10 SOUND TRANSMISSION IN BUILDINGS

10.1 DIFFUSE FIELD SOUND TRANSMISSION

Reverberant Source Room

The problem of sound transmission between rooms is one of considerable interest in architectural acoustics. When two rooms are separated by a common wall having an area S_w, as shown in Fig. 10.1, we model (Long, 1987) the behavior by first assuming that there is a diffuse field in the source room that produces a sound pressure p_s and a corresponding intensity

$$I_s = \frac{p_s^2}{4\,\rho_0\,c_0} \tag{10.1}$$

that is incident on the intervening partition. A fraction τ of the incident energy is transmitted into the receiving room

$$W_r = I_s\,S_w\,\tau = \frac{p_s^2\,S_w\,\tau}{4\,\rho_0\,c_0} \tag{10.2}$$

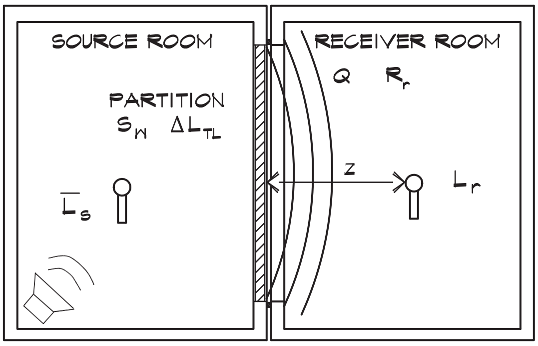
where it generates a sound pressure due to both the direct and the reverberant field contributions. Since the partition is a planar surface, we use Eq. 2.91 for the direct field and Eq. 8.83 for the reverberant field portion of the energy. The receiving room sound energy is

$$\frac{p_r^2}{\rho_0 c_0} = \frac{p_s^2\,S_w\,\tau\,Q}{16\,\pi\,\rho_0\,c_0\left[z + \sqrt{\dfrac{S_w\,Q}{4\,\pi}}\right]^2} + \frac{p_s^2\,S_w\,\tau}{R_r\,\rho_0\,c_0} \tag{10.3}$$

which we can convert to a level relationship by taking 10 log of each side and using the definition of the transmission loss

$$\Delta\,L_{TL} = -10\,\log\,\tau \tag{10.4}$$

FIGURE 10.1 Sound Transmission between Rooms



to obtain the expression for the transmission between two rooms for a diffuse source field and a combination of a direct and diffuse receiving room sound field

$$L_r = \overline{L}_s - \Delta L_{TL} + 10 \log \left[\frac{S_w Q}{16\,\pi \left[z + \sqrt{\dfrac{S_w Q}{4\,\pi}} \right]^2} + \frac{S_w}{R_r} \right] \tag{10.5}$$

where L_r = sound pressure level at a point in the receiver room (dB)
$\overline{L}_s$ = diffuse sound pressure level in the source room (dB) the line over the L denotes a spatial average throughout the room
ΔL_{TL} = transmission loss (dB)
S_w = area of the transmitting surface (m^2 or ft^2)
R_r = room constant in the receiving room (m^2 or ft^2 sabins)
z = distance from the surface of the source to the receiver (m or ft)
Q = directivity of the wall (usually 2)

If the receiving room is very reverberant, the S_w/R_r term is larger than the direct field term and Eq. 10.5 can be simplified to the equation we obtained in Chapt. 9 for the transmission loss between two reverberant rooms

$$\overline{L}_r \cong \overline{L}_s - \Delta L_{TL} + 10 \log \left[\frac{S_w}{R_r} \right] \tag{10.6}$$

It is important to realize that although Eq. 10.6 is accurate for reverberant spaces with good diffusion, it is not accurate when the receiver is close to a transmitting surface or when the absorption in the receiving space is large. For example, if the receiving space is outdoors where the room constant is infinite this equation predicts that no sound will be transmitted.

Sound Propagation through Multiple Partitions

When two reverberant rooms are separated by a partition consisting of two separate components, such as a wall with a window in it, each having a different transmission loss, a *composite transmission loss* may be calculated based on Eqs. 10.4 and 10.6

$$\Delta L_{TL} = 10 \log \left(\frac{S_w}{S_1 \tau_1 + S_2 \tau_2 + \cdots + S_n \tau_n} \right) \tag{10.7}$$

Using this expression, it soon becomes clear that the component having the lowest transmission loss will control the process. It is much like having a bucket full of water with several holes in it. The largest hole (lowest transmission loss) controls the rate at which water flows out. Let us take, for example, the case where a $3\overset{0}{-} \times 4\overset{0}{-}$ (915 mm × 1220 mm) window having a 25 dB transmission loss occupies part of a $20\overset{0}{-} \times 8\overset{0}{-}$ (6.1 m × 2.4 m) gypboard and stud wall having a transmission loss of 45 dB. The composite transmission loss may be calculated

$$\Delta L_{TL} = 10 \log \left(\frac{160}{12(.0034) + 148(.00003)} \right) = 35.5 \text{ dB}$$

Thus, although the window has a much smaller area than the wall, it significantly reduces the overall transmission loss of the composite structure.

Composite Transmission Loss with Leaks

An even more dramatic example of a reduction in composite transmission loss is that produced by a zero transmission loss path such as an opening under a door. Using a $3\overset{0}{-} \times 6\overset{8}{-}$ (0.9 m × 2 m) solid core door having a transmission loss of 30 dB and a 1/2" (13 mm) high opening under the door with a transmission loss of zero dB (at high frequencies), we obtain an overall loss of

$$\Delta L_{TL} = 10 \log \left(\frac{20.125}{20(.001) + .125(1)} \right) = 21.4 \text{ dB}$$

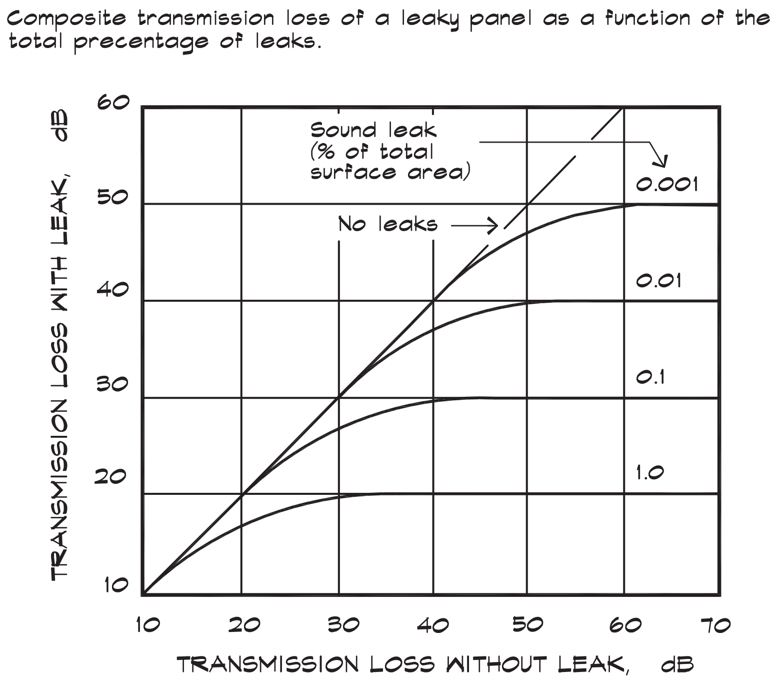
In this case, 8 dB, more sound energy comes through the slot under the door than through the remainder of the door. Figure 10.2 shows the effects leaks on the overall transmission loss of a structure. The relative area of the leak when compared with the overall area of the partition determines the composite transmission loss of the structure in the diffuse field model.

Transmission into Absorptive Spaces

Where sound is transmitted from a reverberant space, through a partition, and into an absorbent space, we can no longer use the approximations given in Eqs. 10.6 and 10.7. Instead, we must use Eq. 10.5, which includes consideration of the direct field contribution in the receiving space. Under these conditions, the composite transmission loss equation becomes inaccurate and we must calculate the energy contribution from each transmitting surface separately, and combine the levels in the receiving space. The results are then dependent on the physical proximity of the receiver to each transmitting surface.

If we repeat the calculation we just did using the half-inch crack under a solid core door, we will get a different answer for different distances between the observer and the

FIGURE 10.2 Composite Transmission Loss with Leaks (Reynolds, 1981)



transmitting surfaces. Let us assume that the receiver is located 2 feet (0.6 m) away from the door in a space having a room constant of 1000 sq. ft. (93 sq. m) sabins, and that there is an 80 dB sound pressure level in the source room. A computation of the level through the door yields a 39 dB level in the receiving room through this path. We then perform a separate calculation for the hole. If the observer is kneeling 2 feet from the hole, the resulting level is 51 dB and the combined (door + hole) level is also 51 dB. If instead, he is standing 2 feet from the door and 6 feet from the hole, the resultant level is 44 dB and the combined level is 45 dB, which is significantly less. Note that for the same conditions Eq. 10.6 and 10.7 would predict 42 dB—less than either of the other two answers since there is no direct-field contribution.

For sound that is radiated from an enclosed reverberant space into the outdoors there is no longer a reverberant field in the receiving space so the room constant goes to infinity. Equation 10.5 then reduces to

$$L_r = \overline{L}_S - \Delta L_{TL} + 10 \log \left[\frac{S_w\, Q}{16\, \pi \left[z + \sqrt{\dfrac{S_w\, Q}{4\, \pi}} \right]^2} \right] \tag{10.8}$$

If we use Eq. 10.8 to calculate the expected level for a receiver in the free field, close to a radiating surface, where z is nearly zero, we obtain

$$L_r \cong \overline{L}_S - \Delta L_{TL} - 6 \tag{10.9}$$

When the distance between the surface and the receiver is large, Eq. 10.8 becomes

$$L_r \cong \overline{L}_S - \Delta L_{TL} + 10 \log \left(S_w \, Q / 16 \, \pi \, z^2 \right) \tag{10.10}$$

A similar approximation can be made in an enclosed receiving space when the receiver is sufficiently far from the transmitting surface that the receiving area is large compared with the area of the surface

$$L_r \cong \overline{L}_S - \Delta L_{TL} + 10 \log \left[\frac{S_w \, Q}{16 \, \pi \, z^2} + \frac{S_w}{R_r} \right] \tag{10.11}$$

When there are multiple transmitting surfaces, the energy contribution through each surface must be calculated and the energies added to obtain the overall receiver level.

Transmission through Large Openings

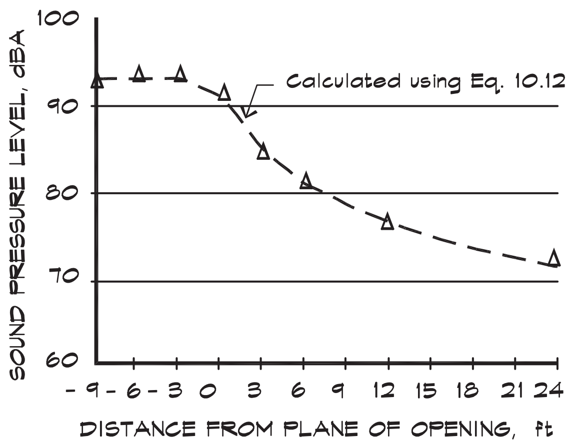
When sound is transmitted through an opening in a wall that is large compared with a wavelength, an adjustment must be made to Eq. 10.8. When the formula for transmission loss is derived, it is based on the intensity passing through an area, a fraction of which is transmitted into a partition. The reason the intensity, a vector quantity, is used is that for the mass law model a panel moves as a monolithic object along one axis, normal to its surface. The only forces that move it are those with components along the normal. When reverberant sound energy passes through a large opening, all the energy falling on the opening passes through, not just the components normal to the surface. Consequently the energy transmitted is twice the reverberant-field intensity times the area as in Eq. 8.80. The difference lies in the fact that there is no longer a cosine term to integrate in the conversion from energy into intensity. If we use Eq. 10.8, whose derivation was based on intensity, the calculated value underpredicts the actual result. For transmission through a large opening in a wall, such as a door or window having a zero transmission loss,

$$L_r = \overline{L}_S + 10 \log \left[\frac{S_w \, Q}{8 \, \pi \left[z + \sqrt{\dfrac{S_w \, Q}{4 \, \pi}} \right]^2} \right] \tag{10.12}$$

Hessler and Sharp (1992) have tested this relationship by measuring the sound pressure level, generated by a reciprocating compressor in a reverberant concrete-and-steel mechanical equipment room, passing through a doorway into an open yard. The results are shown in Fig. 10.3 along with calculated levels for a Q of 4. The measured values closely match the predicted levels, indicating baffling by both the wall and the ground. It is interesting to note in the figure that the measured level at $z = 0$ is 3 dB below the interior level. This transitional behavior can be expected to occur not only for an opening, but also with any porous material, whose impedance was primarily due to flow resistance rather than mass. If the transmission loss of such a material were measured in the laboratory, the effect would be included in the measured data so the normal equation could be used, although negative transmission loss values might be found for light materials.

FIGURE 10.3 Sound Level Falloff from an Open Doorway (Hessler and Sharp, 1992)

Measured (Δ) and calculated sound levels emanating from an open 3' x 8' doorway.



Noise Transmission Calculations

Calculations of sound propagation between spaces are done with diffuse-field transmission loss data, in individual octave or third-octave bands, and the receiving levels are combined to obtain an overall result. Most transmission loss data on walls and other components are measured in third octaves and source data (either sound power levels or sound pressure levels) are available in octave bands. Absorption coefficient data also are published primarily in octave bands. If third octave transmission loss data are used in an octave-band calculation, a composite value should be calculated.

$$\Delta L_{TL} = -10 \log \frac{1}{3} \sum_{i=1}^{3} 10^{-0.1 \Delta L_{TL_i}} \tag{10.13}$$

The exact value of course depends on the actual source spectrum and cannot be determined a priori. The same equation can be applied to the composite dynamic insertion loss of silencers.

When laboratory transmission loss data are used to predict sound levels under field conditions, the standard expectation is about a 5 dB underestimation of the receiver levels when Eq. 10.6 is used. This is acknowledged in many standards. For example, the California Noise Insulation Standards (1974) require the use of minimum STC 50 rated walls and floor-ceiling systems between dwelling units, but allow an FSTC rating of 45 under a field test. The normal reason given for this difference is the care taken in the construction of laboratory test partitions as compared to typical construction practice. A portion of the difference between laboratory and field test results may be due to the lack of consideration of the direct field contribution as well as the lack of the purely diffuse field in the receiving space assumed in the standard formula.

10.2 STC RATINGS OF VARIOUS WALL TYPES

Laboratory vs Field Measurements

The sound transmission class (STC) ratings of various construction elements are of considerable interest to architects and acoustical engineers. Although these ratings are in general use, it is also important to examine the third octave band transmission loss data that form the basis for the rating and to compare it to the theoretical predictions discussed previously. Several sets of measured data are included, which are based in part on the State of California compendium of STC and IIC ratings. It is important to note that an STC rating should not be the sole basis on which a decision to use a particular construction is made. This is particularly true in the case of floor-ceilings, where the length of the structural span and floor coverings play a major role.

Measurements of the sound transmission class in the field, as contrasted to the laboratory, are designated FSTC ratings. It is generally agreed that these ratings are five or more points lower than the laboratory ratings. The reason for this difference is attributed to the extra care in blocking the various flanking paths associated with laboratory tests and the lack of electrical outlets and other paths. It may also be in part attributable to more absorption in a typical receiving space and to the fact that the direct field transmission is not considered in the standard equation. In either case, it is prudent to design critical partitions with a margin of safety, which takes into account the expected in-field performance.

Single Wood Stud Partitions

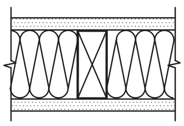
Several single wood stud walls are shown in Fig. 10.4. Note that the effectiveness of batt insulation is much less than the ideal improvement from Fig. 9.19. This is because much of the sound is transmitted through structural coupling by the studs. Nevertheless, it is important to include batt insulation for sound control even in single stud walls.

Single Metal Stud Partitions

Examples of metal stud partitions are shown in Fig. 10.5. Single lightweight (26 Ga) metal studs are more effective than wood studs since they are inherently flexible. The studs themselves act as vibration isolators and decouple one side from another, thereby reducing structureborne noise transmission. Consequently, it is of little value to add resilient channel or other flexible mounts to nonstructural metal studs. The method of attachment also affects the transmission loss. Panels that are glued continuously to studs yield lower transmission loss values than panels that are screw attached. The gluing apparently increases the stiffness of the stud flange, which then increases transmission via the studs (Green and Sherry, 1982).

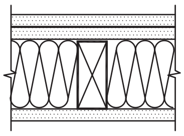
Gypsum board panels are lifted into place during construction using a spacer under their bottom edge, so there is a 3 mm to 6 mm (1/8” to 1/4”) gap at the bottom of the sheet. Holes such as these must be sealed if the transmission loss of the construction is to be maintained. Closing off openings in partitions is critical to acoustical performance, particularly for the case of high transmission loss partitions. Gaps are closed off with a nonhardening caulk so the acoustical rating of the wall can be maintained. Figure 10.6 shows the effect of gaps on the STC ratings. Similar openings can be left by electrical box penetrations, pipe penetrations, cutouts for medicine cabinets, light fixtures, and duct openings. Caulk should not be used

FIGURE 10.4 Transmission Loss of Single Wood Stud Walls (California Office of Noise Control, 1981)



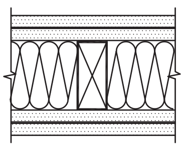
Single Wood Stud Wall - 2 x 4 Stud
1 Layer 5/8" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	15	15	20	24	27	29	32	36	39	41	41	40	37	36	39	43	34
B	17	15	25	35	34	32	37	40	40	43	44	45	37	34	41	47	36



Single Wood Stud Wall - 2 x 4 Stud
1 Layer 5/8" Drywall One Side
Two Layers Opposite Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	19	19	23	26	28	28	34	36	39	38	38	41	43	44	49	52	36
B	19	21	27	30	32	32	36	40	42	40	40	43	44	46	50	52	39



Single Wood Stud Wall - 2 x 4 Stud
2 Layers 1/2" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	15	19	35	35	34	42	43	43	47	48	50	52	53	48	46	50	39
B	21	24	40	37	36	42	45	46	48	50	51	54	55	50	47	51	45

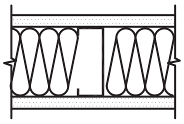
to span more than a 6 mm (1/4”) gap. Larger openings should be filled with drywall mud or gypboard.

Resilient Channel

Resilient channel is a flexible strip of metal designed to support layers of gypboard, while providing a measure of mechanical isolation against structure borne vibrations. A group of wall constructions is shown in Fig. 10.7. Note that the channel is attached to the studs only on one side. Resilient channel should be installed with the open side up so that the weight of the gypboard tends to open the gap between the stud and the board. A filler strip is used at the base plate as a solid protection against impact. The gypboard is attached with drywall screws to the channel and care must be exercised to avoid screwing through the channel and into the studs, which short-circuits the isolation. When there are bookcases or other heavy objects that must be wall mounted, resilient channel is not a good choice since these items must be bolted through into the structure.

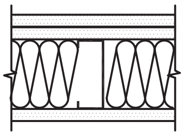
There are a number of products called resilient channel on the market. Some are more effective than others. A type that is spoon-shaped and can be attached only on one side is preferable to the furring channel type, which is hat-shaped and may be attached on both sides. The latter is often improperly installed, rendering it ineffective.

FIGURE 10.5 Transmission Loss of Single Metal Stud Walls (California Office of Noise Control, 1981)



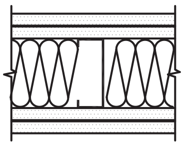
Single Metal Stud Wall - 3 5/8" Stud
1 Layer 5/8" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	20	23	30	31	30	34	40	41	45	48	49	47	39	38	40	46	39
B	29	35	40	42	43	48	52	55	57	57	57	54	45	40	44	50	44



Single Metal Stud Wall - 3 5/8" Stud
1 Layer 5/8" Drywall One Side
Two Layers Opposite Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	29	31	35	38	41	44	48	47	49	51	53	56	53	44	41	46	45
B	35	37	40	39	40	42	44	47	50	54	56	55	50	44	46	50	47



Single Metal Stud Wall - 3 5/8" Stud
2 Layers 5/8" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	27	31	38	41	42	44	47	51	52	52	53	52	49	46	46	49	48
B	32	37	42	45	48	50	51	52	52	52	51	49	49	48	48	50	50

FIGURE 10.6 Dependence of the STC Rating on Caulking (Ihrig, Wilson. 1976)

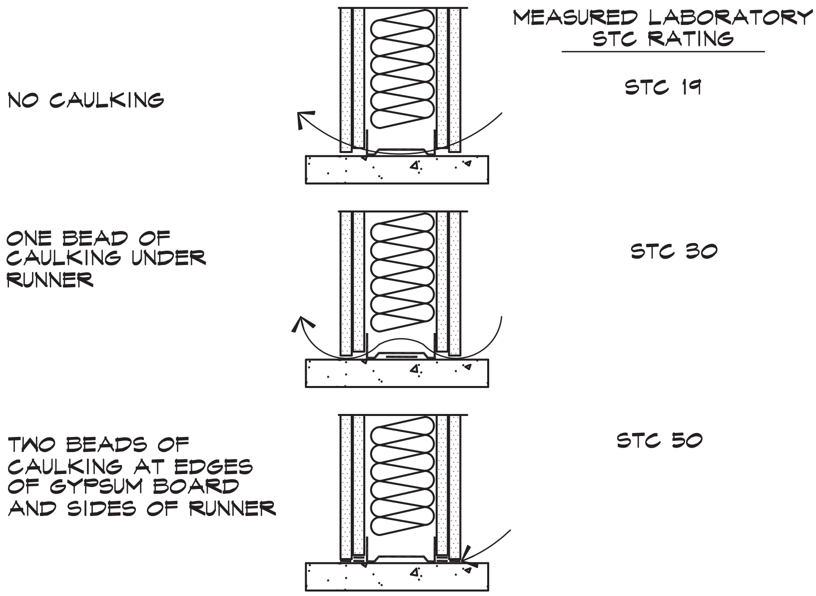
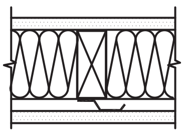
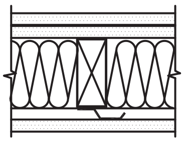


FIGURE 10.7 Transmission Loss of Single Stud Resilient Walls (California Office of Noise Control, 1981)



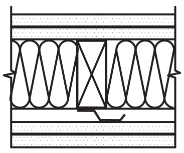
Single Wood Stud Wall - 2 x 4 Stud
1 Layer 5/8" Drywall Each Side
One Side on Resilient Channel
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	16	19	26	26	32	33	37	40	44	45	47	46	40	40	44	48	38
B	29	33	37	40	45	50	51	53	53	54	54	53	47	42	51	57	46



Single Wood Stud Wall - 2 x 4 Stud
1 Layer 5/8" Drywall on Resilient Channel One Side
Two Layers Opposite Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	27	28	34	33	34	37	40	42	44	45	46	49	49	49	53	54	43
B	30	38	41	43	46	47	49	50	51	49	49	51	52	53	55	56	50



Single Wood Stud Wall - 2 x 4 Stud
2 Layers 1/2" Drywall Each Side
One Side on Resilient Channel
A - Without Insulation B - R-11 Batt Insulation

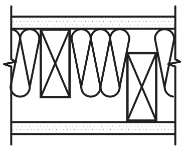
	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	28	33	41	43	44	51	51	53	56	56	60	60	61	55	52	57	52
B	33	39	43	46	50	56	58	59	62	61	62	63	62	59	57	58	56

The purpose of resilient channel is to provide a flexible connection to mechanically decouple the partitions on either side of the framing. When the panels are already separately or flexibly supported, the addition of resilient channel does little to improve the transmission loss. Thus there is little or no advantage in adding channel to double stud, staggered stud, or single lightweight metal stud construction.

Resilient channel is not effective when it is installed between two layers of gypboard, since the air gap is small (typically 13 mm or 1/2") and the trapped air creates an air spring, which makes an additional mass air mass resonance. If a single metal stud wall with batt insulation has drywall on each side and another layer is added on resilient channel, the result is worse than without the additional layer (Green and Sherry, 1982).

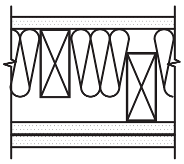
Resilient channel is utilized in floor-ceilings more often than in walls since it is compromised by mounting bookcases or cabinets to the supporting studs. It is only effective in isolating small-amplitude vibrations that are much less than the structural deflection under load. It is generally not effective in preventing the transmission of low-frequency sound created by the large-scale deflection of long-span joists under a dynamic load. However, it can provide an improvement at high frequencies to both the STC and IIC ratings in floor-ceiling systems. In floor-ceilings, it should be installed so that the ceiling gypboard is butted

FIGURE 10.8 Transmission Loss of Staggered Stud Walls (California Office of Noise Control, 1981)



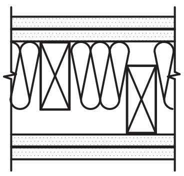
Staggered Wood Stud Wall
2 x 4 Studs on a 2 x 6 Plate
1 Layer 5/8" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	29	30	33	36	39	43	44	44	46	46	50	50	43	39	46	51	43
B	34	36	40	43	45	45	45	46	47	49	50	49	45	42	46	53	46



Staggered Wood Stud Wall
2 x 4 Studs on a 2 x 6 Plate
1 Layer 1/2" Drywall One Side
Two Layers Opposite Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	32	32	35	36	39	46	46	49	50	53	54	55	47	44	50	55	47
B	38	41	41	44	47	51	51	53	54	55	56	57	58	54	50	55	53



Staggered Wood Stud Wall
2 x 4 Studs on a 2 x 6 Plate
2 Layers 5/8" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	31	35	36	42	45	47	49	51	54	54	56	56	53	51	55	59	51
B	35	39	45	45	49	49	52	53	54	55	56	57	54	50	53	57	53

against the wall gypboard, leaving the resiliently supported surface free to move. If the ceiling surface rests on the wall gypboard, the mechanical isolation is compromised at the edges.

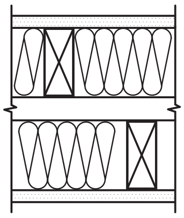
Staggered-Stud Construction

Staggered stud wall construction represents a compromise between single-stud and double-stud construction. The use of staggered wood studs on a common 2 × 6 (38 mm × 140 mm) base plate, which is shown in Fig. 10.8, can provide some mechanical decoupling between the panels on either side of a wall, but is limited by the flanking transmission through the plates. It produces transmission loss values that are comparable to resilient channel and, since a solid stud is used, this wall construction will support bookcases and the like and is thus preferred. It is difficult to use a staggered stud configuration with metal studs because at the top and bottom plates, a continuous runner cannot be used. A 3 5/8” (92 mm) 26 Ga metal stud has significant decoupling, due to its inherent softness, so there is little advantage to staggering metal studs. If a higher transmission loss is required and the width is limited, a double 2 1/2” (64 mm) metal stud with a 1/2” (13 mm) air gap will yield the same wall thickness as a staggered wood stud system and better isolation.

Double-Stud Construction

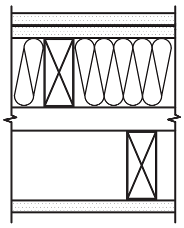
Where high transmission loss values are desired, double-stud construction, with multiple layers of gypboard or heavy plaster, is preferred. The losses are limited by the flanking transmission through the structure, which can be improved by setting one or both sides of the wall on a floating floor or isolated stud supports in specialized applications such as studios. Typical double-stud constructions are given in Fig. 10.9. There is no appreciable difference

FIGURE 10.9 Transmission Loss of Double-Stud Walls (California Office of Noise Control, 1981)



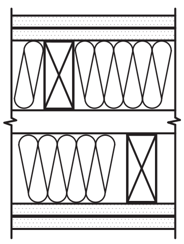
Double Wood Stud Wall
2 x 4 Studs Separated by a 1" Gap
1 Layer 5/8" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation
C - 2 Layers R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	31	34	37	42	43	51	47	50	51	52	54	51	41	41	46	52	45
B	36	41	44	44	51	56	56	58	61	62	63	62	53	52	58	62	56
C	35	39	42	49	52	53	55	56	59	62	64	65	62	59	62	66	57



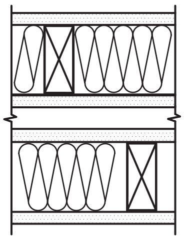
Double Wood Stud Wall
2 x 4 Studs Separated by a 1" Gap
1 Layer 5/8" Drywall One Side - 2 Layers Opposite
A - Without Insulation B - R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	33	37	40	47	50	55	53	56	57	56	59	57	48	48	53	58	52
B	38	45	48	49	54	60	60	60	62	62	63	62	55	57	61	63	59



Double Wood Stud Wall
2 x 4 Studs Separated by a 1" Gap
2 Layers 5/8" Drywall Each Side
A - Without Insulation B - R-11 Batt Insulation
C - 2 Layers R-11 Batt Insulation

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	35	39	42	45	48	50	52	55	55	54	56	54	53	53	53	55	54
B	37	38	43	48	51	54	57	59	61	65	69	70	70	67	68	70	58
C	41	46	50	55	58	59	61	62	64	67	69	70	67	66	68	69	63



Double Wood Stud Wall
2 x 4 Studs Separated by a 2 1/4" Gap
1 Layer 5/8" Drywall Each Side of Both Studs
2 Layers R-11 Batt Insulation

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
22	23	34	45	46	44	49	57	61	65	67	67	60	57	63	68	44

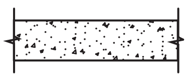
in the performance of wood and metal double studs, since there is no additional decoupling due to the intrinsic stiffness of the stud.

Gypboard layers placed in the air gap between the studs reduce the transmission loss because a bridging air pocket is formed. For a given number of layers it is most effective to place them on the outside faces of the double studs. For example, the last wall shown in Fig. 10.9 rates an STC 44 with inner drywall layers as compared to a 63 rating for the same number of layers on the outside. As the air gap increases this disadvantage is offset by the effectiveness of the separation. If the distance between the studs is several feet, such as two stud walls separated by a corridor, the mass-air-mass resonance is so low that it would have no appreciable effect.

High-Mass Constructions

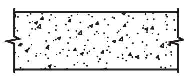
Heavy materials such as concrete, grouted cmu blocks, concrete-filled metal decking, and similar products can provide substantial transmission loss due to their intrinsic mass. Although a single panel structure is less efficient in the loss per mass than a multiple layer construction, in many cases there is no viable substitute. Figure 10.10 shows the measured

FIGURE 10.10 High Mass Wall Construction (California Office of Noise Control, 1981)



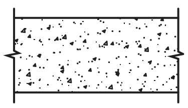
4" Solid Concrete Panel - 54 lbs/sq ft

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
48	44	43	42	39	41	45	46	48	56	53	51	57	62	65	66	44



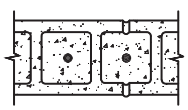
6" Solid Concrete Panel - 75 lbs/sq ft

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
38	41	41	43	45	48	52	54	57	59	62	65	67	69	71	73	55



8" Solid Concrete Panel - 95 lbs/sq ft

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
44	44	45	48	51	53	55	56	56	58	60	62	63	65	66	67	58



8 x 8 x 16 3-cell Lightweight Concrete Masonry Unit
A No Center Grout - 28 lbs/block
B Center Grouted + #5 Rebar
C Center Grouted + #5 Rebar + 2 Coats Flat Oil Base Paint Each Side

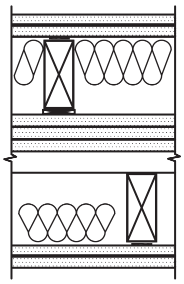
	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	34	31	37	36	37	38	41	45	43	44	48	49	52	52	54	55	45
B	35	33	37	37	41	40	44	45	49	54	57	60	64	66	70	73	48
C	36	37	39	44	46	49	54	54	57	59	62	66	69	71	75	75	55

transmission loss values of concrete panels used in wall or floor construction. Note the difference in the grouted block data between painted and nonpainted conditions. Blocks are intrinsically porous and must be sealed with a bridging (oil-based) paint to achieve their full potential.

High Transmission Loss Constructions

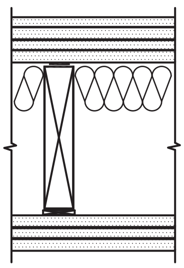
An important study was undertaken by Sharp (1973) to try to develop construction methods that would achieve transmission loss ratings 20 dB or more above the mass law. In this work several techniques were utilized, not normally seen in standard construction practice but which could easily be implemented. These included spot lamination, which has been previously discussed, and point mounting. The point mounting technique he devised was to use 1/4” (6 mm) thick foam tape squares between the gypboard and the stud and then to attach the sheet with drywall screws through the tape into the stud. This technique resulted in panel isolation that approaches the theoretical point mounting discussed in Eq. 9.54. A triple panel wall having an STC of 76 utilizing these techniques is shown in Fig. 10.11. This wall has a relatively low transmission loss value of 33 dB in the 80 Hz band.

FIGURE 10.11 High Transmission Loss Wall Construction (Sharp, 1973)



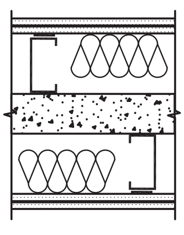
Double Wood Stud Wall
2 x 4 Studs Separated by a 3" Gap
Outside Layers 3/8" + 1/2" Drywall on 1/4" Foam Tape
Inside 5/8" + 1/2" + 5/8" Drywall on 1/4" Wood Squares
All Layers Spot Laminated at 24" OC and Screwed Through Mounts - 2" Batt Insulation in all Cavities

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
53	56	60	66	70	75	78	80	78	79	83	83	84	87	88	89	76



Single Wood Stud Wall - 2 x 8 Studs
1/2" + 3/8" + 1/2" + 3/8" Drywall on 1/4" Foam Tape
5/8" + 1/2" + 5/8" Drywall on 1/4" Wood Squares
All Layers Spot Laminated at 24" OC and Screwed Through Mounts - 2" Batt Insulation in all Cavities

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
49	53	54	57	60	62	64	66	68	74	79	80	82	83	84	85	69



Concrete and Metal Double Stud Wall
2" Reinforced Concrete Panel
2 Layers 1/4" Drywall On 1/4" Foam Tape Each Side
2 1/2" Metal Studs - All Panels Spot Laminated at 24" OC and Screwed Throught the Mounts
2" Batt Insulation in the Airspace

125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
49	53	60	63	66	68	71	73	76	78	77	78	81	83	87	88	72

Figure 10.11 also shows a double panel wall having the same mass as the previous construction. This has a lower rating (STC 69) due to reduced performance in the mid-frequencies but much better performance at low frequencies (41 dB at 80 Hz). The multiple layers of spot laminated drywall significantly reduce the coincidence effects. Similar performance should be obtained using separate double stud construction assuming that flanking paths have been controlled.

10.3 DIRECT FIELD SOUND TRANSMISSION

Direct Field Sources

We previously examined the transmission of sound through partitions for a diffuse or reverberant source field. For a direct source field the behavior of the transmission loss is somewhat different. A direct field consists of a plane or nearly plane wave that proceeds unimpeded from the source to the transmitting surface. The energy density and thus the relationship between the sound pressure levels and the sound intensity levels for a plane wave differs by 6 dB from the relationship for a diffuse field. The transmission loss of a surface is also dependent on the angle of incidence, and this must be taken into account in any comprehensive theory.

In a plane wave the power transmitted through a surface is simply related to the intensity incident on the surface

$$W = I\, S \cos\theta\ \tau(\theta) \tag{10.14}$$

where W = power transmitted through a surface (W)
I = direct field intensity incident on the surface(W/m^2)
S = area of the surface(m^2)
θ = angle of incidence with the normal to the surface (rad)
$\tau(\theta)$ = transmissivity of the surface for angle θ

For an exposed surface and an interior observer Eq. 10.14 can be inserted into Eq. 8.87 to obtain

$$\begin{aligned} L_r &= L_s - \Delta L_{TL}(\theta) + 10 \log\,(4 \cos\theta) \\ &\quad + 10 \log \left[\frac{S_w\, Q}{16\,\pi \left[z + \sqrt{\dfrac{S_w\, Q}{4\,\pi}} \right]^2} + \frac{S_w}{R_r} \right] \end{aligned} \tag{10.15}$$

where L_s = direct field sound pressure level near, but in the absence of, reflections from the transmitting surface (dB)
L_r = direct plus reverberant field sound pressure level in the receiving space (dB)
$\Delta L_{TL}(\theta)$ = direct field transmission loss of a partition for a given angle θ, (dB)

Let us define a receiver correction C, such that

$$C = 10 \log \left[\frac{S_w Q}{16 \pi \left[z + \sqrt{\frac{S_w Q}{4 \pi}} \right]^2} + \frac{S_w}{R_r} \right] \tag{10.16}$$

Then for normal incidence

$$L_r = L_s - \Delta L_{TL} (\theta = 0) + C + 6 \tag{10.17}$$

This is the same form as Eq. A3 in ASTM Standard E336 for normal incidence sound transmission loss. Note that if $z = 0$ and $\Delta L_{TL} (\theta = 0)$ at the center of an open window, then $L_r = L_s$. This is the correct result since the transmission loss of large openings for plane waves is zero.

Direct Field Transmission Loss

Transmission loss measurements are conducted in two highly reverberant laboratory test rooms. On the source side, by control of the absorption in the room and the number and orientation of the loudspeakers, a diffuse (reverberant) field is achieved at the test partition. Under these conditions, Eq. 10.6 holds and defines the diffuse field transmission loss. The bulk of the transmission loss data are measured in this manner. There is some difficulty in applying these data to direct-field calculations, since there is no specific angular dependence in the laboratory data. We can return to the fundamental mass law relationship given in Eq. 9.18

$$\Delta L_{TL} (\theta) = 10 \log \left[1 + \left(\frac{\omega \, m_s \cos \theta}{2 \rho_0 c_0} \right)^2 \right] \tag{10.18}$$

where $\Delta L_{TL} (\theta)$ = direct field transmission loss of a partition for a given angle θ, (dB)
ω = radial frequency (rad / s)
ρ_s = surface mass density (kg / m^2)
ρ_0 = density of air (kg / m^3)
c_0 = velocity of sound in air (m / s^2)

In Chapt. 9 this equation was integrated over values of θ between 0° and about 78° to obtain agreement with the measured results. The laboratory transmission loss data are found to be some 5 dB below the $\Delta L_{TL} (\theta = 0)$ data (Ver and Holmer, 1971). For this treatment we assume that the angular dependence of the transmission loss is given by Eq. 10.18. This does not preclude the use of actual measured transmission loss data, but only means that this angular dependence is assumed. We also assume that the density of most walls is large so that $\left(\omega \, m_s \cos \theta / 2 \rho_0 c_0\right)^2 >> 1$ for angles less than 78°. Under these conditions the angular dependence can be written as

$$\Delta L_{TL} (\theta) \cong \Delta L_{TL} (\theta = 0) + 20 \log (\cos \theta) \tag{10.19}$$

and substituting in Eq. 9.22

$$\Delta L_{TL}(\theta) \cong \Delta L_{TL} + 5 + 20 \log(\cos\theta) \tag{10.20}$$

Note that while this equation is used in subsequent calculations, if the transmission loss is zero, then we must revert to Eq. 10.15 to obtain accurate results.

Using these components we can assess the sound transmission due to an exterior plane wave passing through the structure of a building.

$$L_r = L_s - \Delta L_{TL} - \Delta L_{SH} + C + G \tag{10.21}$$

where ΔL_{SH} = correction for self shielding, (dB)
G = geometrical factor, which includes the orientation of the source relative to the transmitting surface, (dB)
$G = 10 \log(4 \cos\theta) + [-5 - 20 \log(\cos\theta)]$
$= 10 \log(1.26/\cos\theta) = 1 - 10 \log(\cos\theta)$

Equation 10.21 includes the diffuse field transmission loss measured in a laboratory with the angular behavior included in the G term. The other terms are defined in Eq. 10. 15.

Free Field—Normal Incidence

When a plane wave is normally incident on a transmitting surface,

$$L_r = L_s - \Delta L_{TL} + C + 1 \tag{10.22}$$

Free Field—Non-normal Incidence

For angles of incidence other than zero the value of G is shown in Table 10.1.

Line Source—Exposed Surface Parallel to It

The line source G factor for an exposed surface, whose normal is perpendicular to the line source, can be determined by energy averaging the G term over all values of θ. The G factors at 0° and 80° are single counted, and all others are double counted. The result is

$$G = 3.6 - 10 \log(\cos\phi) \tag{10.23}$$

where ϕ is the angle between the normal to the transmitting surface and the normal to the line source that intersects the center of the surface. The geometry is shown in Fig. 10.12.

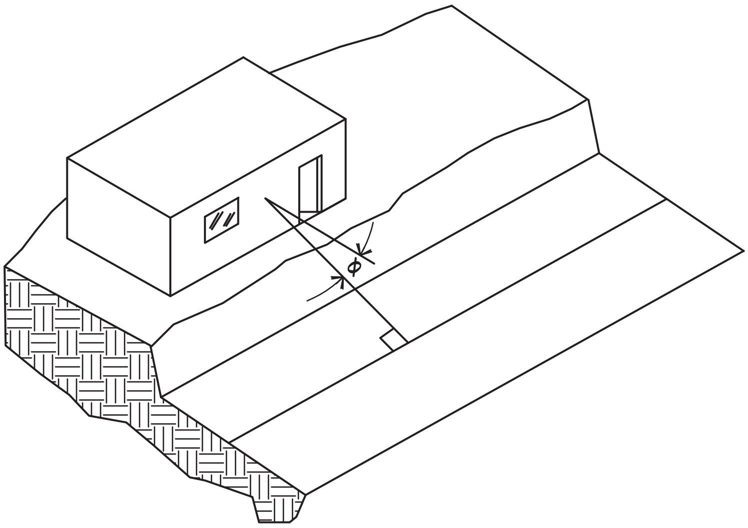
Since the transmission loss is highest when the sound is normally incident, there is often an increase in noise level in high rise buildings with height of the floor above the

TABLE 10.1 Geometrical (G) Factor

	Angle θ, Degrees								
	0	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**
G (dB)	**1.0**	**1.1**	**1.3**	**1.6**	**2.2**	**2.9**	**4.0**	**5.7**	**8.6**

It is common practice not to include angles above 78°.

FIGURE 10.12 Angle between a Plane and a Line Source



street. As one goes from floor to floor the distance from the street increases so the noise level decreases. The G factor, however, increases as well since the angle ϕ is increasing. This effect offsets the distance loss. The result is that frequently, the loudest interior sound levels occur, not on the first floor, but on about the third floor above street level.

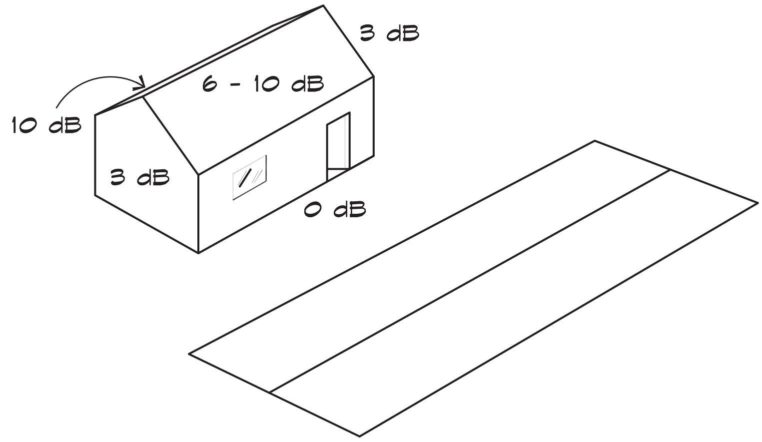
Self Shielding and G Factor Corrections

When a building element is exposed to sound emanating from a point source, the interior level may be calculated using the G factors given in Table 10.1. If the source is shielded by the side of a building it will be attenuated by an amount that can be calculated from the barrier loss relationships previously discussed.

In the case of a line source, where the transmitting surface is a side wall, parallel to the normal, the G factor is theoretically the same as for a wall perpendicular to the normal since for a line source equal energy is radiated from equal angular segments. There is a difference in the self shielding factor, which arises from the fact that the building cuts off half of the line source as seen by the side wall. Figure 10.13 shows ground level self shielding factors for various surface orientations. Both the self shielding and the changes in the G factor are most conveniently subsumed into the self shielding correction.

The difficulty in accurately assessing the geometrical and self shielding corrections for all site configurations is apparent. For odd orientations relative to a line source there is always a tradeoff between the two. For practical calculations shielding is more important than orientation, but it can be influenced by reflections from other structures. If the primary transmitting surface is not facing the roadway, but is within 30° or so, it makes little difference in the G factor while making about a dB difference in the shielding. In general, changes in the two factors due to surface orientation offset one another. For aircraft and other elevated sources, roofs are given a zero shielding factor. Side walls facing the direction of takeoff are considered unshielded, but walls on the approach side are given a 3 dB shielding factor. Surfaces on the side opposite the line of travel are given a 10 dB shielding factor so long as there is no significant sound reflection from nearby structures.

FIGURE 10.13 Line Source Self Shielding Factors



10.4 EXTERIOR TO INTERIOR NOISE TRANSMISSION

As was the case for room to room transmission loss, exterior to interior noise transmission depends on the weakest link in the chain, which in most cases is either the windows or the doors. Where a site is located in a noisy area and a quiet interior noise environment is desired, windows and doors that have a high transmission loss values are critical. Unless exterior levels are quite high, standard California building practices, including stucco exterior walls on wood studs with R-11 (3 1/2" or 90 mm) batt insulation, and 5/8" interior drywall, are adequate to obtain STC ratings that exceed those available in heavy double paned glass windows by a large margin. Thus the doors, both wood and glass, and windows are the main transmission path.

Exterior Walls

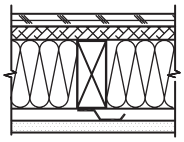
The sound transmission characteristics of several types of exterior walls have been measured by the National Bureau of Standards (Sabine et al., 1975) and are summarized in Fig. 10.14. Where the exterior surface is a lightweight material such as wood or aluminum siding, thin sheet metal or skim coat plaster over Styrofoam, a layer of 5/8" plywood against the stud is usually necessary to bring the mass up to satisfactory levels. It can be seen from Fig. 10.14 that most windows and doors have STC ratings that fall well below the ratings of the commonly used exterior walls. Thus it is necessary to use resilient mounts or separate stud construction on exterior walls only when there are no windows or doors on the wall or where the ratings of these penetrating elements are higher than standard construction will produce.

Windows

Sound transmission through windows depends on the intrinsic rating of the glazing itself and on the treatment of cracks or openings in the window frame. For single paned sealed glazing, the STC ratings are primarily dependent on the thickness of the glass and somewhat dependent on damping provided by a sandwiched interlayer. Figure 10.15 gives transmission loss ratings of various thicknesses of fixed glazing.

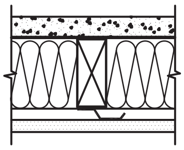
Laminated glazing can provide improved transmission loss performance, especially around the critical frequency. Recognize that although a thinner sheet of laminated glass

FIGURE 10.14 Transmission Loss of Exterior Walls (National Bureau of Standards, 1975)



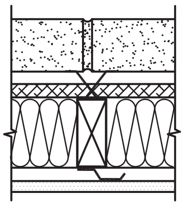
Single Wood Stud Wall - 2 x 4 Stud
1 Layer 5/8" Redwood Siding
3/4" Insulation Board Sheathing
1 Layer 5/8" Drywall
A - Without Insulation B - R-11 Batt Insulation
C - No Insulation - With Resilient Channel
D - R-11 Batt Insulation - With Resilient Channel

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	16	16	22	26	33	35	36	39	43	46	50	51	52	51	48	49	37
B	18	18	28	30	33	34	40	42	45	47	50	50	51	50	50	53	39
C	24	22	26	32	35	38	43	45	50	51	56	57	58	56	54	57	43
D	26	27	30	35	41	43	49	52	56	58	59	60	61	60	58	60	47



Single Wood Stud Wall - 2 x 4 Stud
1 Layer 7/8" Stucco
1 Layer 5/8" Drywall
A - R-11 Batt Insulation
B - No Insulation - With Resilient Channel
C - R-11 Batt Insulation - With Resilient Channel

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	25	30	42	41	44	43	45	45	46	45	46	48	50	50	50	55	46
B	28	32	34	37	41	46	50	50	50	51	54	55	57	55	55	58	49
C	35	41	50	49	53	55	58	58	58	59	59	60	58	57	60	64	57



Red Brick Wire Tied to 2 X 4 Studs
1/2" Airspace
3/4" Insulation Board Sheathing
1/2" Drywall
A - R-11 Batt Insulation - No Resilient Channel
B - No Insulation - With Resilient Channel
C - R-11 Batt Insulation - With Resilient Channel

	125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
A	39	36	42	46	49	51	54	56	58	61	67	67	69	69	70	73	56
B	33	34	41	41	47	50	52	55	59	61	65	66	68	68	69	72	54
C	38	39	46	47	52	54	57	58	60	61	69	68	71	71	72	74	58

may have a higher STC rating, it may be less effective than a heavier sheet of plate glass at low frequencies. The selected product should be based on the actual noise spectrum and the transmission losses in all bands. Transmission loss values for several thicknesses of laminated glass are shown in Fig. 10.16.

When sealed insulating glass is used, the STC rating depends both on the thickness of the glass and the interior air space thickness. Double wall transmission loss theory predicts that a double panel system has a higher transmission loss than a single panel of the same surface weight. This only occurs above the mass-air-mass resonant frequency, which is determined by the weight of each layer and the separation. At or near the resonant frequency the transmission loss of a double panel system is lower than that of a single panel. Even above

FIGURE 10.15 Transmission Loss of Window Glass (National Bureau of Standards, 1975)

Single Strength (3/32" - 2 mm) Glass

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
20	19	18	21	23	22	25	26	26	26	29	30	31	30	33	30	28

Double Strength (1/8" - 3 mm) Glass

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
23	23	21	23	24	24	27	27	28	28	31	32	34	34	30	25	29

7/16" (11 mm) Insulating Glass

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
25	24	23	23	23	21	24	26	30	30	34	35	37	38	40	42	30

3/16" (5 mm) Glass

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
21	23	23	24	25	27	27	28	28	28	28	30	30	27	28	31	28

1/4" (6 mm) Glass

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
21	18	19	24	25	26	27	28	30	31	31	28	25	27	29	32	29

3/8" (9 mm) Glass

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
20	21	24	27	28	29	31	32	33	30	28	26	32	36	38	40	30

1" (25 mm) Insulating Glass (1/8 + 3/4 + 1/8)

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
27	23	20	24	26	28	33	34	37	36	37	38	39	32	35	41	34

this frequency the improvement is limited by mechanical coupling between the two sides. In general it is not effective to use thin double paned windows with air spaces of less than about 3/4” (19 mm) for noise control. Typical transmission loss data are given in Fig. 10.17 for these types of windows.

If window glass is installed in an operable frame there can be a significant degradation in the transmission loss performance due to leakage of air through the seals as well as direct transmission through the frame itself. If we examine the performance of single strength (3/32” or 2.4 mm) glass in various types of frames we find (NBS, 1975) the results shown in Table 10.2. In the case of an aluminum sliding frame, there is a drop of 4 to 5 STC points from the sealed condition.

FIGURE 10.16 Transmission Loss of Laminated Glass

3/16" (5 mm) Safety Glass

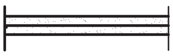
125	160	200	250	315	400	500	630	800	1 k	1.3 k	1.6 k	2 k	2.5 k	3.2 k	4 k	STC
23	24	25	26	27	28	30	30	31	32	34	34	31	27	30	34	31

1/4" (6 mm) Laminated Glass

125	160	200	250	315	400	500	630	800	1 k	1.3 k	1.6 k	2 k	2.5 k	3.2 k	4 k	STC
27	25	26	28	30	30	33	33	33	33	34	35	36	36	38	41	34

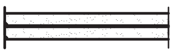
3/8" (9 mm) Laminated Glass

125	160	200	250	315	400	500	630	800	1 k	1.3 k	1.6 k	2 k	2.5 k	3.2 k	4 k	STC
29	30	31	34	32	33	35	35	35	35	34	35	34	38	42	45	36



1/2" (13mm) Laminated Glass

125	160	200	250	315	400	500	630	800	1 k	1.3 k	1.6 k	2 k	2.5 k	3.2 k	4 k	STC
29	30	31	34	33	34	35	35	35	35	33	35	39	42	45	46	37

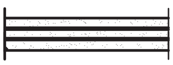


5/8" (16 mm) Laminated Glass

125	160	200	250	315	400	500	630	800	1 k	1.3 k	1.6 k	2 k	2.5 k	3.2 k	4 k	STC
29	30	31	36	35	36	35	35	35	35	37	40	43	45	47	49	38

3/4" (9 mm) Laminated Glass

125	160	200	250	315	400	500	630	800	1 k	1.3 k	1.6 k	2 k	2.5 k	3.2 k	4 k	STC
35	33	33	34	36	36	37	36	35	34	39	41	46	48	50	52	39



3/4" (9 mm) Laminated Glass (3 Layer)

125	160	200	250	315	400	500	630	800	1 k	1.3 k	1.6 k	2 k	2.5 k	3.2 k	4 k	STC
33	30	33	36	38	37	39	38	37	37	39	42	44	47	49	53	41

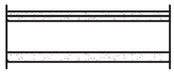
Similar behavior is given in Table 10.3 for insulating glass in various types of frames (NBS, 1975).

When operable frames are part of the window assembly the losses are typically lower than those of the glass alone and can be manufacturer dependent. In critical locations laboratory test data should be obtained from a prospective window supplier and calculations performed using these data.

Doors

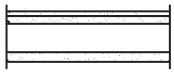
Like windows, exterior and interior doors are a major source of sound leakage in critical applications. Unlike windows, doors are frequently opened and closed and it is the gaps at the joints and at the threshold that present the greatest problem in controlling noise. The standard exterior door thickness in the United States is 1 3/4” (44 mm), and a solid core

FIGURE 10.17 Transmission Loss of Double Glazed Windows



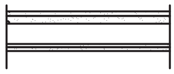
1/4" (6 mm) + 3/4" (19 mm) AS + 1/4" (6 mm) Laminated

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
18	24	23	28	32	33	36	39	39	43	43	42	38	37	42	48	38



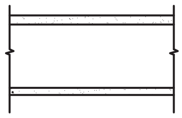
1/4" (6 mm) + 5/8" (16 mm) AS + 3/8" (9 mm) Laminated

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
20	26	26	30	34	34	37	39	40	41	41	40	39	39	46	49	39



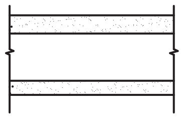
3/16" (5 mm) Lam + 1/2" (13 mm) AS + 3/8" (9 mm) Lam

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
24	26	27	32	32	35	37	38	41	42	39	38	44	50	56	61	40



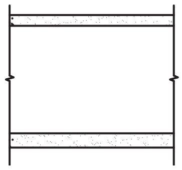
3/16" (5 mm) + 2 1/2" (64 mm) AS + 1/4" (6 mm)

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
23	23	32	31	37	38	41	43	47	50	52	52	48	43	50	46	43



3/8" (9 mm) + 2 1/2" (64 mm) AS + 1/2" (13 mm)

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
28	31	29	35	40	40	44	45	47	46	49	52	53	52	49	51	46



3/8" (9 mm) + 4" (100 mm) AS + 1/4" (6 mm)

125	160	200	250	315	400	500	630	800	1K	1.3K	1.6K	2K	2.5K	3.2K	4K	STC
30	33	39	39	41	46	50	51	54	54	52	55	56	59	65	69	51

TABLE 10.2 STC Ratings of Single Strength Glass in Various Frames

Frame Configuration	STC Rating
Sealed (Average of 5 Tests)	**28–29**
Wood Double-hung, Locked	**26**
Wood Double-hung, Unlocked	**26**
Aluminum Sliding, Latched	**24**

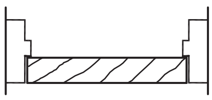
wood door typically weighs about 4–5 lbs/sq ft (20–25 kg/sq m). Based on the mass law one would expect a transmission loss at 500 Hz of about 32 dB for a sealed door. Figure 10.18 shows that this is about what we measure.

In field installations there can be considerable leakage through a door seal at the jamb, head, and threshold. These seals tend to degrade in time due to wear and mechanical failure.

TABLE 10.3 STC Ratings of 7/16" Insulating Glass in Frames

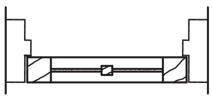
Frame Configuration	STC Rating
Sealed (Average of 2 Tests)	28–30
Wood Double-hung, Locked	26
Wood Double-hung, Unlocked	22
Aluminum Single-hung, Locked	27
Aluminum Single-hung, Unlocked	25

FIGURE 10.18 Transmission Loss of Openable Doors (National Bureau of Standards, 1975)



1 3/4" (45 mm) Hollow Core Door
A - Sealed into Frame
B - Mounted in Frame with Brass Weatherstrip

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	14	14	14	15	15	17	17	17	15	18	22	22	22	24	27	29	21
B	16	15	15	15	16	17	18	17	15	18	24	24	27	28	30	32	20

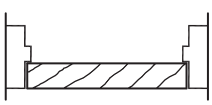


1 3/4" (45 mm) French Door - Single Strength Glass
A - Sealed into Frame
B - Mounted in Frame with Brass Weatherstrip

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	23	20	24	23	24	24	26	29	30	30	32	32	34	35	36	35	31
B	20	20	24	25	23	24	28	29	28	28	25	25	23	25	27	28	26

1 3/4" (45 mm) Hollow Metal Door
A - Sealed into Frame
B - Mounted in Frame with Magnetic Weatherstrip

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	22	21	27	28	28	29	30	31	32	33	33	27	24	34	35	37	28
B	23	21	25	26	26	27	28	29	31	31	32	27	24	32	36	39	28



1 3/4" (45 mm) Solid Core Door
A - Sealed into Frame
B - Mounted in Frame with Brass Weatherstrip

	125	160	200	250	315	400	500	630	800	1 K	1.3 K	1.6 K	2 K	2.5 K	3.2 K	4 K	STC
A	14	14	14	15	15	17	17	17	15	18	22	22	22	24	27	29	30
B	21	24	27	27	27	27	30	30	28	26	25	25	25	27	28	29	27

The most common types of threshold in residential doors are a bulb seal, brass v-shaped strips, and a brush seal. Of these the bulb seal is probably the most effective. All weather stripping in order to be effective must seal against a solid threshold of wood, metal, or smooth concrete or vinyl tile. Carpet is ineffective since the sound passes through it under the door.

For the head and jamb, weather stripping is commercially available as foam tape, bulb, or neoprene seals. Steel door frames are also available with a bulb seal built into the frame. This type of device is very effective since it gives the bulb an area to move into when the door is closed. Seals that are located between the door and the jamb can become crushed over time and lose their effectiveness. Note that all seals must be used in compression, rather than in shear if they are to perform effectively.

In moderately critical applications such as a private office, drop closures can be used. These are mechanical devices that are spring loaded and drop down when a latch pin is activated by the closure of the door. They may be mortised into the bottom of the door or surface applied. When they are mortised the appearance of the door is more pleasing but they are more difficult to adjust and maintain. Over time drop closures can malfunction and leave a gap under the door so that periodic maintenance and adjustment is required.

Commercially available sound rated doors are the most effective choice in highly critical applications. STC ratings from 45 to 53 are available in steel doors and from about 40 to 49 in wood doors. The most effective seals are made using a cam lift hinge that lifts the door as it is opened. The bottom of the door incorporates a piece of hard rubber with no moving parts to go out of adjustment. These doors are provided with custom steel frames and adjustable head and jamb seals to close off these paths.

Some sound rated doors are available with flexible magnetic strips that are attracted to the metal surface. These require less maintenance than compression seals and do not cause the door to warp in time. A compression seal requires constant pressure to maintain closure. Most of the force is provided by the latch at the door knob near the center of the panel. In time the top and bottom corners can be pushed out by the force of the seals, which can cause leakage. Since the magnetic seals do not depend on a constant compressive force there is no pressure on the corners.

Where there is a pair of doors in an opening, one of the leaves should be fixed and held into place with a sliding bolt at the top and bottom. At the center the doors should overlap with a dadoed joint or a separate astrigal so that the two leaves do not have a butt joint, which is difficult to seal.

Other transmission paths in doors include louvered openings, undercut thresholds, and lightweight vision panels. Return air paths under or through doors generally preclude effective sound isolation. When these paths are closed off an alternate route for the return air flow must be provided. When vision panels are included in sound rated doors, they require a transmission loss equivalent to that of the door itself.

Electrical Boxes

In many buildings flanking paths between rooms occur through electrical boxes. Nightingale and Quirt (1998) have investigated the phenomenon in gypsum board walls in some detail. They tested boxes in various locations built into a double stud double drywall wall, as illustrated in Fig. 10.19.

FIGURE 10.19 Electrical Box Test Configuration (Nightingale and Quirt, 1998)

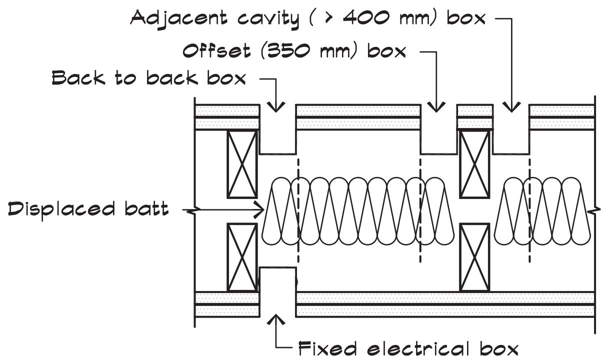


TABLE 10.4 STC Ratings of Walls with Electrical Boxes in Various Locations (Nightingale and Quirt, 1998)

Untreated Metal Boxes			Electrical Box Location		
Wood stud framing	Cavity absorption	Reference case	Back to back no offset	Same cavity offset 350 mm	Adjacent cavity
Double	None	55	51	49	53
	90 mm displaced	61	55	60	61
	90 mm	62	61	61	61
Single	90 mm displaced	55	50	54	54

The technique they used was to construct the boxes, as shown in Fig. 10.19, and to cover the unused ones with two sheets of drywall. The wall was tested with selected boxes exposed. Three insulation configurations were used: 1) no insulation, 2) insulation displaced around the box, and 3) insulation filling the cavities. The test results are summarized in Table 10.4. When the boxes are offset by a stud space (> 400 mm) the ratings are virtually unchanged, particularly with insulation in the cavity.

Figure 10.20 shows the transmission loss data for double stud walls with back-to-back boxes. At low frequencies the transmission loss through the box is high enough, due to the impedance mismatch, that there is little effect. At mid and high frequencies the flanking transmission becomes apparent through the boxes both with and without insulation.

Transmission through the boxes can be blocked by adding a drywall baffle to the inside face of the studs on the box side. Baffles in this research covered one stud cavity, extending from the sole plate to 300 mm (1 ft) above the top of the electrical box. The results are summarized in Table 10.5 and Fig. 10.21. The baffle solution is quite effective and simpler to construct than wrapping the box with drywall. Blocking the back of the box with mastic was shown in this study to be less effective than a baffle. The sides of the box still need to be caulked at the penetration through the drywall surface.

FIGURE 10.20 Measured Transmission Loss of a Double Wood Stud Wall with Cavity Absorption Displaced around the Back-to-Back Metal Boxes (Nightingale and Quirt, 1998)

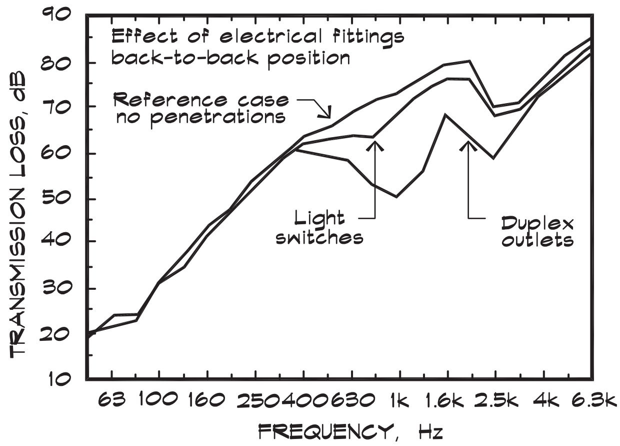
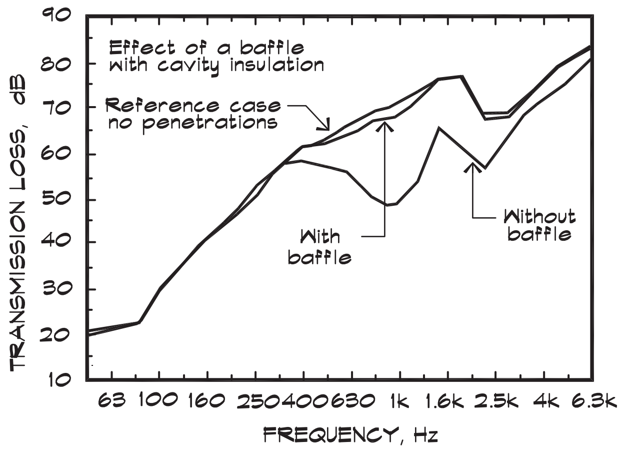


TABLE 10.5 STC Ratings of Walls with Electrical Boxes with Baffles (Nightingale and Quirt, 1998)

Untreated Metal Boxes			Electrical Box Location		
Cavity Absorption	Reference Case	Back to back No treatment	Same cavity offset 350 mm Baffle	No treatment	Baffle
None	55	51	52	49	52
90 mm displaced	61	55	62	60	61

FIGURE 10.21 Effect of a Baffle Separating Back-to-Back Electrical Boxes in a Double Wood Stud Wall that Has 90 mm Glass Fiber Cavity Absorption (Nightingale and Quirt, 1998)



Aircraft Noise Isolation

With structures located in high noise level areas adjacent to major commercial or military airports, particular care must be exercised to insure a comfortable interior noise environment. In a study at LAX (Long, 1980) Ldn levels were near 80 dBA and the maximum allowable level was an Ldn 45 in the bedrooms. This required an A-weighted noise reduction of 35 dB. A 2 dB safety factor was included, which meant that the design was carried out based on a noise reduction of 37 dB. In homes in this area STC 38 double glazed windows were used along with heavy solid core doors, which were shielded by the structure and a roof overhang and alcove.

For control of aircraft noise the roof is the most critical parameter. Ceiling roofs are generally the largest exposed area, the most complicated structure, and acoustically the least well known. If the roof is a concrete slab or steel deck with a lightweight concrete fill, the problem of sufficient mass usually is ameliorated.

In wood structures, roofs must be solid sheeted with plywood and coverings added to increase the mass to the design level. An inexpensive way of increasing the roof mass is by using layers of 90 lb (0.9 lb/sq ft or 4.4 kg/sq m) felt roofing paper with a cap sheet and shingles or built-up roofing over it. With gravel, concrete tile, or mission tile roofs, the weight is significantly increased and additional layers of roofing paper are not required.

Estimation of the transmission loss of roofs is particularly difficult since there is no directly measured data for peaked roofs and no single separation distance. Flat roof data can be measured in a laboratory or approximated using floor-ceiling data. In the LAX study (Long, 1980), roof transmission losses were estimated using the mass law value of the heavier of the roof or ceiling panel plus two-thirds of the mass law value of the lighter panel. All roofs had solid plywood sheathing with wood shingles over. Eave vents were baffled with lined sheet-metal elbows.

Blocking, where the roofs meet the outside wall, is particularly difficult to control. In plaster homes the most practical solution is to stucco under the eaves to avoid having to caulk the blocking. Since attics must be ventilated, openings are required that must be acoustically treated—usually with a lined sheet metal duct having at least one 90° bend, located in the gable end.

Ceilings are one to two layers of gypsum board. In flat roofs resilient channel can be helpful. Where an open beam look is desired the ceiling can span between the beams but this reduces the airspace dimension and increases the length of joint.

Windows are generally heavy double glazed in noisy sites, although 1/4” laminated glass can be used up to about a 30 dB noise reduction. Highly rated French or sliding glass doors are difficult to find, although some manufacturers can provide a separate storm window or door that can be helpful.

HVAC outside air requirements can be met by providing a sheet metal duct with a commercial silencer. Where bathrooms require an exhaust fan, it too must have a treated duct with either a silencer or an appropriate length of lined duct. For noise reductions on the order of 30 dB, an 8’ length of nonmetallic flex duct nested in a fiberglass-filled cavity between two joists will usually provide sufficient loss.

Traffic Noise Isolation

Control of interior noise levels from traffic is much the same as with aircraft noise. The major difference is that, when residences are located above the roadways, ceiling-roofs play a less significant part and windows a more significant part in the overall transmission path. Roofs or patios that overhang a window or sliding glass door can reflect the sound down toward these surfaces and offset shielding that might otherwise have reduced the exterior sound pressure level. In areas of significant truck traffic, exterior windows should be heavy single glazed or double glazed with a wide airspace between panes. Trucks generate significant energy in the 125 and 250 Hz octave bands so the mass-air-mass resonance should be positioned below these bands. Where barrier shielding is present it is important to remember to use the shielded noise spectrum, which will contain a greater contribution from the lower bands than the unshielded spectrum.

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