PHYS 536

R. J. Wilkes

Session 13

Decibels

Loudness

Sound level measurements

Environmental noise

2/14/2023

Course syllabus and schedule

See : http://courses.washington.edu/phys536/syllabus.htm

Session	date	Day	Readings:	K=Kinsler, H=Heller	Topic
8	26-Jan	Thu	K: Ch. 7	H: Ch. 7	Absorption losses; Pulsating spheres and simple sources; pistons and dipoles; Near field, far field; Radiation impedance; Waves in pipes *UPDATED BELOW HERE:*
9	31-Jan	Tue	K. Ch. 8-10	H: Ch. 13	Rectangular cavities; Helmholtz resonators; Resonant bubbles; Acoustic impedance; physical acoustic filters; Doppler effect; Interference effects
10	2-Feb	Thu	K. Ch 9	H: Chs. 23-25	Musical acoustics: pitch, musical tones and frequency; timbre; beats
11	7-Feb	Tue		H: Chs. 16, 18	Musical instruments: winds and string instruments
12	9-Feb	Thu		H: Chs. 17, 19	Musical instruments: piano, human voice REPORT 1 PAPER DUE by 7 PM; REPORT 2 PROPOSED TOPIC DUE
13	14-Feb	Tue	K. Ch. 11	H: Ch. 21	Human hearing: the inner ear; pitch perception; acoustics of speech
14	16-Feb	Thu	K. Ch. 12	H: Chs. 21-22	Decibels and sound level measurements Environmental acoustics and noise criteria; industrial and community noise regulations; noise mitigation;
15	21-Feb	Tue	K. Chs. 13-14	H: Chs. 27-28; Ch. 6	Room acoustics; Transducers for use in air and water: Microphones and loudspeakers; hydrophones and pingers; Underwater acoustics: sound absorption underwater, the sonar equation
16	23-Feb	Thu	K. Ch 15		Underwater acoustics applications: acoustical positioning, seafloor imaging, sub-bottom profiling; Course wrap-up: review
17	28-Feb	Tue			Student report 2 presentations
18	2-Mar	Thu			Student report 2 presentations
19	7-Mar	Tue			Student report 2 presentations
20	9-Mar	Thu			Student report 2 presentations. TAKE-HOME FINAL EXAM ISSUED
--	17-Mar	Fri			FINAL EXAM ANSWERS DUE by 5 PM

Tonight

Class is over after you turn in your take-home exam. No in-person final exam during finals week.

Announcements

- Submission portal on Canvas for Term paper 1 is closed
    - It will take at least a week for us to grade the papers – please be patient
- **If you have not done so already:**
    - term project 2 presentation proposal is overdue

    –Please email yours to me ASAP

    Goal is to make sure your topic is appropriate, you have adequate sources, and your scope fits into a 15 min talk

Decibels for ratios over a large range of magnitudes

- Decibels are used to describe any quantity expressed as a ratio when a log scale is needed
  - Originated at Bell Laboratories (bel = unit for base-10 ratios, after Alexander Graham Bell) – bel is "too large" for most applications
  - Commonly used in many engineering and applied science fields
- For intensities (power ratios)

$$\beta[dB] = 10\log_{10}\left(\frac{I}{I_0}\right) \quad I_0 = \text{sound } \textit{intensity} \text{ reference level}$$

  - For acoustics, we use threshold of hearing as the reference level

$$\beta[dB] = 10\log_{10}\left(\frac{I}{I_0}\right) \quad I_0 = 10^{-12}\,\text{W/m}^2$$

  - So a sound intensity at the threshold of hearing is 0 dB
  - Sound at the threshold of pain has

$$\beta[dB] = 10\log_{10}\left(\frac{I}{I_0}\right) = 10\log_{10}\left(10^{13}\right) = 130\,\text{dB}$$

Sound Level meter (www.extech.com)

Decibels for ratios of amplitude and power

- Note: dB are used for ratios of two kinds of physical quantities
  - Power-like quantities (intensity of sound, power in E-M waves)
  - Amplitude-like quantities (sound **pressure** levels, electric field **amplitude** in E-M waves)
- For such quantities, power ~ amplitude^2
- Usually, we can measure power, but not amplitude
  → dB definition = 10 log(X/X_0) assumes power or intensity ratio
- So, to use dB for an amplitude-like quantity, we must insert a factor of 2 in the log10 (=squaring the ratio); factor is 20 instead of 10

$$\beta[dB] = 10\log_{10}\left(\frac{I}{I_0}\right) \approx 10\log_{10}\left(\frac{p^2}{p_0^2}\right) = 2\left[10\log_{10}\left(\frac{p}{p_0}\right)\right]$$

$$\rightarrow \alpha[dB] = 20\log_{10}\left(p / p_0\right) \quad p_0 = \text{ sound } \textit{pressure} \text{ reference level}$$

$$I_0 = 10^{-12} W/m^2 \rightarrow \text{corresponding } p_0^2 = 2\rho_0 c I_0 \rightarrow |p_0| = 2.9x10^{-5}\,Pa \quad (\textit{amplitude} \text{ of } \mathrm{p}_0)$$

$$p_0\Big|_{RMS} = |p_0| / \sqrt{2} = 20.4\mu Pa \rightarrow \text{standard } p_0 = 2.0x10^{-5}\,Pa$$

  - This gives amplitude ratios the same dB relationships as their corresponding intensity/power ratios -

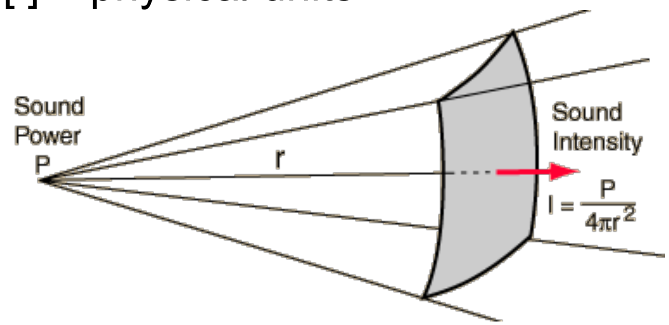
Sound intensity vs distance

- Intensity = energy per unit time per unit area = power/unit area

So

$$I = \frac{E[J]}{A[m^2]\,t[s]} = \frac{P[W]}{A[m^2]} = [W/m^2]$$

[ ] = physical units



- For a point source, sound power P is spread over an expanding sphere
  - So intensity drops off as $1/R^2$
    - proportional to surface area of sphere of radius R : $A=4\pi R^2$
    - For a given sound source (amount of power P emitted),

$$I_{R1} = \frac{P}{4\pi R_1^2} \qquad I_{R2} = \frac{P}{4\pi R_2^2} \quad \rightarrow \quad \frac{I_{R2}}{I_{R1}} = \frac{R_1^2}{R_2^2}$$

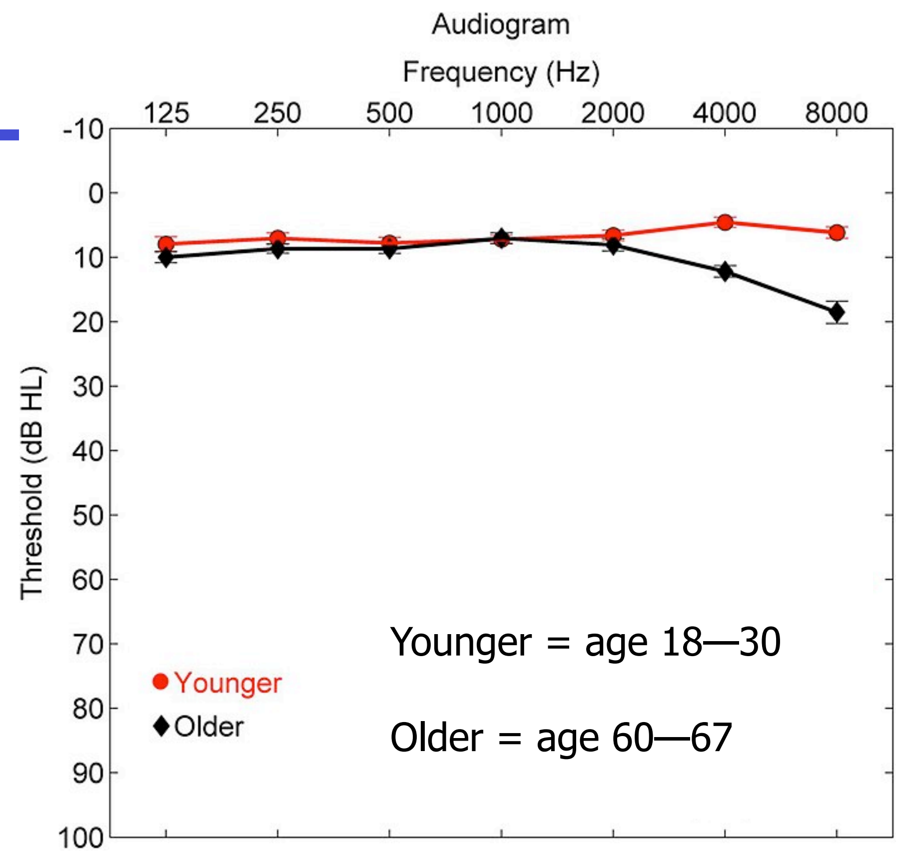
  - Threshold of hearing (avg person can just hear) $I_0 = 10^{-12}\ \mathrm{W/m^2} = 10^{-16}\ \mathrm{W/cm^2}$
  - Threshold of pain (avg person can't stand it!) $I_P = 10^{13} I_0$
  - Our ears handle 13 orders of magnitude!

Note: I_0 and p_0 values are for sound in air – different reference values for water

Thresholds

- Threshold of hearing = quietest sound a young human with undamaged hearing can detect at 1 kHz
  - Varies with frequency →
- Threshold of pain: how to define?

WW-II researchers told subjects *"You will hear a tone which will get louder and louder. Tell me when you reach the point where you feel a sharp pain deep in the ear. Be alert only for the pain sensation. When the pain point is reached, say 'pain' and I will shut off the tone. Are you ready?"*



→ Result: about 138 dB for "normal hearing", but 135 for "Hard-of-hearing" !

"hard-of-hearing have difficulty detecting softer sounds, but louder sounds are still perceived as being loud."

Decibel levels for sound **intensity** and sound **pressure**

Sound Sources Examples with distance	Sound Pressure Level L_p dBSPL	Sound Pressure p $N/m^2 = Pa$	Sound Intensity I W/m^2
Jet aircraft, 50 m away	140	200	100
Threshold of pain	130	63.2	10
Threshold of discomfort	120	20	1
Chainsaw, 1 m distance	110	6.3	0.1
Disco, 1 m from speaker	100	2	0.01
Diesel truck, 10 m away	90	0.63	0.001
Kerbside of busy road, 5 m	80	0.2	0.0001
Vacuum cleaner, distance 1 m	70	0.063	0.00001
Conversational speech, 1 m	60	0.02	0.000001
Average home	50	0.0063	0.0000001
Quiet library	40	0.002	0.00000001
Quiet bedroom at night	30	0.00063	0.000000001
Background in TV studio	20	0.0002	0.0000000001
Rustling leaves in the distance	10	0.000063	0.00000000001
Threshold of hearing	0	0.00002	0.000000000001

20 dB

10 dB

http://www.sengpielaudio.com/TableOfSoundPressureLevels.htm

Factor of 10 increase in **intensity** = **addition** of 10 to dB level

Factor of 10 increase in **pressure** = **addition** of 20 to dB level

Examples and applications

- One person talking to another produces, at 1m distance, $I_1 = 10^{-6} W/m^2$

How far away can you be and still (just barely) hear her words?

To hear and understand, assume sound intensity must be : $I_X = 10^{-10} W/m^2$

20 dB

$$\frac{I_X}{I_1} = \frac{(1m)^2}{x^2} \quad \rightarrow \quad x = 1m\sqrt{\frac{I_1}{I_X}} = 1m\sqrt{\frac{10^{-6} W/m^2}{10^{-10} W/m^2}} = 100m$$

Seems like too long a distance! What's wrong?

This assumes there is no background noise to cover the whispery sound level at 100 m - i.e., you must be in a soundproof, totally silent room!

(in practical terms: total silence = background noise must be below the threshold of hearing) $I_1 = 10^{-12} W/m^2$,

Exercise for you: suppose background noise intensity is $I_{BG} = 10^{-8}\ W/m^2$

So we would need voice intensity to be larger, say: $I_X = 10^{-7}\ W/m^2$

Now how close would you have to be?

Sound *perception*

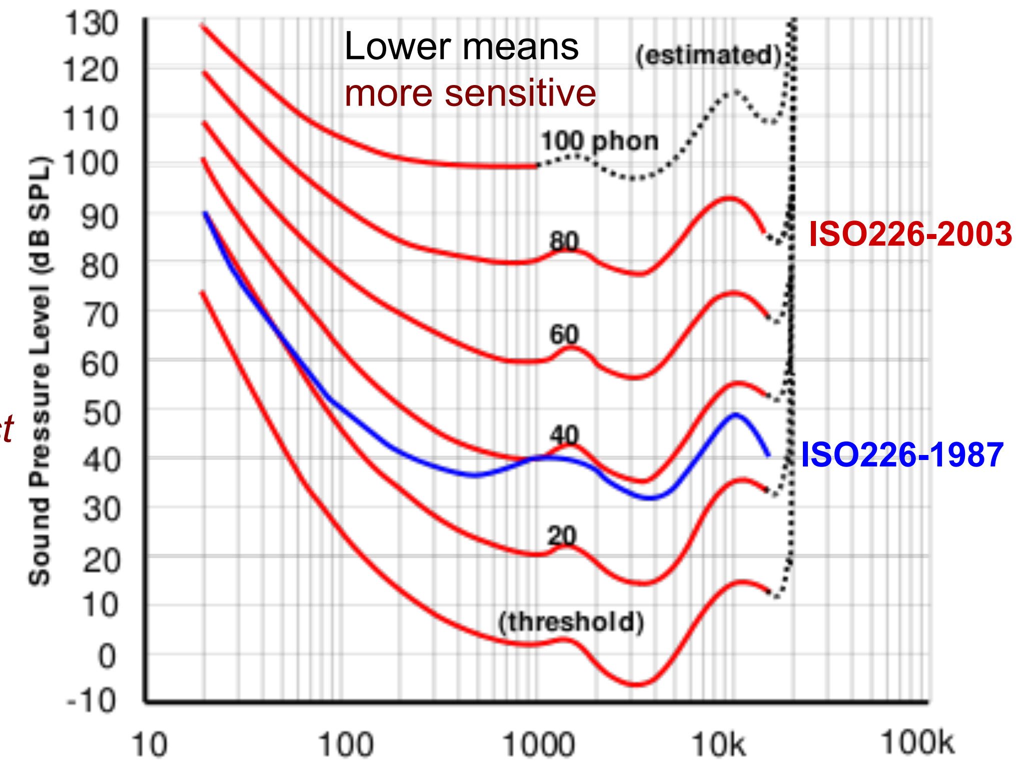
- Loudness = perceived intensity → "logarithmic" human perception
  - If we think one sound is twice as loud as another, it probably has 10X higher intensity
    - Similar logarithmic-scale perception for light intensities, and similar frequency-dependent sensitivity spectrum for eyes
  - Define unit of loudness: **phon**:

Measure dB vs frequency for perceived loudness levels for average person (surveys with many subjects)

International standard (ISO226) is subject to occasional updates - last revision was 2003, but "reviewed and confirmed" in 2014

Lines show dB levels corresponding to perceived equal loudness vs frequency.

0 phon = 0 dB at 1000 Hz

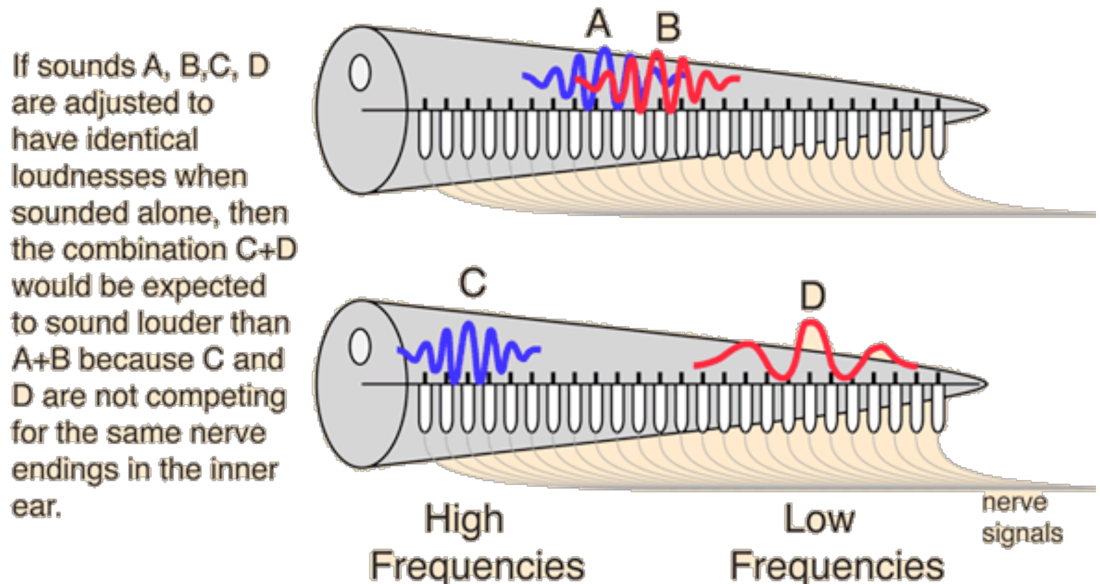


Equal-loudness contours (red) (from ISO 226:2003 revision)
Original ISO standard shown (blue) for 40-phons

Loudness and the cochlea

- Assumption: perceived loudness doubles for every 10 phon increase in sound loudness level = X10 increase in intensity
  - Only applies when adding loudness for same-f sounds
    - "same f" = within critical bandwidth (last time)
  - Two sounds with equal intensity but far apart in f may just double perceived loudness: intensity X2 but loudness X2 also
    - Do not use the same nerve endings on the basilar membrane of the inner ear – pulse rates from nerves do not reach max rate and saturate

Recall place theory of hearing: position along cochlea ~ corresponds to f → log loudness perception when nerves reach max firing rate Hz rate and response weakens



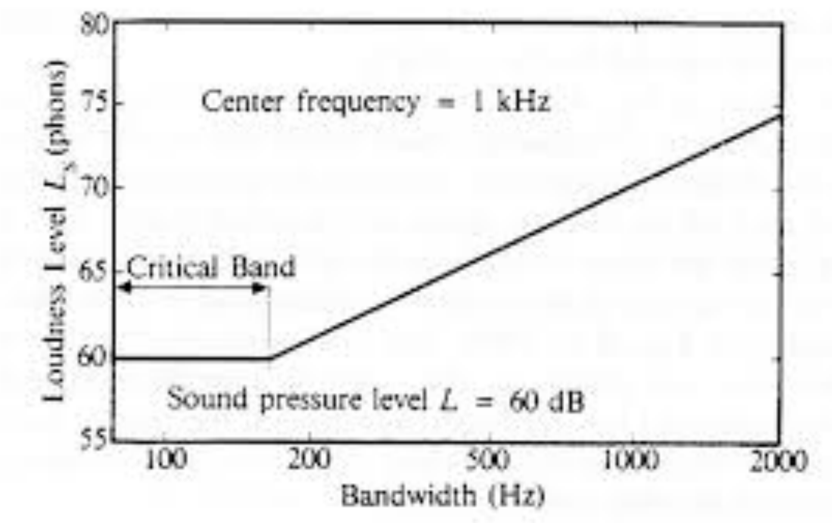
http://hyperphysics.phy-astr.gsu.edu

Last time

Critical bandwidth and the cochlea

- Critical band = Δf within which a second tone interferes with perception of the first tone
- One way of observing:
  - Increase bandwidth of a *noise* signal while decreasing amplitude to keep power constant.
  - When Δf is greater than CB, subjective stimulus covers >1 auditory CB

    → perceived loudness increases



Standard audiometric critical bands

CB rate	Center frequency	Frequency	CB bandwidth
Bark	*Hz*	*Hz*	*Hz*
0	50	20	80
1	150	100	100
2	250	200	100
3	350	300	100
4	450	400	110
5	570	510	120
6	700	630	140
7	840	770	150
8	1000	920	160
9	1170	1080	190
10	1370	1270	210
11	1600	1480	240
12	1850	1720	280
13	2150	2000	320
14	2500	2320	380

Critical bands have
Δf ~ constant below 500 Hz :
Compare to Békésy map of cochlea location vs frequency

Loudness in sones

- Alternate loudness unit: **sone** – additive scale
  - Human subjects judge what sounds twice as loud as a sample tone → define scale representing subjective loudness doubling
  - Sone scale is “linear”, not log: 2X loudness → 2X sone level
    - Perceived doubling of loudness ~ 10 dB increase in sound level
    - Apply same factor to phon scale: 10 phon increase → 2X sones

Set 1 sone = 40 phons → 0.5 sone = 30 phon; 2 sones = 50 phon, 4 sones = 60 phon, etc.

Dynamic Level	Decibels at C_6(1024 Hz)	Multiple of Threshold	Phons	Sones
Threshold of pain	120	10^{12}	120	256
fff	100	10^{10}	100	64
f(orte)	80	10^{8}	80	16
p(iano)	60	10^{6}	60	4
ppp	40	10^{4}	40	1
Threshold of hearing	0	1	0	…

Spectrum levels

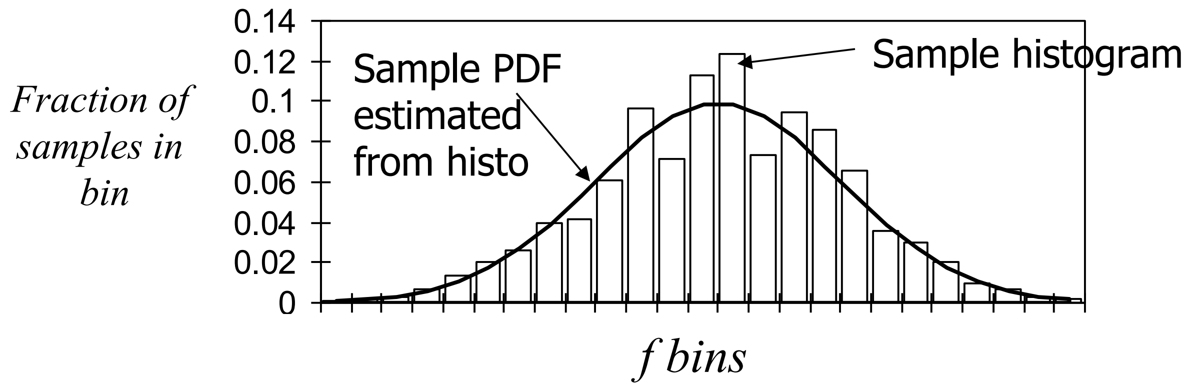
- To describe sound spectrum of a source, we need to specify intensity at each frequency
  - What does that mean? Intensity level in a slice Δf at f :
    - Spectral density distribution

Another example of a probability density distribution – Recall:

- Sample of data can be displayed as a histogram

  Bar graph showing how often measured x falls in range $x_k \leq x < x_{k+1}$

- *Sample* PDF = *f(x)* = what we *estimate* from the data histogram
  - Sample PDF value at center of each bin ~ histogram bin contents/N_{TOTAL}
  - May differ from underlying PDF due to *limited statistics* (finite N_{TOTAL})



Density distributions

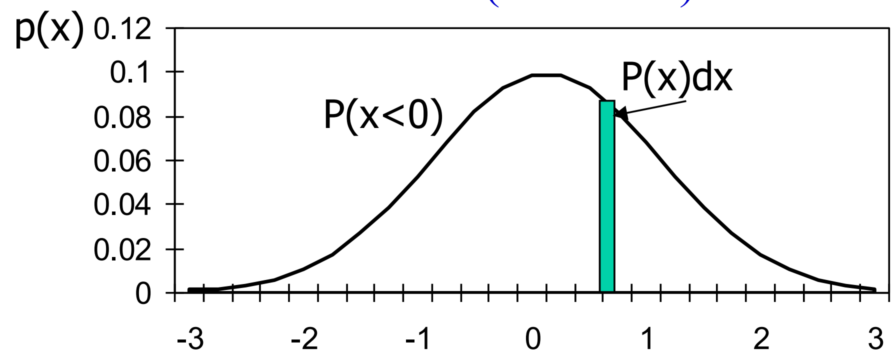
- Probability density p(x)=probability of x in range x' to x'+dx

  p(x) = continuous function

  Density, not a "probability"!

  Prob(x within Δx) = p(x)Δx

Normal (Gaussian) PDF



$$p(x) = \frac{1}{\sqrt{2\pi}} \exp(-\frac{x^2}{2})$$

- Apply to sound spectra:

$$\mathcal{I}(f) = \frac{\Delta I}{\Delta f} \quad \rightarrow \quad I(\Delta f) = \int_{f_1}^{f_2} \mathcal{I}(f)\,df$$

$$f_1 \leftrightarrow f_2 = \textit{frequency band}$$

note: $\mathcal{I} = \mathcal{I}(f,t) \rightarrow$ take $\mathcal{I}(f) = \left\langle \frac{\Delta I}{\Delta f} \right\rangle$, time average

- Choose 1 Hz as Δf: intensity *spectrum* level $ISL = 10\log\frac{\mathcal{I}(f)\cdot 1Hz}{I_0}$
- Intensity level is:

(From now on, assume "log" means log10)

$$IL = 10\log\frac{I}{I_0}$$ so if $\mathcal{I}(f)$ =constant over bandwidth $w = f_2 - f_1$

$$IL = 10\log \mathcal{I}(f)\cdot w \cdot 1Hz / I_0 = 10\log \mathcal{I}(f)\cdot 1Hz / I_0 + 10\log w[Hz] = ISL + 10\log w$$

Frequency dependent Intensity Spectrum Level

- If ISL is not constant over bandwidth of interest, typically we can use standard band/bandwidth definitions:

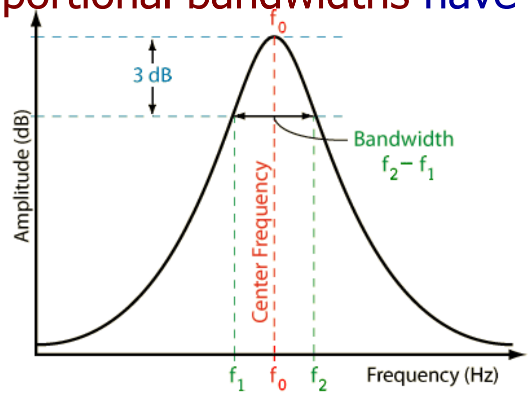
"Preferred proportional bands"

- Octave bands are used for slowly varying spectra; 1/3-octave bands or 1/10-octave, if needed
- Instruments used to measure band spectra may be "constant BW" or "proportional BW"
  - Constant BW: narrow-band filters, with center frequencies defined as geometric means of limits: $f_c = \sqrt{f_1 f_2}$

Octave band			1/3 octave band		
Lower Frequency f_1(Hz)	Center Frequency f_0(Hz)	Upper Frequency f_2(Hz)	Lower Frequency f_1(Hz)	Center Frequency f_0(Hz)	Upper Frequency f_2(Hz)
22	31.5	44	22.4	25	28.2
			28.2	31.5	35.5
			35.5	40	44.7
44	63	88	44.7	50	56.2
			56.2	63	70.8
			70.8	80	89.1
88	125	177	89.1	100	112
			112	125	141
			141	160	178
177	250	355	178	200	224
			224	250	282
			282	315	355
355	500	710	355	400	447
			447	500	562
			562	630	708
710	1000	1420	708	800	891
			891	1000	1122
			1122	1250	1413

Proportional bands

- Instruments to measure sound levels using proportional bandwidths have upper and lower half-power (3 dB) f's so that



$$f_2 / f_1 = constant:$$
$$f_2 / f_1 = 2: \text{ octave band,}$$
$$f_2 / f_1 = 2^{1/3} = 1.26: \text{ 1/3 octave}$$
$$f_2 / f_1 = 2^{1/10} = 1.07: \text{ 1/10 octave}$$

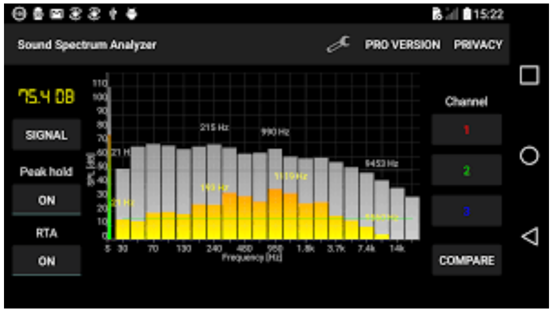
For sound levels in air, with intensity and pressure levels compatible, the pressure spectrum level **PSL** is defined as power per hertz of a sound

Connection to SPL: $SPL = PSL + 10\log w, \quad w = bandwidth, Hz$

- Typically, get PSL from SPL measured using filter of bandwidth w (not necessarily any preferred band definition): $PSL = SPL - 10\log w$
  - "smoothed" level estimate

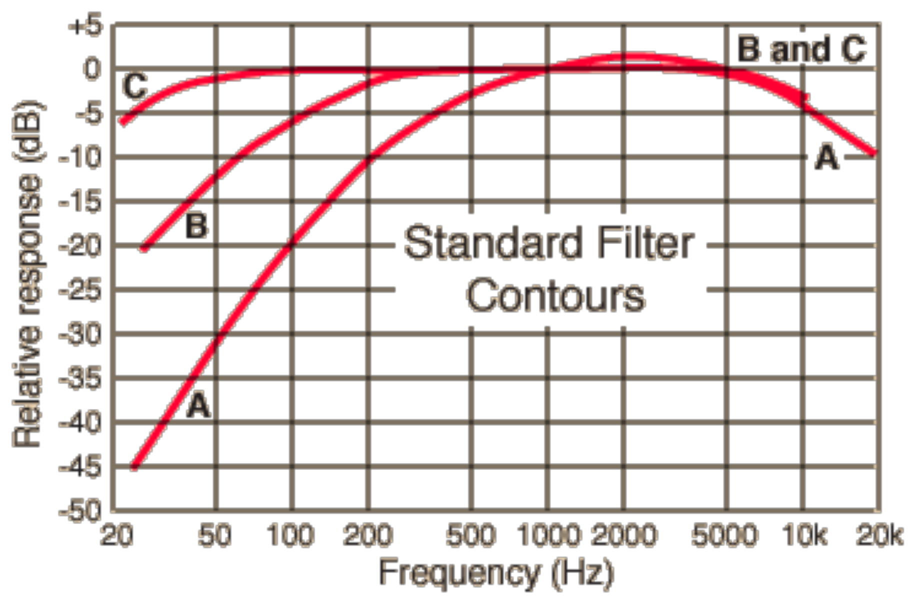
Digital instruments typically provide both dB meter and spectrum analyzer functions

www.nti-audio.com/en/products/sound-level-meters



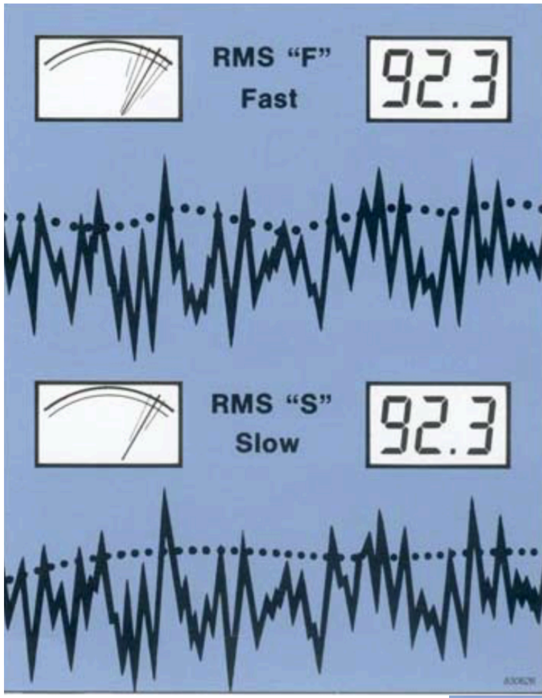
Filters for sound level measurements

- For noise measurements, standard filters are applied to shape the sensitivity spectrum of the dB meter
- Most commonly-used standard profiles are
  - "A" scale – sensitivity follows inverse of the 40 db @ 1 kHz loudness curve = human hearing at moderate levels → dBA
  - "C" scale – flat sensitivity over ~100 Hz, used for objective dB (not loudness) measurements at high sound levels (eg aircraft noise) → dBC
  - "B" scale is rarely used, often not implemented on dB meters
    - Approximates human hearing sensitivity at higher sound levels



Some material from engineering.iastate.edu/~leeuwen/CE524/, J (Hans) van Leeuwen

Sound measurements: dB meters



In addition to spectrum filters A and C, standard dB meters have response speed options:

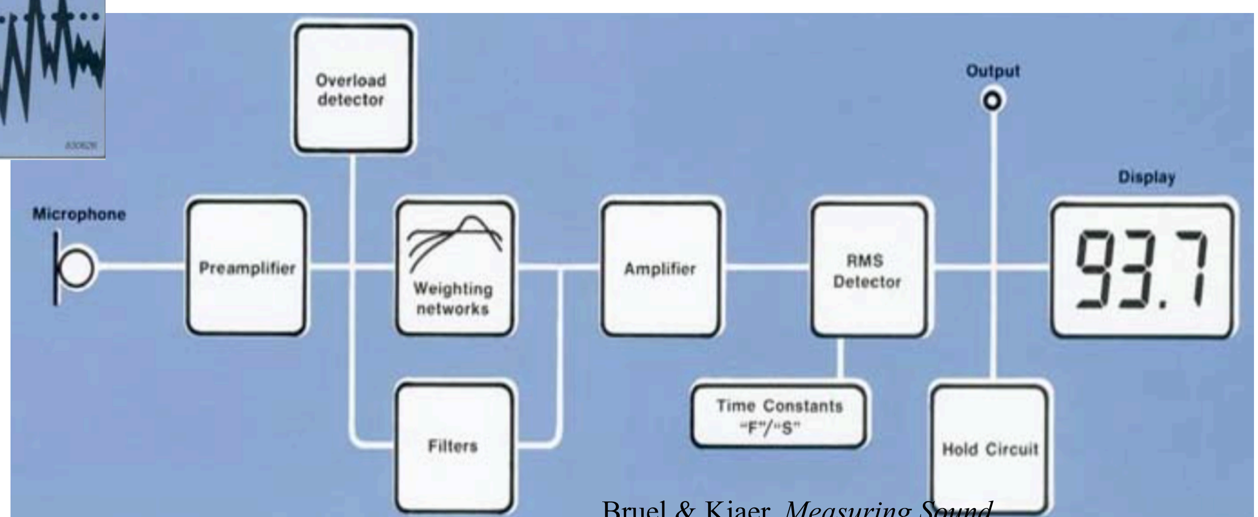
Fast = integrates over 125 ms

(for rapidly varying sound)

Slow = time constant 1 sec

(smooths over fluctuations)

B&J 732A Sound Level meter



Bruel & Kjaer, *Measuring Sound*

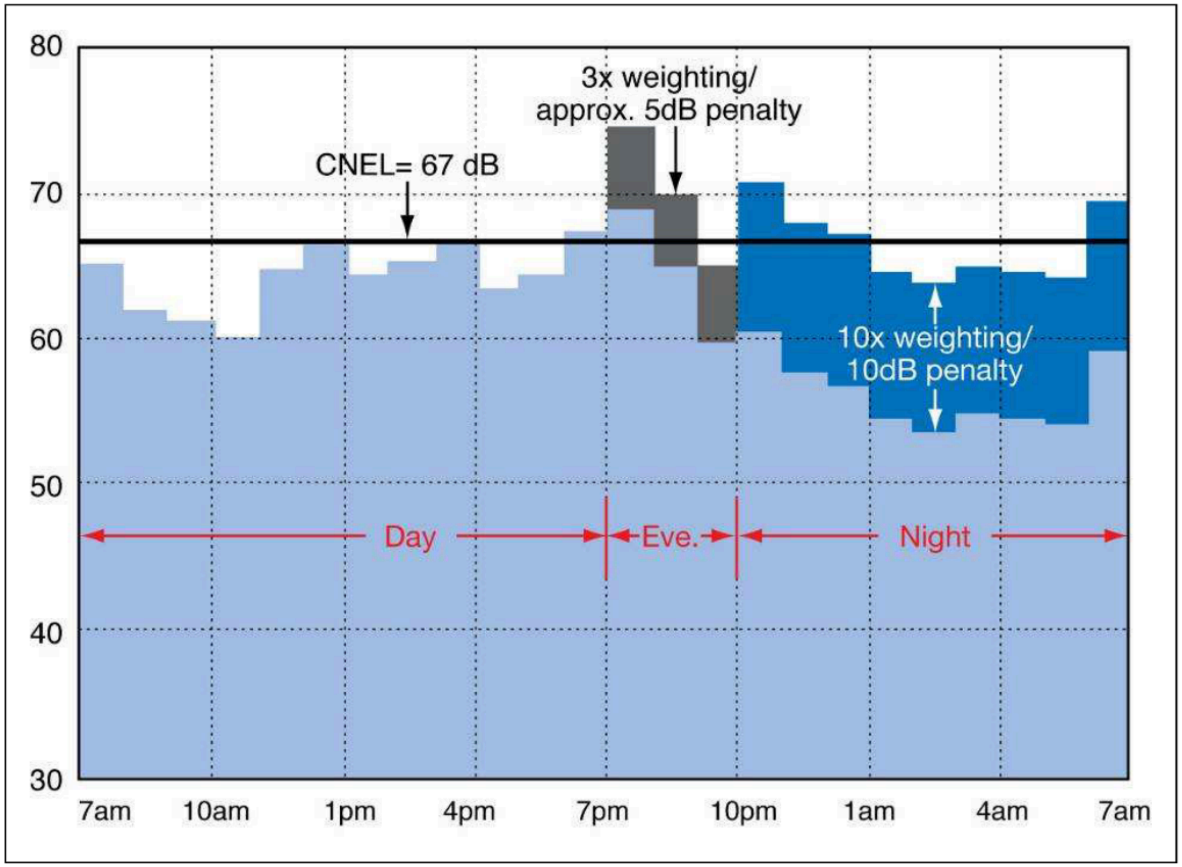
Typically used sound level statistics

- **Equivalent** sound level L_{eq} = constant L that provides same total acoustical energy as a time-varying sound level integrated over a given time period.
- **Percentile** sound level L_x = SPL exceeded by x percent of samples during the observation time interval

  eg, L_{50} = median SPL observed
- **Day-night average** sound level L_{DN} = L_{eq} calculated over a 24-h period, with penalty decibels added during night hours (10 pm – 7 am), to overweight impact of nighttime noise
- **Sound Exposure** Level SEL = constant SPL acting for 1 s that delivers the same amount of acoustic energy as the actual sound.
  - SEL typically used for the noise energy of a single event, eg, aircraft flying over. As
  - All SEL measurements are based on 1 s interval → energy content of different types of events can be compared

Another statistic: CNEL vs L_{DN}

- Variant on day-night: CNEL (Community Noise Equivalent Level)
  - Includes "evening" (7 pm – 10 pm) period where noise events are weighted by a factor of three → +4.77 dB penalty.



California Division of Aeronautics noise standards

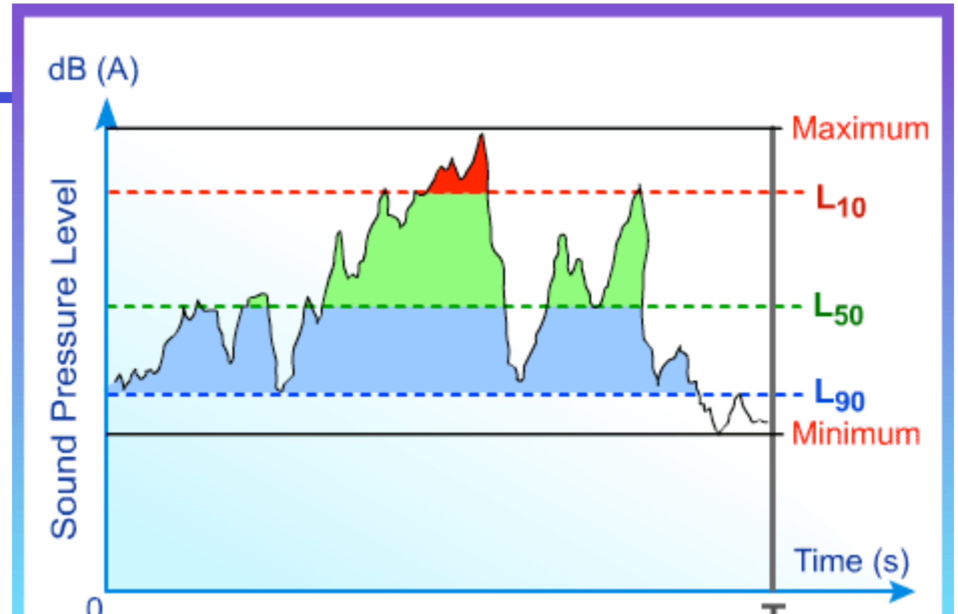
L_x noise statistics

- Reporting various L_x statistics:

L_{90} = SPL exceeded 90% of the time during sample

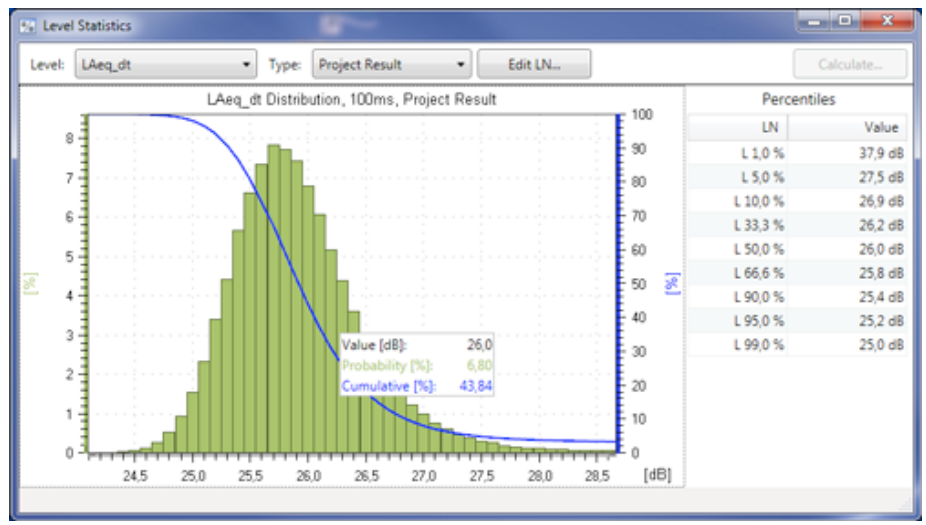
L_{10} = SPL exceeded 10% of the time

(So L_{10} = median)



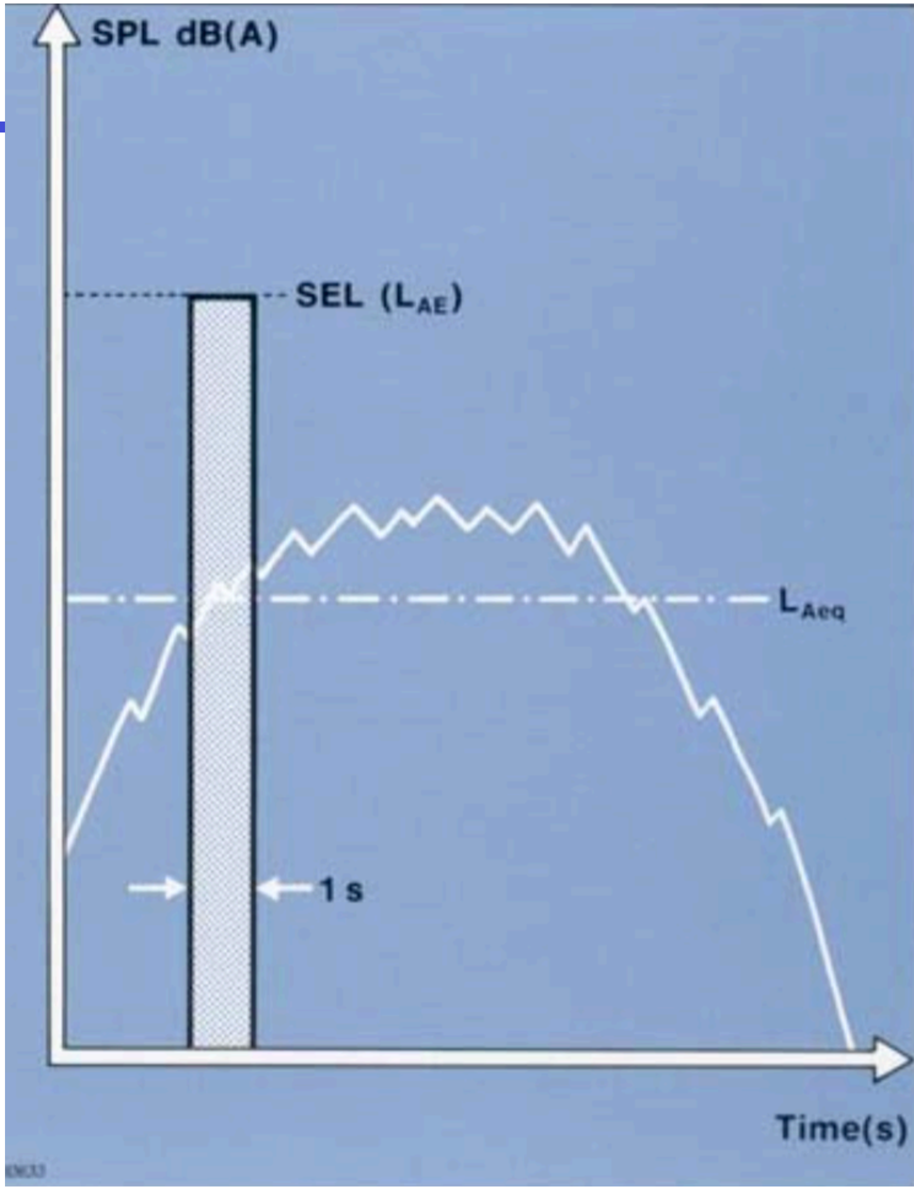
pulsarinstruments.com

- sound meter provides handy integral distribution



www.nti-audio.com/en/support

SEL vs L_{EQ}



- L_{EQ} gives an idea of the "average" SPL, calculated in a physically meaningful way (energy delivered)
- SEL gives a single statistic that can be compared between different situations, regardless of time span or fluctuations

- SEL can be related to L_{EQ} :

$$L_{EQ}(T) = SEL - 10\log\left[\frac{T}{1s}\right]$$

To find combined SEL for multiple events:

$$L_{EQ}(T) = 10\log\sum_{i=1}^{N}10^{SEL/10} - 10\log\left[\frac{T}{1s}\right]$$

Bruel & Kjaer, *Measuring Sound*

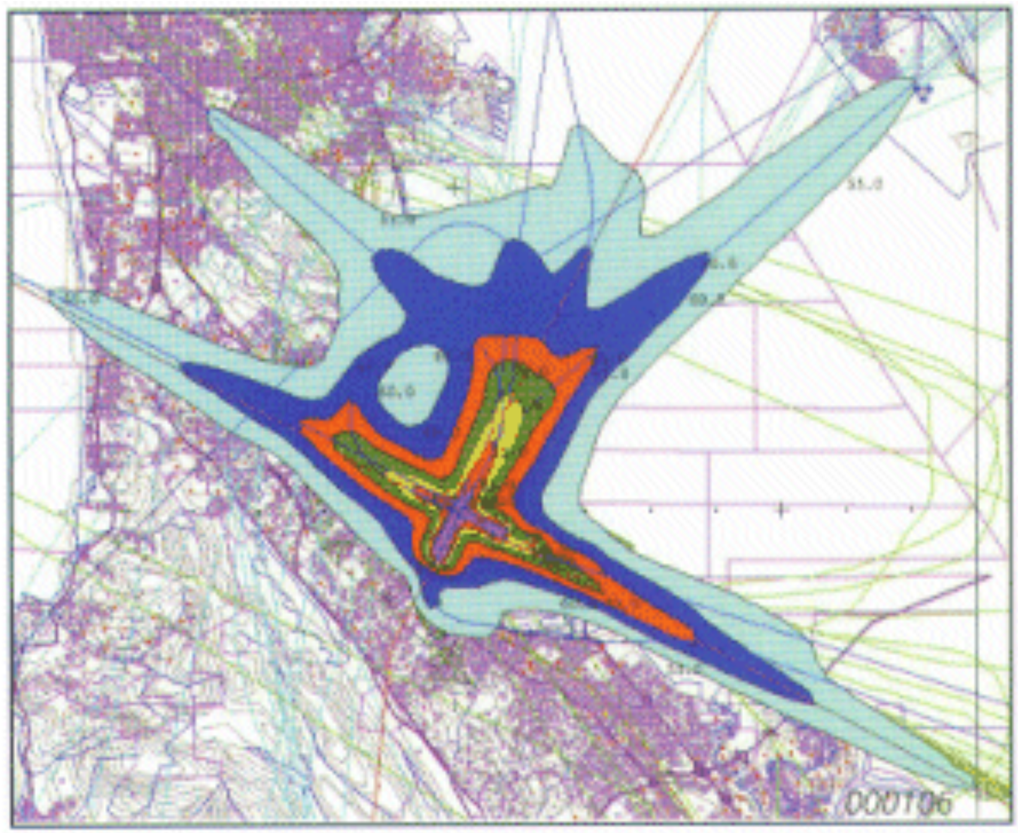
Example: combining events with SEL → L_{EQ}

- Repeating noise (eg, machine that turns on and off) appears 400 times in 8 hr; each episode has SEL=105 dBA
- Find L_{EQ} for this period

$$
\begin{aligned}
L_{EQ}(T) &= 10\log\sum_{i=1}^{N}10^{SEL/10} - 10\log\left[\frac{T}{1s}\right] \\
&= 10\log\left[400\cdot 10^{105/10}\right] - 10\log\left[\frac{8\cdot 3600s}{1s}\right] \\
&= 10\left[\log 400 + 105/10\right] - 10\log\left[28800\right] \\
&= 26 + 105 - 44.6 \\
&= 86.4 \quad \text{dBA}
\end{aligned}
$$

Aircraft Noise

- Airports are a major community noise impact
  - Aircraft are loud, high-pitched
  - Heavy ground traffic nearby



From *Environmental Noise*, Brüel & Kjær Sound & Vibration Measurement A/S, 2001

Map shows noise contours around an airport calculated by model software tuned with actual noise measurements

55 - 60 dB = Light blue
60 - 70 dB = Dark blue
70 - 75 dB = Red
75 - 80 dB = Green
80 - 85 dB = Yellow
> 85 dB = Pink

Highway traffic noise

Noise sources

Highway traffic = "line source" of noise (compared to "point sources" like a machines)

- Noise level depends on traffic volume, vehicle type, and speed
- Regulations limit the amount of noise from some vehicle types (trucks, cars, motorcycles) can produce -- but
  - → Noise levels typically reduced only 5 to 10 dBA since regulations were imposed

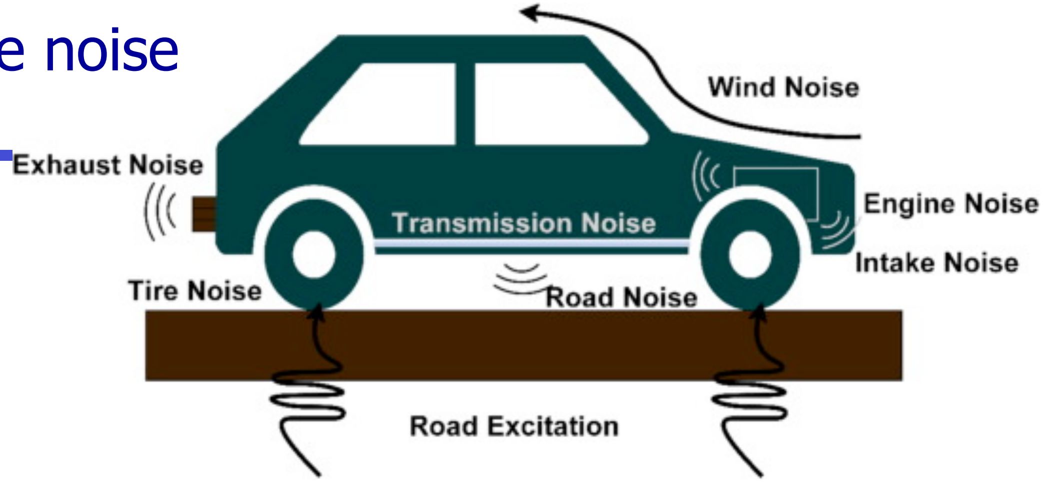
Noise barriers

Reduce community noise by surrounding highway with:

- Buffer zones
- Earth berms/wooden fences/concrete walls
- Dense vegetation (trees are ineffective – too sparse)
- Sound-absorbing pavement (asphalt vs concrete)

Concrete noise wall - www.fhwa.dot.gov

Sources of vehicle noise

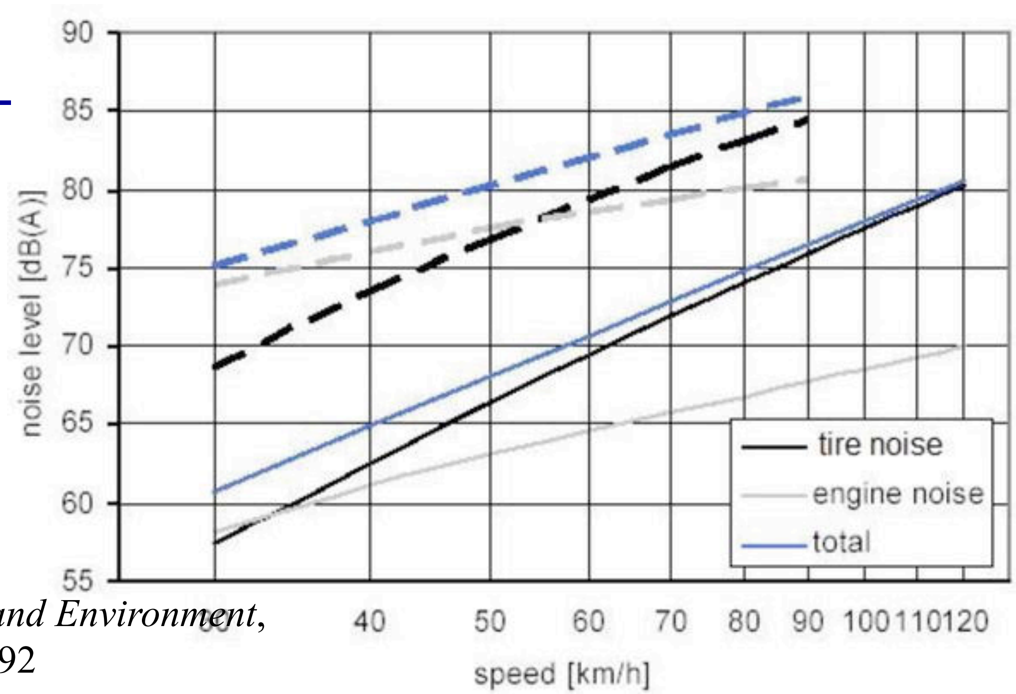


Applied Acoustics163:107212, 2020

Noise comes from

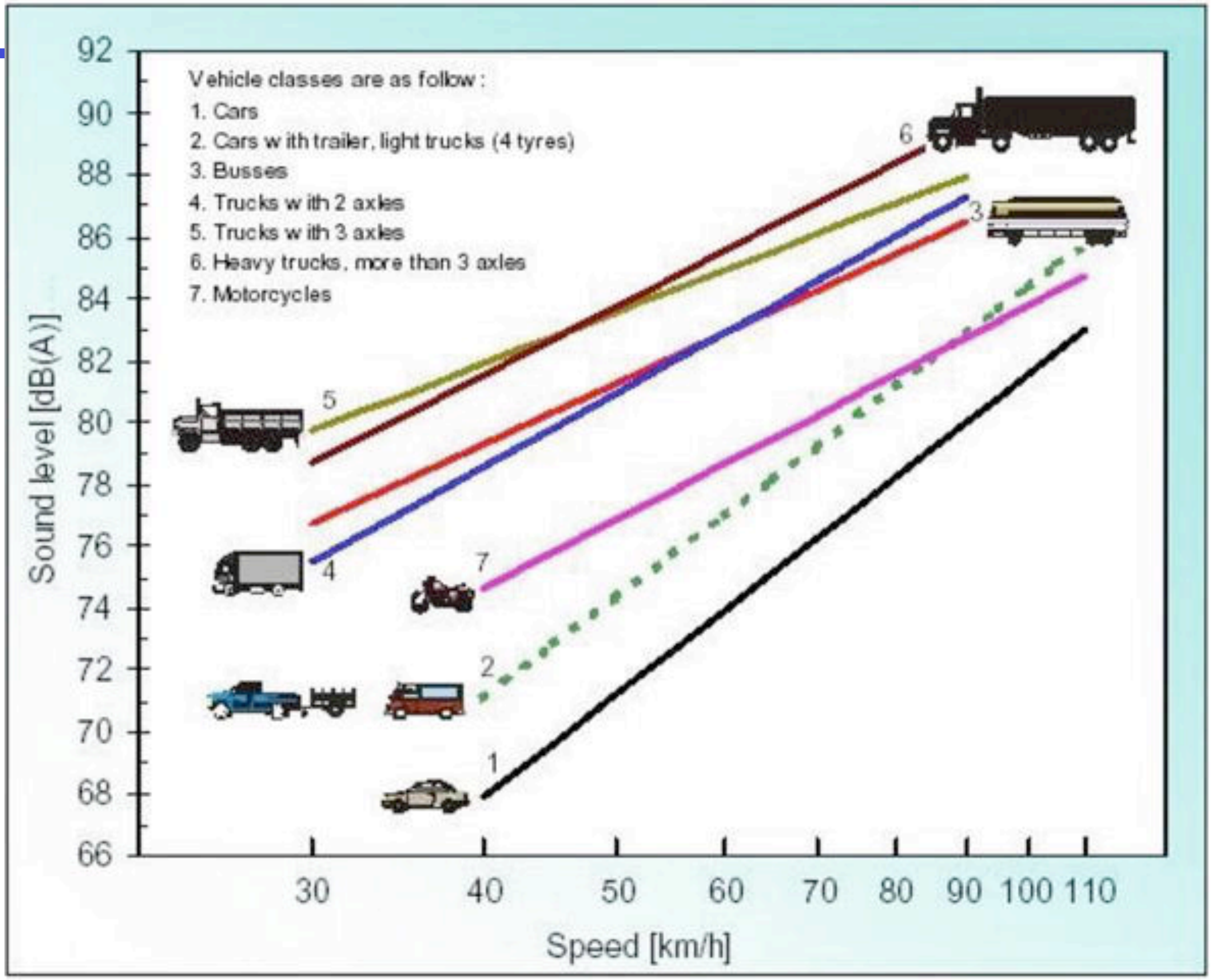
- Engines
- Tires
- Air flow
- Exhaust pipe

- All factors are speed-dependent



S. Grubesa and M. Suhanek, *Noise and Environment*, 2020, DOI: 10.5772/intechopen.92892

Vehicle type → height and slope of SPL vs speed



S. Grubesa and M. Suhanek, *Noise and Environment*, 2020, DOI: 10.5772/intechopen.92892

Highway noise criteria

- Noise abatement criteria from Federal Highway Administration (FHWA): allowed levels of Leq depend on land use:

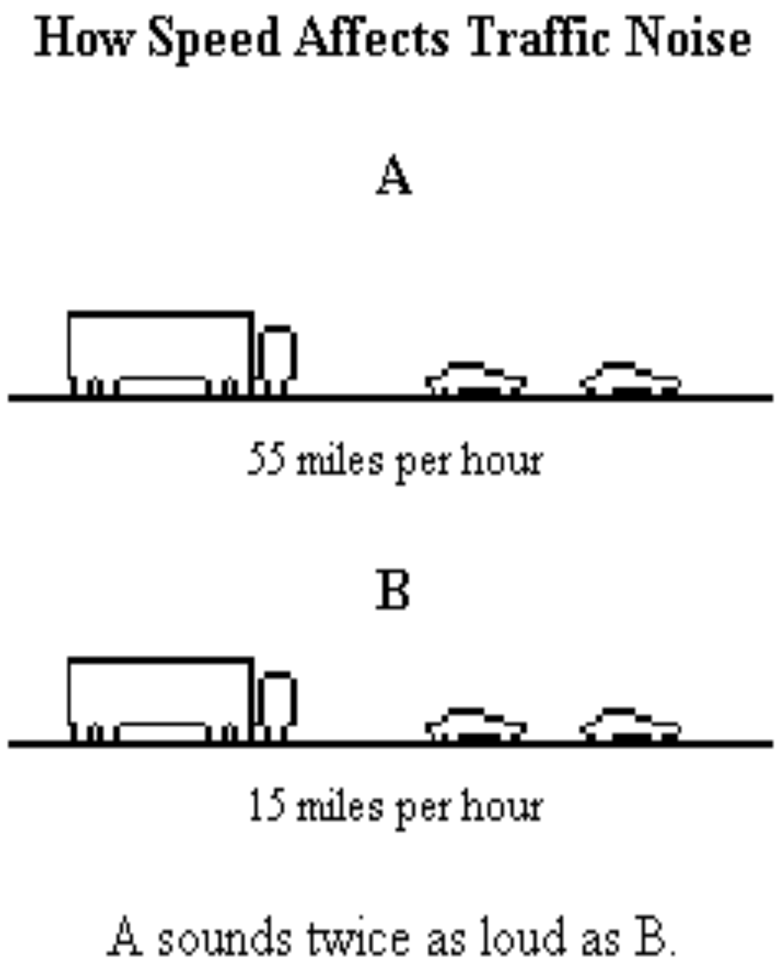
Table 1. FHWA Noise Abatement Criteria in dBA (hourly A-weighted sound level).

Activity Category	NAC, $L_{eq}(h)$	Description of Activity Category
A	57 (Exterior)	Lands on which serenity and quiet are of extraordinary significance and serve an important public need and where the preservation of those qualities is essential if the area is to continue to serve its intended purpose.
B	67 (Exterior)	Picnic areas, recreation areas, playgrounds, active sports areas, parks, residences, motels, hotels, schools, churches, libraries, and hospitals.
C	72 (Exterior)	Developed lands, properties, or activities not included in Categories A or B above.
D	--	Undeveloped lands.
E	52 (Interior)	Residences, motels, hotels, public meeting rooms, schools, churches libraries, hospitals, and auditoriums.

NOTE: These sound levels are only to be used to determine impact. These are the absolute levels where abatement must be considered. Noise abatement should be designed to achieve a substantial noise reduction - not the noise abatement criteria.

www.fhwa.dot.gov

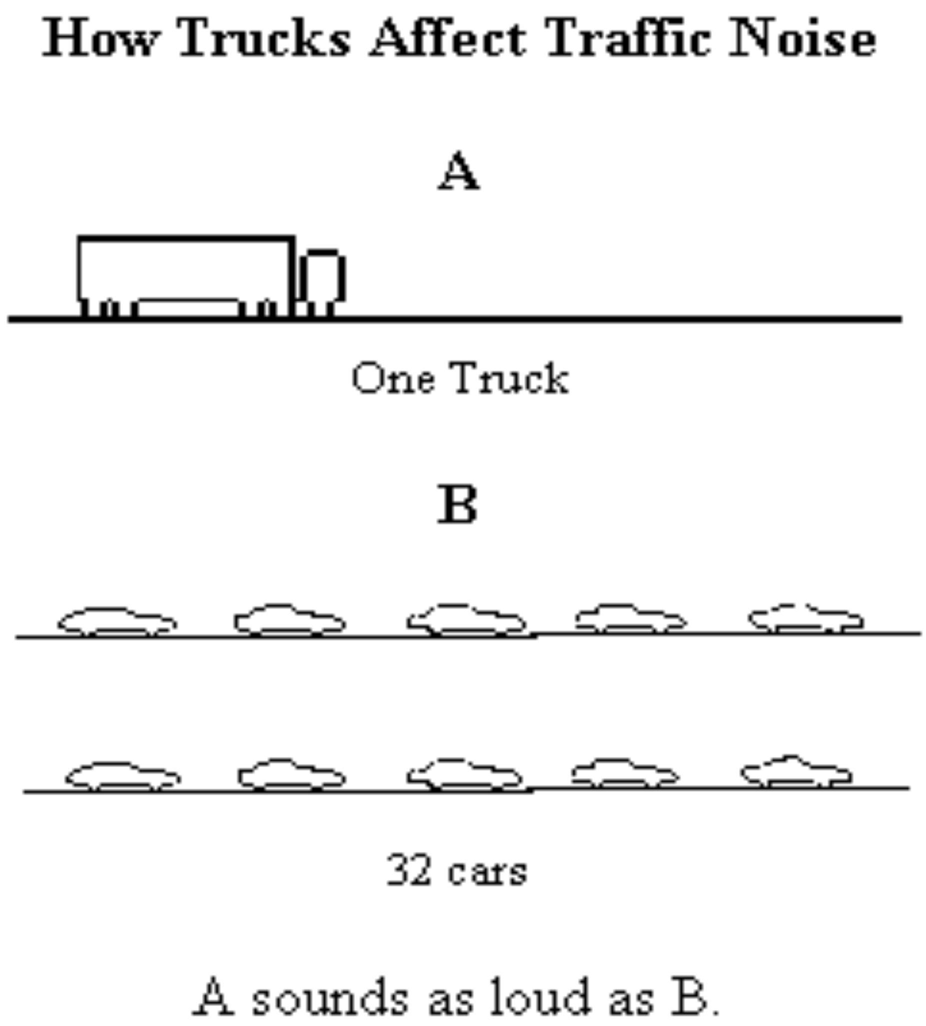
Source factors affecting received noise



10 phon increase
2X sones

http://www.nonoise.org/library/highway/traffic/traffic.htm

Source factors affecting received noise



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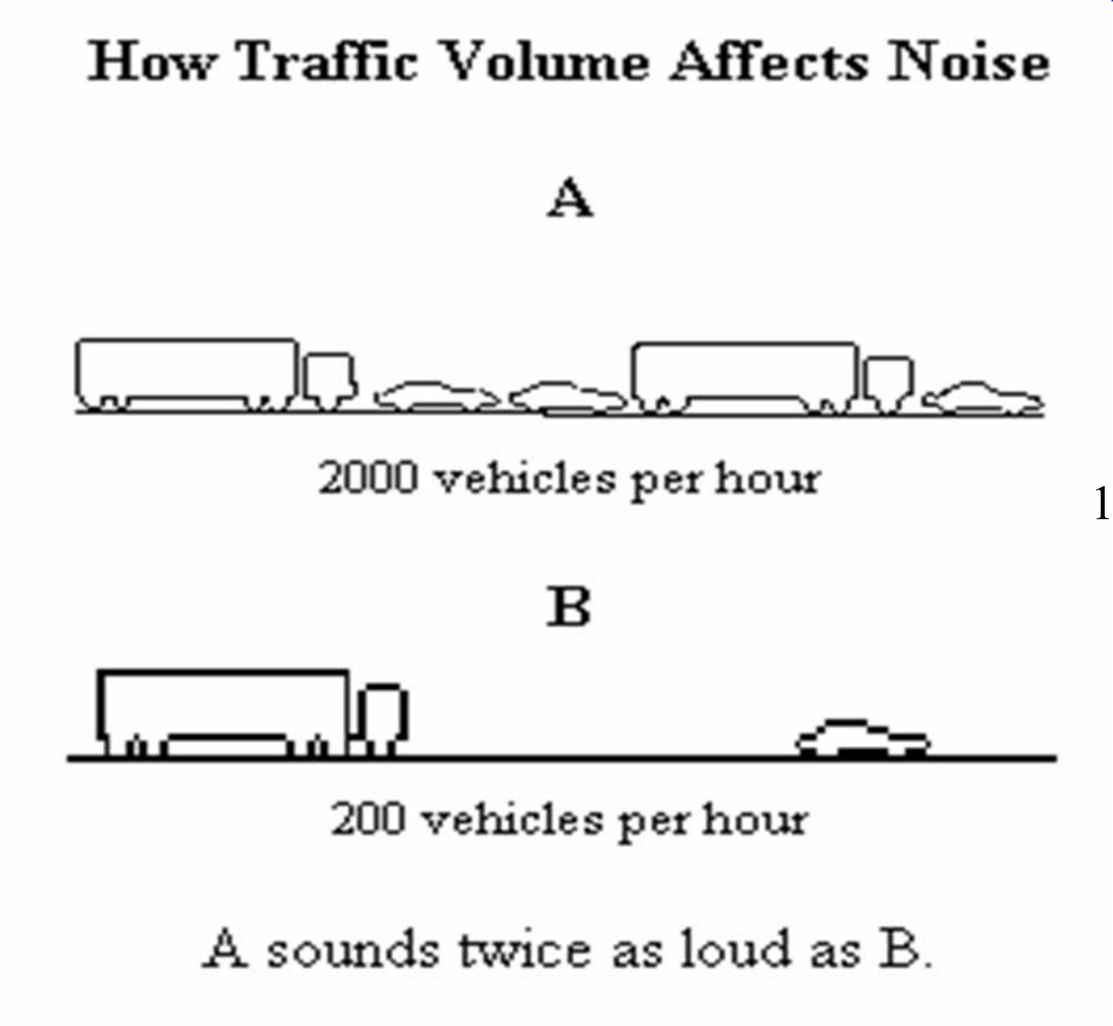
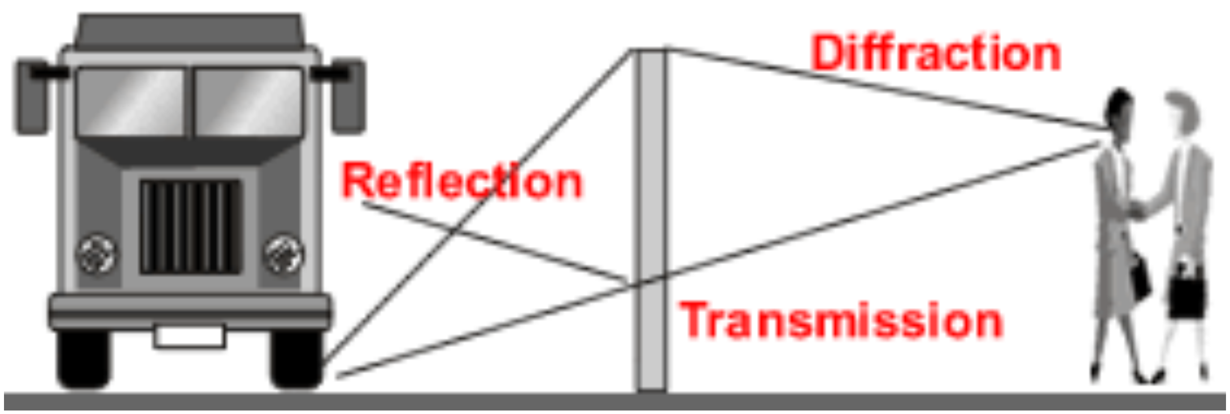
Source factors affecting received noise



10 phon increase
2X sones

Miigation: Noise Barriers

- Walls are commonly used to abate highway noise
- Sound is absorbed by the wall
  - but also reflected and diffracted over the top of the wall!
- Height required to get really significant abatement may be considered “too big” by residents, or “too expensive” by local authorities



Source:http://www.urbislighting.com/uap1.html

Mitigation: Building walls as absorbers

Table 6 Approximate reduction of outside noise provided by typical exterior wall construction

Octave Band Center Frequency (Hz)	A	B	C	D	E	F	G	H
63	0	9	13	19	14	24	32	21
125	0	10	14	20	20	25	34	25
250	0	11	15	22	26	27	36	30
500	0	12	16	24	28	30	38	37
1,000	0	13	17	26	29	33	42	42
2,000	0	14	18	28	30	38	48	44
4,000	0	15	19	30	31	43	53	45
8,000	0	16	20	30	33	48	58	46
approx. dB(A)	0	12	16	24	27	30	38	33

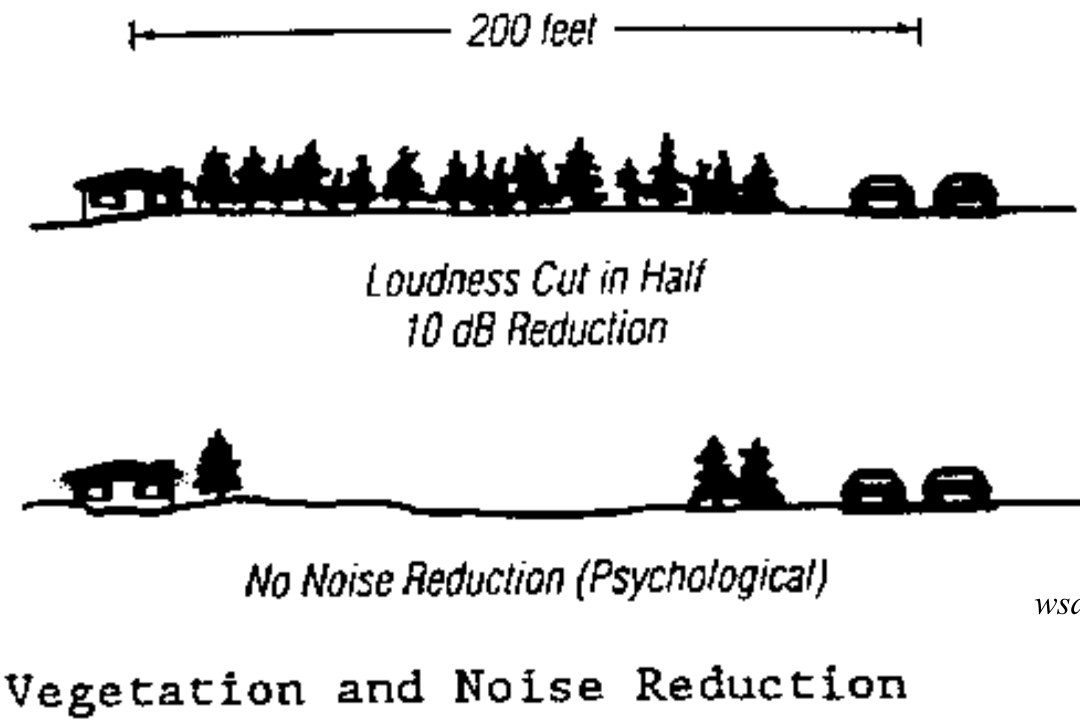
A: No wall; outside conditions.
B: Any typical wall construction, with open windows covering about 5% of exterior wall area.
C: Any typical wall construction, with small open air vents of about 1% of exterior wall area, all windows closed.
D: Any typical wall construction, with closed but operable windows covering about 10-20% of exterior wall area.
E: Sealed glass wall construction, 1/4-in glass thickness over approximately 50% of exterior wall area.
F: Approximately 20 lb./ft^2 solid wall construction with no windows and no cracks or openings.
G: Approximately 50 lb/ft^2 solid wall construction with no windows and no cracks or openings.
H: Any typical wall construction, with closed double windows (panes at least 3/32" thick, air space at least 4 in.) and solid-core gasketed exterior doors.

Table 7: Building Noise Reduction Factors

Building Type	Window Condition	
All	Open	10 dB
Light Frame	Ordinary Sash (closed)	20 dB
	Storm Windows	25 dB
Masonry	Single Glazed	25 dB
Masonry	Double Glazed	35 dB

Green noise Barriers

Vegetation can abate highway noise, but:
Sound is significantly absorbed only by a thick zone of dense vegetation (eg, shrubs, not tall trees)



http://www.nonoise.org/library/highway/traffic/traffic.htm

"It would take at least 100 feet of dense vegetation to provide the same benefit as our smallest feasible noise wall...
The FHWA has not approved using vegetation for noise abatement."

wsdot.wa.gov/construction-planning