BLDG 366
Acoustics and Lighting

Week 4: Sound Transmission

January 29th, 2016

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Outline

- Review of week 3: room acoustics
- Sound Transmission
  - Transmission Loss (TL)
  - Sound Transmission Class (STC)

Review of week 3

- Reflection, diffusion and diffraction
- Sound field in room: free field, reverberation field, near field, far field

$$L_p = L_w + 10 \log_{10} \left(\frac{Q_\theta}{4\pi r^2} + \frac{4}{R} \right) \quad \text{dB}$$

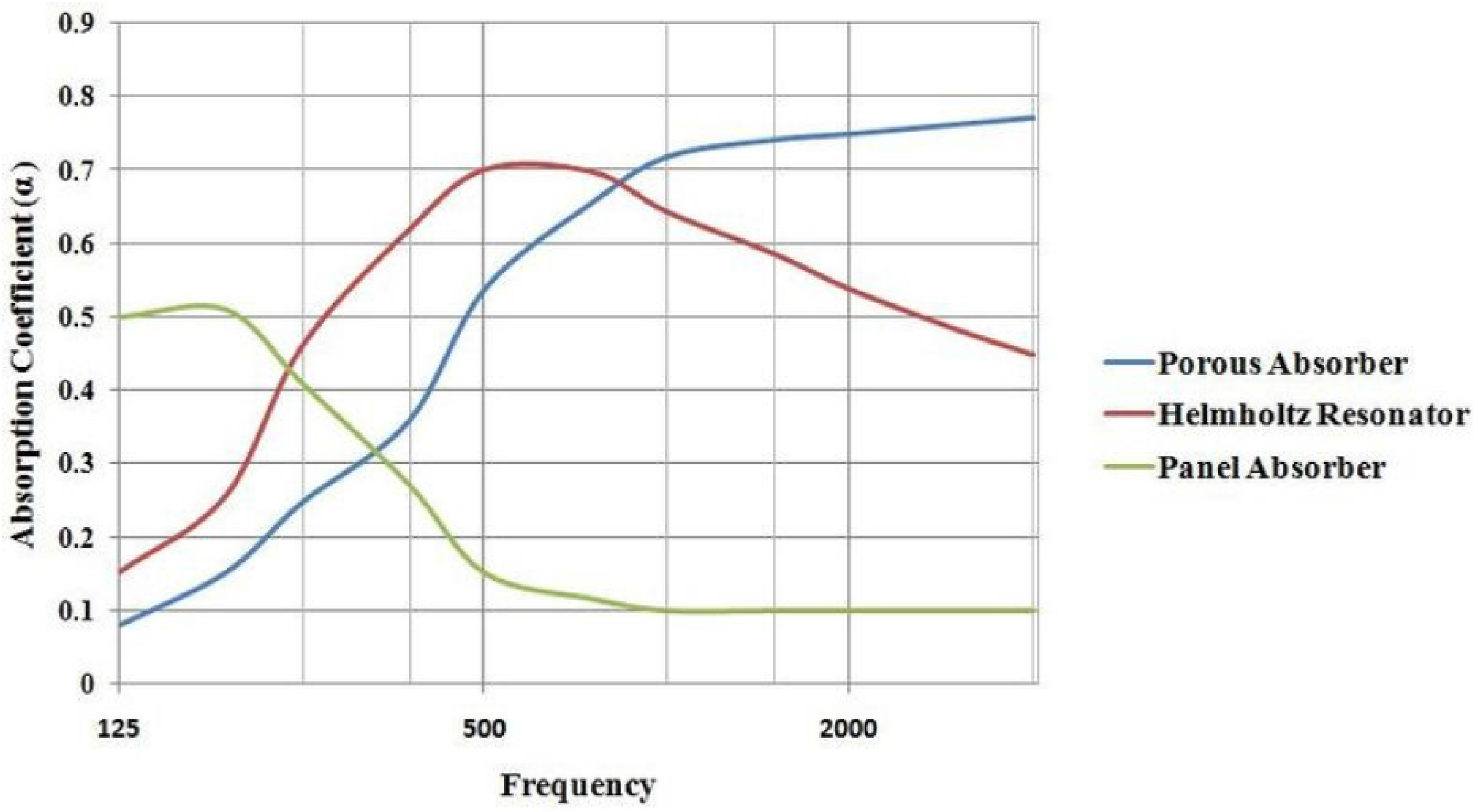
- Reverberation Time

$$RT = \frac{0.16\ V}{\Sigma A}$$

  - Sound absorption:
    - Types of sound absorbers: porous absorber; panel absorber; volume resonator absorber
    - Sound absorption coefficient: $\alpha = 1 - \frac{I_R}{I_I}$
    - Sabine: $A = S\alpha$
    - Noise Reduction: $NR = 10 log \frac{A_2}{A_1}$
  - Optimum RT
  - Room Constant

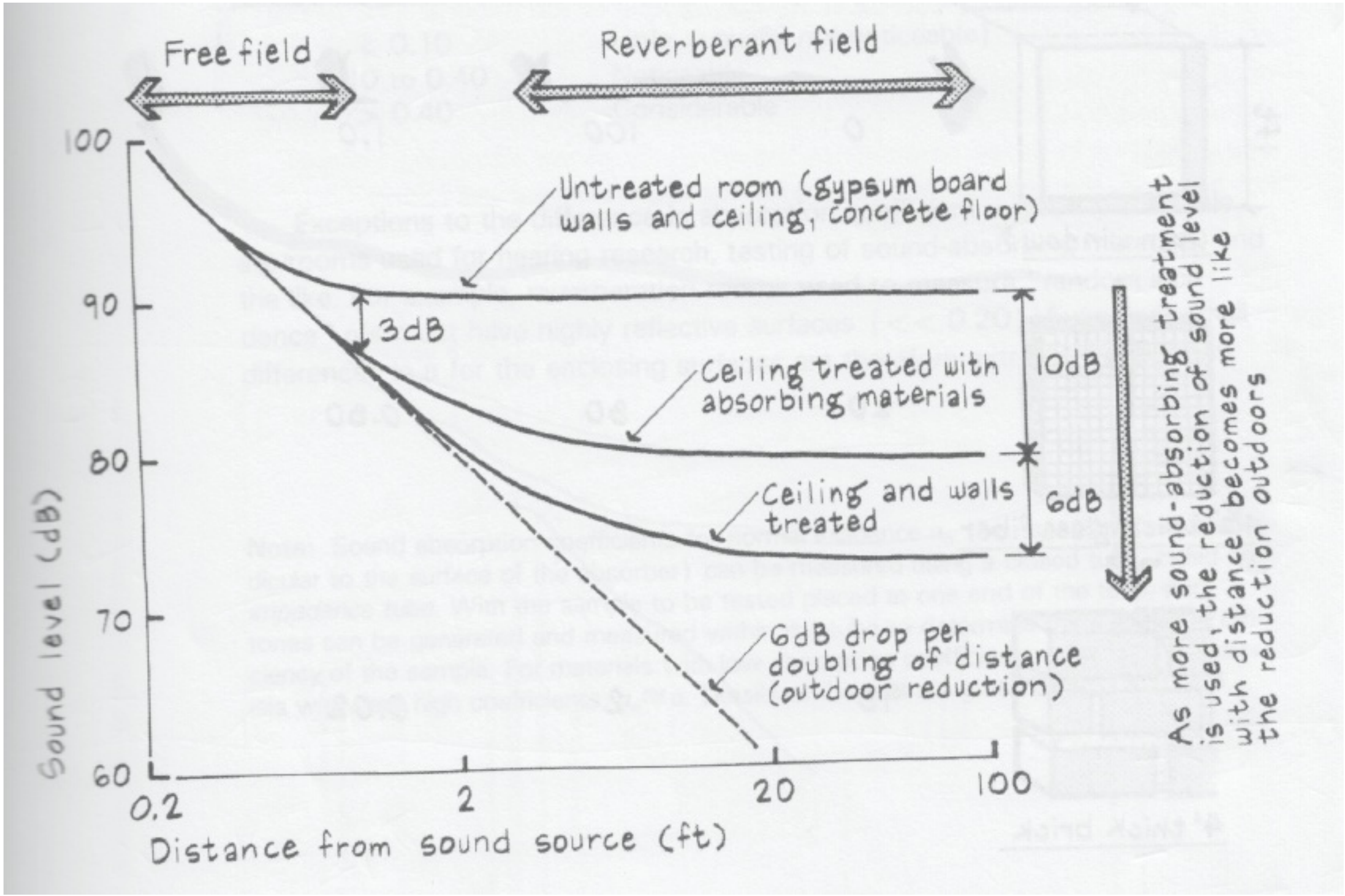
$$R = \frac{S\bar{\alpha}}{1-\bar{\alpha}}$$

Sound absorbers-Volume (Helmholtz) Resonator Absorbers



Source: www.wikipedia images

Noise Reduction (NR)

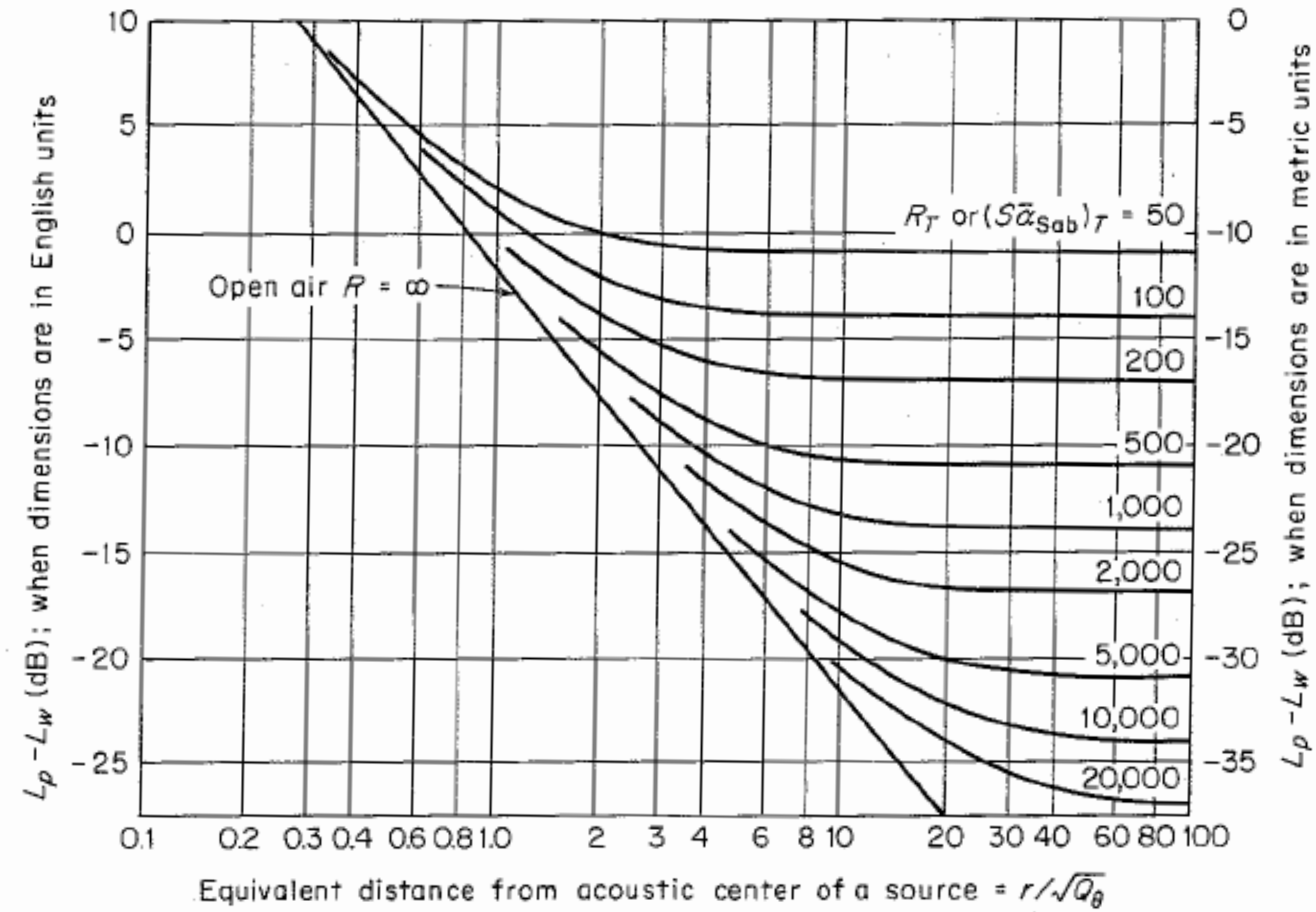


David Egan, "Architectural Acoustics"

Sound level in rooms

Effect of room constant

$$R = \frac{S\overline{\alpha}}{1-\overline{\alpha}}$$



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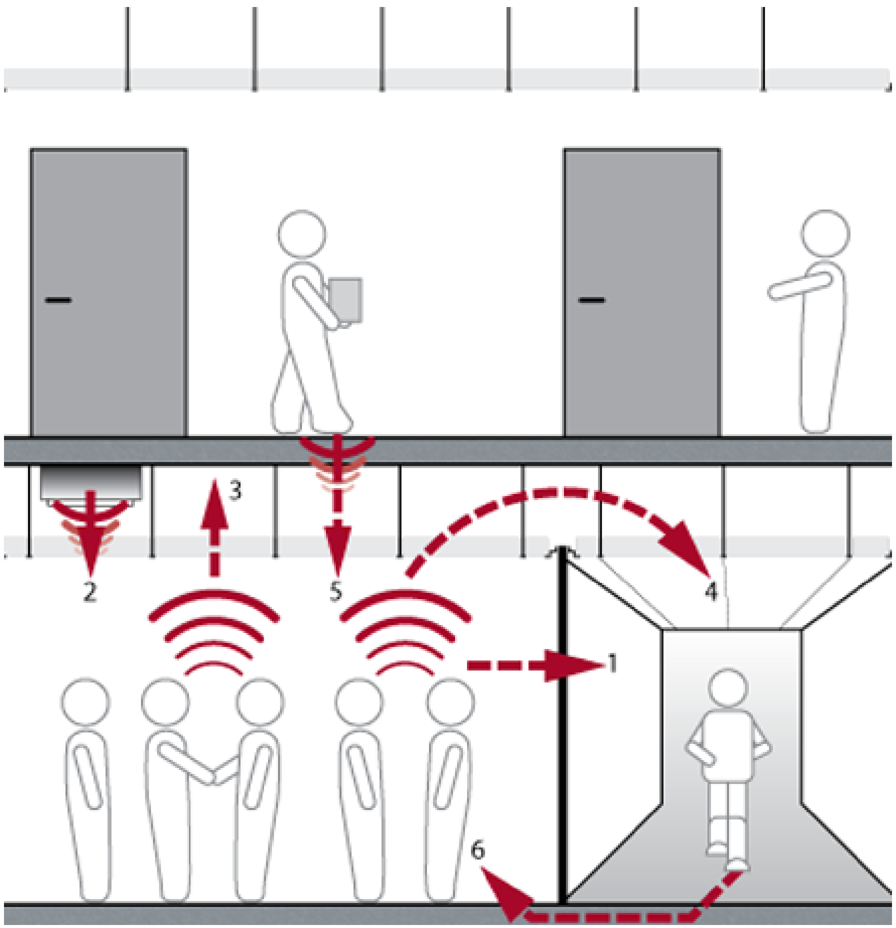
Sound Transmission

- In buildings, sound can transfer to adjacent spaces in various ways:
  - **Direct sound:** through certain constructions such as a partition wall, or from the plenum through a suspended ceiling (1, 2 and 3).
  - **Flanking sound:** sound energy can bypass constructions through indirect paths (called *flanking*), e.g. poorly insulated floors, corridor, common ceiling plenums, etc. (6).
  - **Impact sound: transferred** by direct contact with the construction, e.g. footsteps (5)



http://www.rockfon.co.uk/acoustics/the+science+of+sound/sound+insulation

Sound Transmission

- Most sounds in buildings are ***airborne*** sounds, such as sounds generated by human conversation and musical instruments.
- Structure borne sound is produced by an impact of some sort on building elements-walls, floors, roofs, etc. The impact causes building elements to vibrate, and as they vibrate, they radiate sound, also referred to as ***impact sound***.
- Reducing sound transmission by constructing barriers of low sound transmission is referred to as ***sound insulation***.

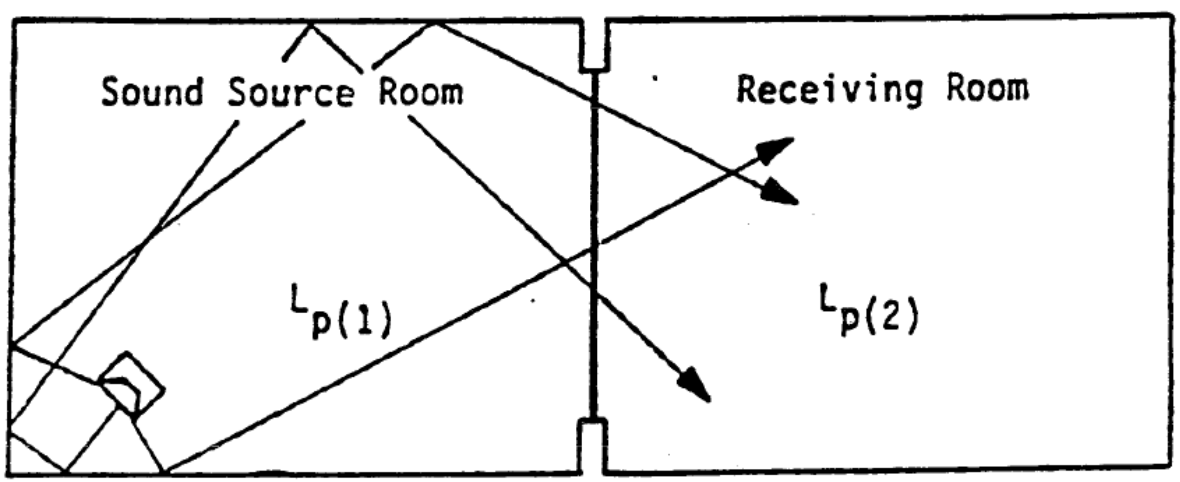
Transmission Loss (TL)

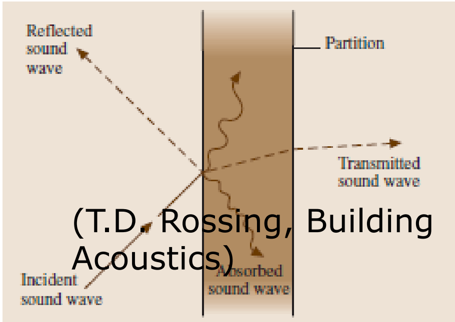
- Transmission Loss (TL) is a measure of how much sound energy is reduced in transmission through materials

  $TL = L_{P1} - L_{P2}$

  $TL = 10\log(1/\tau)$ in dB

- The greater TL of a panel, the greater the sound insulation provided by it
- The transmission coefficient (τ) is: the ratio of the sound energy transmitted by a material to the incident sound energy (commonly used walls and floors varies from 10^{-2} to 10^{-8}); e.g. 6” concrete slab has a transmission coefficient of 10^{-6}





(T.D. Rossing, Building Acoustics)

Fig. 11.5 The interaction of a sound wave with a partition

Transmission Loss (TL)

Ex. 1:

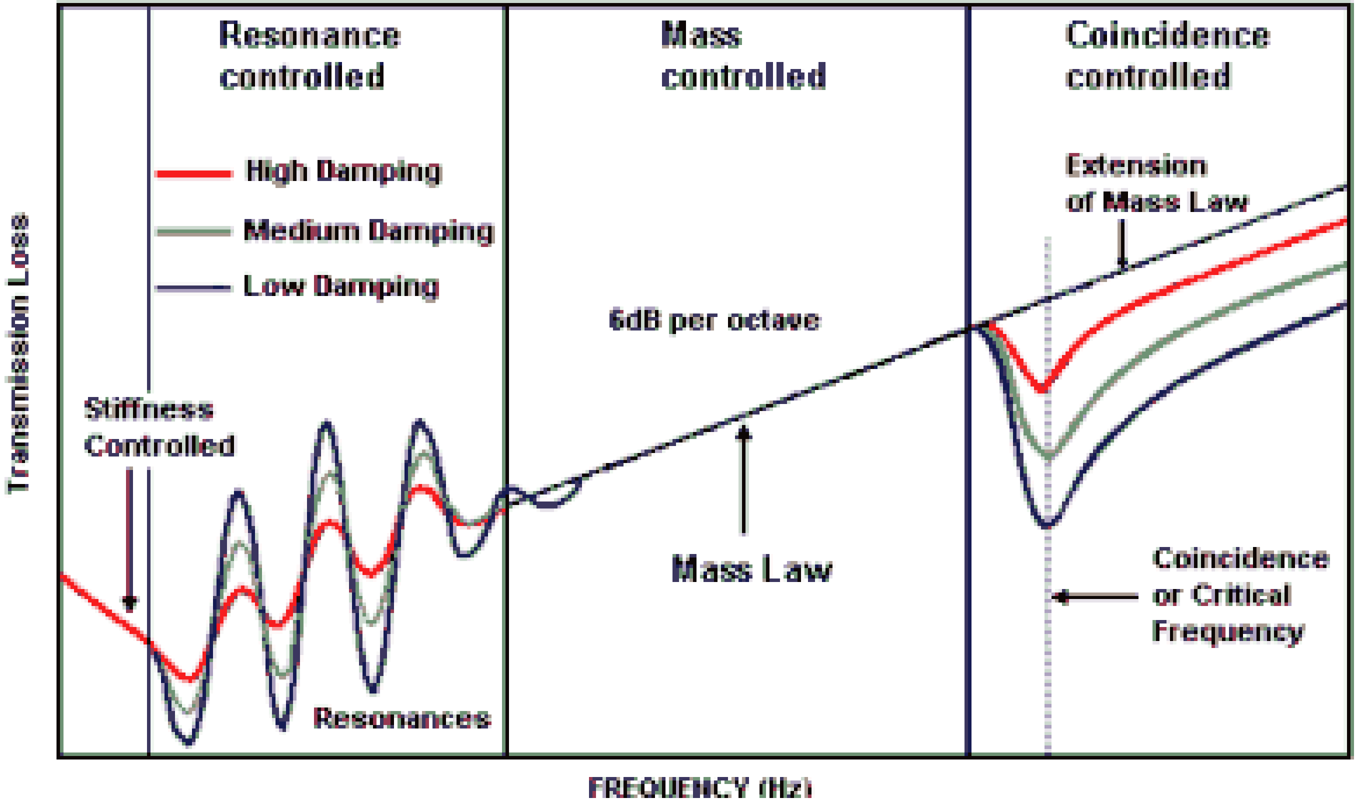
Determine the transmission loss of a : 1) 6 mm thick glass sheet for which τ= 7.8 x 10^{-4}; 2) a 150mm thick concrete slab for which τ= 6.3 x 10^{-6};3) 100mm thick fiberglass sound absorber with absorption coefficient of 0.95 and transmission coefficient of 0.05.

$$TL=10\log(1/\tau)$$

- Fiberglass is a good sound absorber but a poor sound insulator. For a material to be a good sound insulator, it must be of impermeable and airtight construction.

Transmission Loss (TL)-single leaf panel

- Single leaf panel refers to one leaf of the same material



The performance of a barrier is divided into four regions controlled by stiffness, resonance, mass and coincidence

Transmission Loss (TL)-single leaf panel

- Stiffness controlled: extremely low frequencies
- Resonance: due to the mechanical resonance of the barrier $$f_{Res} = \frac{600}{\sqrt{m\,d}}$$

  e.g. 10 cm dense concrete with m=235kg/m^2, f_{res} is 12.3Hz

- Mass law: $$TL = 20 \log_{10}\left[\pi f m/(\rho c)\right] - 5.5 \quad \text{(dB)}$$

  where *f* is the frequency (Hz), *m* is the mass per unit area (kg/m^2) and ***ρ****c* is the characteristic impedance of air (basically, *density* times the *speed of sound* for 20°C and 1 atm).

  TL = 20 log(fm) – 47.5 dB

Transmission Loss (TL)-single leaf panel

- Mass law:
  - Mass law applies to limp panel (inelastic/zero stiffness only): each part of the panel oscillates independent of the other
  - The transmission loss increases ***6 decibels*** for each doubling of frequency, or each doubling of the wall mass per unit area, up to a plateau frequency.
  - At any particular frequency, the heavier the barrier, the greater the TL
  - For any given barrier, the higher the frequency, the greater the transmission loss

Ex.2:

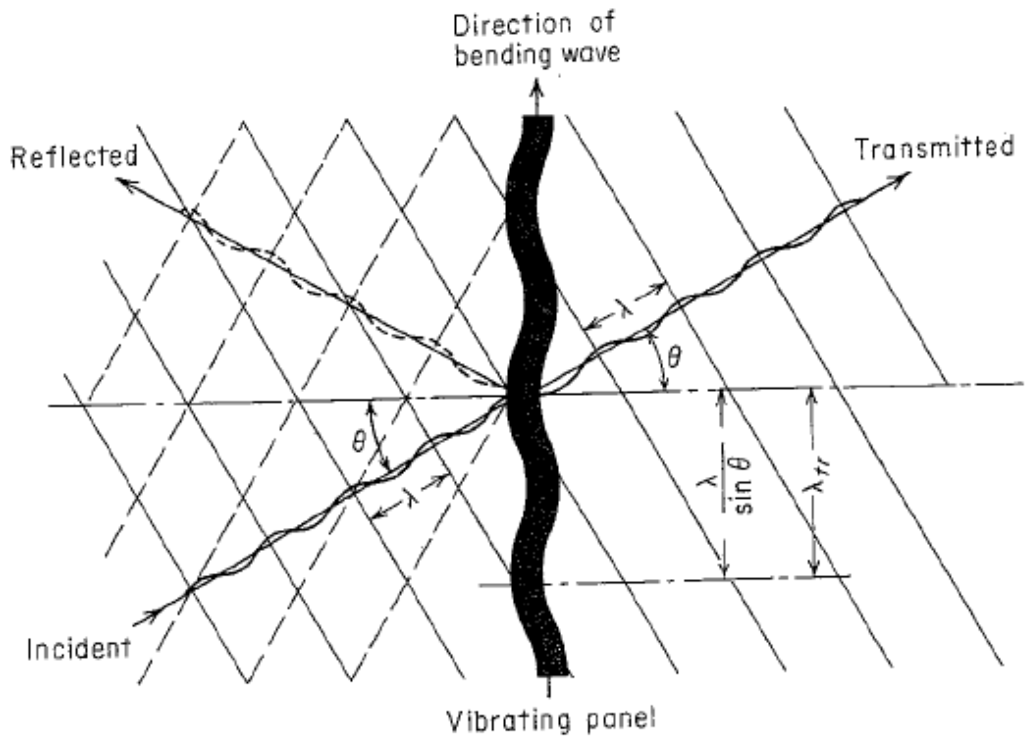
100mm dense concrete with m=235kg/m^2,

Frequency	**50**	**100**	**250**	**500**	**1000**
TL(dB)	34	40	46	53	60
50mm concrete				47	

$$\mathbf{TL = 20\log(fm) - 47.5\ \ dB}$$

Transmission Loss (TL)-single leaf panel

- **Coincidence effect**:
  - A real panel is not limp, individual parts are coupled to each other by elastic forces, therefore, the bending of one part leads to the propagation of a bending wave in the panel
  - when the wavelength of the incident sound coincides with the wavelength of the bending waves in the panel, the ***bending oscillations*** of the panel will be amplified and the sound energy will be transmitted through the panel with reduced attenuation

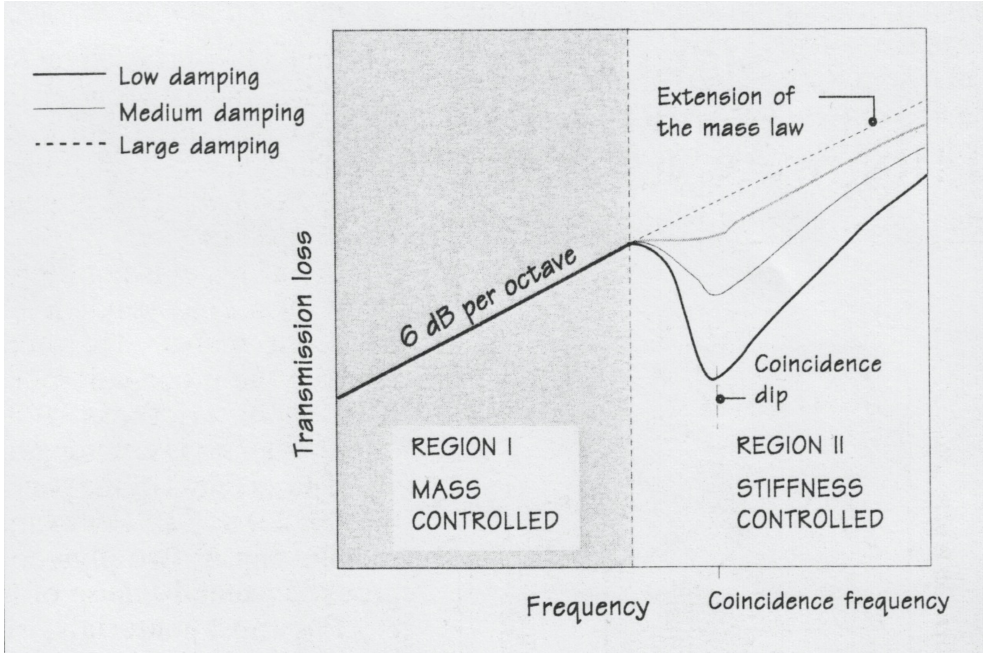


Transmission Loss (TL)-single leaf panel

- **Coincidence effect**:
  - Incident sound covers a wide range of frequencies and arrives at all angels, but the overall result is that the coincidence effect creates "acoustic hole" over a narrow range of frequencies giving rise to what is called the ***coincidence dip****; the frequency called* ***coincidence frequency***
  - In many thin materials (such as glass), the coincidence frequency begins somewhere between 1000 and 4000 Hz, which includes important speech frequencies.
  - TL of a single leaf of a ***real panel*** is a function of (5dB TL per double frequency or mass): *reduced effectiveness with increasing panel thickness*
    - Mass (increase mass, increase TL)
    - Stiffness (increase stiffness, lower TL)
    - Damping (internal friction/resistance)

Transmission Loss (TL)-single leaf panel

- Coincidence frequency is a function of three factors:
  - Density
  - Elasticity and
  - Thickness of the panel
- Coincidence frequency is ***inversely proportional*** only to the ***thickness*** for a given material since density & elasticity are constant
- Coincidence frequency is of concern only in relatively thin panels (e.g. gypsum board) given that the coincidence frequency is low in large thickness materials such as concrete or masonry



- Minimizing coincidence effect
  - Increase/decrease thickness
  - Increase damping by adding viscoelastic materials; the greater the damping the flatter the coincidence dip; e.g. laminated glass

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Transmission Loss (TL)-single leaf panel

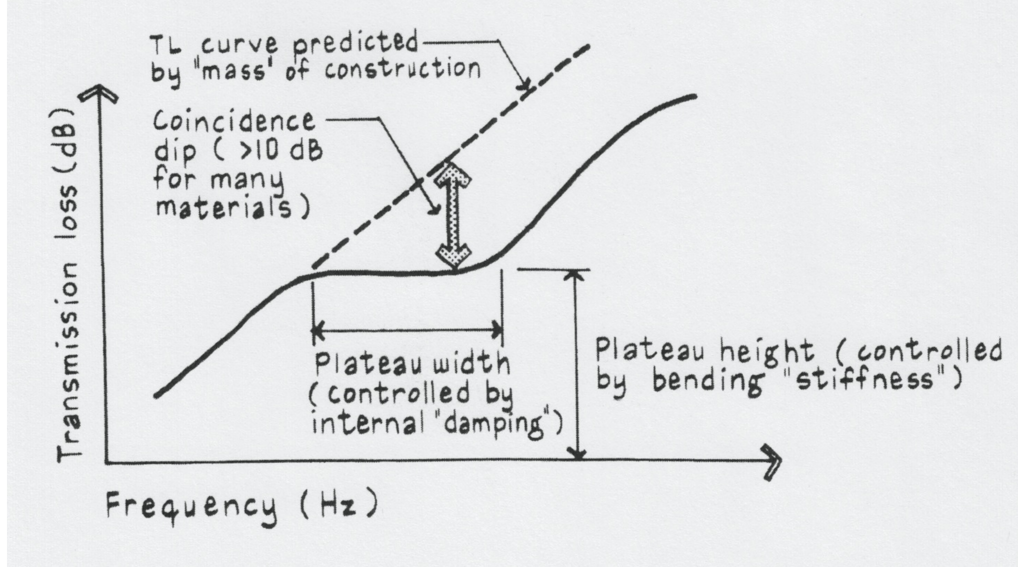
Table 11.3 Critical frequencies for common building materials

Material	Thickness (cm)	Critical frequency (Hz)
Concrete	8	100
Plywood	1.2	1700
Gypsum wall board	1.2	3100
Steel or aluminum	0.3	4100
Lead	1.2	4400
Glass	0.3	4900
Plexiglass	0.3	9800

(T.D. Rossing, Building Acoustics)

Transmission Loss (TL)-single leaf panel

- Transmission loss increases 6 decibels for each doubling of frequency, or each doubling of the wall mass per unit area, up to a plateau frequency.
- The lower the plateau the stiffer a wall, the lower the plateau height, meaning the poorer the sound-isolating performance.
- The more damping a wall has (i.e. energy loss from internal friction), the narrower the plateau width, resulting in better sound-isolating performance.



TL Curve for Single-Layer Wall

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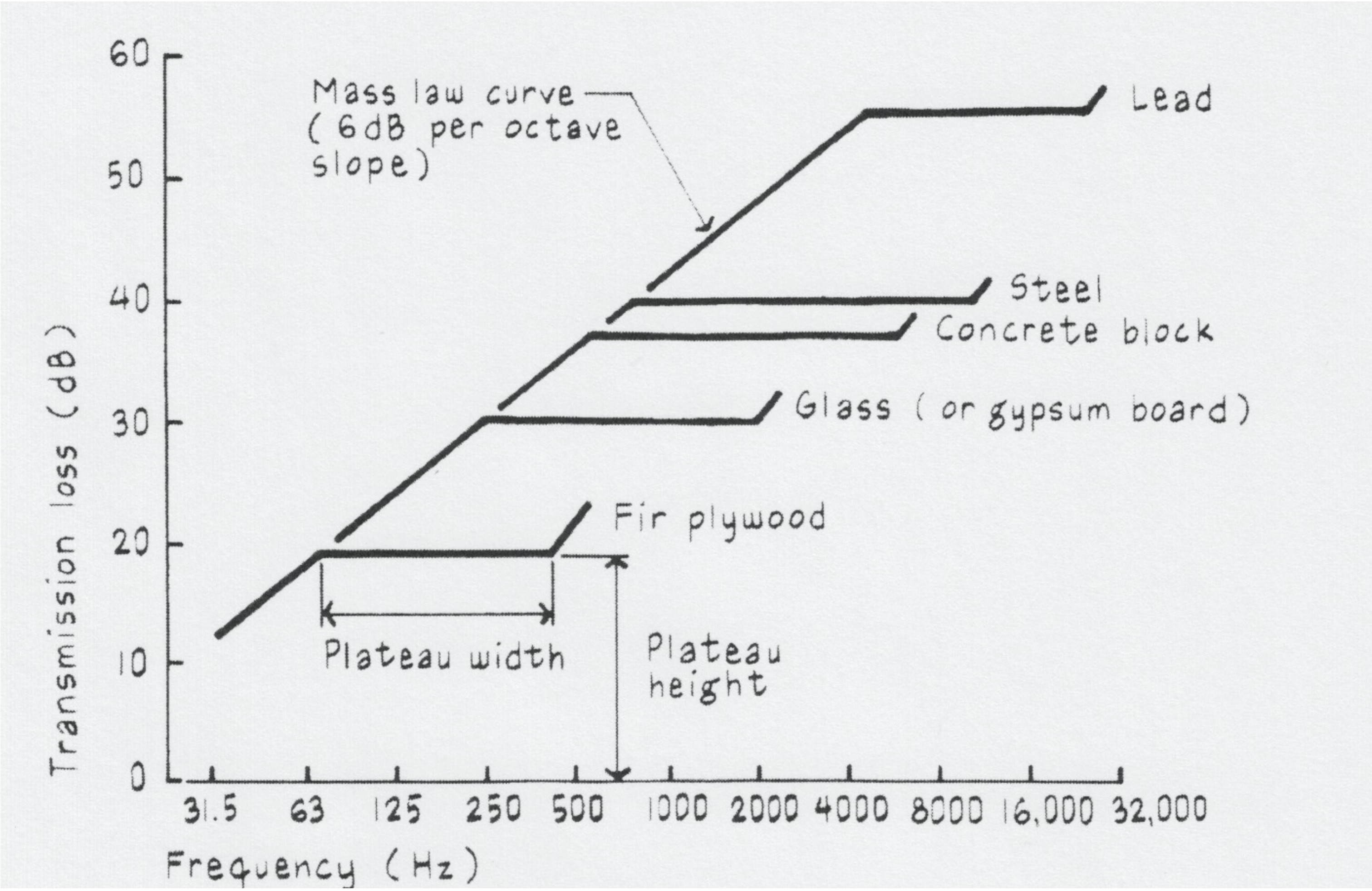
Transmission Loss (TL)-single leaf panel



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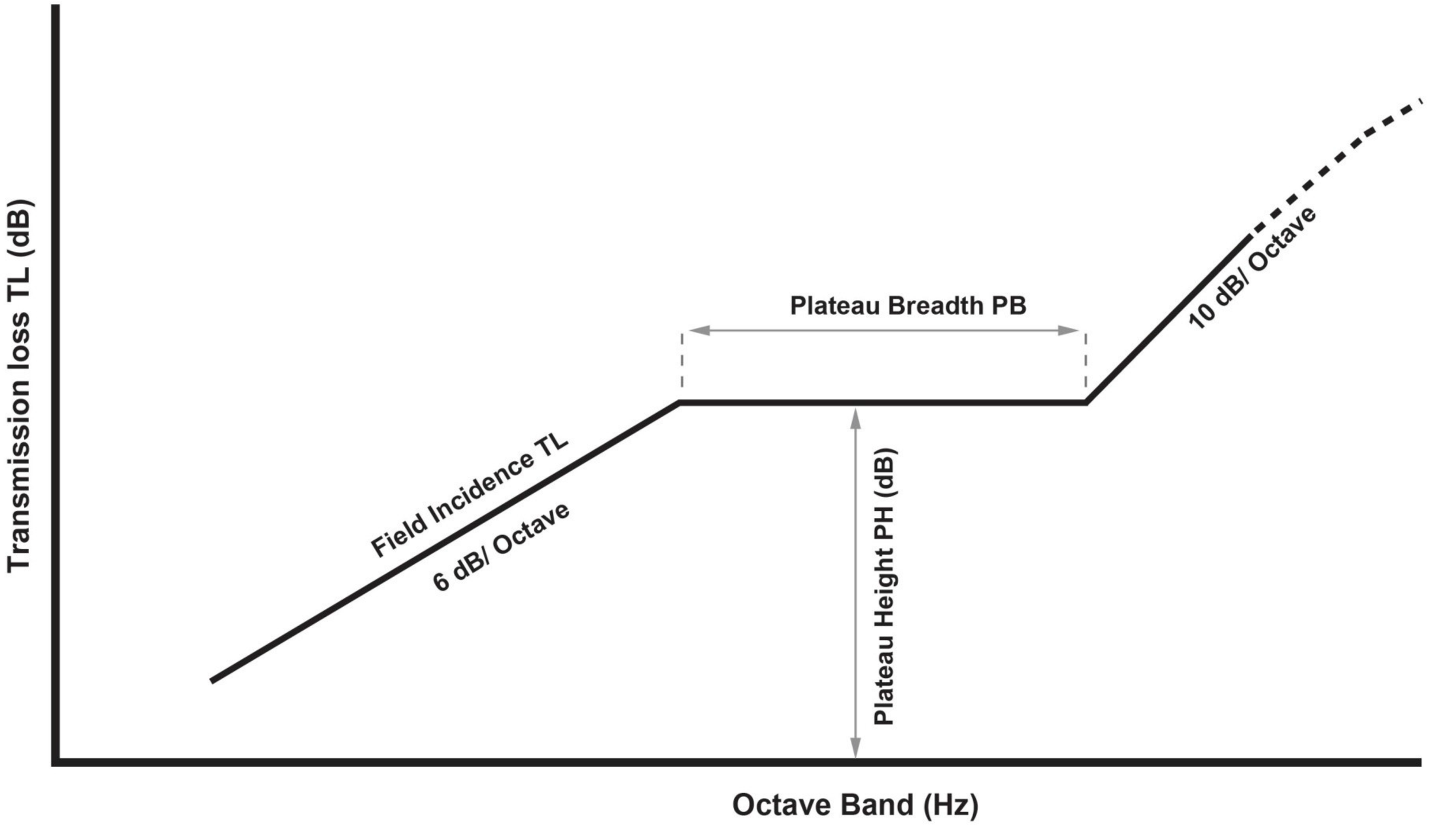
Transmission Loss (TL)

- Plateau method



Transmission Loss (TL)

Material	Specific Surface Density		Plateau Height, dB	Plateau Breadth Frequency Ratio
	lb/ft^2 Per in	kg/m^2 Per cm		
Aluminum	14	26.6	29	11
Dense Concrete	12	22.8	36	4.5
Glass	13	24.7	27	10
Lead	59	112	56	4
Plaster: Sand	9	17.1	30	8
Plywood, Fir	3	5.7	19	6.5
Steel	40	76	40	11
Brick	11	21	37	4.5
Cinder Block	6	11.4	30	6.5

TL-Plateau method

- Ex. 3:

A single pane window has a glass thickness of 0.3"

a) Calculate the theoretical transmission loss using the mass Law at the 16 third-octave bands.

b) Using the Plateau method calculate the T.L. at the 16 third-octave bands.

Given: Weight =24.7 $kg/m^2/cm$; Thickness = 0.3" = 0.762 cm

a) TL = 20 log(fm) – 47.5 dB

Using the above Equation, we get all the TL (16 of them) values.

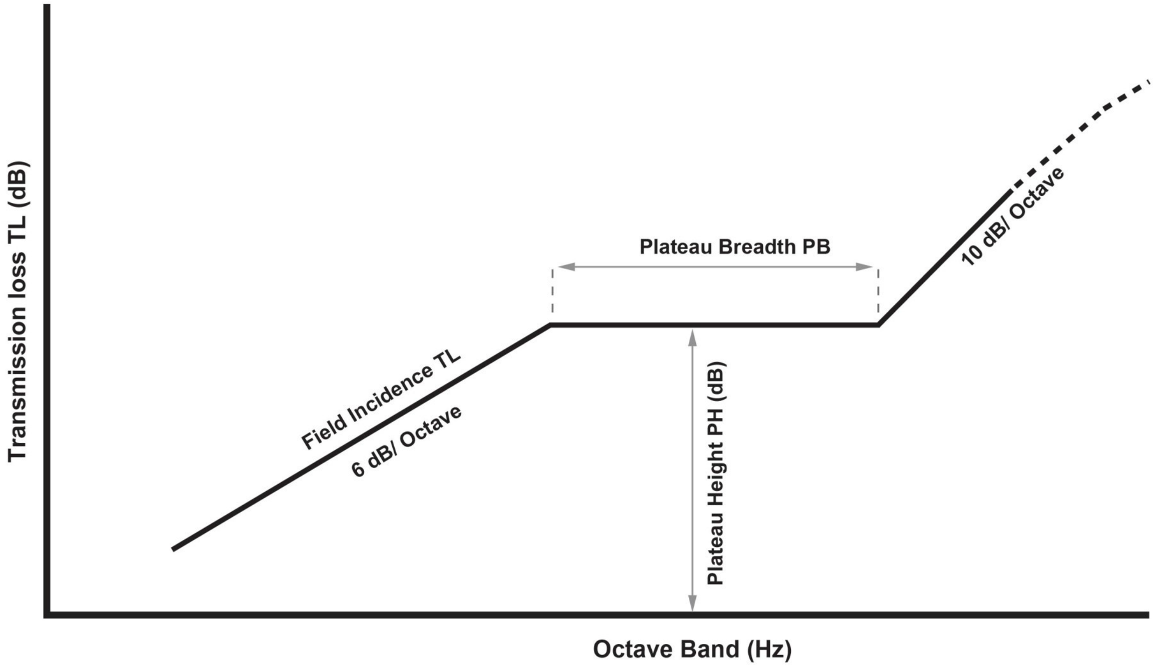
Frequency, Hz	125	160	200	250	315	400	500	630
TL, dB	20	22	24	26	28	30	32	34

Frequency, Hz	800	1000	1250	1600	2000	2500	3150	4000
TL,dB	36	38	40	42	44	46	48	50

TL-Plateau method

Solution:

b)

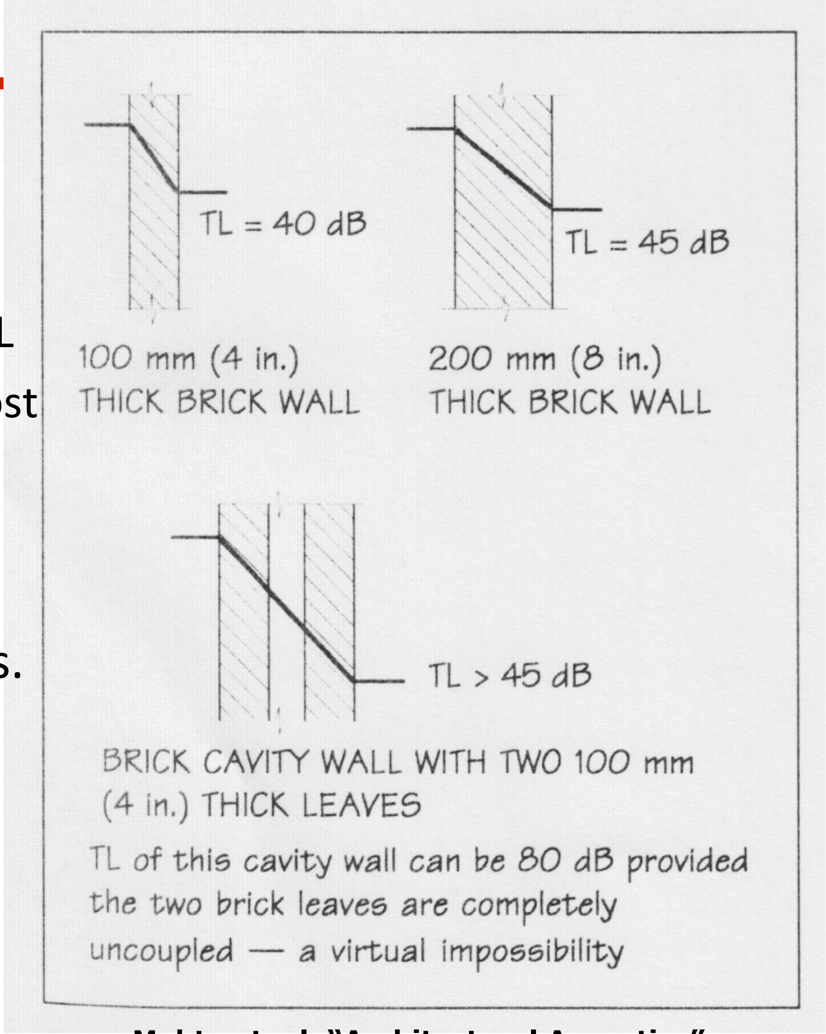


Frequency	125	160	200	250	315	400	500	630
TL, dB	20	22	24	26	27	27	27	27
Frequency	800	1000	1250	1600	2000	2500	3150	4000
TL, dB	27	27	27	27	27	27	28	31

Transmission Loss (TL)-double leaf panel

- Mass law follows the law of diminishing returns
  - For most materials, the increase in surface mass increases its stiffness, which reduces TL
  - It is the initial doubling that provides the most practical improvement
- Complex constructions are required when it is necessary to achieve high TL improvements, especially at low frequencies.

- A partition's TL can be increased by:
  - Adding mass
  - Increasing or adding air space
  - Resilient channels
  - Adding absorptive material within the partition



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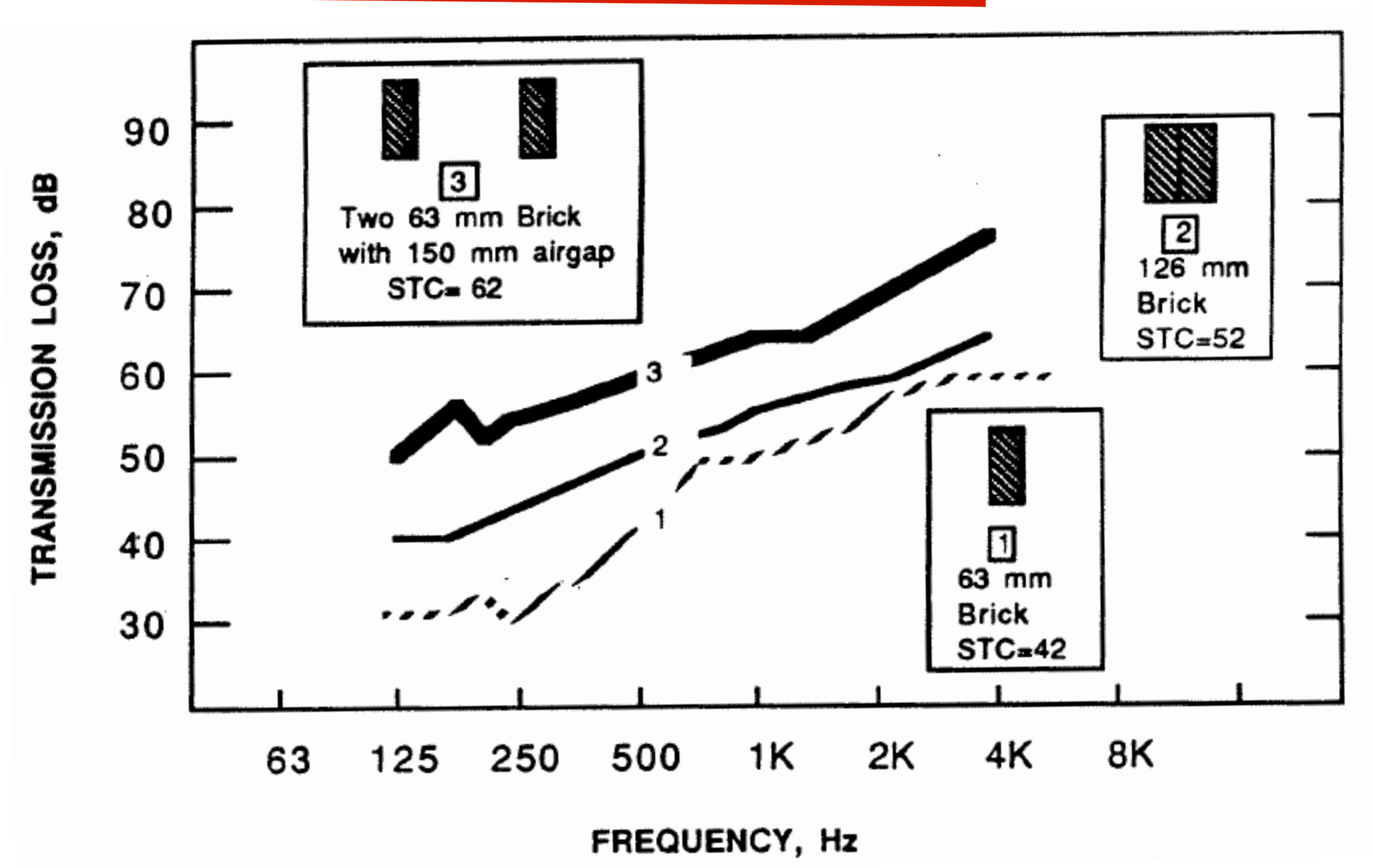
Double leaf wall TL



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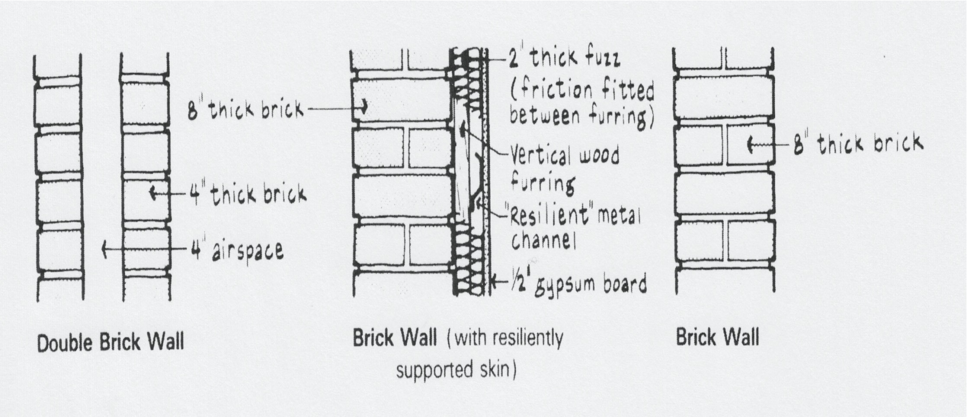
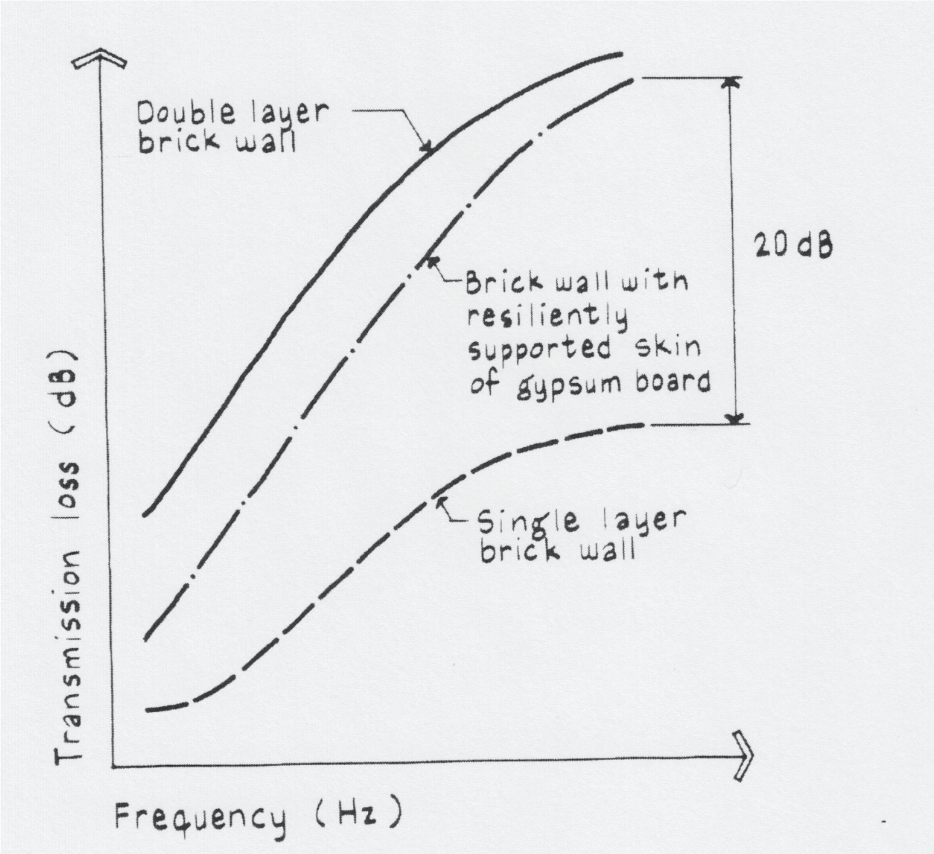
Double-leaf panel TL

- Factors that help maximize the TL of a double-leaf panel:
  - Surface mass: mass law
  - Stiffness: lower stiffness, higher TL
  - Decoupling of leaves: adding air space or using resilient channels
  - Cavity depth: maximized as much as possible; to achieve a significant improvement in low frequency TL, a cavity space of at least 100 mm is recommended
  - Porous absorber in cavity: increase internal damping & reduce cavity resonance
  - Dissimilar leaves: either different material or different thickness, reducing the coincidence dip

Double leaf wall TL-improvement





Double-leaf panel TL

- Importance of a large cavity depth
  - Resonance frequency of cavity air is inversely proportional to cavity depth

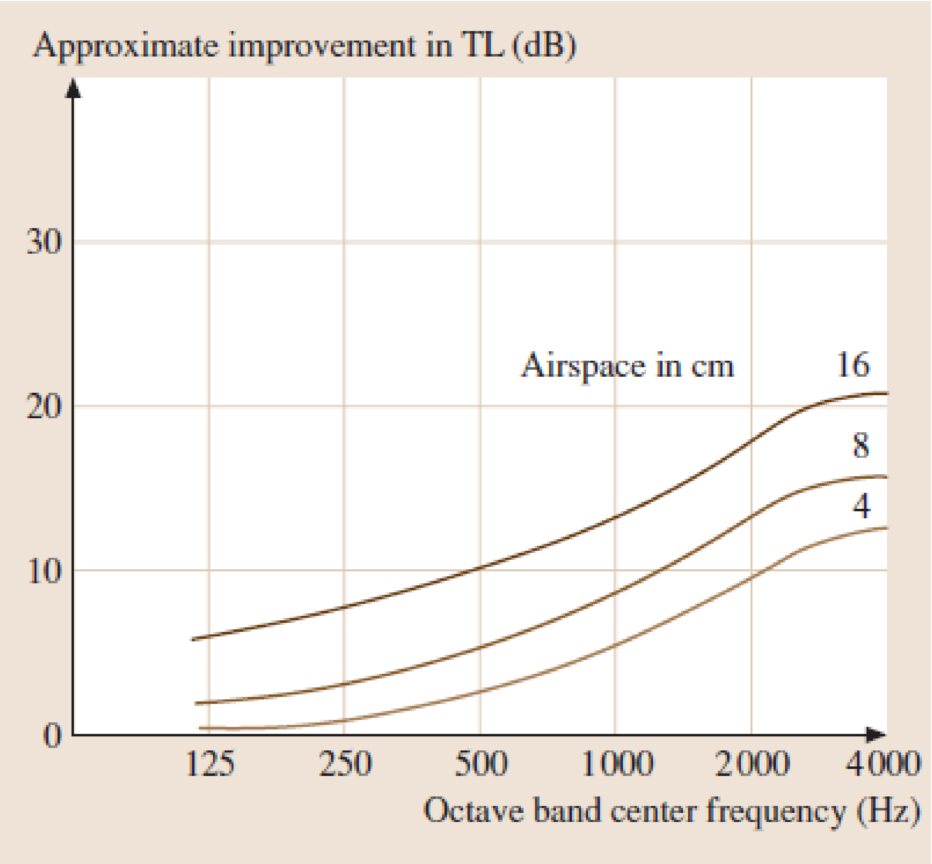
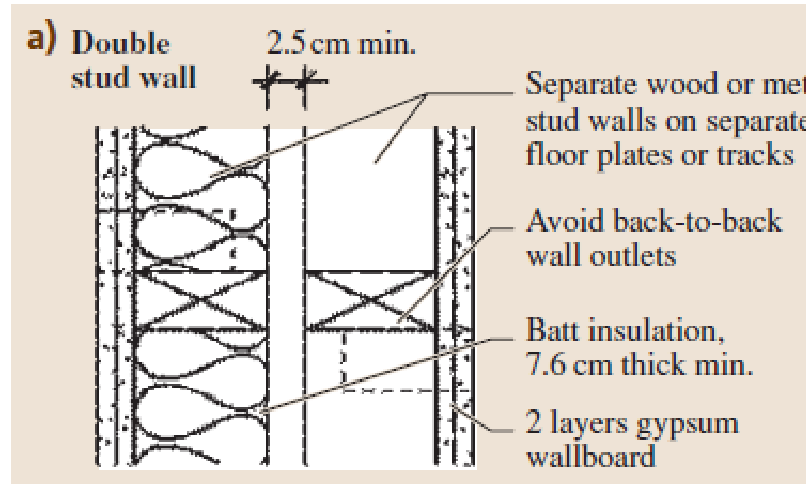


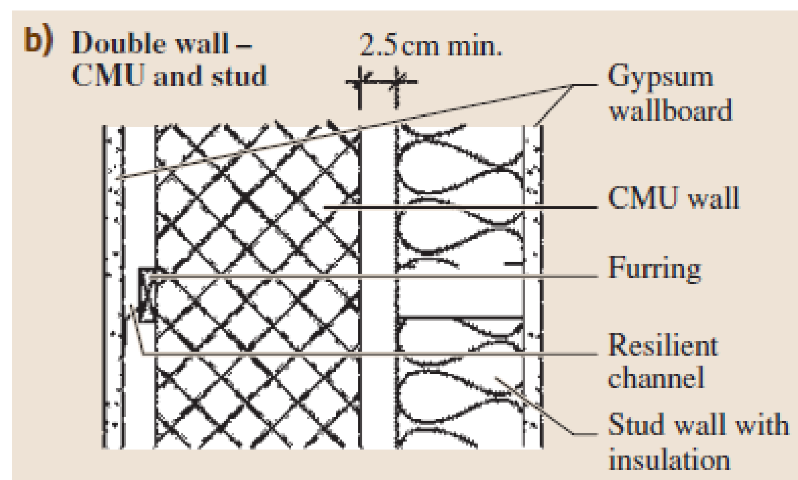
Fig. 11.19 General TL improvement that can be expected from air spaces in partitions

(T.D. Rossing, Building Acoustics)

Double-leaf panel TL

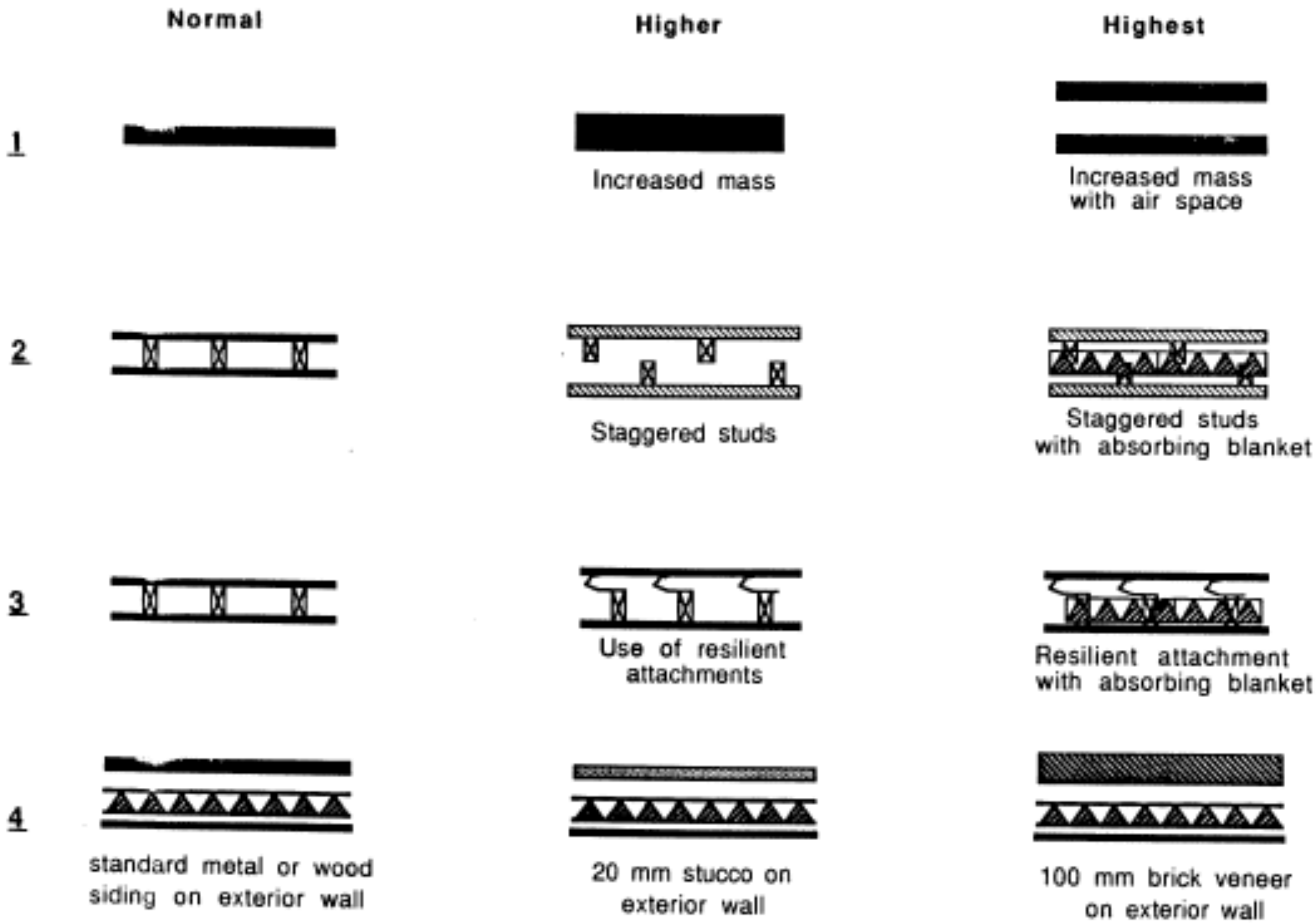
- Decoupling is the concept of detaching partitions from each other, in order to improve sound isolation.
- The most common methods of decoupling are:
  - Air gaps or air spaces between two partitions
  - Using resilient channels between layers and structural framing members for walls and ceilings





(T.D. Rossing, Building Acoustics)

Double leaf wall TL-improvement



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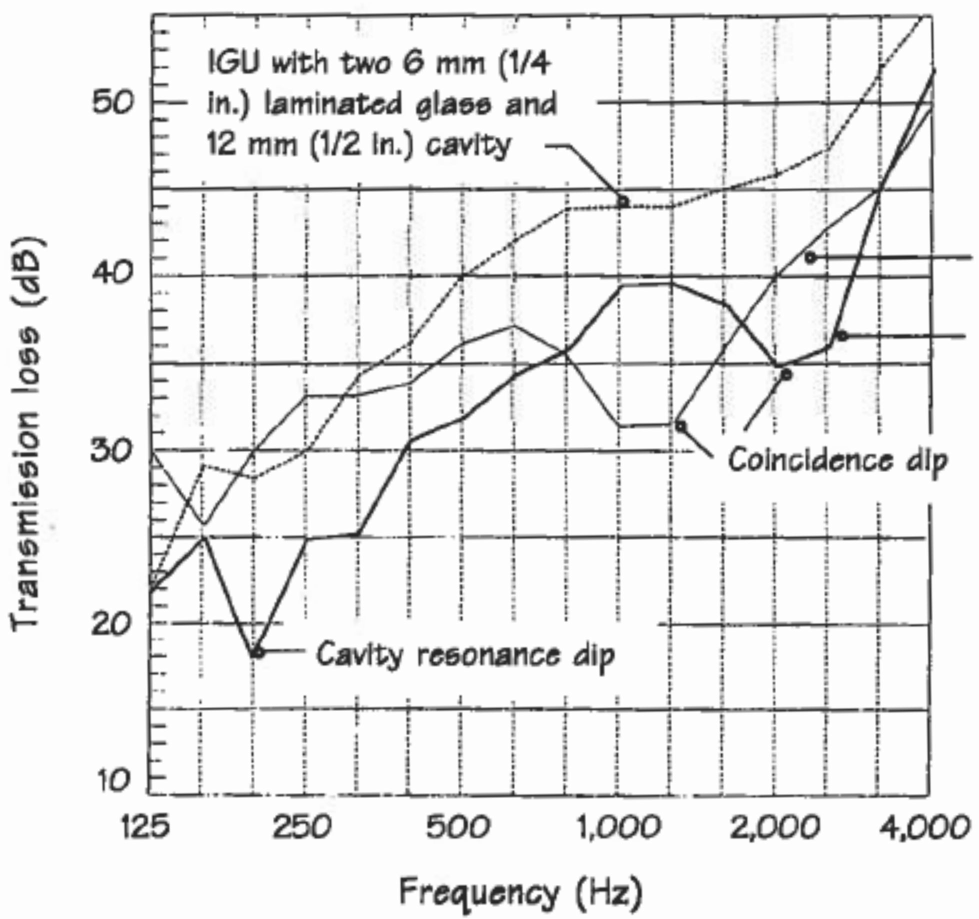
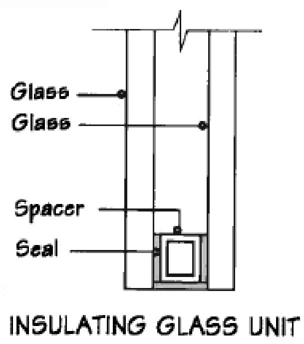
Window TL



$$f_{Res} = \frac{600}{\sqrt{m\,d}}$$



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Window TL

Window Type	Field Insulation
	*estimated values
Normal opening lights, single glazing, (closed)	
3 mm to 6 mm glass	*21
13 mm glass	*30
Sealed or fixed single glazing	
3 mm glass	29
4 mm glass	30
5 mm glass	*31
6 mm glass	32
10 mm glass	*34
13 mm glass	*35
20 mm glass	36
26 mm glass	37
Normal opening lights, double glazing, (closed)	
3mm - 4 mm glass with 100 mm air space without absorbent between panes	*35
3mm - 4 mm glass with 100 mm air space with absorbent between panes	*39
6mm glass with 100 mm air space with absorbent between panes	*41

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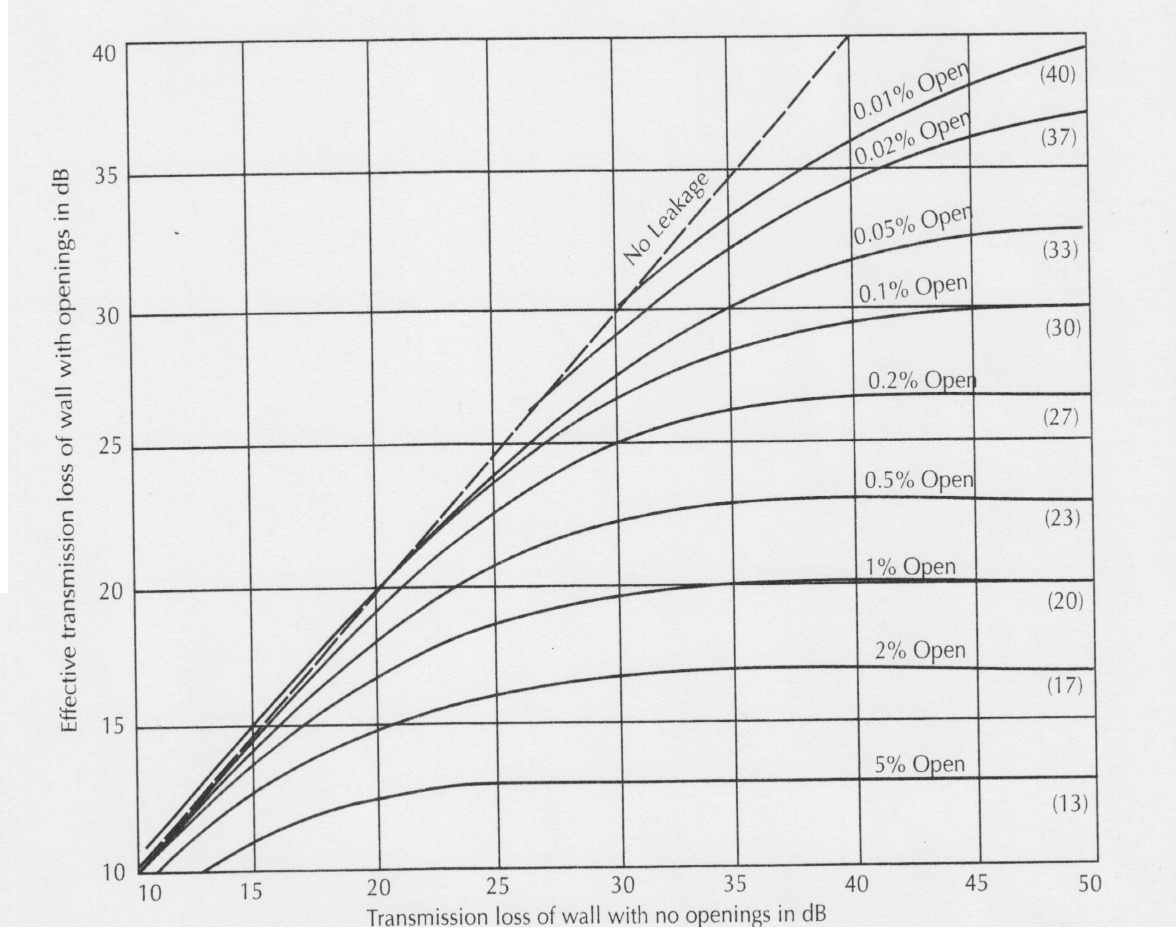
TL reduction due to air gaps

Table 11.6 Transmission loss reduction as a function of air opening*

Wall area having air opening (%)	Resultant wall TL (dB)	Resultant reduction in TL (dB)
0.01	39	6
0.1	30	15
0.5	23	22
1	20	25
5	13	32
10	10	35
20	7	38
50	3	42
75	1	44
100	0	45

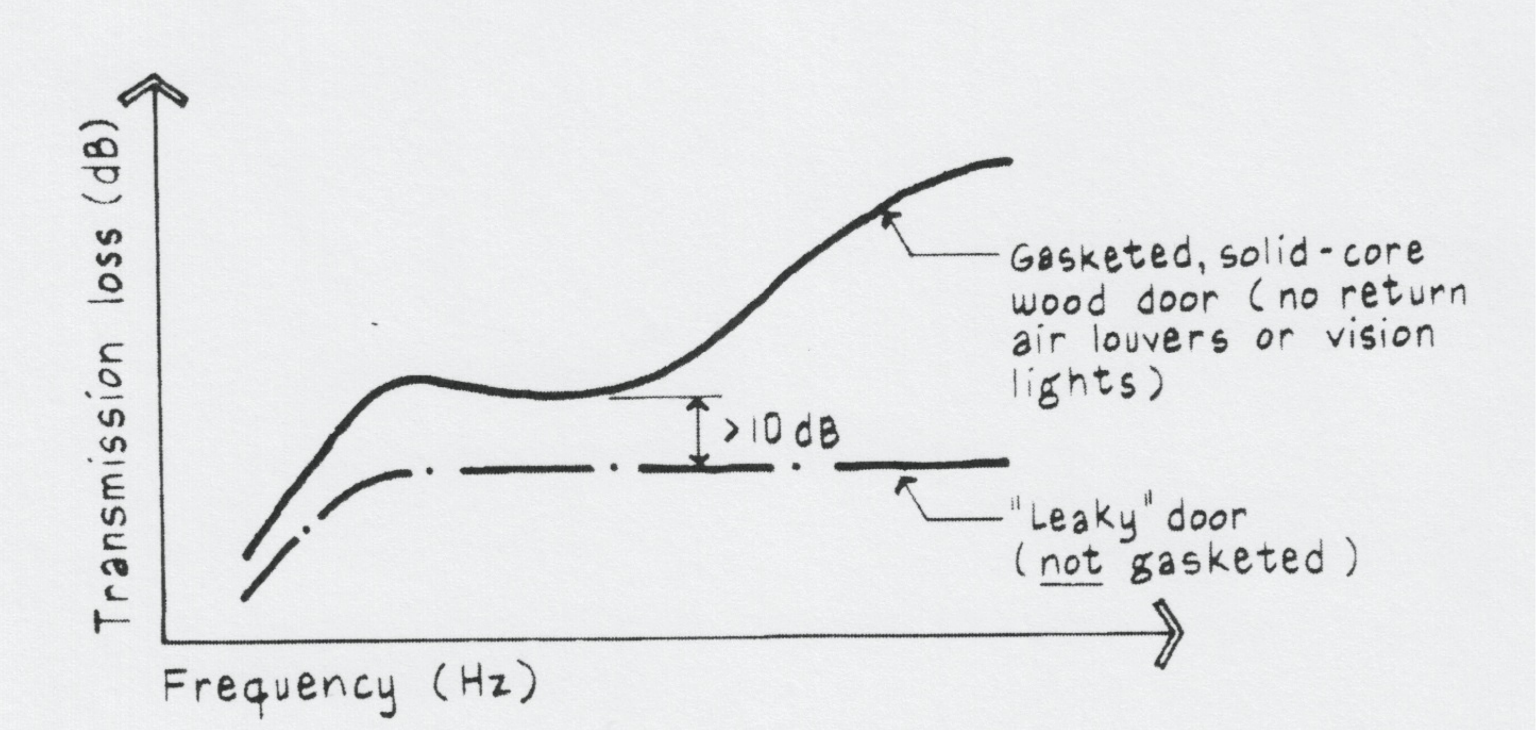
* based on original wall TL of 45 dB

(T.D. Rossing, Building Acoustics)



G. M. Ballou "Handbook for sound engineers

TL reduction due to air gaps



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TL-Doors

Type of Door	Closed	Sealed
Wood, solid core 46 mm, 20 kg/m^2	30	35
Same wood, solid core with aluminum storm door	34	42
Wood, hollow core 46 mm, 6.3 kg/m^2	20	21
Steel, flush pane with foamed-in polyurethane, 16 kg/m^2	27	28
Fiberglass reinforced, plastic with foamed-in polyurethane, 12 kg/m^2	25	26

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TL-non-homogeneous partitions

- If a partition is composed of more than one element, for example a wall and a door, then the effective transmission coefficient must be found as an average of the area weighted sum of each component's transmission loss.

$$\tau_{\mathrm{comp}} = \left(\sum_{i=1}^{n} \tau_i S_i \right) / S = (\tau_1 S_1 + \tau_2 S_2 + \ldots + \tau_n S_n)/S \,,$$

$$\mathrm{TL} = 10 \log_{10}(1/\boldsymbol{\tau})$$

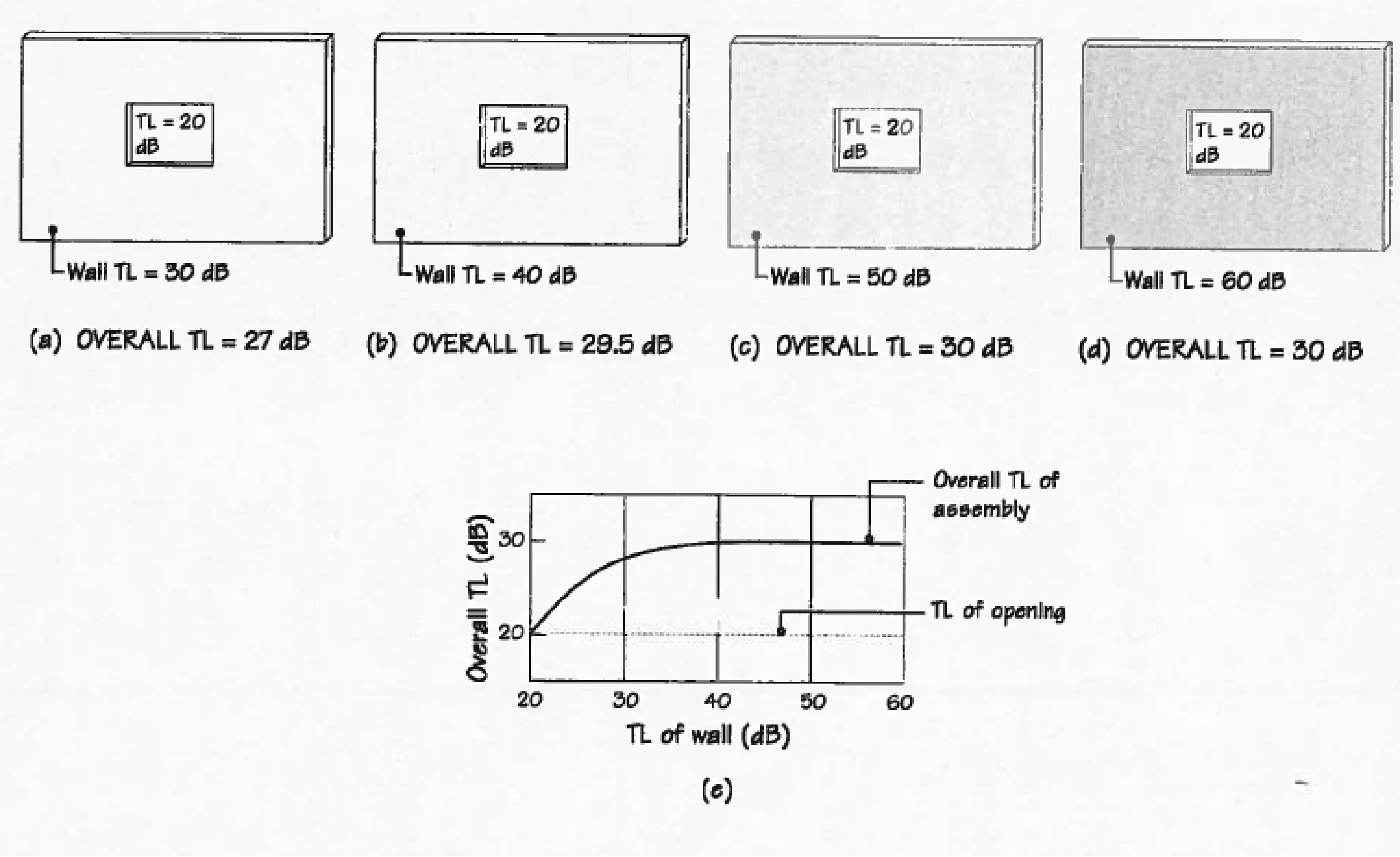
$$\boldsymbol{\tau} = 10^{-0.1TL}$$

where τ_1, τ_2, etc., are the transmission coefficients of each wall component while S_1, S_2, etc. are the surface areas corresponding to the surfaces having the same subscript value as those for the transmission coefficients, and S is the surface area of the entire partition. The

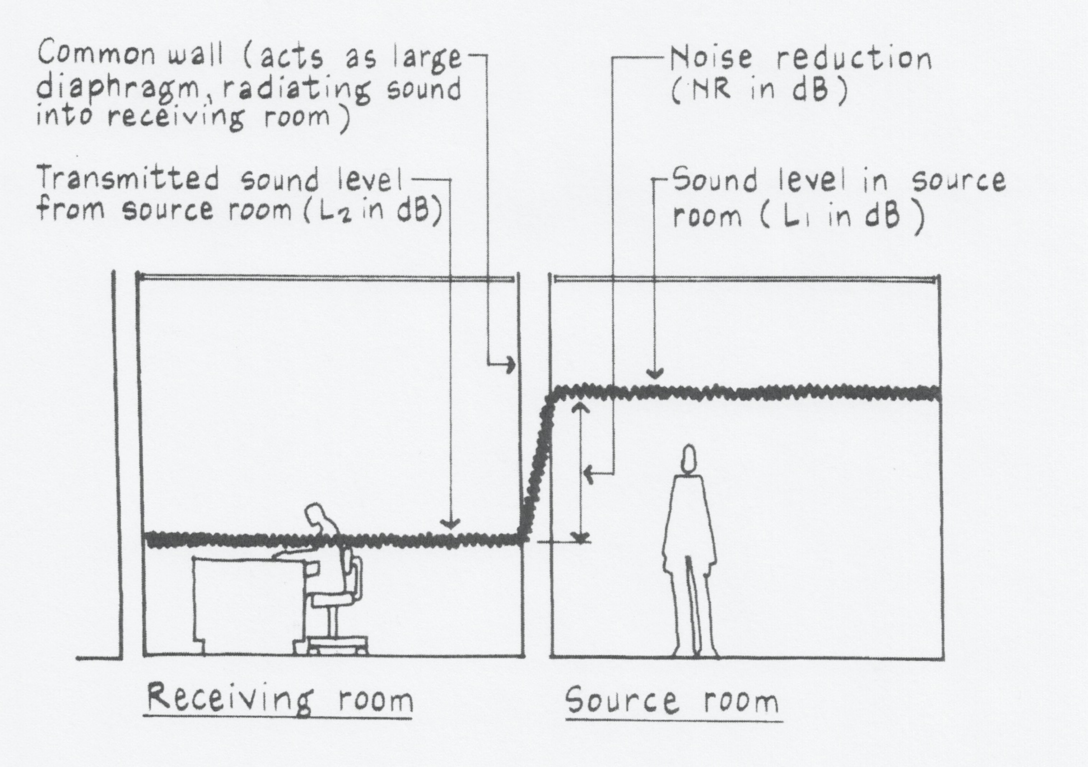
TL-non-homogeneous partitions

Ex. 4: A 12.5ft^2 window with a TL of 20dB is in a 100ft^2 brick wall which has a TL of 50dB. Find the composite TL of this window-wall construction.

TL-non-homogeneous partitions



Noise Reduction between rooms



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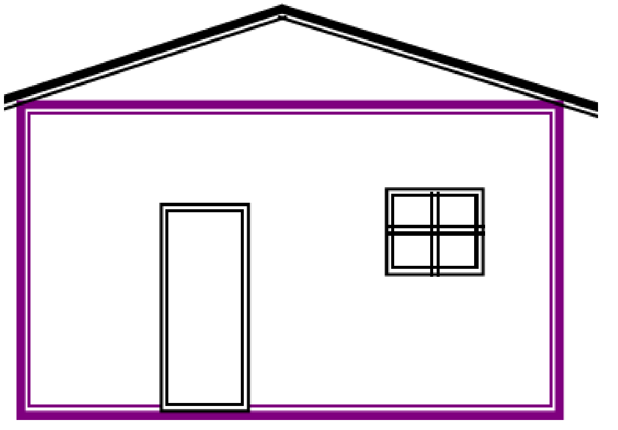
$$NR=TL+10\log(A_2/S)$$

A_2 is absorption in receiving room (sabins)
S-surface area of common barrier (m^2 or ft^2)

Noise Reduction between rooms

Ex. 5 A partition wall consists of a 3.7 m x 30 m concrete wall (TL = 50 dB) with a 1.2 m x 1.8 m window (TL = 25 dB), a 2.1 m x 1.0 m door (TL = 30 dB), and an opening (leak) 0.012 m x 1 m under the door. Determine the noise reduction through this wall in the 500 Hz band. The total absorption of the room on the receiving side of the wall is 29 m^2 sabins.

2) What if the door is well sealed?



1) With the door gap

$$\bar{\tau} = \frac{\tau_1 S_1 + \tau_2 S_2 + \ldots\ldots + \tau_n S_n}{S_1 + S_2 + \ldots\ldots + S_n} = 2.8\text{x}10^{-4}$$

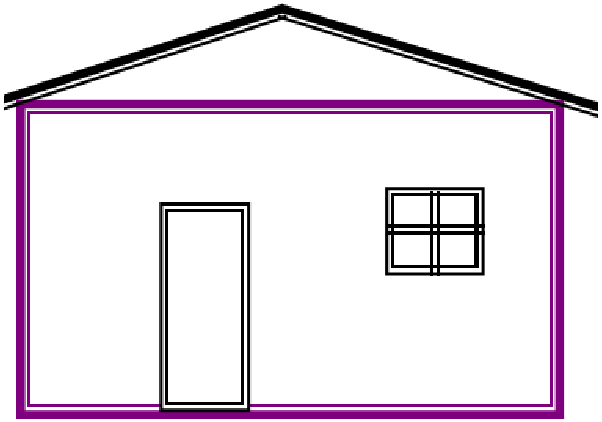
$$\overline{TL} = 10\log\left(\frac{1}{\bar{\tau}}\right) = 35.5\text{dB}$$

$$NR = \overline{TL} - 10\log\left(\frac{S_{wall}}{A_{room}}\right) = 29.7 \text{ dB}$$

Noise Reduction between rooms

If the gap under the door is properly sealed,

$$\bar{\tau} = \frac{\tau_1 S_1 + \tau_2 S_2 + ... + \tau_n S_n}{S_1 + S_2 + ... + S_n} = 9\text{x}10^{-5}$$

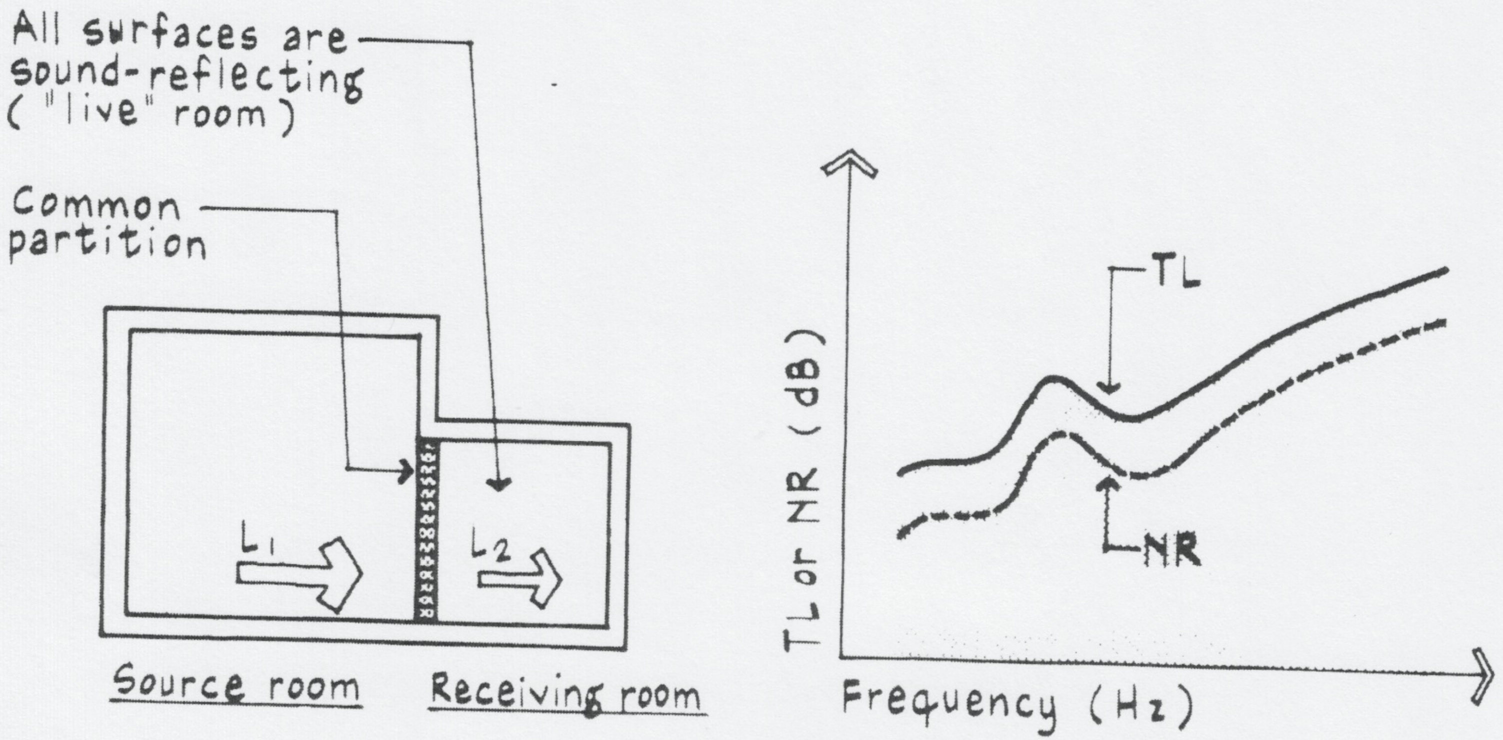


$$\overline{TL} = 10\log(\frac{1}{\bar{\tau}}) = 40.6\text{dB}$$

$$NR = \overline{TL} - 10\log(\frac{S_{wall}}{A_{room}}) = 40.6 - 10\log(111/29) = 34.6\text{ dB}$$

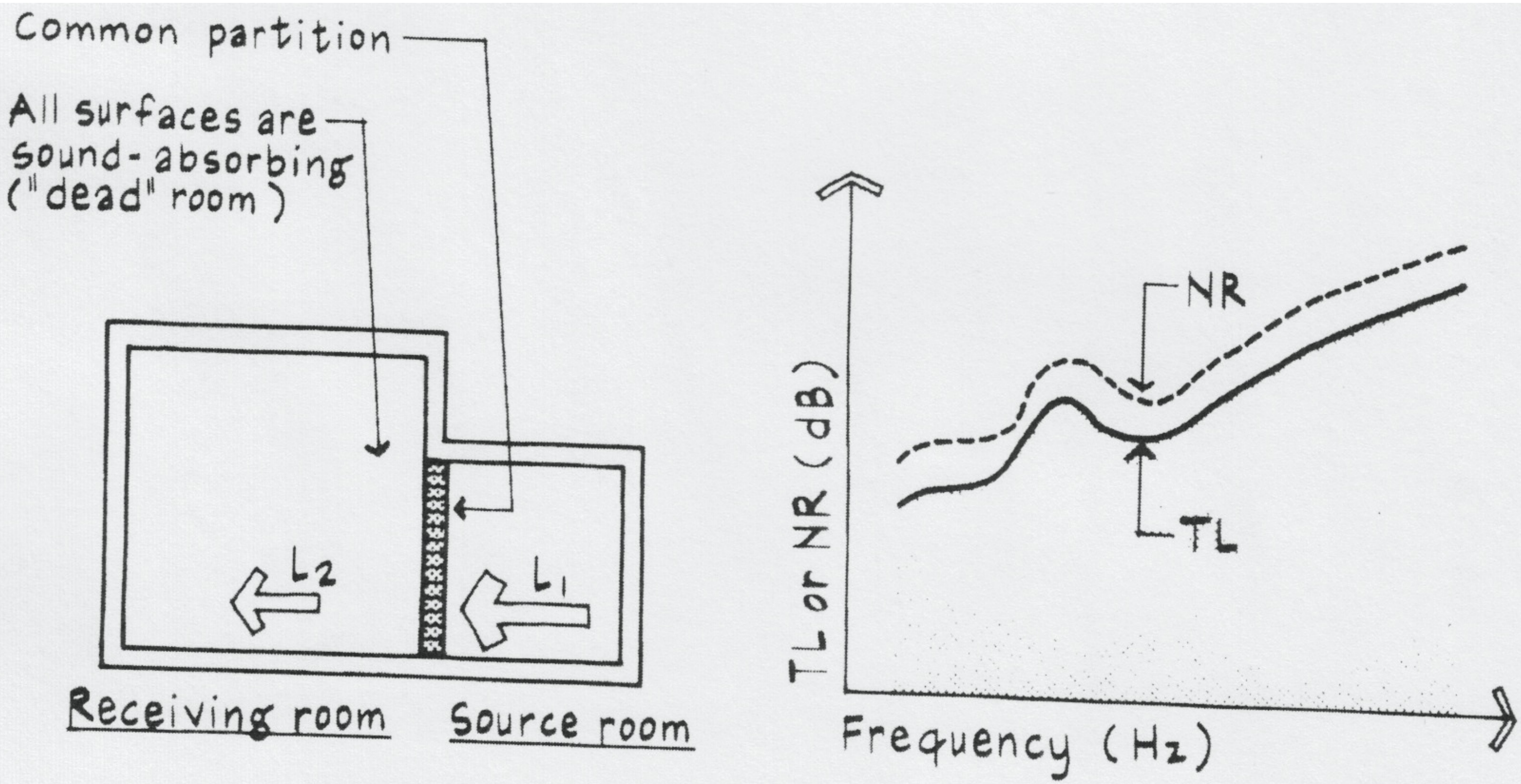
The above example only considers noise reduction at one frequency band. A complete analysis should include similar computations for all significant frequency bands. The band levels can then be combined to estimate the weighted levels, using methods illustrated before.

Noise Reduction between rooms



Small, Reverberant Receiving Room

Noise Reduction between rooms



Large, Absorbent Receiving Room

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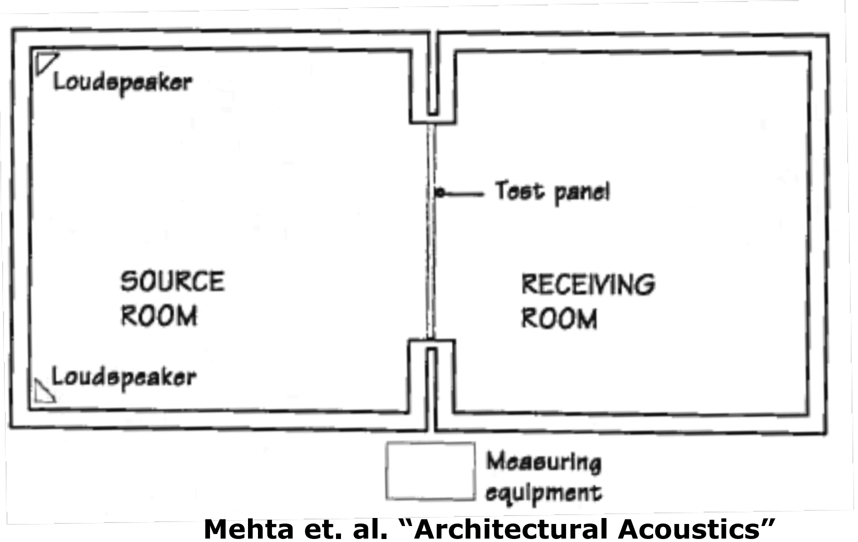
Sound Transmission Class (STC)

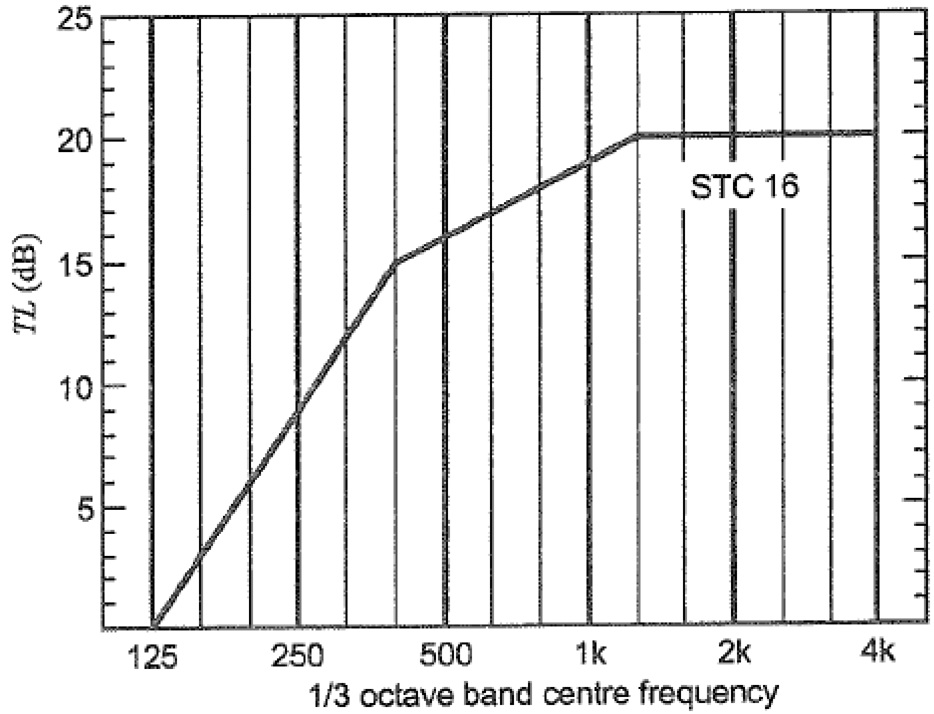
- STC is a single-number rating of the air-borne sound transmission loss TL performance of a construction measured at standard ***one-third octave*** band frequencies with centre frequencies from 125 to 4000Hz
  - ASTM E413-Classification of Sound Insulation
  - 16 one-third octave band frequencies (125, 160, 200, 250, 315, 400, 500, 630, 800, 1000, 1250, 1600, 2000, 2500, 3150, 4000Hz)



Mehta et. al. "Architectural Acoustics"

Sound Transmission Class (STC)

- The STC of a construction is determined by comparing the 16-frequency TL curve with a standard STC contour;
  - This contour consists of 3 segments: 125-400Hz (15 dB), 400-1250Hz (5 dB) and 1250-4000Hz (0 dB);
  - The standard STC contour is similar in shape to the TL curve for 9-in-thick brick



Sound transmission

- A particular STC contour is identified by its TL value at 500 Hz

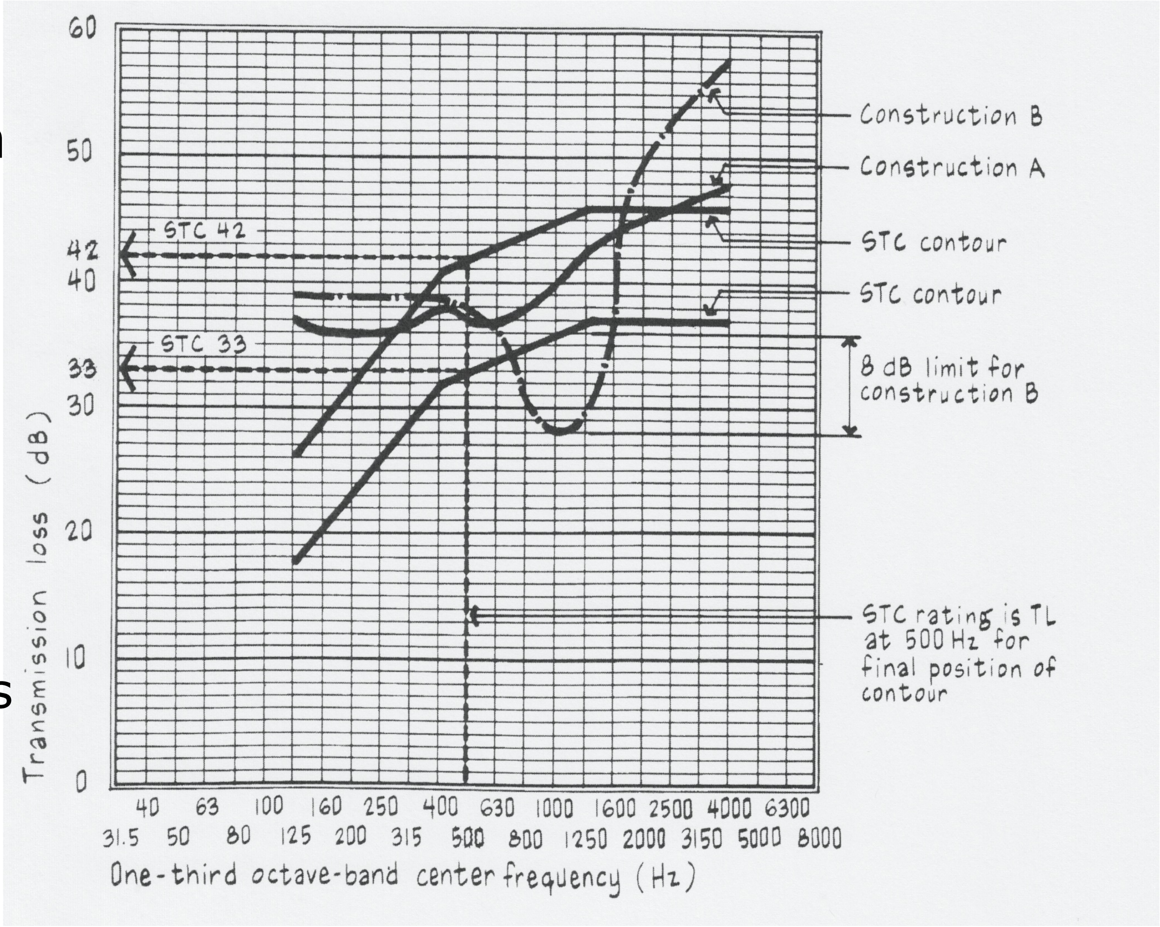
TABLE I-5—TRANSMISSION LOSS VERSUS FREQUENCY FOR A RANGE OF SOUND TRANSMISSION CLASS CONTOURS

Note: A particular contour is identified by its *TL* value at 500 Hz.
(From ASTM E413)

Hz	125	160	200	250	315	400	500	630	800	1,000	1,250	1,600	2,000	2,500	3,150	4,000
	44	47	50	53	56	59	60	61	62	63	64	64	64	64	64	64
	43	46	49	52	55	58	59	60	61	62	63	63	63	63	63	63
	42	45	48	51	54	57	58	59	60	61	62	62	62	62	62	62
	41	44	47	50	53	56	57	58	59	60	61	61	61	61	61	61
	40	43	46	49	52	55	56	57	58	59	60	60	60	60	60	60
	39	42	45	48	51	54	55	56	57	58	59	59	59	59	59	59
	38	41	44	47	50	53	54	55	56	57	58	58	58	58	58	58
	37	40	43	46	49	52	53	54	55	56	57	57	57	57	57	57
	36	39	42	45	48	51	52	53	54	55	56	56	56	56	56	56
	35	38	41	44	47	50	51	52	53	54	55	55	55	55	55	55

Sound Transmission Class (STC)

- Two rules used to determine STC of a particular construction
  - Rule 1 – the maximum deficiency at any single test point shall not exceed 8 dB
  - Rule 2 – Sum of all deficiencies (i.e. the deviations below the contour) shall not be grater than ≤ 32 dB
- A deficiency is defined as any point on the TL-frequency relationship that is below the STC contour



David Egan, "Architectural Acoustics"

Sound Transmission Class (STC)

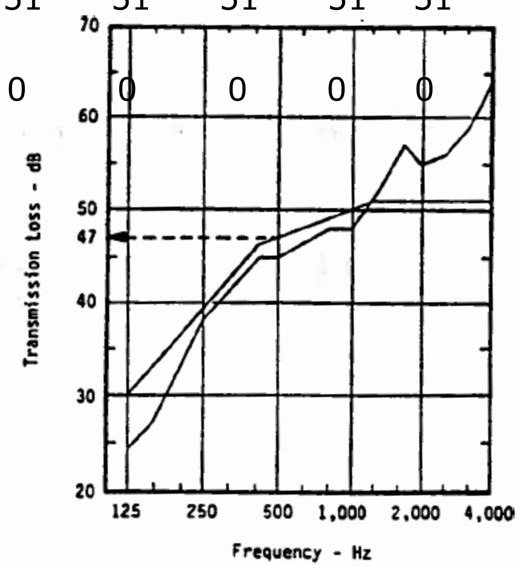
- Ex. 6

Freq. - Hz	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000
TL - dB	24	27	33	38	41	45	45	46	48	48	51	56	54	55	58	64
STC 48	32	35	38	41	44	47	48	49	50	51	52	52	52	52	52	52
deficiencies	8	8	5	3	3	2	3	3	2	3	1	0	0	0	0	0

Total deficiencies: 41dB>32dB

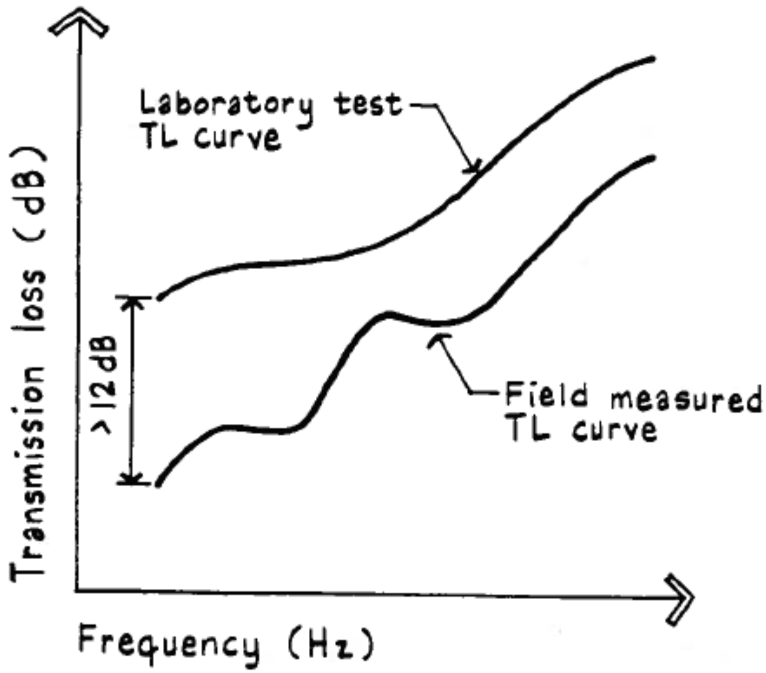
STC 47	31	34	37	40	43	46	47	48	49	50	51	51	51	51	51	51
deficiencies	7	7	4	2	2	1	2	2	1	2	0	0	0	0	0	0

Total deficiencies: 30dB<32dB
Max. deficiency: 7<8dB



Sound Transmission Class (STC)

- Laboratory TL data reflect idealized conditions; carefully crafted and installed specimens only from components which have passed very strict inspections
  - Much higher than field measured TL curves
  - Typically lab tested STC is more than 5 and by more than 15 if the construction is not carefully supervised



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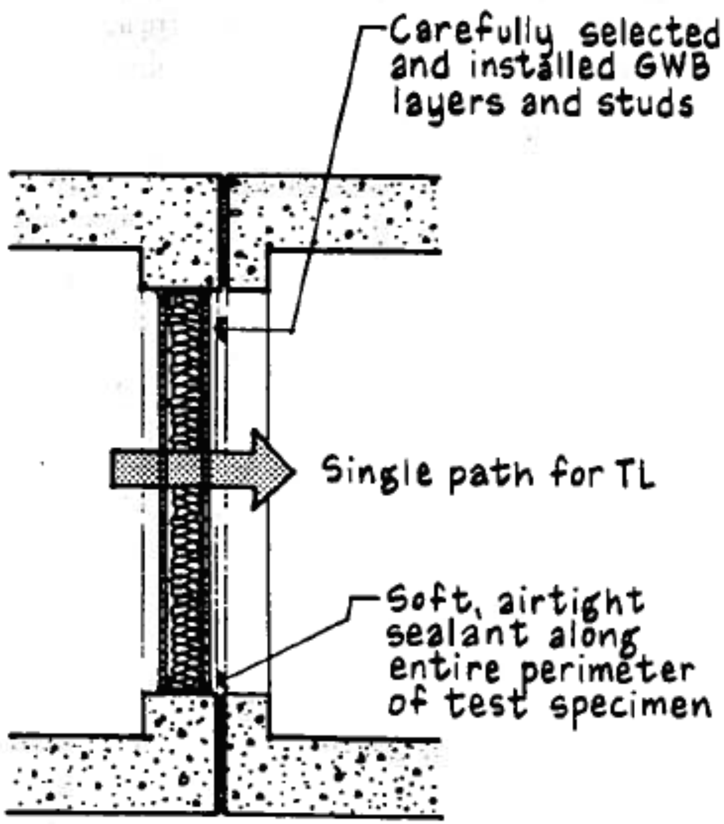
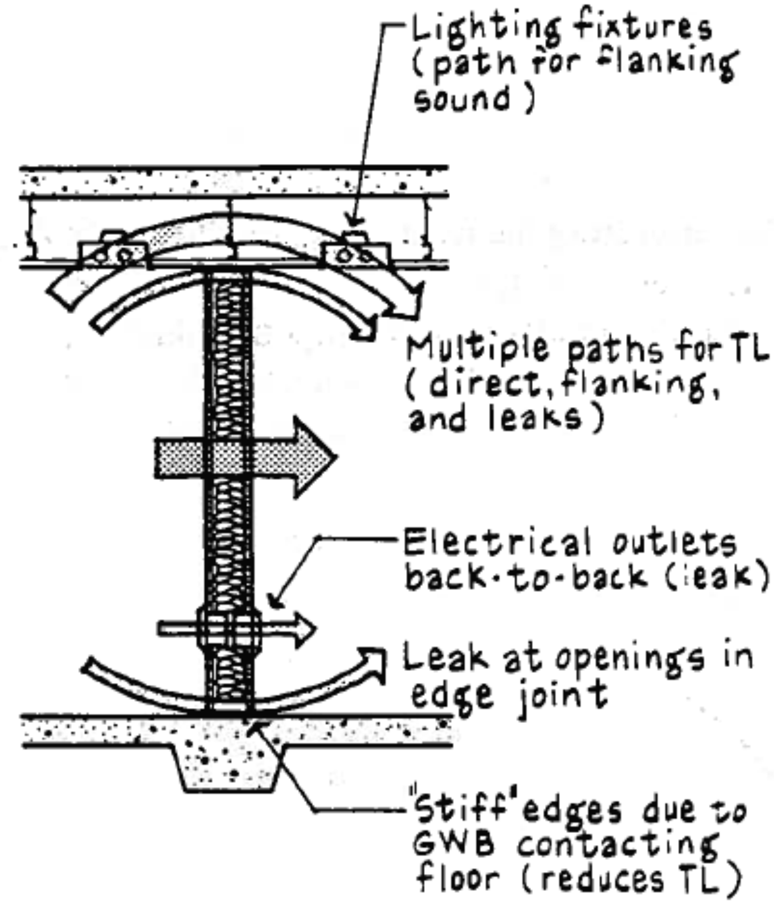
Sound Transmission Class (STC)

- Flanking loss, leaks, etc..



Laboratory Test Setup



Field test

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Sound Transmission Class (STC)

Changes in STC Rating	Changes in Apparent Loudness
+/- 1	Almost imperceptible
+/- 3	Just perceptible
+/- 5	Clearly noticeable
+/- 10	Twice (or half) as loud

Sound Transmission Class (STC)

Table 11.5 Speech privacy associated with STC ratings*

STC range	Sound privacy
0 to 20	No privacy (voices heard clearly between rooms)
20 to 40	Some privacy (voices heard in low** background noise)
40 to 55	Adequate privacy (only raised voices heard in low background noise)
55 to 65	Complete privacy (only high level noise heard in low background noise)
70	Practical limit

* assuming no significant flanking paths or openings in walls
** in the 35 dBA range

(T.D. Rossing, Building Acoustics)

Table 11.4 Transmission loss and STC values for common partitions

Partition	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	STC
1/2 inch drywall on both sides of wooden studs	17	31	33	40	38	36	33
1/2 inch drywall on wooden studs with 2 inches of insulation	15	30	34	44	46	41	37
Double layer of 1/2 inch drywall on wooden studs	25	34	41	51	48	50	41
1/2 inch drywall on staggered wooden studs	23	28	39	46	54	44	39
1/2 inch drywall on staggered wooden studs with 2 inches of insulation	29	38	45	52	58	50	48
1/2 inch drywall on metal studs	22	27	43	47	37	46	39
1/2 inch drywall on metal studs with 2 inches of insulation	26	41	52	54	45	51	45
8 inch thick concrete masonry units	36	44	50	54	58	56	53
Open-plane office partition	10	12	12	12	12	11	12
4 inch thick brick wall	32	34	40	47	55	61	45
1/2 inch drywall inside/1 inch stucco outside on wooden studs	21	33	41	46	47	51	42
Single-paned 1/8 inch thick glass	18	21	26	31	33	22	26
1/2 inch thick laminated glass	31	34	38	40	37	46	40
Double-paned 1/8 inch thick glass with 2 inch air gap	13	25	35	44	49	43	37
Hollow wooden door, 1 3/4 inch thick	14	19	23	18	17	21	19
Solid wooden door, 1 3/4 inch thick	29	31	31	31	39	43	34
Hollow metal door, 1 3/4 inch thick	24	23	29	31	24	40	28
Filled metal door, 1 3/4 inch thick	26	34	40	48	44	52	43
Wood joist floor/ceiling with 1/2 inch plywood subfloor and 1/2 inch drywall	23	32	36	45	49	56	37
8 inch thick concrete slab floor	32	38	47	52	57	63	50
Wood plank shingled roof	29	33	37	44	55	63	43
Wood plank shingled roof with 1/2 inch drywall ceiling, 4 inches of insulation	35	42	49	62	67	79	53
Corrugated steel roof with 1 inch of sprayed cellulose	17	22	26	30	35	41	30

(T.D. Rossing, Building Acoustics)

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