Fundamentals of Highway Traffic Noise

California Department of Transportation
Environmental Program
Environmental Engineering
Noise, Vibration, and Hazardous Waste Management Office

Caltrans

Jones & Stokes

Introduction

- Course in highway traffic noise fundamentals

Purpose

- Teach students fundamental concepts related to traffic noise generation and propagation.
- Provide students with some hands on experience through the use of examples.

Assumptions Regarding Students Experience

- This is an introductory course and assumes that students have no background in traffic noise analysis
- Students have a functional knowledge of algebra, geometry, and trigonometry.

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Summary of Course Topics

- Physics of sound
- Characteristics of sound
- Sound pressure levels and decibels
- Addition and subtraction of sound pressure levels
- Frequency spectra and frequency bands
- A-Weighted sound levels
- Sound propagation
- Human reaction to noise
- Noise Descriptors
- Traffic Noise Barrier Fundamentals

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Sound vs Noise

- Sound - A vibratory disturbance capable of being detected by hearing organs or an acoustic detector (i.e. microphone)
- Noise - Sound that is loud, unpleasant, unexpected,or undesired.
- Source, path, receiver concept

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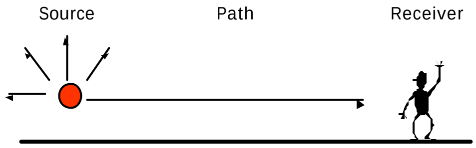
Source-Path-Receiver Concept



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Acoustics

- Acoustics - The science that deals with the production, propagation, reception, effects, and control of sound.

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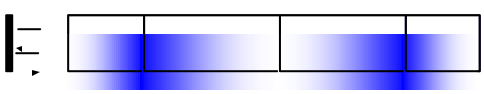
Creation of Sound Waves

- Sound pressure waves are created from a vibrating surface in air.



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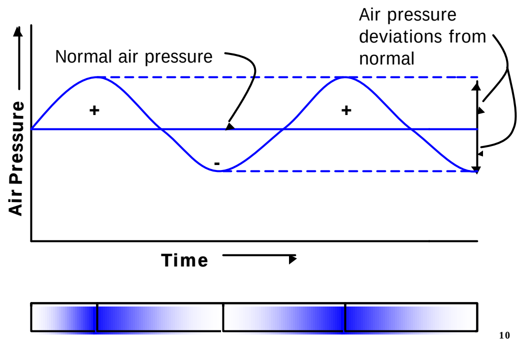
Amplitude vs Time



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Frequency

- Frequency - The number of pressure peaks or pressure cycles that pass per second is called the frequency of the sound wave
- Frequency = cycles per second = Hertz (Hz)
- Human hearing is in the range of 20 to 20,000 Hz
- Low frequency sounds are low in pitch (like low notes on a piano) and high frequency sounds are high in pitch (like high notes on a piano.)

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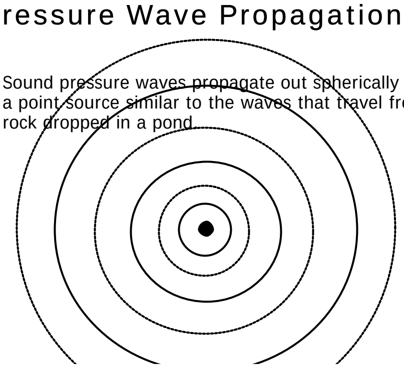
Pressure Wave Propagation

- Sound pressure waves propagate out spherically from a point source similar to the waves that travel from a rock dropped in a pond.



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Speed of Sound

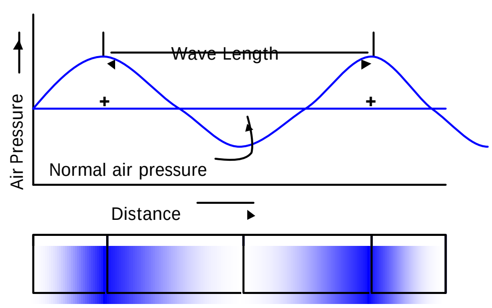
- The speed at which the sound wave propagates is called the speed of sound.

  -Sound travels at a rate of 1,126 feet per second in air of 20 degree C (68 degrees F).

  -This corresponds to about 1 mile every 5 seconds.

- Speed of sound is proportional to the square root of temperature

Amplitude vs Distance



Relationships

Frequency, Speed of Sound, Wavelength

- Frequency (f) - cycles per second
- Speed of sound (c) - feet per second
- Wavelength (l) - feet
- Relationships:

  $\lambda = c/f$ feet = feet per second / cycles per second

  $f = c/\lambda$ cycles per second = feet per second / feet

  $c = f \times \lambda$ feet per second = cycles per second x feet

Example

- What is the wavelength of a sound with a frequency of 100 Hz? Assume the speed of sound is 1,126 feet per second?

$$\lambda = \frac{1{,}126 \text{ ft./sec}}{100 \text{ cycle/sec}} = 11.3 \text{ ft.}$$

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Example

- What is the wavelength of a sound with a frequency of 8,000 Hz? Assume the speed of sound is 1,126 feet per second?

$$\lambda = \frac{1{,}126 \text{ ft./sec}}{8{,}000 \text{ cycles/sec}} = 0.14 \text{ ft.} = 1.7 \text{ inches}$$

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Sound Pressure

- Air pressure amplitude determines the loudness of the sound.
- Air sound pressures can be measured in units of micro Newtons per square meter ($\mu N/m^2$) or micro-Pascals (μPa)
- The human hear is sensitive to a very wide range of sound pressures. The pressure of the weakest audible sound is at about 20 μPa and an extremely loud sound might be 200,000,000 μPa.

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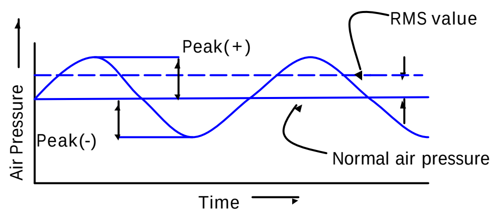
Sound Pressure



Root-mean-square (RMS) value ~ 0.7 X peak value

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Sound Pressure

200,000,000 mPa
20,000,000 mPa
2,000,000 mPa
200,000 mPa
20,000 mPa
2,000 mPa
200 mPa
20 mPa

It's cumbersome to work with this wide range of pressure values

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Sound Pressure

200,000,000 mPa	2×10^8 mPa
20,000,000 mPa	2×10^7 mPa
2,000,000 mPa	2×10^6 mPa
200,000 mPa	2×10^5 mPa
20,000 mPa	2×10^4 mPa
2,000 mPa	2×10^3 mPa
200 mPa	2×10^2 mPa
20 mPa	2×10^1 mPa

Logarithms and decibels are used to take advantage of the compressed range of the exponents

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Logarithms 1A

log (10) = log (10^1) = 1

log (100) = log (10^2) = 2

log (1000) = log (10^3) = 3

log (5) = log ($10^{.7}$) = 0.7

log (500) = log ($10^{2.7}$) = 2.7

log (1500) = log ($10^{3.17}$) = 3.17

Antilog (1) = 10^1 = 10

Antilog (2) = 10^2 = 100

Antilog (3)= 10^3 = 1000

Antilog (0.7) = $10^{.7}$ = 5

Antilog (2.7) = $10^{2.7}$ = 500

Antilog (3.17)= $10^{3.17}$ = 1500

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Sound Pressure Levels and Decibels

- The square of sound pressure is proportional to sound power or sound energy:

$$dB = 10 \log_{10} (P_1/P_0)^2$$

where:

P_1 = pressure value of interest
P_0 = a standard reference value of 20 µPa RMS

- dB value here is referred to as the “sound pressure level” or SPL.
- The quantity $(P_1/P_0)^2$ is called the “relative energy.”

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Sound Pressure Levels and Decibels

- The relative energy can be calculated from a dB value using the following equation:

$$dB = 10Log_{10} (P_1/P_0)^2$$

$$dB/10 = Log_{10} (P_1/P_0)^2$$

$$10^{(dB/10)} = (P_1/P_0)^2$$

$$(P_1/P_0)^2 = 10^{(dB/10)} = \text{relative energy}$$

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Sound Pressure Levels and Decibels

Relative Pressure: P_1/P_0		Relative Energy $(P_1/P_0)^2$		Decibel, dB $10 \text{ Log } (P_1/P_0)^2$
10^0 =	1	10^0 =	1	0
$10^{0.5}$ =	3.16	10^1 =	10	10
10^1 =	10	10^2 =	100	20
$10^{1.5}$ =	31.6	10^3 =	1000	30
10^2 =	100	10^4 =	10,000	40
$10^{2.5}$ =	316	10^5 =	100,000	50
10^3 =	1,000	10^6 =	1,000,000	60
$10^{3.5}$ =	3,162	10^7 =	10,000,000	70
10^4 =	10,000	10^8 =	100,000,000	80
$10^{4.5}$ =	31,623	10^9 =	1,000,000,000	90
10^5 =	100,000	10^{10} =	10,000,000,000	100

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Addition and Subtraction of Sound Pressure Levels (SPLs)

- Rules:

  -dB values may not be added or subtracted directly

  -relative energy values may be added and subtracted directly

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Addition and Subtraction of Sound Pressure Levels (SPLs)

Example: A compressor produces a sound pressure level of 70 dB at a distance of 50 feet. A second compressor producing the same sound level is placed next to the first compressor.

What is the combined sound level of the two compressors?

- 70 dB + 70 dB ≠ 140 dB. Relative energy values must be added.
- Relative energy for each source = $10^{(70/10)}$ = 10,000,000
- Relative energy for both sources is the 20,000,000.
- SPL for both sources = 10 log(20,000,000) = 73 dB.

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Addition and Subtraction of Sound Pressure Levels (SPLs)

- Adding the sound levels of N sources with equal SPL value:

Calculate the relative energy: $10^{(dB/10)}$
Calculate the total energy: $N \times 10^{(dB/10)}$
Calculate the SPL of the total energy: $10\log(N \times 10^{dB/10})$

Short cut: $10\log(N \times 10^{dB/10})$
$= 10 \log(10^{dB/10}) + 10 \log N$
$= dB + 10 \log N$

N can also be viewed as the ratio of a subsequent number of sources to an initial number of source.

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Examples

Example 1. 70 dB+70 dB+70 dB+70 dB
= 70 dB + 10 log 4
= 70 dB + 6 dB = 76 dB

Example 2.

4 compressors produce 76 dB.
How much noise do 12 compressors produce?

76 + 10log (12/4)
= 76 + 10log(3)
= 76 + 5 = 81 dB

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Addition and Subtraction of Sound Pressure Levels (SPLs)

- Shortcut:

2 sources of equal value, add 3 dB
3 sources of equal value, add 5 dB
4 sources of equal value, add 6 dB
5 sources of equal value, add 7 dB
10 sources of equal value, add 10 dB

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Exercise

Present Traffic = 4000 vehicles per hour
Present Noise Level = 65 dB

Future Traffic = 6000 vehicles per hour
What is the future noise level?

- Future Noise Level = ?
  65 dB + 10 log (6000/4000) =
  65 dB + 10 log 1.5 =
  65 dB + 1.8 dB = 66.8 dB

Addition and Subtraction of Sound Pressure Levels (SPLs)

- Use the same process to add sources with differing dB values:
  - calculate the relative energy for each source
  - calculate the total relative energy by summing the relative energies for each source
  - calculate the dB value by multiplying the log of the sum by 10.

$$dB_1 + dB_2 + \ldots dB_n = 10\log(10^{dB_1/10} + 10^{dB_2/10} + \ldots 10^{dB_n/10})$$

Example

- 60 dB + 70 dB + 73 dB
  $= 10\log(10^6 + 10^7 + 10^{7.3})$
  = 10log (30,952,600)
  = 74.9 dB

Addition of Sound Pressure Levels (SPLs)

Short cut for the addition of two decibel values

When Two Values Differ By:	Add to Higher Value
0 to 1 dB	3 dB
2 to 3 dB	2 dB
4 to 9 dB	1 dB
10 or more dB	0 dB

Example: 65 dB+ 70 dB = 71 dB

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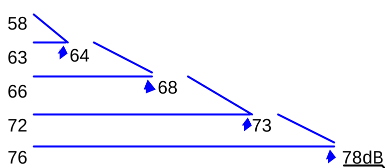
Addition and Subtraction of Sound Pressure Levels (SPLs)

- Addition of multiple decibel values

Example: Add 72, 63, 76, 66, 58 dB.

First, rank from low to high. Then add two at a time.



(77.9 dB calculated)

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Exercise

- Find the total sound level produced by the following:
  - Automobiles 63 dB
  - Medium duty trucks 69 dB
  - Heavy duty trucks 65 dB
  - Buses 62 dB
- A. Use manual method: answer to nearest 1 dB.
- B. Check with the calculator: answer to nearest 0.1 dB.

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Exercise

A. Manual method:

62 dB plus 63 dB = 66 dB
66 dB plus 65 dB = 69 dB
69 dB plus 69 dB = 72 dB

B. Calculator method:

$10^{(62/10)} + 10^{(63/10)} + 10^{(65/10)} + 10^{(69/10)} =$

$(1.58 \times 10^6) + (2.00 \times 10^6) + (3.25 \times 10^6) + (7.94 \times 10^6) = 14.8 \times 10^6$

$10 \log(14.8 \times 10^6) = 71.7$ dB

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Addition and Subtraction of Sound Pressure Levels (SPLs)

- To subtract dB values converted the dB values to relative energy first, then convert the result back to dB.

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Example

- The background SPL at a site is 68 dB. A compressor is placed on the site and the combined SPL of the background and the compressor is 70 dB. What is the SPL of the compressor?

Compressor SPL = $10\log(10^7 - 10^{6.8}) = 65.7$ dB

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Sound Power

- A sound source radiates acoustic (i.e. sound) energy or power similar to the way that a light source radiates light energy or power.
- Sound power tells how much sound energy is produced by a sound source just like the wattage of light bulb tells how much light energy is produced by the light bulb.
- Examples:
  - A light bulb produces 75 watts of light energy.
  - An 75 HP air compressor produces 1.2 X 10^{-12} watts of sound energy

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Sound Power

- Sound power does not tell us how loud a sound source is; just like the wattage on a light bulb does not tell us how much light we will perceive from a light bulb.
- The perceived loudness or brightness depends on the amount of reflected sound or light.

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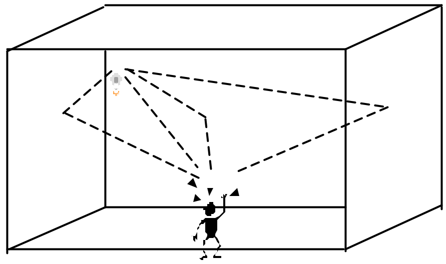
Sound Power



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Sound Power

- $dB = 10 \log_{10} (W_1/W_0)$
  where:
  - W_1 = power value of interest
  - W_0 = a standard reference value of 10^{-12} watts RMS
- The word “level” is used to indicate use of a logarithm and the ratio of a quantity to a reference quantity.
- The dB value here is therefore referred to as the “sound power level.”

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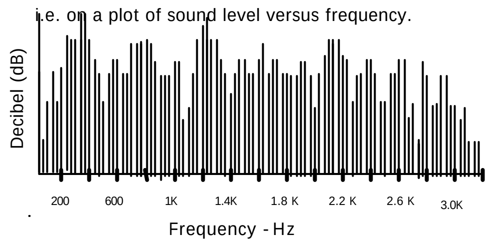
Frequency Spectra and Frequency Bands

- Sound level can be viewed in the frequency domain, i.e. on a plot of sound level versus frequency.



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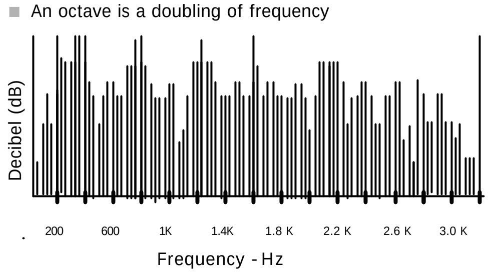
Frequency Spectra and Frequency Bands

- An octave is a doubling of frequency



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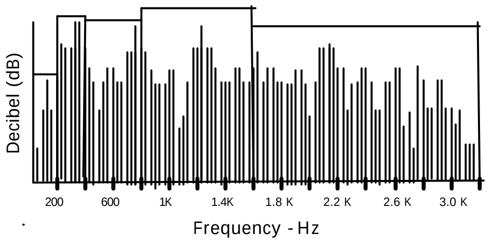
Frequency Spectra and Frequency Bands

- An octave is a doubling of frequency



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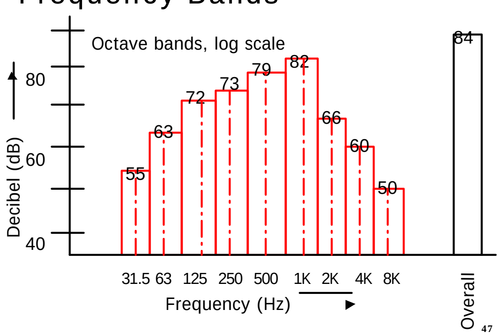
Frequency Spectra and Frequency Bands



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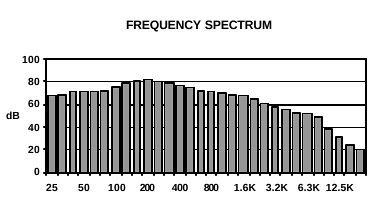
Frequency Spectra and Frequency Bands

One-third octave spectrum



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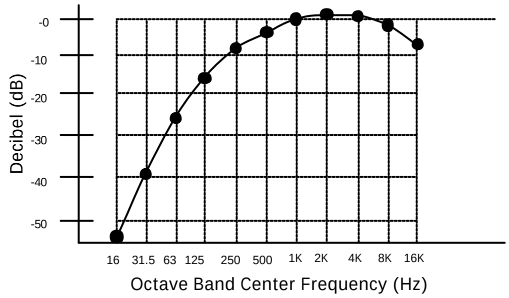
Frequency Spectra and Frequency Bands



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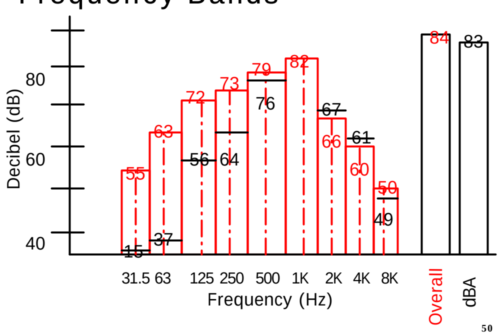
Frequency Spectra and Frequency Bands



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Typical Noise Levels

Common Outdoor Activities	Noise Level (dBA)	Common Indoor Activities
	— 110 —	Rock band
Jet fly-over at 300 meters (1000 feet)		
	— 100 —	
Gas lawn mower at 1 meter (3 feet)		
	—90—	
Diesel truck at 15 meters (50 feet) at 80 kph (50 mph)		Food blender at 1 meter (3 feet)
	—80—	Garbage disposal at 1 meter (3 feet)
Noisy urban area, daytime		
Gas lawn mower, 30 meters (100 feet)	—70—	Vacuum cleaner at 3 meters (10 feet)
Commercial area		Normal speech at 1 meter (3 feet)
Heavy traffic at 90 meters (300 feet)	—60—	
		Large business office
Quiet urban daytime	—50—	Dishwasher next room
Quiet urban nighttime	—40—	Theater, large conference room (background)
Quiet suburban nighttime		
	—30—	Library
Quiet rural nighttime		Bedroom at night, concert
	—20—	
		Broadcast/recording studio
	—10—	
Lowest threshold of human hearing	—0—	Lowest threshold of human hearing

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Sound Propagation

- Geometric Spreading
- Ground Absorption
- Atmospheric Conditions
- Obstacles/Vegetation/Barriers.

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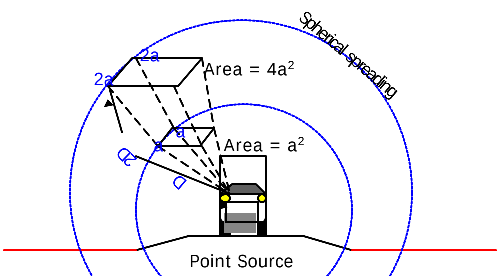
Geometric Spreading



At twice the distance, the energy per unit area is reduced to 1/4 of the initial energy per unit area. 10log (.25) = -6

Therefore 6 dB reduction per doubling of distance.

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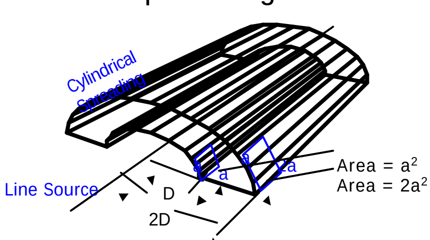
Geometric Spreading



At twice the distance, the energy per unit area is reduced to 1/2 of the initial energy per unit area.

10log (.5) = -3

Therefore 3 dB reduction per doubling of distance.

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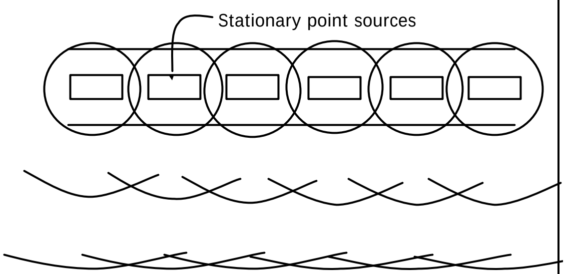
Line Source vs Moving Point Source



Sound level attenuates at 3 dB per doubling of distance

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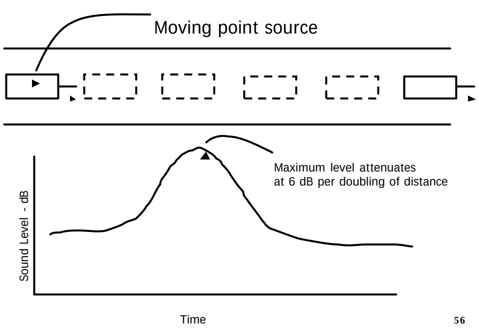
Line Source vs Moving Point Source



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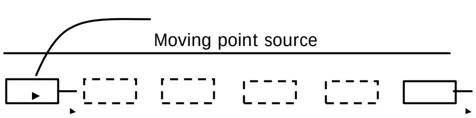
Line Source vs Moving Point Source



Energy average sound level attenuates at 3 dB per doubling of distance

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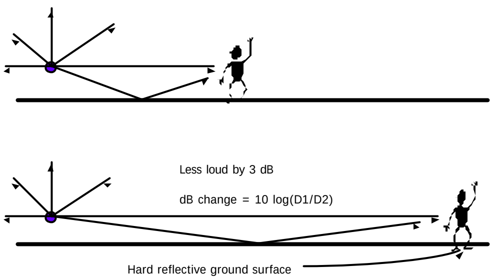
Geometric Relationship Between Traffic and Receiver



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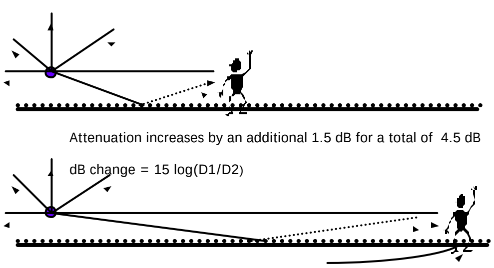
Geometric Relationship Between Traffic and Receiver



(Based on simple FHWA-RD-77-108 model. TNM models the actual attenuation)

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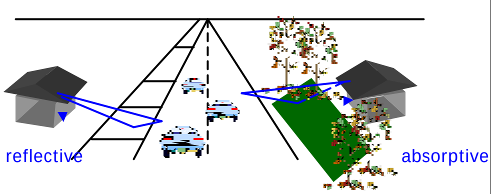
Line Source Attenuation Rates

Hard Site
-3 dBA/DD

Soft Site
-4.5 dBA/DD



(Based on simple FHWA-RD-77-108 model. TNM models the actual attenuation)

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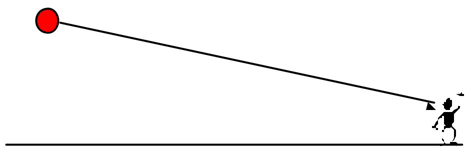
Line Source Attenuation Rates

- If the source or the receiver are located more than 3 meters above the ground or when the line of sight averages more than 3 meters above ground use hard site attenuation (i.e. 3 dB per doubling of distance)



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Summary of Noise Attenuation Rates

Source	Site	X log(D_2/D_1)	dB/DD
Line	Hard	X = 10	3
	Soft	X = 15	4.5
Point	Hard	X = 20	6
	Soft	X = 25	7.5

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(Based on simple FHWA-RD-77-108 model. TNM models the actual attenuation)

Example

- Traffic on a roadway produces a sound level of 70 dBA at a distance of 100 feet from the roadway.
  - What is the sound level at 200 feet assuming that the intervening ground is grassy?
  - What is the sound level at 200 feet assuming that the intervening ground is asphalt?
  - How far away from the roadway do you need to be for the sound to be 66 dBA or less?

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Example

- Going from 100 feet to 200 feet is a doubling of distance. On soft site this corresponds to a loss of 4.5 dB.
  70 - 4.5 = 65.5 dBA
  dB change = 15 log(D1/D2)
  dB change = 15log(100/200) = -4.5 dB
- On a hard site the loss is only 3 dB.
  70 - 3 = 67 dBA
  dB change = 10log(100/200) = -3 dB
  10 log(100/200) = -3 dB

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Example

- The sound level needs to be reduced by 4 dB (70 - 66)
  dB change (soft site) = 15log(D1/D2)

  -4 = 15log(100/X)
  -4/15 = log(100/X)
  $10^{-(4/15)}$ = 100/X
  X = 100/.54 = 185 feet

- $10^{(4/15)}$ = 1.85   1.85 x 100 = 185 feet. (soft site)

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Example

- The sound level needs to be reduced by 4 dB (70 - 66)
  dB change (hard site) = 10log(D1/D2)

  -4 = 10log(100/X)
  -4/10 = log(100/X)
  $10^{-(4/10)}$ = 100/X
  X = 100/.40 = 250 feet

- $10^{(4/10)}$ = 2.5   2.5 x 100 = 250 feet. (hard site)

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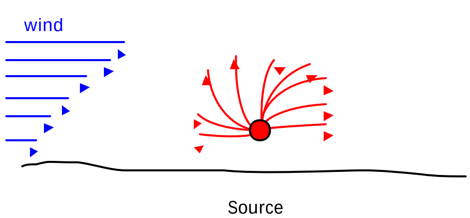
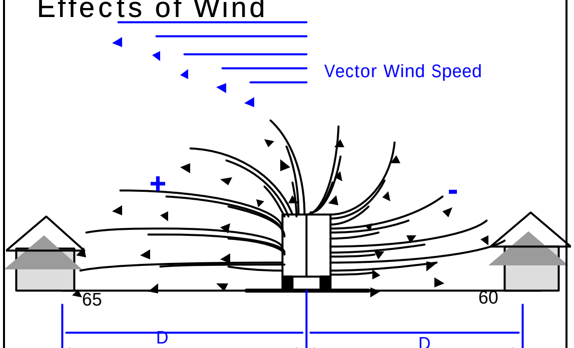
Atmospheric Factors Affecting Noise Propagation

- Wind
- Turbulence
- Temperature/Humidity
- Temperature Profile
- Rain, Snow

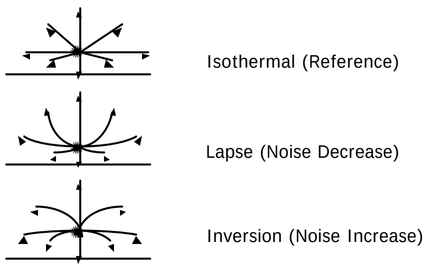
Refraction and Wind Gradients



Effects of Wind



Refraction and Temperature Gradients



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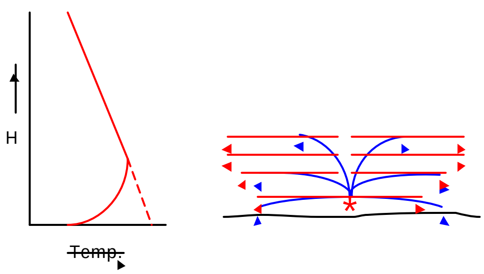
Temperature Inversion



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Vegetation/Obstacles/Barriers

- Noise Barriers:
  - Range: 5-15 dBA
  - Average: 9 dBA
- Vegetation:
  - Freeway shrubs: < 1 dBA
  - Dense Woods, 100' deep, at least 15' above line of sight: 5 dBA
- Houses:
  - 1st Row: 3-5 dBA
  - Each additional row: 1.5 dBA
  - Max. : 10 dBA

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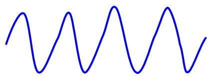
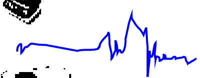
Human Reaction to Noise

- Frequency 
- Noise Level 
- Time Patterns 
- Activity 

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Human Reaction to Noise

Relative Energy	dBA	Human Perception
2 X	+3	Barely perceptible
3.16 X	+5	Readily perceptible
5 X	+10	Twice as loud
10 X	+20	4 times as loud

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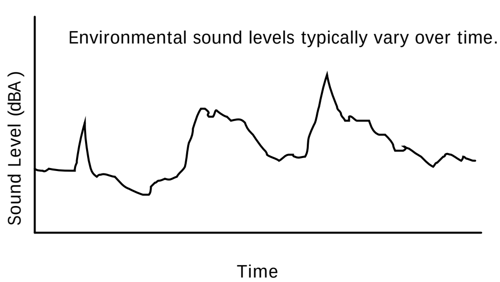
Noise Descriptors



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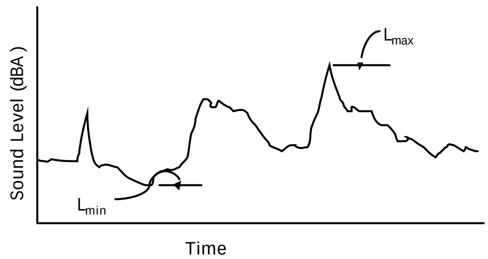
Noise Descriptors



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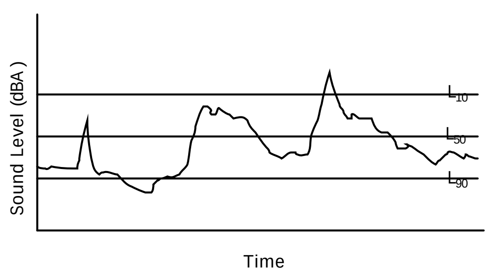
Noise Descriptors



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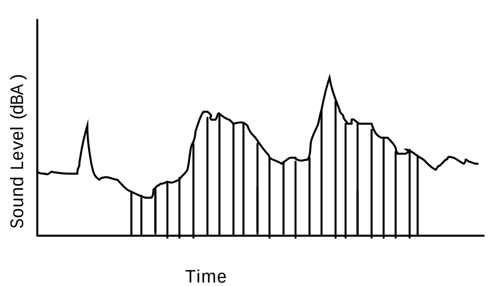
Noise Descriptors



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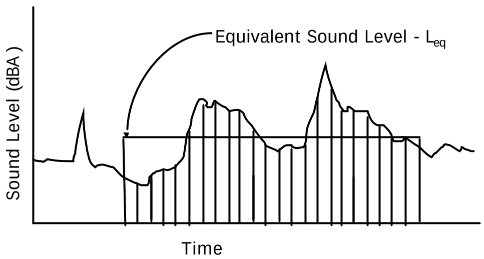
Noise Descriptors



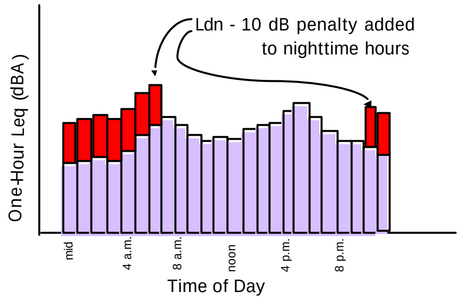
Noise Descriptors

- Caltrans uses the one-hour Leq A-weighted sound level to describe traffic noise.
- Criteria are for the noisiest one hour period during the 24-hour day.

Noise Descriptors

- Day-Night Average Sound Level -Ldn or DNL
- L_{dn} values are calculated from hourly L_{eq} values, with the L_{eq} values for the nighttime period (10:00 p.m.-7:00 a.m.) increased by 10 dB to reflect the greater disturbance potential from nighttime noises.

Noise Descriptors



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Noise Descriptors

- Community Noise Equivalent Level -CNEL
- L_{dn} values are calculated from hourly L_{eq} values, with the L_{eq} values for the nighttime period (10:00 p.m.-7:00 a.m.) increased by 10 dB and the value for the evening period (7:00 p.m. to 10:00 p.m.) increased by 5 dB to reflect the greater disturbance potential from nighttime noises.

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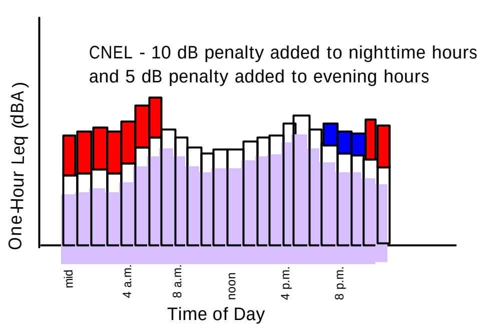
Noise Descriptors



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Traffic Noise Barriers Fundamentals

- Noise paths with a barrier
- Critical points in defining a barrier
- Importance of breaking the line of sight
- Barrier attenuation and path length difference
- Hinge point barriers
- Barrier transmission loss and insertion loss
- Effect of barrier location and extent
- Barrier height restrictions
- Effects of barrier reflections

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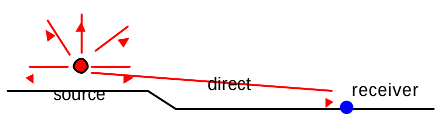
Noise Path without a Barrier



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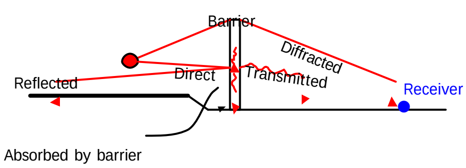
Noise Paths with Barrier



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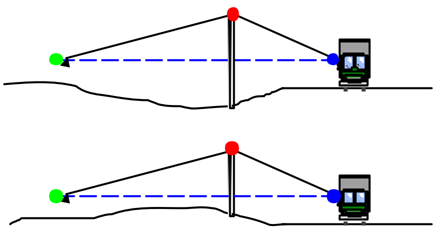
Critical Points in Defining a Barrier



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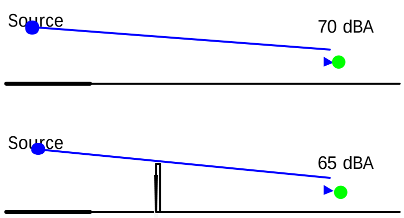
Importance of Breaking the Line of Sight



Line-of-Sight Grazing Wall: -5 dBA

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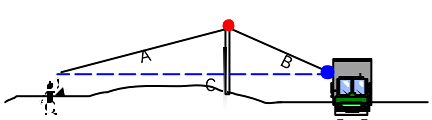
Barrier Attenuation and Path Length Difference

Path length difference (PLD) = (A + B) -C

Barrier attenuation increases at the PLD increases



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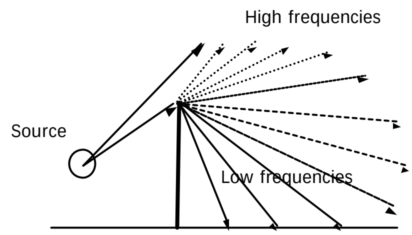
Noise Paths with Barrier



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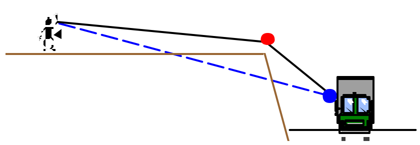
Hinge Point Barrier



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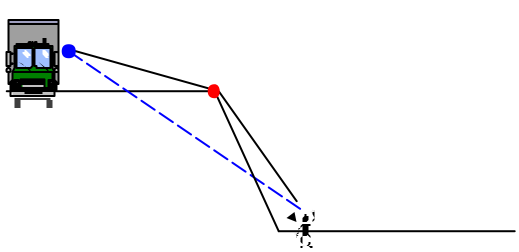
Hinge Point Barrier



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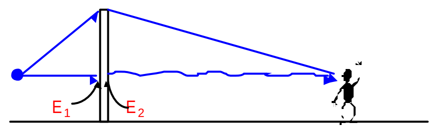
Transmission Loss

$TL = 10 \log (E_1/E_2)$



TL = Transmission loss
E_1 = Acoustic energy in front of wall
E_2 = Acoustic energy in back of wall

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Transmission Loss

- Noise transmitted through the barrier material may be ignored if:
  - TL is at least 10 dBA greater than the desired noise reduction.
- Example:
  - If a 12 dBA noise reduction is desired, the TL of the noise barrier material must be at least 22 dBA.
- Rule of Thumb: 4 lbs./ft^2

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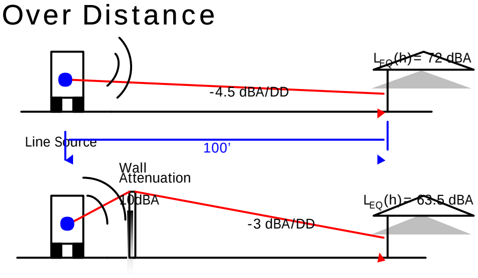
Effect of Barrier on Attenuation Over Distance



Field Insertion Loss = "Before"- "After"= 8.5 dBA
Wall Attenuation = 10 dBA

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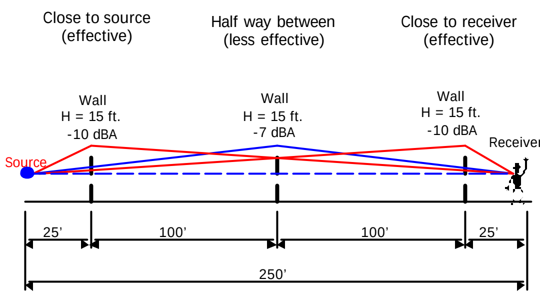
Optimum Barrier Location



(Barrier Attenuation for 8% HT mix)

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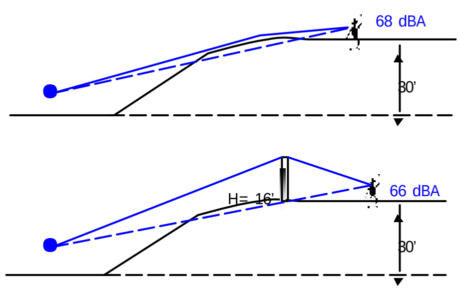
Pre-Existing Shielding



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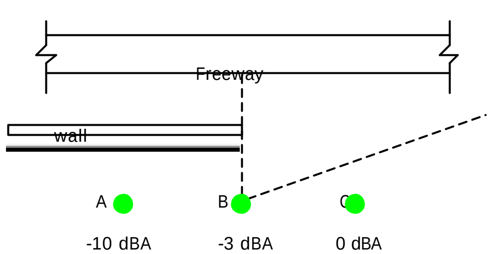
Effect of Partial Barrier



At Receiver B: Exposed to half the traffic = <u>-3 dBA</u>

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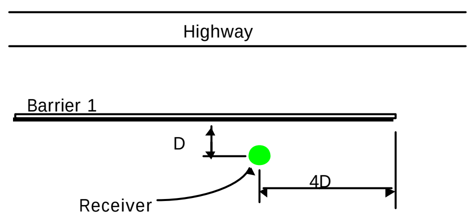
Noise Barrier Length



Use 4:1 ratio as a starting point. Use modeling tools to refine the design.

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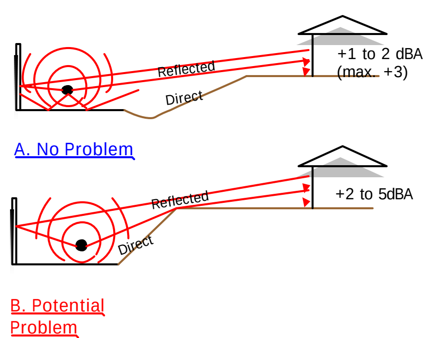
Single Barrier Reflections



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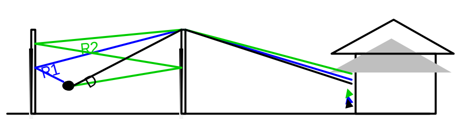
Parallel Barrier Reflections



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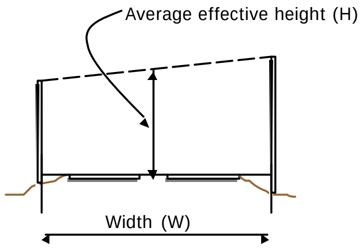
Ratio of Width to Height



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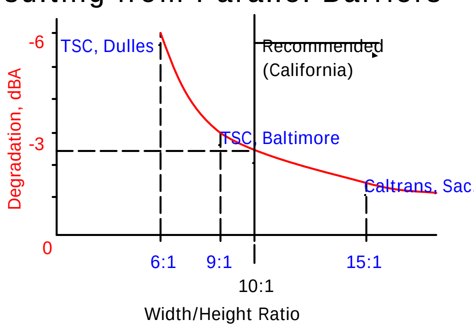
Degradation of Barrier Attenuation Resulting from Parallel Barriers



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Concluding Remarks

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  - Lynn Damme, Jones & Stokes Associates, Sacramento
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  - Lefteris Koumis, Caltrans Headquarters, Sacramento

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