did not create significant bending stresses in the panel of the sound barrier. Thus, most common structural wood listed in the *National Design Specification for Wood Construction* (AF&PA 1991) could be used for the panels. However, the applied stress should always be compared with the allowable bending stress of the material being considered. Therefore, excluding aesthetics, the only factor in determining which quality of panel material to use was its potential for developing sight lines, which would increase sound transmission. A lower grade of wood contains more defects, which have the potential to develop sight lines. For example, No. 1 Southern Pine has fewer knots that may produce holes over time and is more likely to be kiln dried after treating than is No. 2 or No. 3 grade wood, even though those grades have sufficient allowable bending stresses.

Foundations—Several types of foundations can typically be used for post and panel wood sound barriers. These include pier, top collar, spread footing, and continuous spread (trench) footing (Fig. 24).

The pier, top collar, and spread footing foundations were used in the design of the sound barrier system. The trench footing was not considered for design because it could be replaced by the spread footing in most applications, which requires less concrete over the length of the sound barrier.

The pier foundations, which were used in the test sound barrier, were designed using a wind speed of 113 km/h (70 mph) (Exposure B2) in accordance with the *Guide Specifications for Structural Design of Sound Barriers* (AASHTO 1989a). The calculation procedure to determine foundation depths was based on the method outlined in the 1994 Uniform Building Code (UBC 1994) and the *Guide Specifications for Structural Design of Sound Barriers* (AASHTO 1989a) and verified by the post-design equations developed by the American Society of Agricultural Engineers Subcommittee on Post and Pole Foundations (ASAE 1992). The resulting design is shown in Figure 25. The dimensions depended on the loads used in the design, and a 75.6-mm cover was required. The allowable lateral passive soil strength (S) was estimated for design purposes at 30 kPa/m and the angle of internal friction (ϕ) at 30°.

Design of Test Sound Barrier

Design procedures for each element (posts, foundation, and general connections) were developed for the test sound barrier, but they can be applied to all wood sound barrier design options.

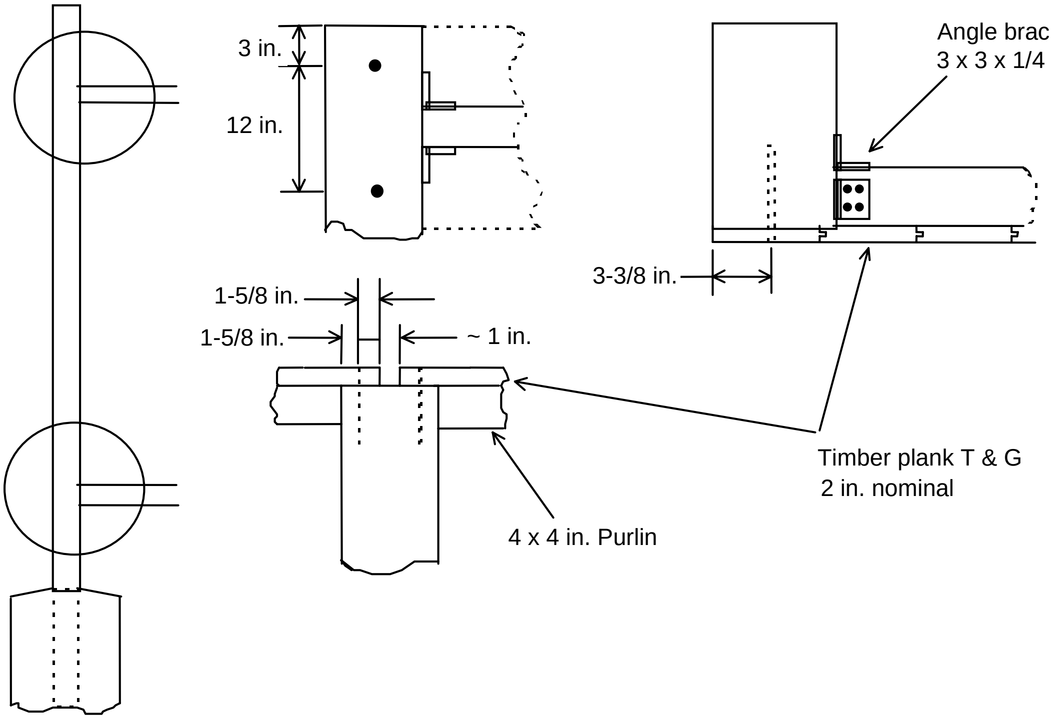


Figure 17—Timber plank vertical nailed or screwed connection.

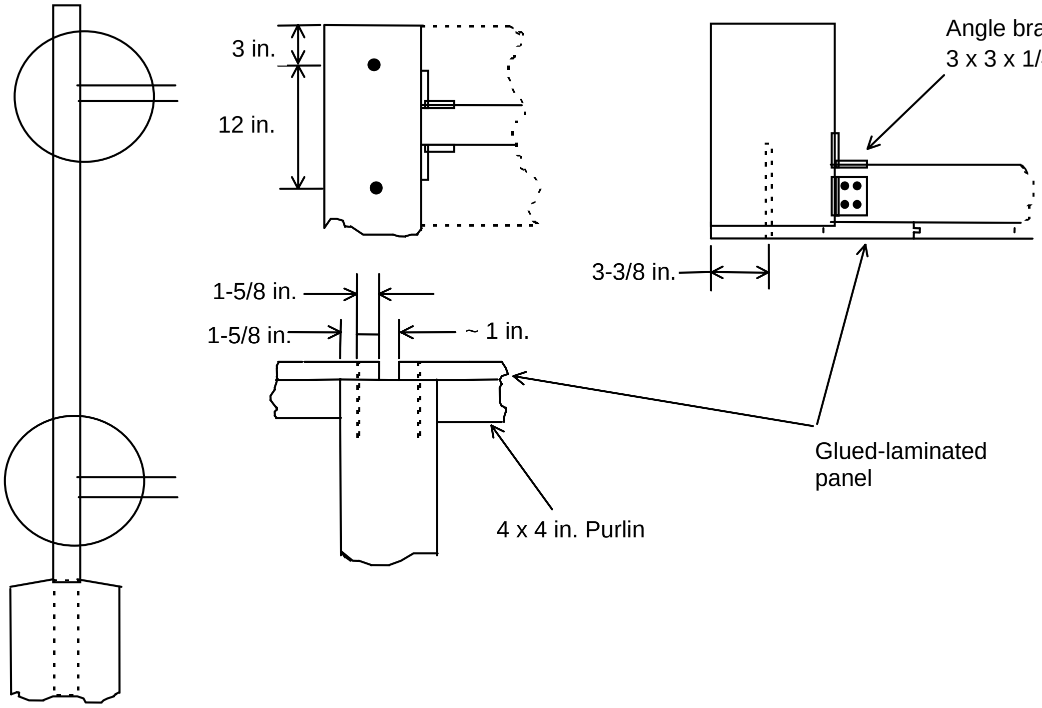


Figure 18—Glued-laminated vertical bolted connection.

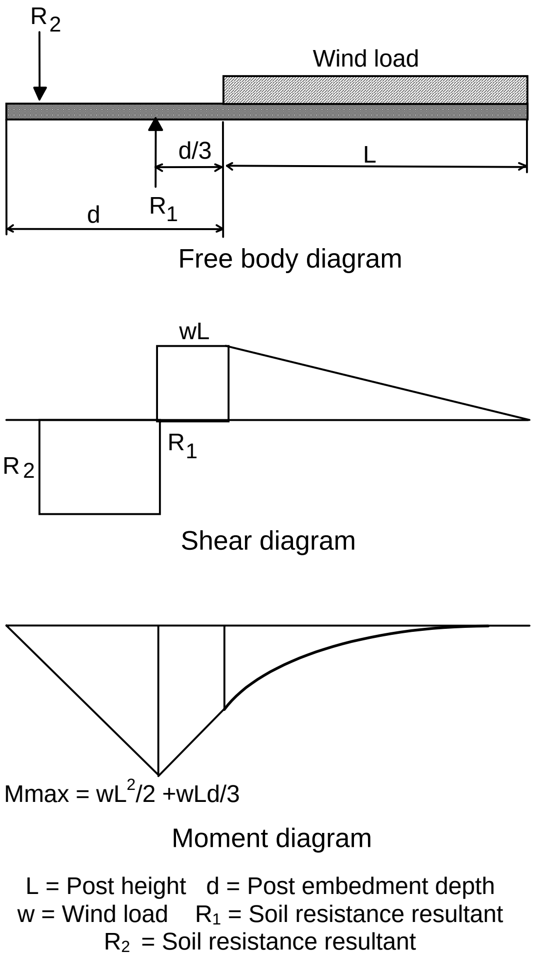


Figure 19—Post-flexure design diagrams.

General Considerations

The test sound barrier was detailed with the acoustic effectiveness and aesthetic characteristics determined from the first phase of the project. It was also detailed and constructed to provide maximum durability independent of preservative treatment. This included using tongue and groove lumber, using threaded galvanized nails (or wood screws), and providing drainage paths along the bottom of the barrier. Naturally occurring sight lines or gaps can develop between planks in the panel over time and will decrease insertion loss. Therefore, the test sound barrier was constructed to provide opportunity to compare its acoustic performance with that of panels with sight lines. This was done by constructing connections that provided vertical movement of the planks through slots 3.2 mm larger than the thickness of the planks (Fig. 26). Shims were placed between the planks to provide the desired gap thickness. The gaps extended the entire length of the test sound barrier.

Note that the sight lines were not a design detail but a method of testing how gaps between planks affect the acoustic effectiveness of the test barrier. Development of sight lines between planks over time caused by uneven drying along the width of a plank is a concern in wood sound barriers. A quantitative measure of sight line effects on a full-scale test model provided useful information for the design of a wood sound barrier.

Design Criteria

American Association of State Highway and Transportation Officials (AASHTO)—*The Guide Specifications for Structural Design of Sound Barriers* (AASHTO 1989a) establishes the following loads to consider in design of sound barriers: loads resulting from wind pressure, seismic occurrences, earth pressure, traffic (impact), and ice and snow, and loads transferred from bridges, guard rails, or retaining walls. Of these loads, only the wind load was considered in this study because the test barrier was built at a location precluding all other live loads. Dead loads to consider are the individual weights of the sound barrier elements. The vertical dead loads were considered negligible in determining structural capacity in relation to the horizontal live loads. Exposure B2 of the Uniform Building Code (1994) and a wind velocity of 113 km/h was used to determine the wind pressure for panel, post, and foundation design. Post and panel design and the foundation design are explained in the following sections.

National Design Specification—The *Guide Specifications for Structural Design of Sound Barriers* (AASHTO 1989a) recommends the use of the *Standard Specification for Highway Bridges* (AASHTO 1989b), Section 13, Timber Structures, or the use of an industry recognized design specification for wood sound barriers. The *National Design Specification for Wood Construction* (AF&PA 1991) was used to design the posts and panels. The posts were designed as a vertically aligned cantilever beam fixed at ground level and based on a unit tributary area of a panel width symmetrically aligned on the centerline of the post. The live load was distributed over an equivalent single panel section of 13.00 m^2 according to a height of 4.27 m and width of 3.048 m.

The panels were designed by the wind load acting on one plank. This calculation shows that the allowable stress in bending for 38-mm (nominal 2-in.) structural lumber is greater than the required stress caused by the design wind load.

The connections for the test sound barrier consisted of 50.4- by 151.2-mm planks arranged to provide a mechanism for easy insertion of the panel material, as shown in Figure 26. The connections were attached to the posts with 60d annularly threaded galvanized nails. Note that an in-service sound barrier would use the connection details previously developed.

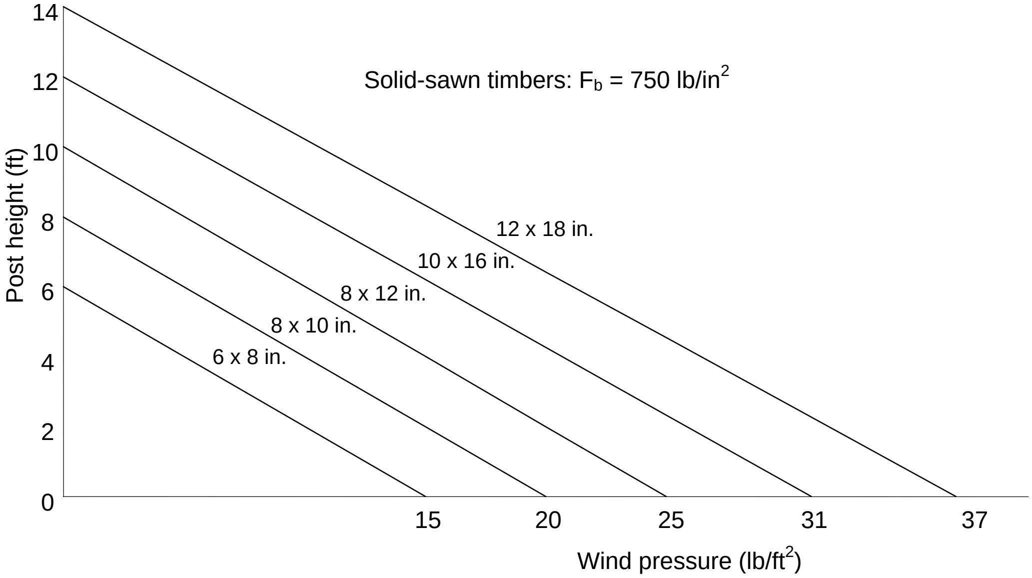


Figure 20—Solid-sawn post design chart for F_b = 750 lb/in^2.

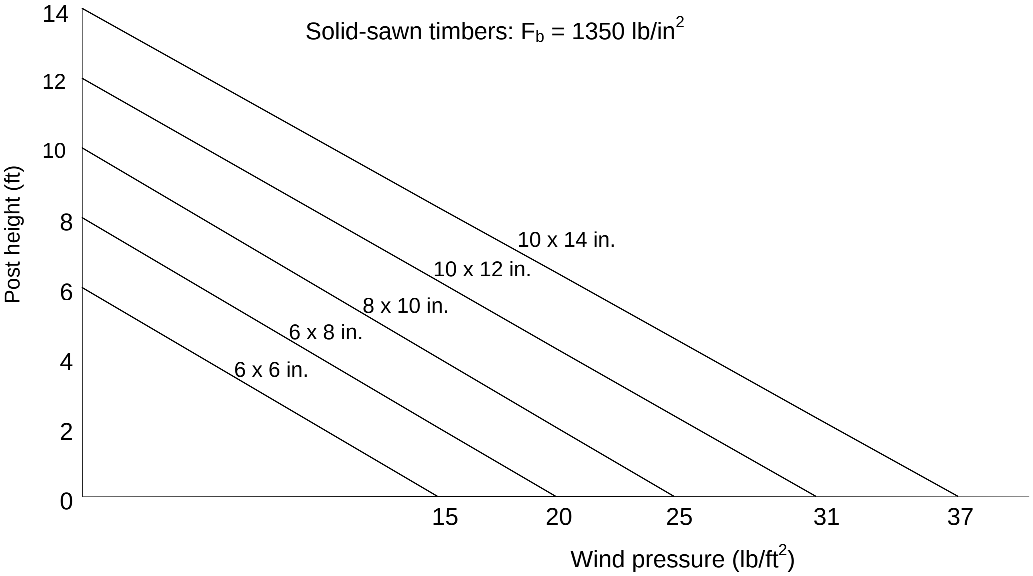


Figure 21—Solid-sawn post design chart for F_b = 1,600 lb/in^2.

Materials and Selection Justification

The test sound barrier was constructed with glued-laminated Southern Pine post combination 16F-V5 with dimensions of 171.45 mm by 314.33 mm by 6.7 m. The panel material was No. 1 Southern Pine tongue and groove, with dimensions of 50.8 mm by 152.4 mm by 3.05 m. A 152.4-mm plank width was used to minimize warp and shrinkage, which leads to the development of sight lines. The length of the barrier (24.4 m) was selected to minimize the diffraction of sound waves around the edges of the barrier. Primary structural design details are presented in Figure 27. Note that half the sound barrier is shown in elevation.

These materials and the flat flush, horizontally aligned timber plank configuration were selected for the test barrier for the following reasons:

- Simplest and most economical to build
- Relatively easy to conduct acoustic tests with sight lines in the panel

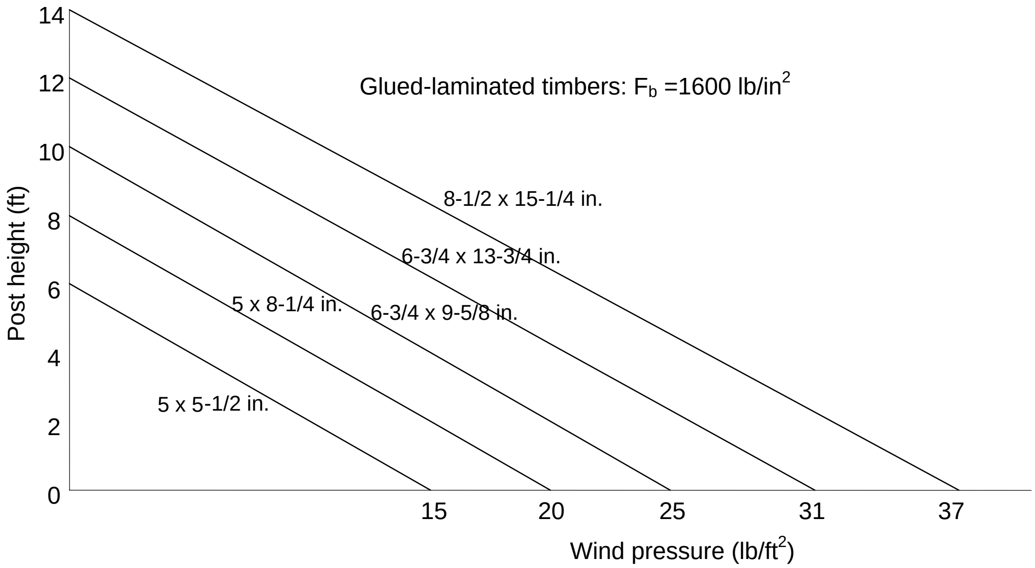


Figure 22—Glued-laminated post design chart for F_b = 1,600 lb/in^2.

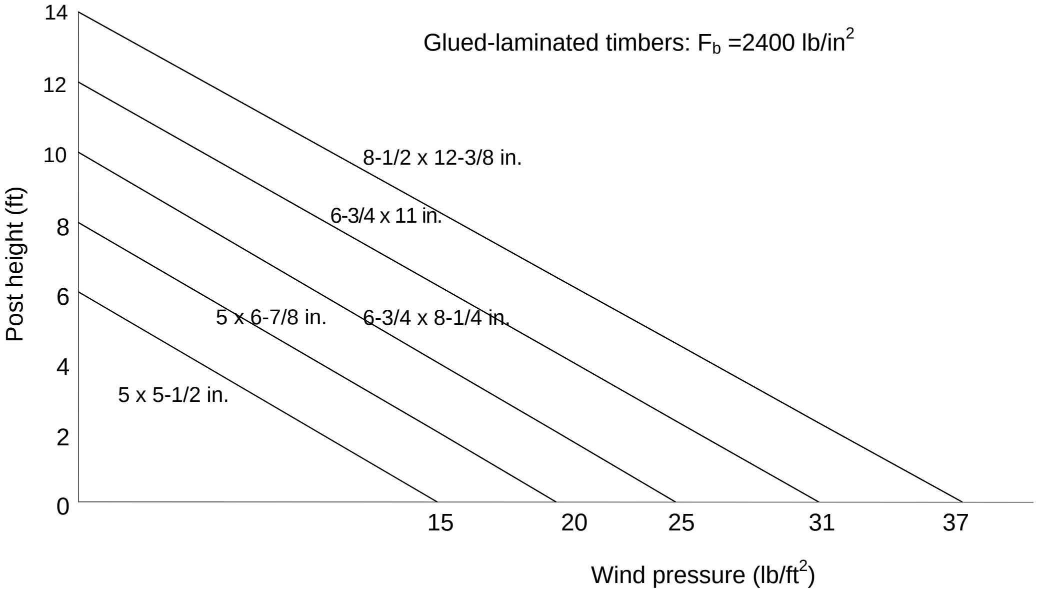


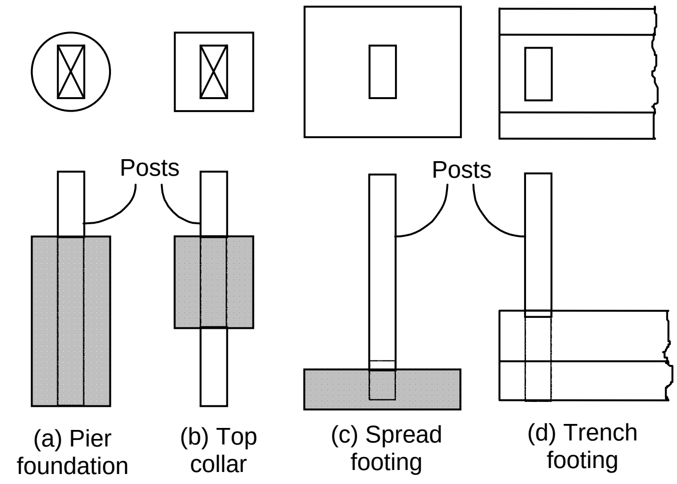
Figure 23—Glued-laminated post design chart for F_b = 2,400 lb/in^2.

- Able to obtain materials in a timely manner
- Easier to manage than larger (>55.9-cm-wide) glued-laminated panels

Table 31 presents the actual costs incurred in the construction of the test barrier. In addition to the costs of the material and equipment, construction of the barrier required about 40 h of construction time. This resulted in a total construction cost of $10,130 for the 24.4-m-long by 4.27-m-high test barrier. The cost of this barrier was less than $100/m^2, which is competitive with that of precast concrete and masonry. For instance, a Florida Department of Transportation study showed an average cost of $193/m^2 for concrete and masonry barriers (Lindeman 1997).

Durability

The durability of the test sound barrier was addressed in two ways. First, the members of the barrier were arranged to maximize durability regardless of preservative treatment. In addition to the design details already discussed, the grooves



(a) Pier foundation (b) Top collar (c) Spread footing (d) Trench footing

Figure 24—Sound barrier foundations.

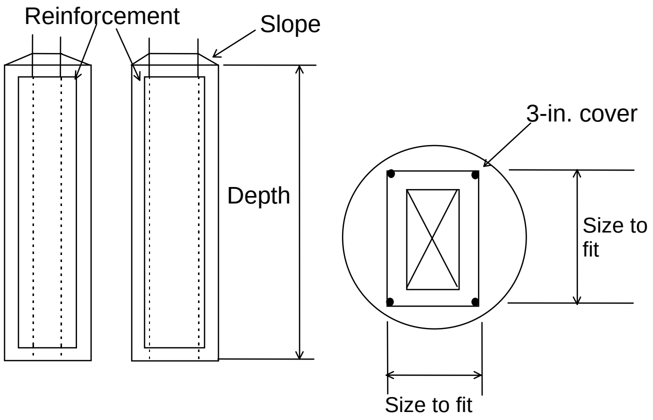


Figure 25—Pier foundation for wood sound barrier.

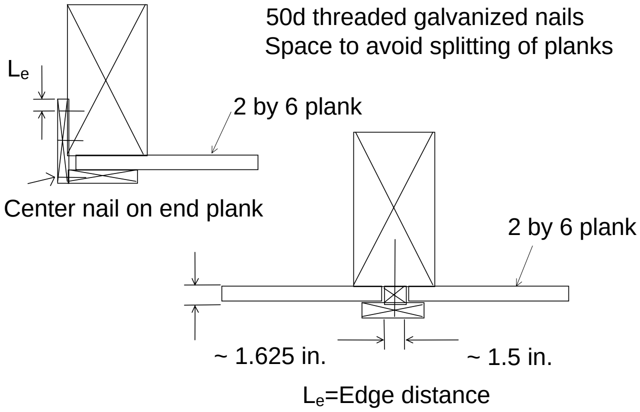


Figure 26—Test sound barrier connections viewed in cross section. 2 by 6 designates nominal 2- by 6-in. (standard 38- by 140-mm) lumber.

of the planks were directed downward and the tongues upward to prevent water from accumulating in the grooves, and a slope was added to the top of the concrete pier foundation to allow water to drain away from the post. Second, the wood was treated with preservative and galvanized steel connectors were used.

The test sound barrier was treated with the waterborne preservative chromated copper arsenate (CCA) in accordance with the American Wood Preservers' Association Standard C14 (AWPA 1994). The timber planks used for panels, treated top, and connection details were treated in accordance with AWPA C2 to a retention of 6.40 kg/m^3. The tongue and groove planks used to construct the panels were kiln dried after treating. This helped increase the compatibility of tongue and groove necessary for a smooth panel (especially during construction) and minimize sight lines. The glued-laminated posts were treated before lamination, also in accordance with AWPA (1994), to a retention of 9.60 kg/m^3. Field application of a commercially available water repellent to all elements of the sound barrier provided weathering resistance. Field application of a commercially available preservative treatment to cut members was done in accordance with AWPA (1994). The waterborne preservative and the additional water repellent left the wood light in color, as required by the public acceptance evaluation.

The dimensional change that results from moisture content fluctuation in the timber planks can cause the development of sight lines. A dimension of a timber plank at a particular moisture content can be calculated using the following:

$$d_0 = d_{30}(1 - S) \tag{12}$$

$$d_m = d_{30}\left(1 - \frac{30 - \mathrm{MC}}{30} S\right) \tag{13}$$

where

S is rate of shrinkage (%) (tangential),

MC moisture content (%),

d_0 width at 0% MC,

d_m width at a given MC (%), and

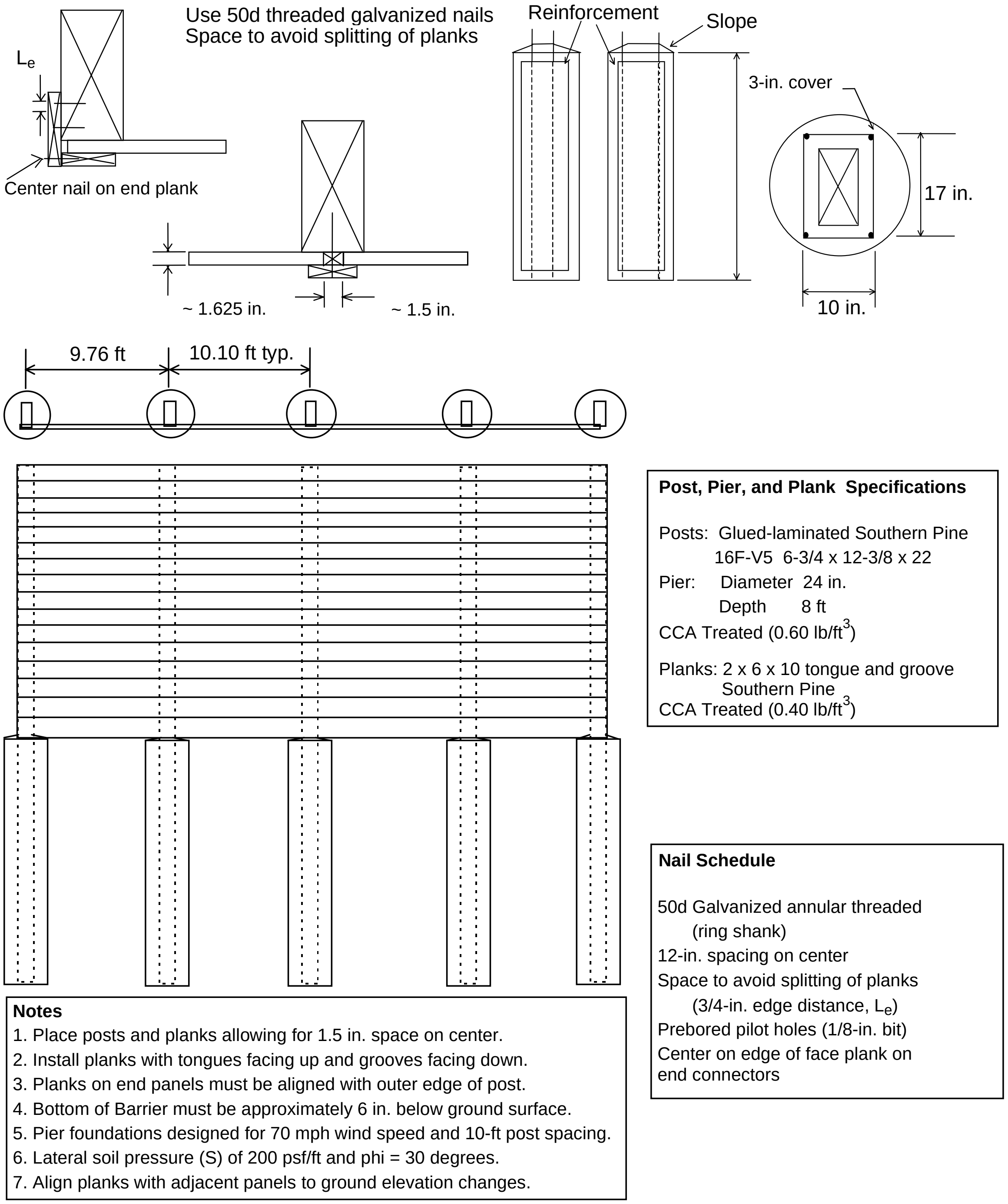
d_{30} width at 30% MC (fiber saturation point).

Note that the fiber saturation point of 30% is an approximate value that varies from species to species. For 50.4-mm-long by 151.2-mm-wide Southern Pine with S of 0.075%, the following widths were calculated for different moisture content levels:

d_{30} = 139.7 mm (green width)

d_{15} = 134.4 mm (MC after kiln drying)

$d_{8.5}$ = 132.1 mm (design low MC)



Post, Pier, and Plank Specifications

Posts: Glued-laminated Southern Pine
16F-V5 6-3/4 x 12-3/8 x 22
Pier: Diameter 24 in.
Depth 8 ft
CCA Treated (0.60 lb/ft^3)

Planks: 2 x 6 x 10 tongue and groove
Southern Pine
CCA Treated (0.40 lb/ft^3)

Nail Schedule

50d Galvanized annular threaded
(ring shank)
12-in. spacing on center
Space to avoid splitting of planks
(3/4-in. edge distance, L_e)
Prebored pilot holes (1/8-in. bit)
Center on edge of face plank on
end connectors

Notes

1. Place posts and planks allowing for 1.5 in. space on center.
2. Install planks with tongues facing up and grooves facing down.
3. Planks on end panels must be aligned with outer edge of post.
4. Bottom of Barrier must be approximately 6 in. below ground surface.
5. Pier foundations designed for 70 mph wind speed and 10-ft post spacing.
6. Lateral soil pressure (S) of 200 psf/ft and phi = 30 degrees.
7. Align planks with adjacent panels to ground elevation changes.

Figure 27—Test sound barrier; 14 ft high and 80 ft long.

Therefore, the total width change of one plank was 2.29 mm. According to Equations (12) and (13), a sight line of 4.57 mm can develop between planks with very low moisture content. In addition, moisture gradients caused by uneven drying throughout the wood can cause warping (bow, crook, and twist). Crook is the most critical defect because it deforms a plank perpendicular to its edge (strong axis direction), which is in line with the vertical plane of the panel. This will cause gaps to develop between planks.

Acoustic Effectiveness of Test Sound Barrier

The acoustic effectiveness of the test sound barrier was determined directly from on-site measurements. The performance of the sound barrier was analyzed under three different conditions. The barrier was first tested with sight lines (gaps) between planks. Subsequently, the sight lines

Table 31—Cost of materials for test sound barrier

Material	Description	Cost ($)
Wood	Glued-laminated posts (9)	2,913.66
	Timber plank panel material (350)	2,446.50
	Connectors (9)	75.00
	Miscellaneous wood	50.00
	Water repellent	390.00
Foundations	Reinforcement (3 & 5)	90.00
	Concrete (7.25 yd^3)	380.63
	Augering holes (9)	740.00
Nails and screws[a]	2d common nails	
	16d common nails	
	16d annular threaded nails	
	60d annular threaded nails	
	Wood screws (3-½ in.)	50.00
Crane service		295.00
Equipment purchase		200.00
Equipment rental		500.00
Total cost		8,130.79

[a] Galvanized.

were removed and the barrier was tested with and without a treated top. The goals of these tests were to determine actual insertion losses, the effect of sight lines, and the effect of using a treated top. Predictions of the insertion loss of the test sound barrier from test measurements were also made.

Test Procedures

Setup

The insertion loss of the test sound barrier was determined according to *Methods of Determination of Insertion Loss of Outdoor Noise Barriers* (ANSI 1987). This standard specifies three methods for determining insertion loss of outside sound barriers: direct measured, indirect measured, and indirect predicted. The direct measured method is recommended by the specification and is used when sound measurements are taken before the sound barrier is installed. This method was used to determine the insertion loss for the test sound barrier. Insertion loss is the difference between the measured sound pressure levels before and after the sound barrier is installed. The standard (ANSI 1987) requires that the reference and receiver microphones have the same positions and that measurements are taken with equivalent sound source, terrain, ground conditions, and atmospheric conditions before and after installation of the sound barrier.

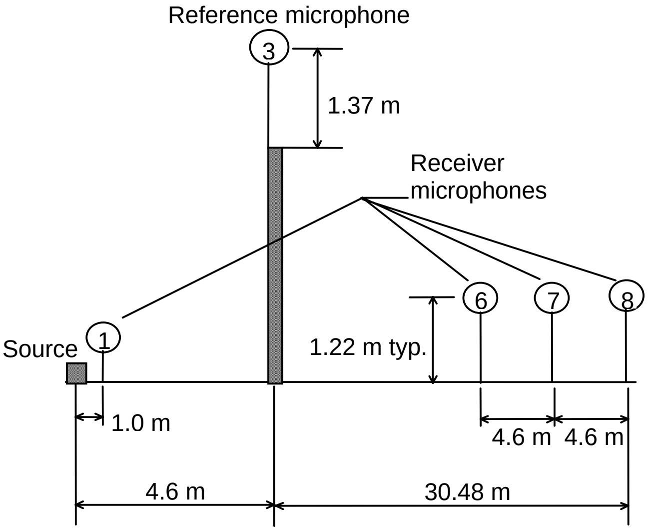


Figure 28—Microphone locations for run 1.

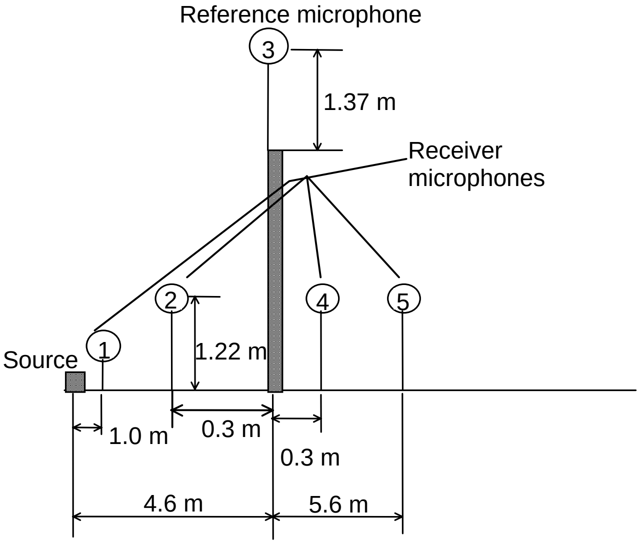


Figure 29—Microphone locations for run 2.

The test procedure involved emanation of a steady sound level from a single loudspeaker source and recording of the sound pressure levels at different positions in front, on top, and behind the sound barrier with microphones. Five microphones were used at one time; therefore, a set of two runs was made to obtain recordings at each of the eight microphone positions. Each microphone was calibrated using a calibrated source with a level of 94 dB at a frequency of 1,000 Hz.

Figures 28 and 29 are elevations of the test configuration for runs 1 and 2. ANSI (1987) requires the use of a reference microphone in position 3 where the sound from the source can be measured with minimum effects from the sound barrier. In the tests, the source microphone (microphone 1) measured the sound pressure level emitted from the source. Average wind velocity and temperature readings were monitored for each run. The point source was positioned 7.62 m (25 ft) in front of the sound barrier for each test. Also, the reference microphone remained 1.37 m above the top and at the center of the barrier for all tests. For run 1, the microphones were set at 15.24, 22.86, and 30.48 m behind the barrier. For run 2, the microphones were set at 4.6 m in front and 0.30 and 7.62 m behind the barrier.

Runs 1 and 2 lasted approximately 11 min each. The first 10 min recorded sound from the source, which was used for analysis, and the last minute recorded ambient sound levels with the source off. Run 2 immediately followed run 1 in each set.

Each receiver microphone (2, 4 to 8; Figs. 28 and 29) received 10 min of noise for each data set. The source microphone (1) and reference microphone (3) received 20 min of noise for each data set because they were used for both runs 1 and 2. Ten data sets were obtained for three conditions: no barrier (before the barrier was installed), barrier installed with gaps, and barrier installed without gaps. Each data set was divided into five 2-min intervals of recorded noise. An average sound level for the 2 min was determined for each third-octave band. Thus, there were 50 data points for each third-octave band for the no barrier condition and for each of the three barrier configurations: with sight lines (gaps), without gaps and no treated top, and without gaps and with treated top.

Instrumentation

Power to the instrumentation was supplied by a portable generator located approximately 30 m from the barrier. The receiver microphones were battery powered. The random noise generator supplied a signal that went through the filter, then to the speaker. An oscilloscope was used to monitor the incoming signal in real time from the receiver microphones. This signal was amplified before being recorded on the cassette recorder. The signal was recorded on cassette tape at a speed of 19 cm/s. Figure 30 displays the instrumentation setup used to conduct acoustical tests, and Table 32 lists the acoustical equipment used.

Site Plan

The site plan of the test sound barrier is shown in Figure 31. There were potential outside sound sources with direct paths to the receiver side of the barrier. Specifically, noise from the test track or road and reflection of sound waves off the metal shed may have had an effect on the measured sound pressure levels at the receivers.

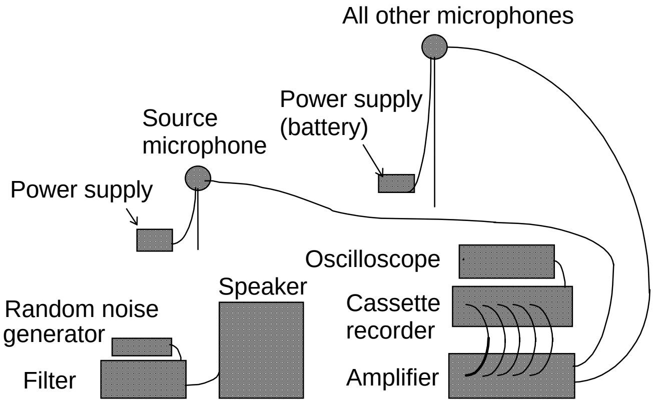


Figure 30—Schematic of instrumentation setup.

Table 32—Acoustical testing equipment

Equipment	Manufacturer or type	Model no.
Portable power generator	Honda (gasoline) (1,000 W)	
Random noise generator	General Radio Company (2 Hz–20 kHz)	1381
Filter	Krohn-Hite	3342
Speaker	JBL (EON) (15 in.)	
Source microphone power supply	Two channel	2807
Microphone battery power supply	Brüel Kjear	2810
Oscilloscope	BK Precision (20 mHz)	2120
Cassette data recorder	TEAC 7 channel	MR–30
Amplifier	ITHACO	453
Microphones	Brüel Kjear ½-in. condenser	
Sound level calibrator	Brüel Kjear (94 dB, 1,000 Hz)	4230

Testing Sequence

The sound pressure levels normalized by the sound pressure levels measured by the source microphone were used to determine insertion loss for the sound barrier with and without gaps. Measurements of sound pressure levels taken before the sound barrier was installed were used to determine insertion loss. The posts were installed at the time of testing and were considered to have no effect on sound propagation. The before-installation measurements were made in the same season as the measurements made with the barrier in place.

The test sound barrier was first constructed with sound leaks made by systematically inserting six 3.18-mm-wide gaps between the planks in the lower, middle, and upper regions of each panel; the gaps extended the entire length of the barrier (Fig. 32). This allowed testing of approximately 0.5% of the panel area with direct sound propagation through the barrier.

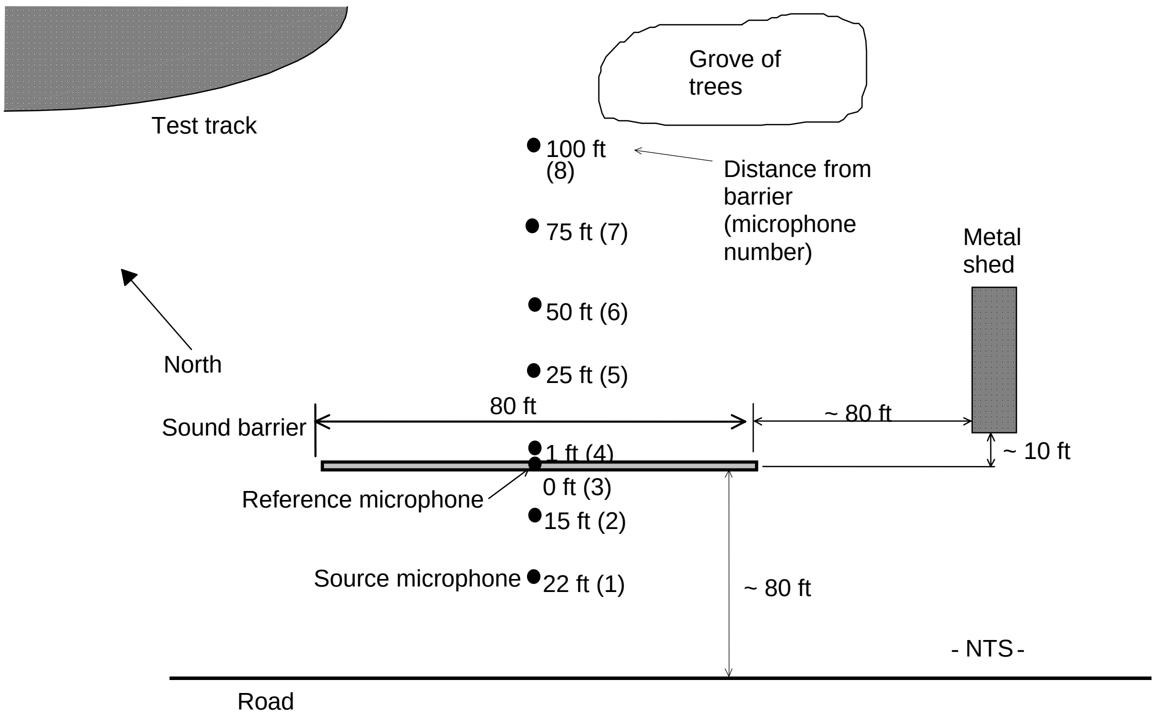


Figure 31—Site plan for test sound barrier.

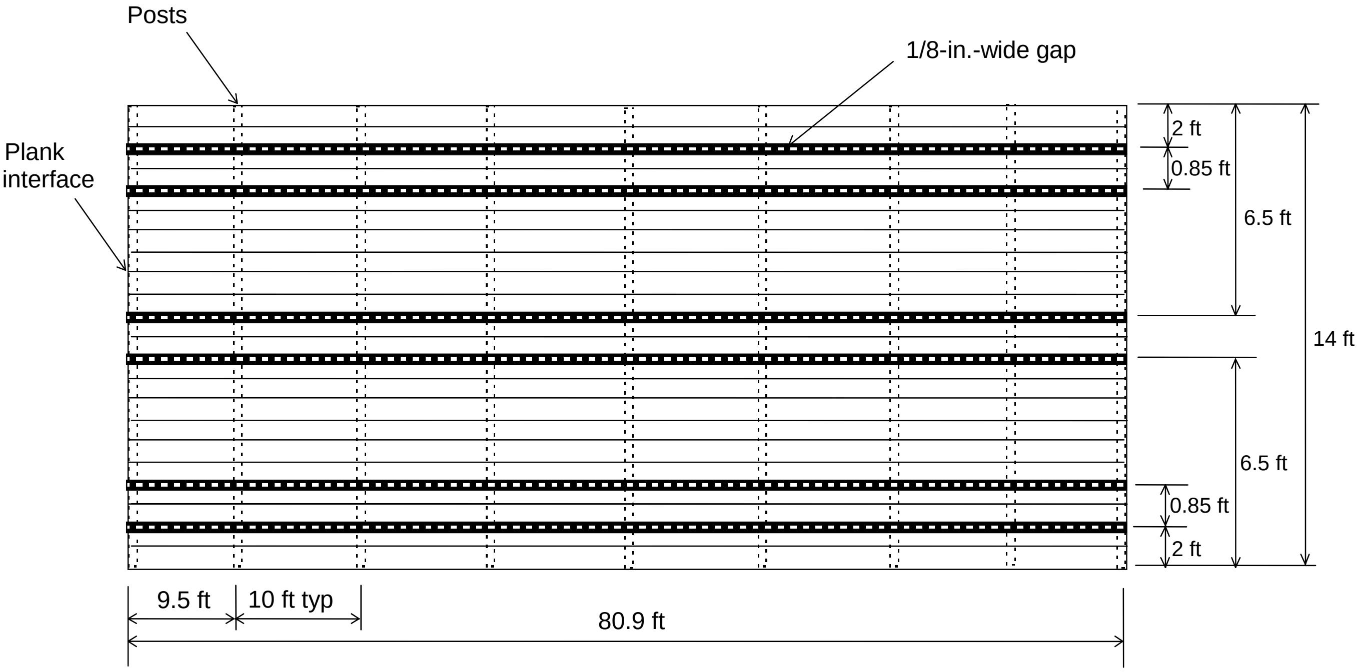


Figure 32—Locations of gaps in test sound barrier.

The test sound barrier was then tested without gaps. This condition best modeled an actual wood sound barrier in service. The planks were entirely interlocked, and shims were placed between the planks and the posts to eliminate gaps and potential sound leaks. A minimum measured insertion loss of 10 dBA was expected at all microphone positions behind the barrier. The treated top was then installed and the measurements repeated.

Determination of Insertion Loss

Data Analysis

Recordings from the two runs were analyzed to determine sound pressure levels in the third-octave bands from 100 to 5,000 Hz. Data were first organized into tables and graphs of non-normalized and normalized sound pressure levels and compared with frequency for each barrier configuration. Normalization was conducted by subtracting the source microphone from the receiver microphone sound pressure levels. This removed the effect of variations in the source output between runs. Insertion loss was determined in the following manner.

1. The non-normalized third-octave band levels measured by the source microphone were A-weighted by adding the A-weightings in Table 9 to the measured levels. The A-weighted levels were combined by adding the squared pressures, then taking the levels of the summed squared pressures using the following equation:

$$L_{\mathrm{A_{tot}}} = 10\log\left(\frac{\Sigma p_i^2}{p_{\mathrm{ref}}^2}\right) \qquad (14)$$

   where $L_{\mathrm{A_{tot}}}$ is A-weighted sound pressure level of the source, p_i A-weighted pressure in each band, and p_{ref} reference pressure (20 μPa).

2. The non-normalized third-octave band levels from the receiver were A-weighted, then combined to produce A-weighted levels of the receiver.

3. The A-weighted receiver levels were normalized by the source A-weighted levels ($\mathrm{SPL_{source}} - \mathrm{SPL_{receiver}}$).

4. The insertion loss was determined as the difference between the “no barrier” A-weighted normalized level and the A-weighted normalized level for both conditions with the barrier installed.

Prediction Model

The prediction model applied the following equation to the recorded normalized sound pressure levels from reference microphone 3 to predict levels at microphone positions at 7.62, 15.24, 22.86, and 30.48 m behind the barrier:

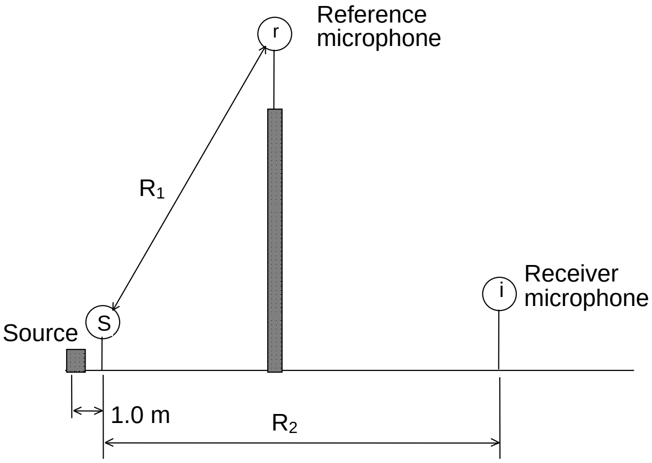


Figure 33—Reference distances for prediction model.

$$\Delta_{\mathrm{L}} = -20\log\frac{r_2}{1} \qquad (15)$$

where Δ_{L} is estimate of sound pressure level at receiver without the barrier, r_1 distance from source microphone to reference microphone, and r_2 distance from source microphone to receiver microphone.

This model is based on spreading loss and does not consider ground effects or atmospheric conditions. Predicted insertion loss was calculated by third-octave band levels and A-weighted levels. Figure 33 shows the geometry for the prediction model.

The calculation procedure for the predicted insertion losses in each third-octave band was conducted by applying Equation (15) to the average normalized sound pressure levels at the reference microphone and subtracting the average normalized sound pressure levels of the receiver microphones.

Discussion of Results

Measured and predicted insertion losses are listed in Table 33. The measured insertion losses were greater than expected, but reasonable. The decrease in insertion losses at the microphone positions furthest from the sound barrier was expected, because insertion loss increases with increasing differences in the direct and diffracted path lengths. Diffraction around the edges may have existed, but its effect was considered small. Based on predictions of insertion losses (Beranek 1992) and considering path length differences, the insertion loss for the path over the top of the barrier was more than 7 dB less than the predicted insertion loss for the receiver located 30.48 m from the barrier.

For locations closer to the barrier, paths around the edges of the barrier will have less effect on insertion loss.

Table 33—A-weighted insertion losses for test sound barrier

		Insertion loss (dBA) at various distances behind barrier			
Value	Barrier type[a]	7.62 m	15.24 m	22.86 m	30.48 m
Measured	Gaps	15	14	12	9
	No gaps	20	17	15	15
	T-top	21	19	17	15
Predicted	Gaps	18	17	17	16
	No gaps	22	21	20	20
	T-top	22	22	22	22

[a] T-top is treated top.

The results in Table 32 show that gaps in the panel dramatically reduce the acoustical effectiveness of the barrier. The transmission loss of 50.4- by 151.2-mm tongue and groove planks was assumed to be no less than 20 dBA (FHWA 1994c), thus minimizing its effect on insertion loss. The treated top increased the insertion loss by 1 to 2 dB.

Conclusions

Acoustic Effectiveness of Existing Barriers

The results of in situ measurements of four precast concrete, two plywood, two glued-laminated, three post and panel wood barriers, and one cement-bonded composite panel barrier are summarized as follows:

- Insertion losses from one glued-laminated barrier, two post and panel barriers, and three precast concrete barriers were similar and satisfied the 10-dBA insertion loss goal.
- One concrete barrier, both plywood barriers, one glued-laminated barrier, and one post and panel barrier did not satisfy the 10-dBA insertion loss goal as a result of poor detailing, low surface mass, and large distance between sound source and barrier.
- The average transmission loss for all concrete barriers and two glued-laminated barriers was 20 dBA. The transmission loss values for the concrete and glued-laminated barriers were high enough to have little impact on the insertion losses.
- The average transmission loss for all the plywood barriers and post and panel barriers was 15 dBA. The low transmission loss values were the result of the low surface mass of the plywood barriers as well as poor detailing for both types of barriers. With proper detailing, these problems could be avoided.

Public Acceptance

The results of public evaluation of wood and concrete barrier designs by semantic-differential and individual ratings led to the following conclusions:

- Wood barrier designs are perceived to have more favorable “rural” qualities than do concrete barriers.
- Wood barriers that have simple flat walls or relief walls are favored.
- To break up the monotony, wood barriers that have many elements or a relief plan layout, but not both, are favored.
- Panel orientation in the elevations may be horizontal or vertical.

Systematic Design Details

The design investigation and construction experience led to the following results and conclusions:

- A systematic set of designs consisting of flush and relief plan layouts with glued-laminated or solid-sawn posts and tongue and groove dimensional lumber planks or glued-laminated panels was developed. Plans for the horizontal panel orientations of dimensional lumber plank walls are presented in Appendix D.
- To minimize weathering and warping of the wood, construction of the sound barrier should begin as soon as possible after the wood materials are obtained.
- The flat flush plan layout with horizontally aligned dimension lumber planks is not easy to construct because it is difficult to keep the panel elements evenly aligned.

Acoustic Effectiveness of Test Barrier

The results of acoustic measurements conducted with the test wood sound barrier are summarized as follows:

- The wood barrier provided insertion losses of 15 dB or greater, exceeding the 10-dB goal given by FHWA for acceptable performance for a highway sound barrier.
- Gaps between planks reduced barrier performance by 3 to 6 dB.
- Top treatment increased insertion loss by 1 to 2 dB.

Recommendations

Acoustical testing, design investigation, and construction experience led to the following recommendations for sound barriers:

- Use vertical battens placed at midspan and extending the entire height of the barrier to resist development of gaps.

- Consider the use of smaller posts and shorter spans, perhaps 1.82- to 2.44-m centers instead of 3.28 m. Such barriers are less likely to develop gaps.
- Consider the use of glued-laminated panels.
- Place an additional horizontal purlin midway between the top and bottom purlins in the vertical oriented plank with a flat flush format. Nail or screw planks to purlin.
- The flat relief design format will facilitate construction because planks can be aligned and attached quickly and easily.

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Appendix A—Existing Barriers Used in Acoustic In Situ Testing

http://www.fpl.fs.fed.us/documnts/fplrp/fplrp596/fplrp596_AppA.pdf (PDF 1.8 MB)

Appendix B—Computer Edited Images Used in Public Acceptance Evaluations

http://www.fpl.fs.fed.us/documnts/fplrp/fplrp596/fplrp596_AppB.pdf (PDF 3.9 MB)

Appendix C—Structural Design Example

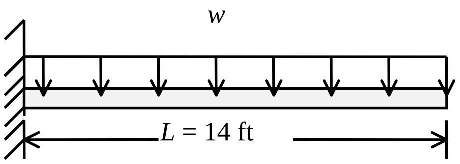
Deflection Criteria

The required moment of inertia, $I_{\text{req'd}}$, for a solid-sawn and glued-laminated post was determined by treating the post as a cantilever beam fixed at the ground surface. The following was used in post-design calculations:

$$\Delta = \frac{wL^4}{8EI} \tag{1}$$

Post Design

Check a 16F-V5 Southern Pine 6-3/4-in. by 12-3/8 in. by 14-ft post for bending adequacy and deflection requirements (sample calculation).



h = one panel width = 10 ft

Figure C1—Post Loading Diagram

Determine Loads:

$$P = whL = 15\ \text{lb/ft}^2 \times 10\ \text{ft} \times 14\ \text{ft} = 2{,}100\ \text{lb} \tag{2}$$

$$M = \frac{wL^2}{2} = \frac{(wL)L}{2} = \frac{PL}{2} \tag{3}$$

$$M = \frac{(2{,}100\ \text{lb})(14\ \text{ft})}{2} = 14{,}700\ \text{ft-lb} = 176.4\ \text{in-kips}$$

Calculate Section Properties: (b is width, d is depth)

$$S = \frac{bd^2}{6} = \frac{(6.75\ \text{in.})(12.375\ \text{in.})^2}{6} = 172.3\ \text{in}^3 \tag{4}$$

$$I = \frac{bd^3}{12} = \frac{(6.75\ \text{in.})(12.375\ \text{in.})^3}{12} = 1{,}066\ \text{in}^4 \tag{5}$$

Check Bending Stress: (use applicable adjustment factors from AF&PA 1991)

$$f'_{\text{b}} = F_{\text{b}} C_{\text{D}} C_{\text{M}} C_{\text{V}} \qquad \text{(Table 2.3.1, AF\&PA 1991)} \tag{6}$$

$C_{\text{D}} = 1.6$ (Table 2.3.2, AF&PA 1991)

$C_{\text{M}} = 0.8$ (Table 5A-Adjustment Factors, AF&PA 1991)

$C_{\text{V}} = 0.9825$ $\quad C_V = \left(\frac{21}{L}\right)^{0.05} \left(\frac{12}{d}\right)^{0.05} \left(\frac{5.125}{b}\right)^{0.05}$

$$f'_{\text{b}} = (1600\ \text{lb/in}^2)(1.6)(0.8)(0.9825) = 2{,}012\ \text{lb/in}^2 \qquad \text{(allowable)}$$

$$f'_{\text{b}} = \frac{M}{S} = \frac{176.4\ \text{in-kips}}{172.3\ \text{in}^3} = 1{,}024\ \text{lb/in}^2 \qquad \text{(actual)} \tag{7}$$

actual stress < allowable stress OK

Check for $I_{\text{req'd}}$:

From Table 5A—Adjustment Factors (AF&PA 1991),

$$E' = EC_M = (1{,}400 \text{ kips/in}^2) \times 0.833 = 1{,}166 \text{ kips/in}^2$$

From Equation (2),

$$I_{\text{req'd}} = \frac{15wL^3}{E'} = \frac{15\left(\dfrac{150 \text{ lb/ft}^3}{12}\right)\left(14 \text{ ft} \times 12 \dfrac{\text{in.}}{\text{ft}}\right)^3}{1{,}166 \text{ kips/in}^2} = 762.5 \text{ in}^4 \qquad (8)$$

Checking Equation (6) with Equation (10) results in the following:

$1{,}066 \text{ in}^4 > 762.5 \text{ in}^4$ OK

Panel Design

Check a 2- by 6-in. Southern Pine No. 1 tongue and groove plank for bending and deflections (sample calculation).

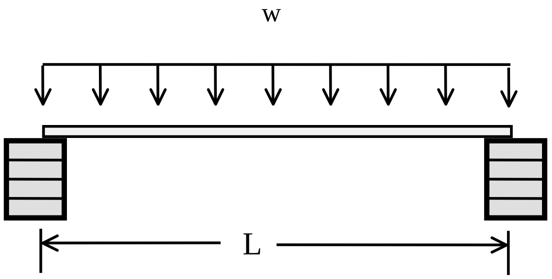


Figure C2. Panel Loading Diagram

Assume load on one plank.

$w = 15 \text{ lb/ft}^3 = 7.5$ lb/ft on one plank

Table 4B (AF&PA 1991)

$f_b = 1{,}650 \text{ lb/in}^2$ $\quad f_v = 90 \text{ lb/in}^2$

$E = 1{,}700 \text{ kips/in}^2$

$A = 8.25 \text{ in}^2$ $\quad S = 2.063 \text{ in}^3$ $\quad I = 1.547 \text{ in}^4$

Table 2.3.1 Applicable Adjustment Factors (AF&PA 1991)

$$f_b' = F_b C_D C_M C_{fu} \qquad (10)$$

$C_D = 1.6$ Table 2.3.2

$C_M = 1.0$ Table 4B Adjustment Factors

$C_{fu} = 1.15$ Table 4B Adjustment Factors

$f_b' = (1{,}650 \text{ lb/in}^2)(1.6)(1.0)(1.15) = 3{,}036 \text{ lb/in}^2$

$$f_v' = F_V C_D C_M \qquad (11)$$

$C_D = 1.6$ Table 2.3.2

$C_M = 0.97$ Table 4B Adjustment Factors

$f_v' = (90 \text{ lb/in}^2)(1.6)(0.97) = 139.7 \text{ lb/in}^2$

$$M = \frac{wL^2}{8} = \frac{(7.5 \text{ plf})(10 \text{ ft})^2}{8} = 93.75 \text{ ft-lb} = 1{,}125 \text{ in-lb} \qquad (12)$$

$$S_{\text{req'd}} = \frac{M}{f_b'} = \frac{1{,}125 \text{ in-lb}}{3{,}036 \text{ lb/in}^2} = 0.371 \text{ in}^3 \quad < \quad 2.063 \text{ in}^3 \quad \text{OK} \qquad (13)$$

$$V = \frac{wL}{2} = \frac{(7.5\text{ plf})(10\text{ ft})}{2} = 37.5\text{ lb} \qquad (14)$$

$$A_{\text{req'd}} = \frac{3V}{2f'_V} = \frac{3 \times 37.5\text{ lb}}{2 \times 139.7\text{ lb/in}^2} = 0.4026\text{ in}^2 \qquad < \qquad 8.25\text{ in}^2 \qquad \text{OK} \qquad (15)$$

$$I_{\text{req'd}} = \frac{5wL^4}{384E'\Delta} = \frac{120 \times 5wL^3}{384E'} = \frac{120 \times 5 \times \left(7.5\text{plf} \times \frac{\text{ft}}{12\text{in.}}\right)\left(10\text{ft} \times \frac{12\text{ in.}}{\text{ft}}\right)^3}{384 \times 1{,}530\text{ kips/in}^2} \qquad (16)$$

$$I_{\text{req'd}} = 1.103\text{ in}^4 \qquad < \qquad 1.547\text{ in}^4 \qquad \underline{\text{OK}}$$

Check Bending Stress of Southern Yellow Pine No. 1, 2 by 6 in.:

$$f'_b = \frac{M}{S} = \frac{1{,}125\text{ in-lb}}{2.063\text{ in}^3} = 545.32\text{ lb/in}^2$$

$$f'_{\text{b}} = F_{\text{b}}C_{\text{D}}C_{\text{M}}C_{\text{fu}}$$

or

$$F_b = \frac{f'_{\text{b}}}{C_{\text{D}}C_{\text{M}}C_{\text{fu}}} = \frac{545.32\text{ lb/in}^2}{(1.6)(1.0)(1.15)} = 296.40\text{lb/in}^2 \qquad (17)$$

Withdrawal Calculations For Nails, Wood Screws, and Lag Bolts

For use in timber planks (2 in. nominal)

NAILS: Table 12.2A (AF&PA 1991)	Species: Southern Pine ($G = 0.50$)
16d Threaded $D = 0.148$ in $L = 3\ 1/2$ in.	$W = 40$ lb/in.
$W' = WC_{\text{D}}C_{\text{M}}C_{\text{t}} = W(1.6)(1)(1)$	$W' = 64$ lb/in.
Penetration[1] = 2 in.	Capacity = 128 lb/nail (80)
50d Threaded $D = 0.177$ $L = 5\ 1/2$ in.	$W = 47$ lb/in.
$W' = WC_{\text{D}}C_{\text{M}}C_{\text{t}} = \text{W}(1.6)(1)(1)$	$W' = 75$ lb/in.
Penetration[2] = 2-3/8 in	Capacity = 176 lb/nail (111)
WOOD SCREWS: Table 11.2A (AF&PA 1991)	Species: Southern Pine ($G = 0.50$)
12 Gauge $D = 0.216$ in $L = 3$ in.	$W = 154$ lb/in.
$W' = (2/3)WC_{\text{D}}C_{\text{M}}C_{\text{t}} = (2/3)W(1.6)(1)(1)$	$W' = 164$ lb/in.
Penetration[1] = 1.5 in.	Capacity = 246 lb/screw (154)

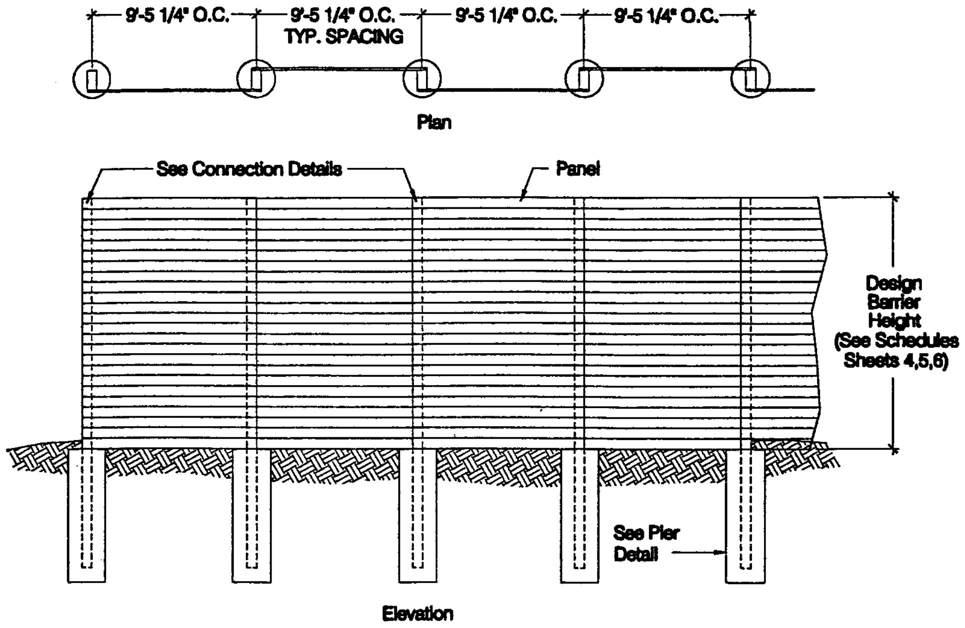
For use in manufactured glued-laminated panels (>2.25 in. thick)

LAG BOLTS: Table 9.2A (AF&PA 1991)	Species: Southern Pine (G = 0.50)
$D = 3/8$ in. $L = 5\text{-}1/2$ in.	$W = 305$ lb/in
$W' = WC_{\text{D}}C_{\text{M}}C_{\text{t}} = W(1.6)(1)(1)$	$W' = 488$ lb/in
Penetration[3] = 3 in.	Capacity = 1,460 lb/bolt (915)

Notes:
1. Nail through 2-in. nominal lumber.
2. Nail through 2-in. nominal plus 1-5/8 in. piece.
3. Bolt through 2-1/4 to 2-1/2 in. glued-laminated panel plus washer.

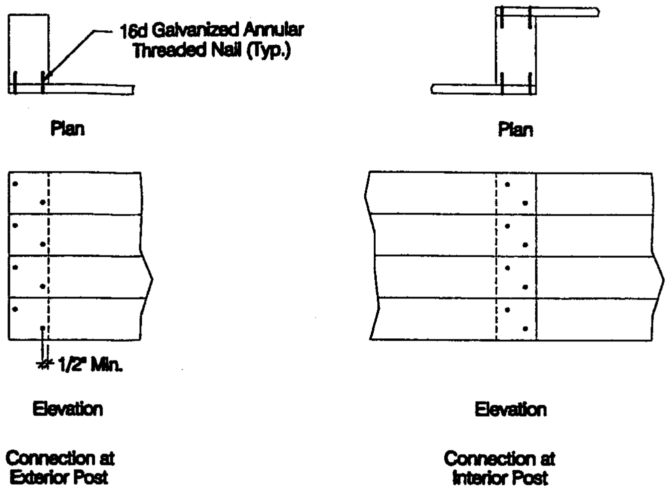
Numbers underlined in parentheses are capacities for $C_{\text{D}} = 1.0$.
Minimum edge distance and spacing is 3/4 in. for nails and wood screws and 1.5 in. for lag bolts.

Appendix D—Highway Sound Barrier Plans



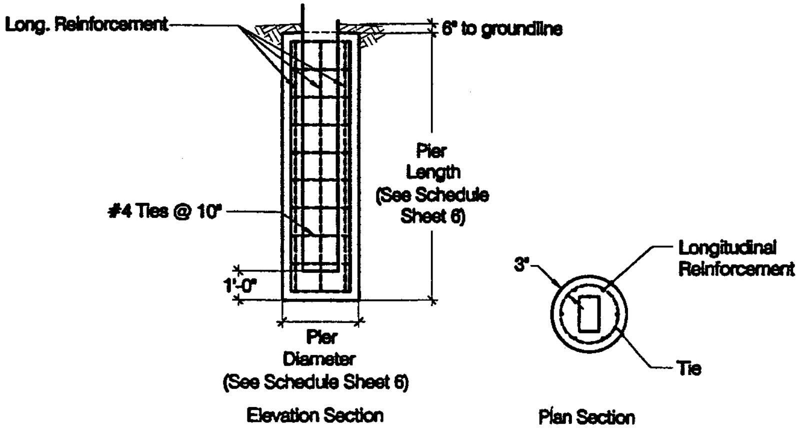
General Configuration

Scale: 1/4" = 1'-0"



Connection Details

Scale: 1/2" = 1'-0"



Pier Details

Scale: 1/4" = 1'-0"

General Notes

1. Pier Foundations are designed for a wind speed of 80 MPH and lateral soil pressure strength(s) of 200 PSF/FT (φ=30°). See pier schedule, sheet 6.
2. Planks are 2" nominal tongue and groove, pressure treated No. 1 Grade. Install planks with tongue facing up and groove facing down.
3. Plank ends must be aligned with edge of post.
4. Bottom of barrier must be embedded 6" below the ground surface.
5. All nails shall be placed at least .5" from plank edges and adjacent nails. For 2x6 or 2x8 planks, use 2 nails per connection to post. For 2x10 or 2x12 planks, use 3 nails per connection to post. Maximum nail spacing 8".
6. Posts to be pressure treated prior to fabrication with CCA to a retention of .60 PCF per AWPA C2.
7. Planks for panels to be pressure treated with CCA to a retention of .40 PCF per AWPA C2.
8. Field treat cut ends per AWPA M4.
9. Post sizes for various heights, design wind velocities, species and grades are provided in schedules on sheets 4-6.
10. Pier and reinforcement sizes for various heights and design wind velocities are provided on sheet 6.

Schedule of Drawings

Sheet	Drawing
1.	Horizontal Relief Timber Plank
2.	Horizontal Flush Timber Plank
3.	Horizontal Skew Relief Timber Plank
4.	Post Schedules- Glue Laminated
5.	Post Schedules- Western Species Solid Sawn
6.	Post Schedules- Solid Sawn / Pier Schedules

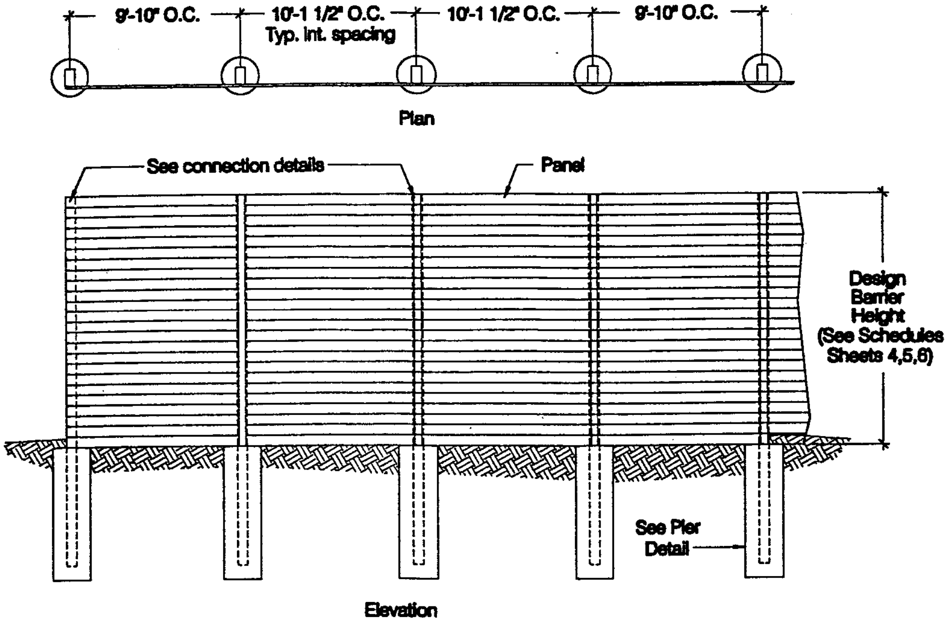
The sound barriers depicted on these drawings were developed and tested under a cooperative research agreement between the Pennsylvania State University, the USDA Forest Service Forest Products Laboratory and the Federal Highway Administration.

Standard Plans for Timber Sound Barriers

Horizontal Relief Timber Plank

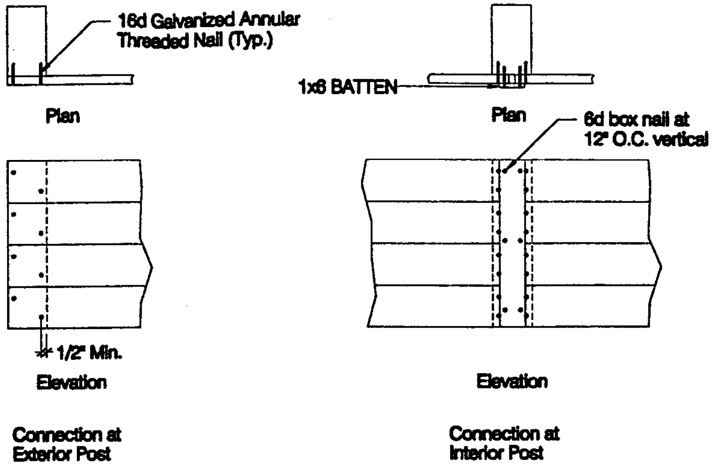
November 1997

Sheet 1 of 6



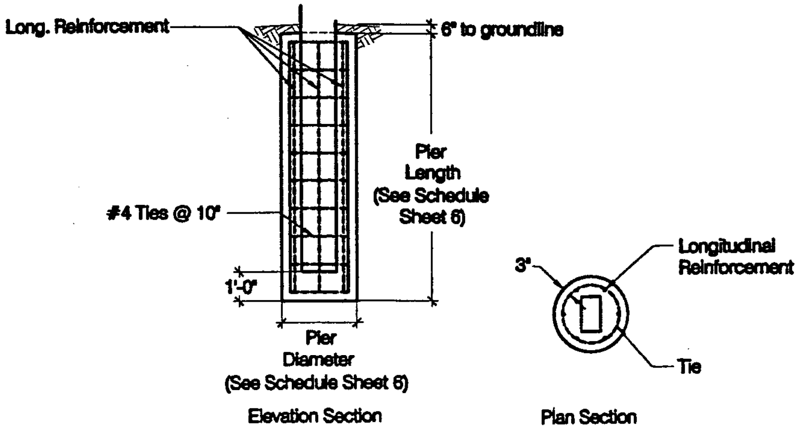
General Configuration

SCALE: 1/4" = 1'-0"



Connection Details

Scale: 1/2" = 1'-0"



Pier Details

Scale: 1/4" = 1'-0"

General Notes

1. Pier Foundations are designed for a wind speed of 80 MPH and lateral soil pressure strength(s) of 200 PSF/FT (ø=30°). See pier schedule, sheet 6.
2. Planks are 2" nominal tongue and groove, pressure treated No. 1 Grade. Install planks with tongue facing up and groove facing down.
3. Plank ends on end panels must be aligned with edge of post.
4. Bottom of barrier must be embedded 6" below the ground surface.
5. All nails shall be placed at least .5" from plank edges and adjacent nails. For 2x6 or 2x8 planks, use 2 nails per connection to post. For 2x10 or 2x12 planks, use 3 nails per connection to post. Maximum nail spacing 8".
6. Posts to be pressure treated prior to fabrication with CCA to a retention of .60 PCF per AWPA C2.
7. Planks for panels to be pressure treated with CCA to a retention of .40 PCF per AWPA C2.
8. Field treat cut ends per AWPA M4.
9. Post sizes for various heights, design wind velocities, species and grades are provided in schedules on sheets 4-6.
10. Pier and reinforcement sizes for various heights and design wind velocities are provided on sheet 6.

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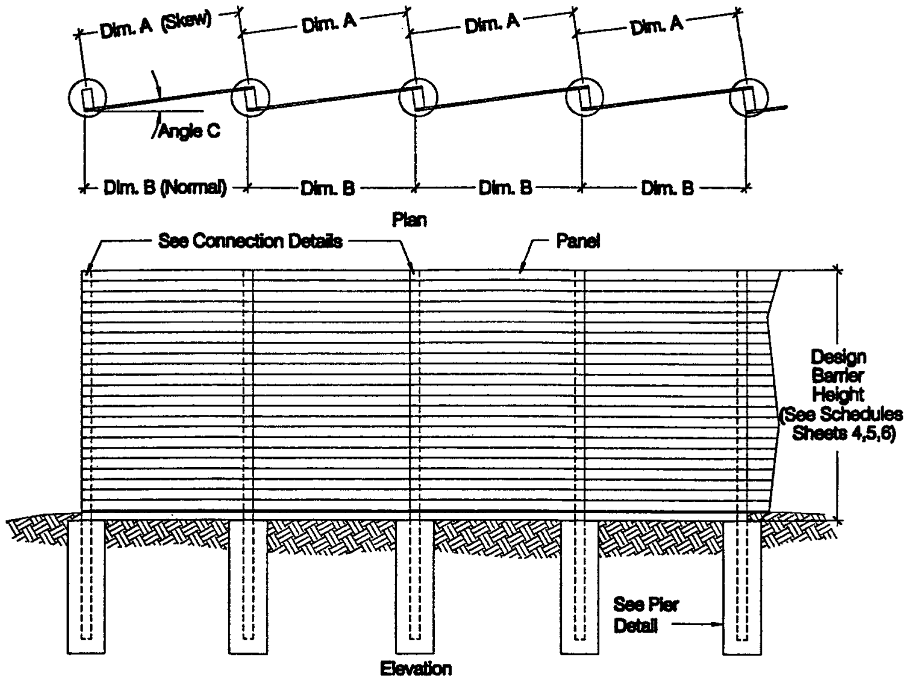
Standard Plans for Timber Sound Barriers

Horizontal Flush Timber Plank

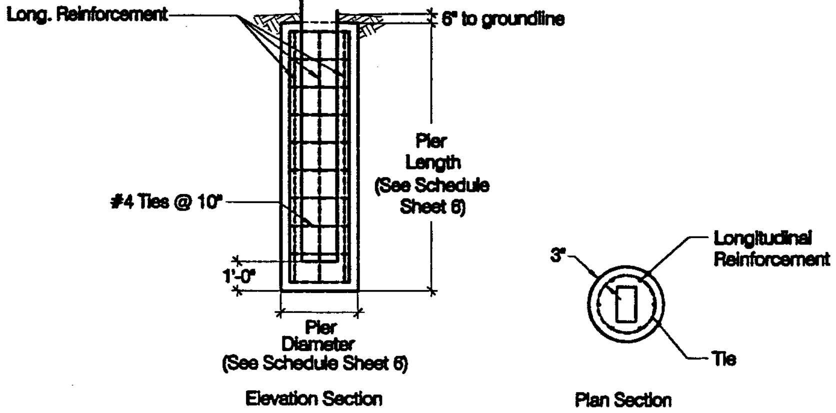
November 1997

Sheet 2 of 6



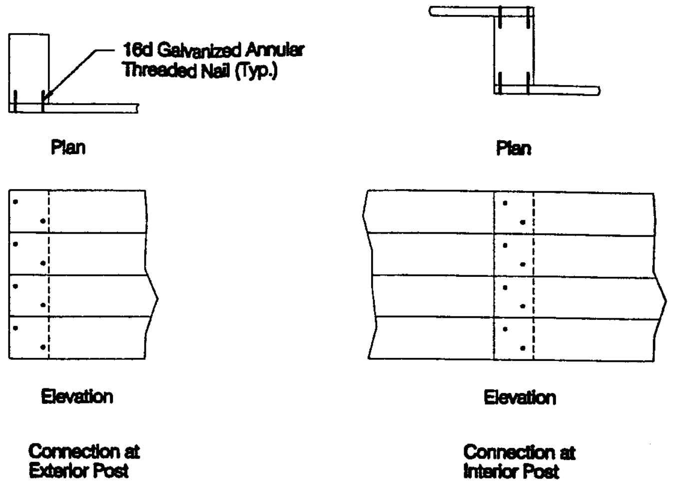
General Configuration

Scale: 1/4" = 1'-0"



Pier Details

Scale: 1/4" = 1'-0"



Note: Details looking normal to panel

Connection Details

Scale: 1/2" = 1'-0"

Post Width	Post Depth	Dim. A	Dim. B	Angle C
Douglas Fir or Hem/Fir: Glue Laminated				
6 3/4"	10 1/2"	9'-3 3/4"	9'-4 1/4"	5.02°
6 3/4"	12"	9'-3 3/4"	9'-4 1/4"	5.73°
6 3/4"	13 1/2"	9'-3 3/4"	9'-4 1/2"	6.45°
6 3/4"	15"	9'-3 3/4"	9'-4 3/4"	7.15°
Southern Pine: Glue Laminated				
6 3/4"	11"	9'-3 3/4"	9'-4 1/4"	5.26°
6 3/4"	12 1/2"	9'-3 3/4"	9'-4 1/4"	5.91°
8 1/2"	12 1/2"	9'-2"	9'-2 1/2"	5.91°
8 1/2"	13 3/4"	9'-2"	9'-2 3/4"	6.56°
8 1/2"	15 1/4"	9'-2"	9'-2 3/4"	7.27°
Solid Sawn (nominal sizes)				
8"	12"	9'-2 1/2"	9'-3"	5.73°
8"	14"	9'-2 1/2"	9'-3 1/4"	6.68°
8"	16"	9'-2 1/2"	9'-3 1/2"	7.63°
10"	14"	9'-1/2"	9'-1 1/4"	6.68°
10"	16"	9'-1/2"	9'-1 1/2"	7.63°
10"	18"	9'-1/2"	9'-1 3/4"	8.57°
1'-0"	18"	8'-10 1/2"	8'-11 3/4"	8.57°
1'-0"	20"	8'-10 1/2"	9'-0"	9.50°

General Notes

1. Pier Foundations are designed for a wind speed of 80 MPH and lateral soil pressure strength(s) of 200 PSF/FT (ø=30°). See pier schedule, sheet 6.
2. Planks are 2" nominal tongue and groove, pressure treated No. 1 Grade. Install planks with tongue facing up and groove facing down.
3. Plank ends must be aligned with edge of post.
4. Bottom of barrier must be embedded 6" below the ground surface.
5. All nails shall be placed at least .5" from plank edges and adjacent nails. For 2x6 or 2x8 planks, use 2 nails per connection to post. For 2x10 or 2x12 planks, use 3 nails per connection to post. Maximum nail spacing 8".
6. Posts to be pressure treated prior to fabrication with CCA to a retention of .60 PCF per AWPA C2.
7. Planks for panels to be pressure treated with CCA to a retention of .40 PCF per AWPA C2.
8. Field treat cut ends per AWPA M4.
9. Post sizes for various heights, design wind velocities, species and grades are provided in schedules on sheets 4-6.
10. Pier and reinforcement sizes for various heights and design wind velocities are provided on sheet 6.

The sound barriers depicted on these drawings were developed and tested under a cooperative research agreement between the Pennsylvania State University, the USDA Forest Service Forest Products Laboratory and the Federal Highway Administration.

Standard Plans for Timber Sound Barriers

Horizontal Skew Timber Plank

November 1997

Sheet 3 of 6

Western Species Glue Laminated

Grade: 16F-V6/ 16F-V7

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	10 1/2	5 1/8	10 1/2	6 3/4	10 1/2	6 3/4	12	6 3/4	15	6 3/4	16 1/2
80	5 1/8	10 1/2	5 1/8	12	6 3/4	12	6 3/4	15	6 3/4	16 1/2	6 3/4	18
90	5 1/8	12	5 1/8	13 1/2	6 3/4	15	6 3/4	16 1/2	6 3/4	18	8 1/2	18
100	5 1/8	12	5 1/8	15	6 3/4	16.5	6 3/4	18	8 1/2	19 1/2		
110	5 1/8	13 1/2	5 1/8	16 1/2	6 3/4	18	6 3/4	19 1/2				

Grade: 20F-V8

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	10 1/2	5 1/8	10 1/2	6 3/4	10 1/2	6 3/4	12	6 3/4	13 1/2	6 3/4	15
80	5 1/8	10 1/2	5 1/8	10 1/2	6 3/4	12	6 3/4	13 1/2	6 3/4	15	6 3/4	16 1/2
90	5 1/8	10 1/2	5 1/8	12	6 3/4	13 1/2	6 3/4	15	6 3/4	16 1/2	6 3/4	18
100	5 1/8	12	5 1/8	13 1/2	6 3/4	13 1/2	6 3/4	16 1/2	6 3/4	18	8 1/2	18
110	5 1/8	12	5 1/8	15	6 3/4	15	6 3/4	18	8 1/2	18		

Grade: 22F-V7

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	10 1/2	5 1/8	10 1/2	6 3/4	10 1/2	6 3/4	12	6 3/4	13 1/2	6 3/4	15
80	5 1/8	10 1/2	5 1/8	10 1/2	6 3/4	10 1/2	6 3/4	12	6 3/4	13 1/2	6 3/4	15
90	5 1/8	10 1/2	5 1/8	12	6 3/4	12	6 3/4	13 1/2	6 3/4	16 1/2	6 3/4	18
100	5 1/8	10 1/2	5 1/8	13 1/2	6 3/4	13 1/2	6 3/4	15	6 3/4	18	6 3/4	19 1/2
110	5 1/8	12	5 1/8	15	6 3/4	15	6 3/4	16 1/2	6 3/4	19 1/2	8 1/2	19 1/2

Grade: 24F-V9

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	10 1/2	5 1/8	10 1/2	6 3/4	10 1/2	6 3/4	12	6 3/4	13 1/2	6 3/4	15
80	5 1/8	10 1/2	5 1/8	10 1/2	6 3/4	12	6 3/4	13 1/2	6 3/4	15	6 3/4	16 1/2
90	5 1/8	10 1/2	5 1/8	12	6 3/4	13 1/2	6 3/4	15	6 3/4	16 1/2	6 3/4	18
100	5 1/8	10 1/2	5 1/8	13 1/2	6 3/4	13 1/2	6 3/4	15	6 3/4	18	6 3/4	19 1/2
110	5 1/8	12	5 1/8	13 1/2	6 3/4	15	6 3/4	16 1/2	6 3/4	18	8 1/2	19 1/2

Southern Pine Glue Laminated

Grade: 16F-V5

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	11	5 1/8	11	5 1/8	12 3/8	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	17 7/8
80	5 1/8	11	5 1/8	12 3/8	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	17 7/8	6 3/4	17 7/8
90	5 1/8	11	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	17 7/8	6 3/4	17 7/8	8 1/2	17 7/8
100	5 1/8	12 3/8	5 1/8	15 1/8	5 1/8	17 7/8	6 3/4	17 7/8	8 1/2	17 7/8	8 1/2	19 3/8
110	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	19 3/8	6 3/4	19 3/8	8 1/2	19 3/8		

Grade: 20F-V5

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	11	5 1/8	11	5 1/8	11	5 1/8	13 3/4	5 1/8	15 1/8	5 1/8	16 1/2
80	5 1/8	11	5 1/8	11	5 1/8	12 3/8	5 1/8	15 1/8	5 1/8	16 1/2	5 1/8	17 7/8
90	5 1/8	11	5 1/8	12 3/8	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	17 7/8	6 3/4	17 7/8
100	5 1/8	11	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	17 7/8	6 3/4	17 7/8	6 3/4	19 3/8
110	5 1/8	12 3/8	5 1/8	15 1/8	5 1/8	17 7/8	5 1/8	19 3/8	6 3/4	19 3/8	8 1/2	19 3/8

Grade: 22F-V5

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	11	5 1/8	11	5 1/8	11	5 1/8	13 3/4	5 1/8	15 1/8	5 1/8	16 1/2
80	5 1/8	11	5 1/8	11	5 1/8	12 3/8	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	17 7/8
90	5 1/8	11	5 1/8	12 3/8	5 1/8	13 3/4	5 1/8	15 1/8	5 1/8	17 7/8	5 1/8	19 3/8
100	5 1/8	11	5 1/8	12 3/8	5 1/8	15 1/8	5 1/8	17 7/8	5 1/8	19 3/8	6 3/4	19 3/8
110	5 1/8	12 3/8	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	19 3/8	6 3/4	19 3/8	8 1/2	19 3/8

Grade: 24F-V5

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/8	11	5 1/8	11	5 1/8	11	5 1/8	12 3/8	5 1/8	15 1/8	5 1/8	16 1/2
80	5 1/8	11	5 1/8	11	5 1/8	12 3/8	5 1/8	13 3/4	5 1/8	15 1/8	5 1/8	17 7/8
90	5 1/8	11	5 1/8	11	5 1/8	13 3/4	5 1/8	15 1/8	5 1/8	16 1/2	5 1/8	19 3/8
100	5 1/8	11	5 1/8	12 3/8	5 1/8	15 1/8	5 1/8	16 1/2	5 1/8	19 3/8	6 3/4	17 7/8
110	5 1/8	11	5 1/8	13 3/4	5 1/8	16 1/2	5 1/8	17 7/8	6 3/4	17 7/8	8 1/2	17 7/8

The sound barriers depicted on these drawings were developed and tested under a cooperative research agreement between the Pennsylvania State University, the USDA Forest Service Forest Products Laboratory and the Federal Highway Administration.

Standard Plans for Timber Sound Bariers

Post Schedules- Glue Laminated

November 1997

Western Species Solid Sawn

Grade: DF No. 2

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2
80	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2
90	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2		
100	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2				
110	5 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2						

Grade: DF No. 1

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	15 1/2	5 1/2	17 1/2
80	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	17 1/2
90	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	17 1/2	7 1/2	19 1/2
100	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2
110	5 1/2	13 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2		

Grade: DF D. No. 1

Height	10		12		14		16		18			
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2
80	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2
90	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2
100	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	17 1/2
110	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	17 1/2	9 1/2	17 1/2	9 1/2	19 1/2

Grade: HF No. 2

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2
80	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	9 1/2	17 1/2				
90	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2						
100	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2						
110	7 1/2	17 1/2	9 1/2	19 1/2								

Grade: HF No. 1

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2
80	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2
90	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2
100	5 1/2	13 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2		
110	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2				

Grade: SPF No. 2

Height	10		12		14		16		18			
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	13 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2		
80	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2				
90	5 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2						
100	5 1/2	19 1/2	9 1/2	17 1/2								
110	7 1/2	19 1/2	9 1/2	19 1/2								

Grade: SPF No. 1

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2
80	5 1/2	11 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2
90	5 1/2	13 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2		
100	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2				
110	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2						

The sound barriers depicted on these drawings were developed and tested under a cooperative research agreement between the Pennsylvania State University, the USDA Forest Service Forest Products Laboratory and the Federal Highway Administration.

Standard Plans for Timber Sound Barriers

Southern Pine Solid Sawn

Grade: No. 2

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2
80	5 1/2	11 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2
90	5 1/2	13 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2		
100	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2				
110	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2						

Grade: D. No. 2

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	15 1/2	5 1/2	17 1/2
80	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	19 1/2	7 1/2	17 1/2
90	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	7 1/2	19 1/2	7 1/2	17 1/2	9 1/2	19 1/2
100	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	9 1/2	19 1/2		
110	5 1/2	13 1/2	5 1/2	17 1/2	7 1/2	19 1/2	9 1/2	19 1/2				

Grade: No. 1

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2
80	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2
90	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2
100	5 1/2	11 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2
110	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	17 1/2	9 1/2	17 1/2		

Grade: D. No. 1

Height	10		12		14		16		18		20	
Wind Velocity	b	d	b	d	b	d	b	d	b	d	b	d
70	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	13 1/2	5 1/2	15 1/2
80	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	15 1/2	5 1/2	17 1/2
90	5 1/2	11 1/2	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	19 1/2	7 1/2	17 1/2
100	5 1/2	11 1/2	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	7 1/2	17 1/2	7 1/2	19 1/2
110	5 1/2	13 1/2	5 1/2	15 1/2	5 1/2	17 1/2	5 1/2	19 1/2	7 1/2	19 1/2	9 1/2	19 1/2

Pier Schedule

Posts < 16" = 24"ø Pier

Height	10		12		14		16		18		20	
Wind Velocity	Length	Reinf.	Length	Reinf.	Length	Reinf.	Length	Reinf.	Length	Reinf.	Length	Reinf.
70	4'-0"	10-#7	5'-0"	10-#7	5'-6"	10-#7	6'-6"	10-#7	7'-0"	10-#7	8'-0"	10-#7
80	5'-0"	10-#7	5'-6"	10-#7	6'-6"	10-#7	7'-6"	10-#7	8'-6"	10-#7	9'-6"	10-#7
90	5'-6"	10-#7	6'-6"	10-#7	7'-6"	10-#7	9'-0"	10-#7	10'-0"	10-#7		
100	6'-6"	10-#7	7'-6"	10-#7	9'-0"	10-#7	10'-0"	10-#7				
110	7'-0"	10-#7	8'-6"	10-#7	10'-0"	10-#7						

Posts > 16" = 36"ø Pier

Height	10		12		14		16		18		20	
Wind Velocity	Length	Reinf.	Length	Reinf.	Length	Reinf.	Length	Reinf.	Length	Reinf.	Length	Reinf.
70	3'-0"	10-#9	4'-0"	10-#9	4'-6"	10-#9	5'-0"	10-#9	5'-6"	10-#9	6'-0"	10-#9
80	4'-0"	10-#9	4'-6"	10-#9	5'-0"	10-#9	6'-0"	10-#9	6'-6"	10-#9	7'-6"	10-#9
90	4'-6"	10-#9	5'-0"	10-#9	6'-0"	10-#9	7'-0"	10-#9	7'-6"	10-#9	8'-6"	10-#9
100	5'-0"	10-#9	6'-0"	10-#9	7'-0"	10-#9	7'-6"	10-#9	8'-6"	10-#9	9'-6"	10-#9
110	5'-6"	10-#9	6'-6"	10-#9	7'-6"	10-#9	8'-6"	10-#9	10'-0"	10-#9	11'-0"	10-#9

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Standard Plans for Timber Sound Bariers

Post Schedules- Solid Sawn / Pier Schedules

November 1997

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