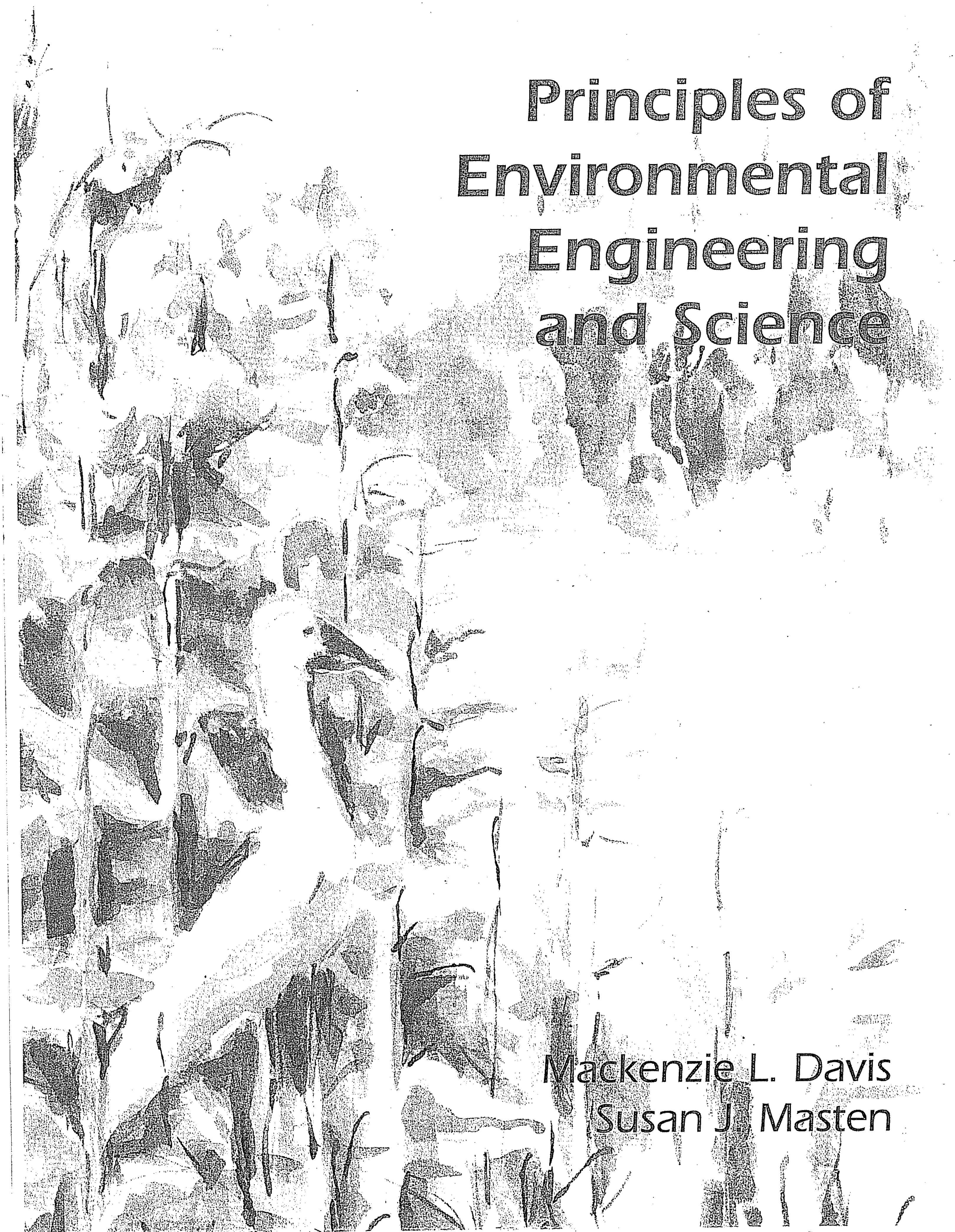

Principles of Environmental Engineering and Science

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15–1 INTRODUCTION

Noise, commonly defined as unwanted sound, is an environmental phenomenon to which we ar exposed before birth and throughout life. Noise can also be considered an environmental pollu tant, a waste product generated in conjunction with various anthropogenic activities. Under th latter definition, noise is any sound—independent of loudness—that can produce an undesire physiological or psychological effect in an individual and that may interfere with the social end of an individual or group. These social ends include all of our activities—communication, work rest, recreation, and sleep.

As waste products of our way of life, we produce two general types of pollutants. The genera public has become well aware of the first type—the mass residuals associated with air and wate pollution—that remain in the environment for extended periods. However, only recently has atten tion been focused on the second general type of pollution, the energy residuals such as the wast heat from manufacturing processes that creates thermal pollution of our streams. Energy in the forr of sound waves constitutes yet another kind of energy residual, but, fortunately, one that does nc remain in the environment for a long time. The total amount of energy dissipated as sound through out the earth is not large compared with other forms of energy; it is only the extraordinary sensitiv ity of the ear that permits such a relatively small amount of energy to adversely affect us.

It has long been known that noise of sufficient intensity and duration can induce temporar or permanent hearing loss, ranging from slight impairment to nearly total deafness. In general, pattern of exposure to any source of sound that produces high enough levels can result in tempc rary hearing loss. Exposure persisting over time can lead to permanent hearing impairment. It ha been estimated that 1.7 million workers in the United States between 50 and 59 years of age hav enough hearing loss to be awarded compensation. The potential cost to industry could be in ex cess of $1 billion. Short-term, but frequently serious, effects include interference with speec communication and the perception of other auditory signals, disturbance of sleep and relaxatior annoyance, interference with an individual's ability to perform complicated tasks, and genera diminution of the quality of life.

Beginning with the technological expansion of the Industrial Revolution and continuin through a post-World War II acceleration, environmental noise in the United States and othe industrialized nations has been gradually and steadily increasing, with more geographic area becoming exposed to significant levels of noise. Where once noise levels sufficient to induc some degree of hearing loss were confined to factories and occupational situations, noise level approaching such intensity and duration are today being recorded on city streets and, in som cases, in and around the home.

There are valid reasons why widespread recognition of noise as a significant environment pollutant and potential hazard or, as a minimum, a detractor from the quality of life, has bee slow in coming. In the first place, noise, if defined as unwanted sound, is a subjective experienc What is considered noise by one listener may be considered desirable by another.

Secondly, noise has a short decay time and thus does not remain in the environment fc long, as do air and water pollution. By the time the average individual is spurred to action t abate, control, or, at least, complain about sporadic environmental noise, the noise may no longer exist.

Thirdly, the physiological and psychological effects of noise on us are often subtle and insidious, appearing so gradually that it becomes difficult to associate cause with effect. Indeed, to those persons whose hearing may already have been affected by noise, it may not be considered a problem at all.

Furthermore, the typical citizen is proud of this nation's technological progress and is generally happy with the things that technology delivers, such as rapid transportation, labor-saving appliances, and new recreational devices. Unfortunately, many technological advances have been associated with increased environmental noise, and large segments of the population have tended to accept the additional noise as part of the price of progress.

The engineering and scientific community has already accumulated considerable knowledge concerning noise, its effects, and its abatement and control. In that regard, noise differs from most other environmental pollutants. Generally, the technology exists to control most indoor and outdoor noise. As a matter of fact, this is one instance in which knowledge of control techniques exceeds the knowledge of biological and physical effects of the pollutant.

Properties of Sound Waves

Sound waves result from the vibration of solid objects or the separation of fluids as they pass over, around, or through holes in solid objects. The vibration or separation causes the surrounding air to undergo alternating compression and rarefaction, much in the same manner as a piston vibrating in a tube (Figure 15–1). The compression of the air molecules causes a local increase in air density and pressure. Conversely, the rarefaction causes a local decrease in density and pressure. These alternating pressure changes are the sound detected by the human ear.

Let us assume that you could stand at point A in Figure 15–1. Also let us assume that you have an instrument that will measure the air pressure every 0.000010 s and plot the value on a graph. If the piston vibrates at a constant rate, the condensations and rarefactions will move down the tube at a constant speed. That speed is the speed of sound (c). The rise and fall of pressure at point A will follow a cyclic or wave pattern over a period (Figure 15–2). The wave pattern is called sinusoidal.

FIGURE 15–1

Alternating compression and rarefaction of air molecules resulting from a vibrating piston.

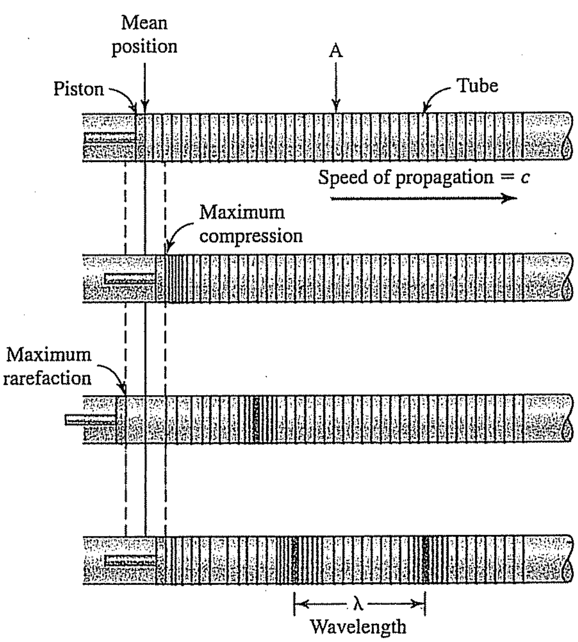
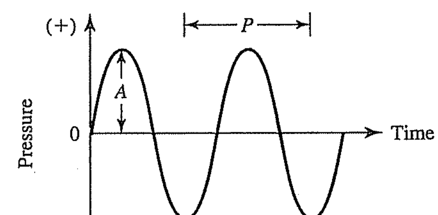


FIGURE 15–2

Sinusoidal wave that results from alternating compression and rarefaction of air molecules. The amplitude is shown as *A* and the period is *P*.



The time between successive peaks or between successive troughs of the oscillation is called the **period** (P). The inverse of this, that is, the number of times a peak arrives in one second of oscillations, is called the **frequency** (f). Period and frequency are then related as follows:

$$P = \frac{1}{f} \tag{15–1}$$

Because the pressure wave moves down the tube at a constant speed, you would find that the distance between equal pressure readings would remain constant. The distance between adjacent crests or troughs of pressure is called the **wavelength** (λ). Wavelength and frequency are then related as follows:

$$\lambda = \frac{c}{f} \tag{15–2}$$

The **amplitude** (A) of the wave is the height of the peak or depth of the trough measured from the zero pressure line (see Figure 15–2). From Figure 15–2 we can also note that the average pressure could be zero if an averaging time was selected that corresponded to the period of the wave. This would result regardless of the amplitude! This, of course, is not an acceptable state of affairs. The **root mean square** (rms) **sound pressure** (p_{rms}) is used to overcome this difficulty.* The rms sound pressure is obtained by squaring the value of the amplitude at each instant in time, summing the squared values, dividing the total by the averaging time, and taking the square root of the total. The equation for rms is

$$\bar{p}_{rms} = (p^2)\frac{1}{2}\left[\frac{1}{t_m}\int p^2(t)\,dt\right]^{1/2} \tag{15–3}$$

where the overbar refers to the time-weighted average and t_m is the time period of the measurement.

Sound Power and Intensity

Work is defined as the product of the magnitude of the displacement of a body and the component of force in the direction of the displacement. Thus, traveling waves of sound pressure transmit energy in the direction of propagation of the wave. The rate at which this work is done is defined as the **sound power** (W).

Sound intensity (I) is the time-weighted average sound power per unit area normal to the direction of propagation of the sound wave. Intensity and power are related as follows:

$$I = \frac{W}{A} \tag{15–4}$$

where A is a unit area perpendicular to the direction of wave motion. Intensity, and hence, sound power, is related to sound pressure in the following manner:

$$I = \frac{(p_{rms})^2}{\rho c} \tag{15–5}$$

where I = intensity (in $W \cdot m^{-2}$)
p_{rms} = root mean square sound pressure (in Pa)
ρ = density of medium (in $kg \cdot m^{-3}$)
c = speed of sound in medium (in $m \cdot s^{-1}$)

Both the density of air and speed of sound are a function of temperature. Given the temperature and pressure, the density of air may be determined from Table A–3 in Appendix A. The speed of sound in air at 101.325 kPa may be determined from the following equation:

$$c = 20.05\sqrt{T} \tag{15–6}$$

where T is the absolute temperature in kelvins (K) and c is in meters per second.

*Sound pressure = (total atmospheric pressure) − (barometric pressure).

Levels and the Decibel

The sound pressure of the faintest sound that a normal healthy individual can hear is about 0.00002 Pa. The sound pressure produced by a Saturn rocket at liftoff is greater than 200 Pa. Even in scientific notation this is an "astronomical" range of numbers.

To cope with this problem, a scale based on the logarithm of the ratios of the measured quantities is used. Measurements on this scale are called levels. The unit for these types of measurement scales is the **bel,** which was named after Alexander Graham Bell:

$$L' = \log \frac{Q}{Q_0} \tag{15–7}$$

where L' = level, bels
Q = measured quantity
Q_0 = reference quantity
log = logarithm in base 10

A bel turns out to be a rather large unit, so for convenience it is divided into 10 subunits called **decibels** (dB). Levels in decibels are computed as follows:

$$L = 10 \log \frac{Q}{Q_0} \tag{15–8}$$

The decibel does not represent any physical unit. It merely indicates that a logarithmic transformation has been performed.

Sound Power Level. If the reference quantity (Q_0) is specified, then the decibel takes on physical significance. For noise measurements, the reference power level has been established as 10^{-12} W. Thus, sound power level may be expressed as

$$L_W = 10 \log \frac{W}{10^{-12}} \tag{15–9}$$

Sound power levels computed with Equation 15–9 are reported as decibels re: 10^{-12} W.

Sound Intensity Level. For noise measurements, the reference sound intensity (Equation 15–4) is $10^{-12}\ \text{W} \cdot \text{m}^{-2}$. Thus the sound intensity level is given as

$$L_I = 10 \log \frac{I}{10^{-12}} \tag{15–10}$$

Sound Pressure Level. Because sound-measuring instruments measure the p_{rms}, the sound pressure level is computed as follows:

$$L_p = 10 \log \frac{(p_{rms})^2}{(p_{rms})_0^2} \tag{15–11}$$

which, after extracting the squaring term, is given as

$$L_p = 20 \log \frac{(p_{rms})}{(p_{rms})_0} \tag{15–12}$$

The reference pressure has been established as 20 μPa (micropascals). A scale showing some common sound pressure levels is shown in Figure 15–3.

Combining Sound Pressure Levels. Because of their logarithmic heritage, decibels don't add and subtract the way apples and oranges do. Remember: adding the logarithms of

FIGURE 15–3

Relative scale of sound pressure levels.

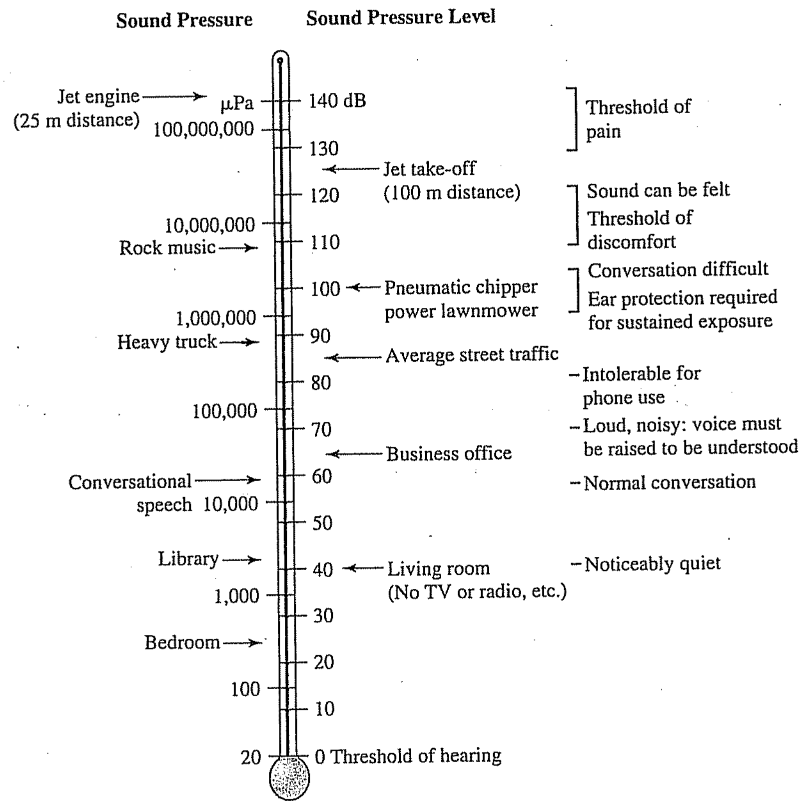
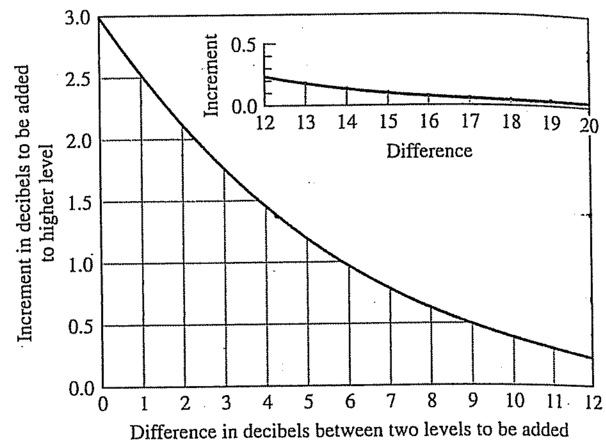


FIGURE 15–4

Graph for solving decibel addition problems.



numbers is the same as multiplying them. If you take a 60-dB noise (re: 20 μPa) and add another 60-dB noise (re: 20 μPa) to it, you get a 63-dB noise (re: 20 μPa). If you're strictly an apple-and-orange mathematician, you may take this on faith. For skeptics, this can be demonstrated by converting the decibels to sound power level, adding them, and converting back to decibels. Figure 15–4 provides a graphical solution for this type of problem. For noise pollution work, results should be reported to the nearest whole number. When several levels are to be combined, combine them two at a time, starting with lower valued levels and continuing two at a time with each successive pair until one number remains. Henceforth, in this chapter we will assume levels are all "re: 20 μPa" unless stated otherwise.

EXAMPLE 15–1 What sound power level results from combining the following three levels: 68 dB, 79 dB, and 75 dB?

Solution This problem can be worked by converting the readings to sound power level, adding them, and converting back to decibels.

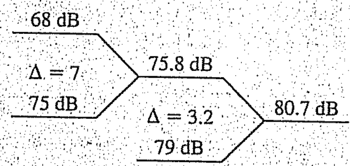
$$L_p = 10 \log \sum 10^{(68/10)} + 10^{(75/10)} + 10^{(79/10)}$$

$$= 10 \log(117{,}365{,}173)$$

$$= 80.7 \text{ dB}$$

Rounding off to the nearest whole number yields an answer of 81 dB re: 20 μPa.

An alternative solution technique using Figure 15–4 begins by selecting the two lowest levels: 68 dB and 75 dB. The difference between the values is 75 − 68 = 7.00. Using Figure 15–4, draw a vertical line from 7.00 on the abscissa to intersect the curve. A horizontal line from the intersection to the ordinate yields about 0.8 dB. Thus, the combination of 68 dB and 75 dB results in a level of 75.8 dB. This, and the remainder of the computation, is shown in the following diagram.



Characterization of Noise

Weighting Networks. Because our reasons for measuring noise usually involve people, we are ultimately more interested in the human reaction to sound than in sound as a physical phenomenon. Sound pressure level, for instance, can't be taken at face value as an indication of loudness because the frequency (or pitch) of a sound has quite a bit to do with how loud it sounds. For this and other reasons, it often helps to know something about the frequency of the noise you're measuring. This is where weighting networks come in [1]. **Weighting networks** are electronic filtering circuits built into the meter to attenuate certain frequencies. They permit the sound level meter (Figure 15–5) to respond more to some frequencies than to others with a prejudice something like that of the human ear. Writers of the acoustical standards have established three weighting characteristics: A, B, and C. The chief difference among them is that very low frequencies are filtered quite severely by the A network, moderately by the B network, and hardly at all by the C network. Therefore, if the measured sound level of a noise is much higher on C weighting than on A weighting, much of the noise is probably of low frequency. If you really want to know the frequency distribution of a noise (and most serious noise measurers do), it is necessary to use a sound analyzer. But if you are unable to justify the expense of an analyzer, you can still find out something about the frequency of a noise by shrewd use of the weighting networks of a sound level meter.

FIGURE 15–5

Precision sound level meter. (Courtesy of Larson-Davis, Inc.)

Figure 15–6 shows the response characteristics of the three basic networks as prescribed the American National Standards Institute (ANSI) specification number S1.4-1971. Wher weighting network is used, the sound level meter electronically subtracts or adds the number decibels shown at each frequency shown in Table 15–1 from or to the actual sound pressure le at that frequency. It then sums all the resultant numbers by logarithmic addition to give a sin reading. Readings taken when a network is in use are said to be "sound levels" rather than "sou pressure levels." The readings taken are designated in decibels in one of the following forr dB(A); dBa; dBA; dB(B); dBb; dBB; and so on. Tabular notations may refer to L_A, L_B, L_C.

FIGURE 15–6

Response characteristics of the three basic weighting networks.

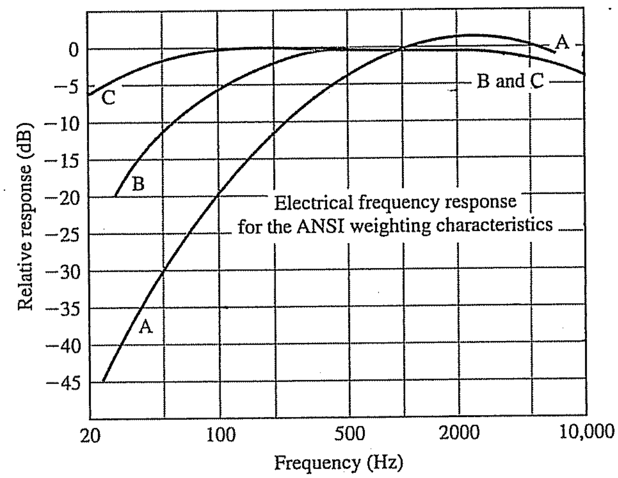


TABLE 15–1 Sound Level Meter Network Weighting Values

Frequency (Hz)	Curve A (dB)	Curve B (dB)	Curve C (dB)	Frequency (Hz)	Curve A (dB)	Curve B (dB)	Curve C (dB
10	−70.4	−38.2	−14.3	500	−3.2	−0.3	0
12.5	−63.4	−33.2	−11.2	630	−1.9	−0.1	0
16	−56.7	−28.5	−8.5	800	−0.8	0	0
20	−50.5	−24.2	−6.2	1,000	0	0	0
25	−44.7	−20.4	−4.4	1,250	0.6	0	0
31.5	−39.4	−17.1	−3.0	1,600	1.0	0	−0.
40	−34.6	−14.2	−2.0	2,000	1.2	−0.1	−0.
50	−30.2	−11.6	−1.3	2,500	1.3	−0.2	−0.
63	−26.2	−9.3	−0.8	3,150	1.2	−0.4	−0.
80	−22.5	−7.4	−0.5	4,000	1.0	−0.7	−0.
100	−19.1	−5.6	−0.3	5,000	0.5	−1.2	−1.
125	−16.1	−4.2	−0.2	6,300	−0.1	−1.9	−2.
160	−13.4	−3.0	−0.1	8,000	−1.1	−2.9	−3.
200	−10.9	−2.0	0	10,000	−2.5	−4.3	−4.
250	−8.6	−1.3	0	12,500	−4.3	−6.1	−6.
315	−6.6	−0.8	0	16,000	−6.6	−8.4	−8.
400	−4.8	−0.5	0	20,000	−9.3	−11.1	−11.

EXAMPLE 15-2 A new type 2 sound level meter is to be tested with two pure tone sources that emit 90 dB. The pure tones are at 1000 Hz and 100 Hz. Estimate the expected readings on the A, B, and C weighting networks.

Solution From Table 15–1 at 1000 Hz, we note that the relative response (correction factor) for each of the weighting networks is zero. Thus for the pure tone at 1000 Hz we would expect the readings on the A, B, and C networks to be 90 dB.

From Table 15–1 at 100 Hz, the relative response for each weighting network differs. For the A network, the meter will subtract 19.1 dB from the actual reading, for the B network, the meter will subtract 5.6 dB from the actual reading, and for the C network, the meter will subtract 0.3 dB. Thus, the anticipated readings would be

A network: $90 - 19.1 = 70.9$, or 71 dB(A)
B network: $90 - 5.6 = 84.4$, or 84 dB(B)
C network: $90 - 0.3 = 89.7$, or 90 dB(C)

EXAMPLE 15-3 The following sound levels were measured on the A, B, and C weighting networks:

Source 1: 94 dB(A), 95 dB(B), and 96 dB(C)
Source 2: 74 dB(A), 83 dB(B), and 90 dB(C)

Characterize the sources as "low frequency or mid/high frequency."

Solution From Figure 15–6, we can see that readings on the A, B, and C networks will be close together if the source emits noise in the frequency range above about 500 Hz. This range may be classified mid/high frequency because we cannot distinguish between "mid" and "high" frequency using a type 2 sound level meter. Likewise, we can see that below 200 Hz (low frequency), readings on the A, B, and C scale will be substantially different. The readings from the A network will be lower than the readings from the B network, and readings from both the A and B networks will be lower than those from the C network.

Source 1: Note that the sound levels on each of the weighting networks differ by 1 dB. From Figure 15–6, it appears that the sound level will be in the mid/high-frequency range.
Source 2: Note that the sound levels on each of the weighting networks differ by several decibels and that the reading from the A network is lower than that from the B network and both are below that from the C network. From Figure 15–6, it appears that the sound level will be in the low-frequency range.

Octave Bands. To completely characterize a noise, it is necessary to break it down into its frequency components, or spectra. Normal practice is to consider 8 to 11 octave bands.* The standard octave bands and their geometric mean frequencies (center band frequencies) are given in Table 15–2. Octave analysis is performed with a combination precision sound level meter and an octave filter set.

*An octave is the frequency interval between a given frequency and twice that frequency. For example, given the frequency 22 Hz, the octave band is from 22 to 44 Hz. A second octave band would then be from 44 to 88 Hz.

TABLE 15–2 Octave Bands

Octave Frequency Range (Hz)	Geometric Mean Frequency (Hz)	Octave Frequency Range (Hz)	Geometric Mea Frequency (Hz)
22–44	31.5	1,400–2,800	2,000
44–88	63	2,800–5,600	4,000
88–175	125	5,600–11,200	8,000
175–350	250	11,200–22,400	16,000
350–700	500	22,400–44,800	31,500
700–1,400	1,000		

Although octave band analysis is frequently sufficient for community noise contro (i.e., identifying violators), more refined analysis is required for corrective action and design One-third octave band analysis provides a slightly more refined picture of the noise source thai the full octave band analysis. This improved resolution is usually sufficient for determinin corrective action for community noise problems. Narrow band analysis is highly refined and ma imply band widths down to 2 Hz. This degree of refinement is only justified in product design an testing or in troubleshooting industrial machine noise and vibration.

Averaging Sound Pressure Levels. Because of the logarithmic nature of the decibel the average value of a collection of sound pressure level measurements cannot be computed i the normal fashion. Instead, the following equation must be used:

$$\bar{L}_p = 20 \log \frac{1}{N} \sum_{j=1}^{N} 10^{(L_j/20)} \qquad (15\text{–}13$$

where $\bar{L}_p$ = average sound pressure level (in dB re: 20 μPa)
N = number of measurements
L_j = the jth sound pressure levels (in dB re: 20 μPa)
$j = 1, 2, 3, \ldots N$

This equation is equally applicable to sound levels in decibels(A). It may also be used to comput average sound power levels if the factors of 20 are replaced with 10s.

EXAMPLE 15–4 Compute the mean sound level from the following four readings (all in decibels): 38, 51, 68 and 78.

Solution First we compute the sum.

$$\sum_{j=1}^{4} = 10^{(38/20)} + 10^{(51/20)} + 10^{(68/20)} + 10^{(78/20)}$$

$$= 1.09 \times 10^4$$

Now we complete the computation.

$$\bar{L}_p = 20 \log \frac{1.09 \times 10^4}{4}$$

$$= 68.7, \text{ or } 69 \text{ dBA}$$

Straight arithmetic averaging would yield 58.7, or 59 dB.

FIGURE 15–7

Type A impulse noise.

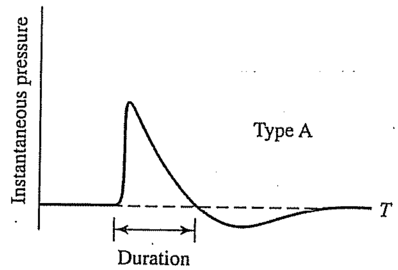
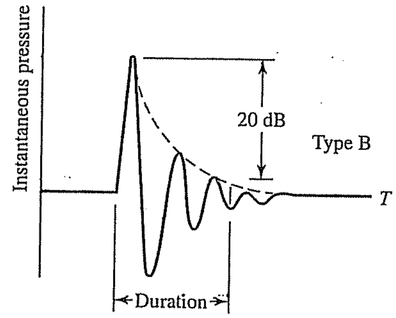


FIGURE 15–8

Type B impulse noise.



Types of Sounds. Patterns of noise may be qualitatively described by one of the following terms: **steady-state,** or **continuous; intermittent;** and **impulse,** or **impact. Continuous noise** is an uninterrupted sound level that varies less than 5 dB during the period of observation. An example is the noise from a household fan. **Intermittent noise** is a continuous noise that persists for more than 1 s that is interrupted for more than 1 s. A dentist's drilling would be an example of an intermittent noise. **Impulse noise** is characterized by a change of sound pressure of 40 dB or more within 0.5 s with a duration of less than 1 s.* The noise from firing a weapon would be an example of an impulsive noise.

Two types of impulse noise generally are recognized. The type A impulse is characterized by a rapid rise to a peak sound pressure level followed by a small negative pressure wave or by decay to the background level (Figure 15–7). The type B impulse is characterized by a damped (oscillatory) decay (Figure 15–8). When the duration of the type A impulse is simply the duration of the initial peak, the duration of the type B impulse is the time required for the envelope to decay to 20 dB below the peak. Because of the short duration of the impulse, a special sound-level meter must be employed to measure impulse noise. You should note that the peak sound pressure level is different from the impulse sound level because of the time-averaging used in the latter.

15–2 EFFECTS OF NOISE ON PEOPLE

For the purpose of our discussion, we have classified the effects of noise on people into the following two categories: auditory effects and psychological–sociological effects. **Auditory effects** include both hearing loss and speech interference. **Psychological–sociological effects** include annoyance, sleep interference, effects on performance, and acoustical privacy.

The Hearing Mechanism

Before we can discuss hearing loss, it is important to outline the general structure of the ear and how it works.

Anatomically, the ear is separated into three sections: the outer ear, the middle ear, and the inner ear (Figure 15–9). The outer and middle ear serve to convert sound pressure to vibrations. In addition, they perform the protective role of keeping debris and objects from reaching the inner ear. The Eustachian tube extends from the middle ear space to the upper part of the throat behind the soft palate. The tube is normally closed. Contraction of the palate muscles during yawning, chewing, or swallowing opens the tubes. This allows the middle ear to ventilate and

*The Occupational Safety and Health Administration (OSHA) classifies repetitive events, including impulses, as steady noise if the interval between events is less than 0.5 s.

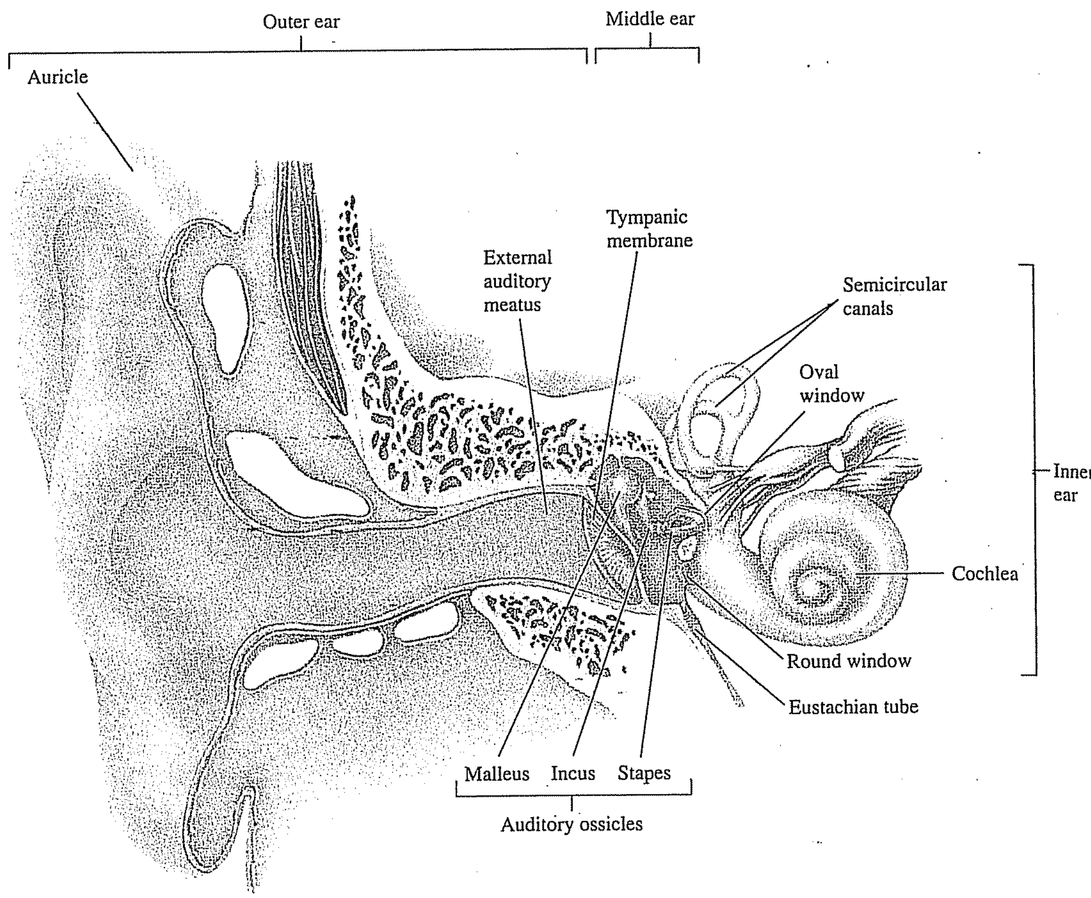


FIGURE 15–9

Anatomical divisions of the ear. (*Source:* Seeley, R., T. Stephens, and P. Tate, *Anatomy and Physiology*, 6th ed., McGraw-Hill, New York, 2003. Reprinted by permission.)

equalize pressure. If external air pressure changes rapidly, for example, by a sudden change in elevation, the tube is opened by involuntary swallowing or yawning to equalize the pressure.

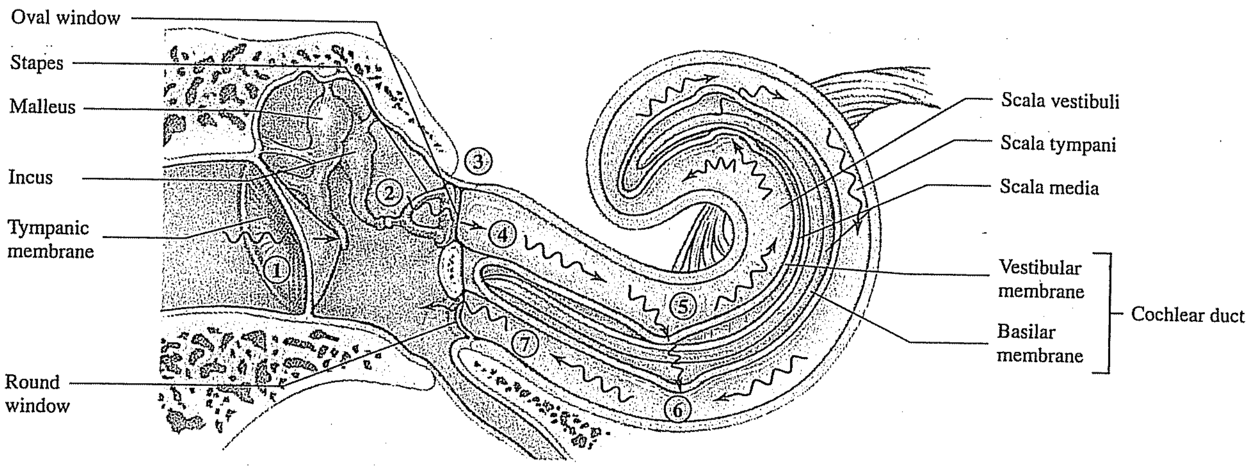
The sound transducer mechanism is housed in the middle ear.* It consists of the **tympanic membrane** (eardrum) and three **ossicles** (bones) (Figure 15–10). The ossicles are supported by ligaments and may be moved by two muscles or by deflection of the tympanic membrane. The muscle movement is involuntary. Loud sounds cause these muscles to contract, which stiffens and diminishes the movement of the ossicular chain. This presumably offers some protection for the delicate inner ear structure from physical injury. According to J. D. Clemis, "More convincing research is still needed to test the validity of this theory of the function of these muscles." The discussion on the middle ear that follows is excerpted from Clemis [2].

> The primary function of the middle ear in the hearing process is to transfer sound energy from the outer to the inner ear. As the eardrum vibrates, it transfers its motion to the malleus. Since the bones of the ossicular chain are connected to one another, the movements of the malleus are passed on to the incus, and finally to the stapes, which is imbedded in the oval window.
>
> As the stapes moves back and forth in a rocking motion, it passes the vibrations into the inner ear through the oval window. Thus, the mechanical motion of the eardrum is effectively transmitted through the middle ear and into the fluid of the inner ear.
>
> The sound-conducting transducer amplifies sound by two main mechanisms. First, the large surface area of the drum as compared to the small surface area of the base of the stapes (footplate) results in a hydraulic effect. The eardrum has about 25 times as much surface area as the oval window. All of the sound pressure collected on the eardrum is transmitted through the ossicular chain and is concentrated on the much smaller area of the oval window. This produces a significant increase in pressure.

*A **transducer** is a device that transmits power from one system to another. In this case, sound power is converted to mechanical displacement, which is later measured and interpreted by the brain.

FIGURE 15–10

The sound transducer mechanism housed in the middle ear. (*Source:* Seeley, R., T. Stephens, and P. Tate, *Anatomy and Physiology*, 6th ed., McGraw-Hill, New York, 2003. Reprinted by permission.)



1. Sound waves strike the tympanic membrane and cause it to vibrate.
2. Vibration of the tympanic membrane causes the three bones of the middle ear to vibrate.
3. The foot plate of the stapes vibrates in the oval window.
4. Vibration of the foot plate causes the perilymph in the scala vestibuli to vibrate.
5. Vibration of the perilymph causes displacement of the basilar membrane. Short waves (high pitch) cause displacement of the basilar membrane near the oval window, and longer waves (low pitch) cause displacement of the basilar membrane some distance from the oval window. Movement of the basilar membrane is detected in the hair cells of the spiral organ, which are attached to the basilar membrane.
6. Vibrations of the perilymph in the scala vestibuli and of the endolymph in the cochlear duct are transferred to the perilymph of the scala tympani.
7. Vibrations in the perilymph of the scala tympani are transferred to the round window, where they are dampened.

The bones of the ossicular chain are arranged in such a way that they act as a series of levers. The long arms are nearest the eardrum, and the shorter arms are toward the oval window. The fulcrums are located where the individual bones meet. A small pressure on the long arm of the lever produces a much stronger pressure on the shorter arm. Since the longer arm is attached to the eardrum and the shorter arm is attached to the oval window, the ossicular chain acts as an amplifier of sound pressure. The magnification effect of the entire sound-conducting mechanism is about 22-to-1.

The inner ear houses both the balance receptors and the auditory receptors. The auditory receptors are in the **cochlea,** a bone shaped like a snail coiled two and one-half times around its own axis (see Figure 15–9). A cross section through the cochlea (Figure 15–11) reveals three compartments: the **scala vestibuli;** the **scala media;** and the **scala tympani.** The scala vestibuli and the scala tympani are connected at the apex of the cochlea. They are filled with a fluid called **perilymph** in which the scala media floats. The hearing organ, the **organ of Corti,** is housed in the scala media. The scala media contains a different fluid, endolymph, which bathes the organ of Corti.

The scala media is triangular in shape and is about 34 mm in length. As shown in Figure 15–11, there are cells growing up from the **basilar membrane.** They have a tuft of hair at one end and are attached to the hearing nerve at the other. A gelatinous membrane (**tectorial membrane**) extends over the hair cells and is attached to the **limbus spiralis.** The hair cells are embedded in the tectorial membrane.

Vibration of the oval window by the stapes causes the fluids of the three scalae to develop a wave-like motion. The movement of the basilar membrane and the tectorial membrane in opposite directions causes a shearing motion on the hair cells. The dragging of the hair cells sets up electrical impulses in the auditory nerves, which are transmitted to the brain.

The nerve endings near the oval and round windows are sensitive to high frequencies. Those near the apex of the cochlea are sensitive to low frequencies.

FIGURE 15–11

Cross section through the cochlea.

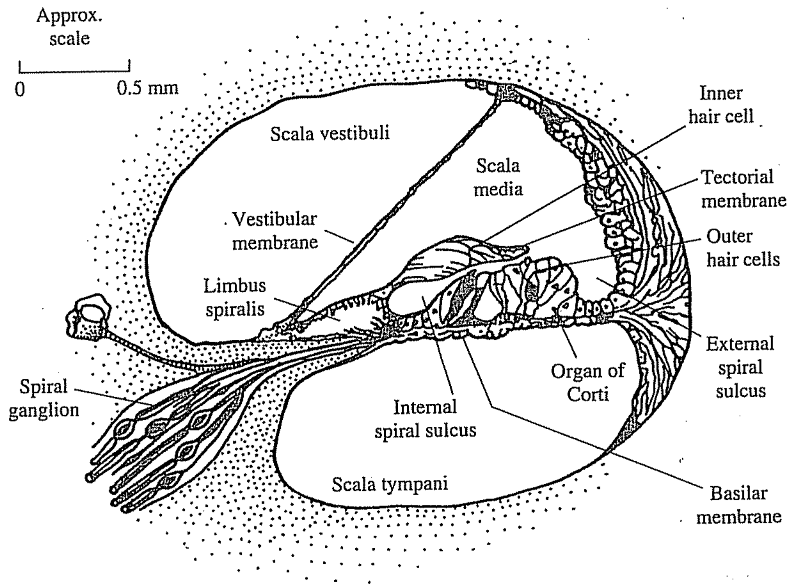
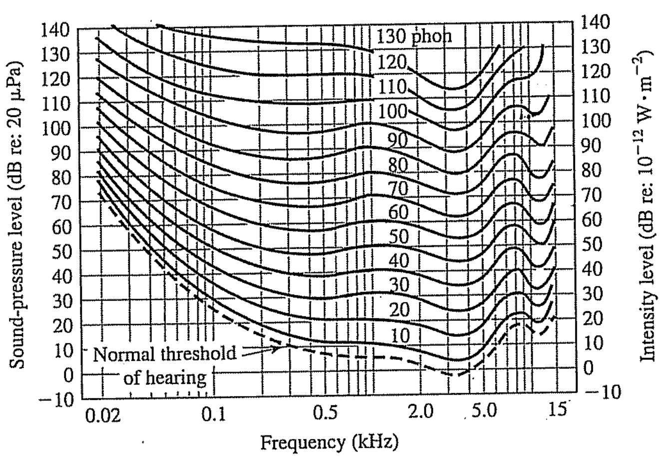


FIGURE 15–12

Fletcher–Munson equal loudness contours. (*Source:* Edward B. Magrab, *Environmental Noise Control,* Wiley, New York, 1975. Reprinted by permission.)



Normal Hearing

Frequency Range and Sensitivity. The ear of the young, audiometrically healthy, adult male responds to sound waves in the frequency range of 20 to 16,000 Hz. Young children and women often have the capacity to respond to frequencies up to 20,000 Hz. The speech zone lies in the frequency range of 500 to 2000 Hz. The ear is most sensitive in the frequency range from 2000 to 5000 Hz. The smallest perceptible sound pressure in this frequency range is 20 μPa.

A sound pressure of 20 μPa at 1.000 Hz in air corresponds to a 1.0-nm displacement of the air molecules. The thermal motion of the air molecules corresponds to a sound pressure of about 1 μPa. If the ear were much more sensitive, you would hear the air molecules crashing against your ear like waves on the beach!

Loudness. In general, two pure tones having different frequencies but the same sound pressure level will be heard as different loudness levels. Loudness level is a psychoacoustic quantity.

In 1933, Fletcher and Munson conducted a series of experiments to determine the relationship between frequency and loudness [3]. A reference tone and a test tone were presented alternately to the test subjects, who were asked to adjust the sound level of the test tone until it sounded as loud as the reference. The results were plotted as sound pressure level in decibels versus the test tone frequency (Figure 15–12). The curves are called the **Fletcher–Munson,** or **equal loudness, contours.** The reference frequency is 1000 Hz. The curves are labeled in **phons,** which are the sound pressure levels of the 1000-Hz pure tone in decibels. The lowest contour (dashed line) represents the "threshold of hearing." The actual threshold may vary by as much as ±10 dB between individuals with normal hearing.

Audiometry. Hearing tests are conducted with a device known as an **audiometer.** Basically, it consists of a source of pure tones with variable sound pressure level output into a pair of earphones. If the instrument also automatically prepares a graph of the test results (an **audiogram**), then it will include a weighting network called the **hearing threshold level** (HTL) scale.

The HTL scale is one in which the loudness of each pure tone is adjusted by frequency such that "0" dB is the level just audible for the average normal young ear. Two reference standards are in use: ASA-1951 and ANSI-1969. The ANSI reference values are shown in Figure 15–13. Note the similarity to the Fletcher–Munson contours. The initial audiogram prepared for an individual may be referred to as the baseline HTL or simply as the HTL.

The audiogram shown in Figure 15–14 reflects excellent hearing response. The average normal response may vary ±10 dB from the "0" dB value. As noted on the audiogram, this test was conducted with the ANSI-1969 weighting network.

You may have noted that we keep stressing young in our references to normal hearing. This is because hearing loss occurs due to the aging process, a type of loss called **presbycusis.**

FIGURE 15–13

The ANSI reference values for hearing threshold level.

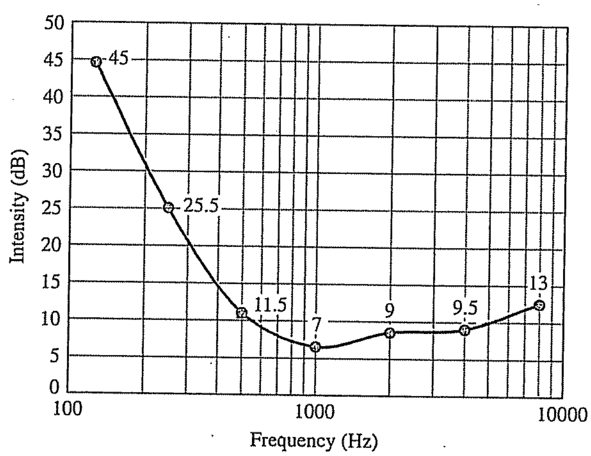


FIGURE 15–14

An audiogram illustrating excellent hearing response.

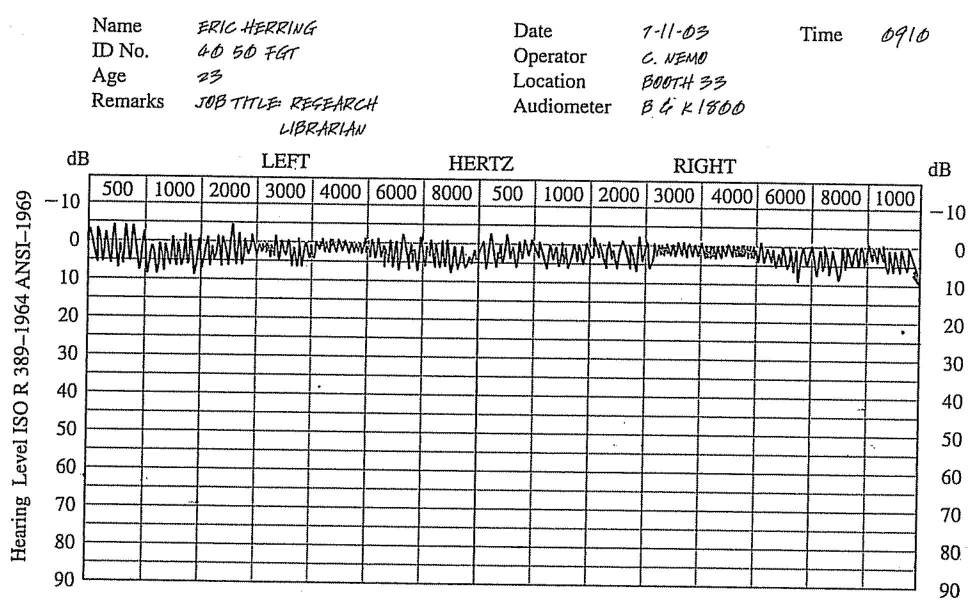
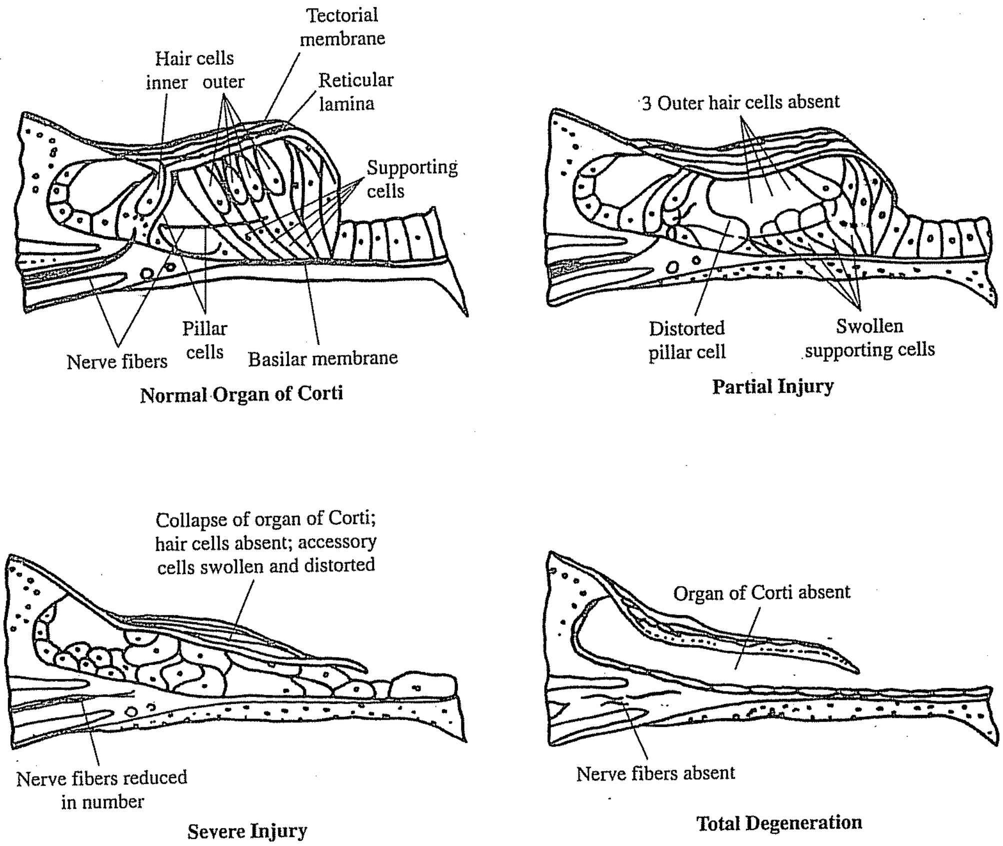


FIGURE 15–15

Various degrees of injury to the hair cells.



Hearing Impairment

Mechanism. With the exception of eardrum rupture from intense explosive noise, the outer and middle ear rarely are damaged by noise. More commonly, hearing loss is a result of neural damage involving injury to the hair cells (Figure 15–15). Two theories are offered to explain noise-induced injury. The first is that excessive shearing forces mechanically damage the hair cells. The second is that intense noise stimulation forces the hair cells into high metabolic activity, which overdrives them to the point of metabolic failure and consequent cell death. Once destroyed, hair cells are not capable of regeneration.

Measurement. Because direct observation of the organ of Corti in persons having potential hearing loss is impossible, injury is inferred from losses in their HTL. The increased sound pressure level required to achieve a new HTL is called **threshold shift.** Obviously, any measurement of threshold shift depends on having a baseline audiogram taken before the noise exposure.

Hearing losses may be either temporary or permanent. Noise-induced losses must be separated from other causes of hearing loss such as age (presbycusis), drugs, disease, and blows on the head. **Temporary threshold shift** (TTS) is distinguished from **permanent threshold shift** (PTS) by the fact that in TTS removal of the noise over stimulation will result in a gradual return to baseline hearing thresholds.

Factors Affecting Threshold Shift. Important variables in the development of temporary and permanent hearing threshold changes include the following [4].

1. *Sound level.* Sound levels must exceed 60–80 dBA before the typical person will experience TTS.
2. *Frequency distribution of sound.* Sounds having most of their energy in the speech frequencies are more potent in causing a threshold shift than sounds having most of their energy below the speech frequencies.

3. *Duration of sound.* The longer the sound lasts, the greater the amount of threshold shift.
4. *Temporal distribution of sound exposure.* The number and length of quiet periods between periods of sound influences the potentiality of threshold shift.
5. *Individual differences in tolerance.* These differences may vary greatly among individuals.
6. *Type of sound.* (steady-state, intermittent, impulse, or impact) The tolerance to peak sound pressure is greatly reduced by increasing the duration of the sound.

Temporary Threshold Shift (TTS). TTS is often accompanied by a ringing in the ear, muffling of sound, or discomfort of the ears. Most of the TTS occurs during the first 2 h of exposure. Recovery to the baseline HTL after TTS begins within the first hour or two after exposure. Most of the recovery that is going to be attained occurs within 16 to 24 h after exposure.

Permanent Threshold Shift (PTS). There appears to be a direct relationship between TTS and PTS. Noise levels that do not produce TTS after 2–8 h of exposure will not produce PTS if continued beyond this time. The shape of the TTS audiogram will resemble the shape of the PTS audiogram.

Noise-induced hearing loss generally is first characterized by a sharply localized dip in the HTL curve at the frequencies between 3000 and 6000 Hz. This dip commonly occurs at 4000 Hz (Figure 15–16). This is the **high-frequency notch.** The progress from TTS to PTS with continued noise exposure follows a fairly regular pattern. First, the high-frequency notch broadens and spreads in both directions. Although substantial losses may occur above 3000 Hz, the individual will not notice any change in hearing. In fact, the individual will not notice any hearing loss until the speech frequencies between 500 and 2000 Hz average more than a 25-dB increase in HTL on the ANSI-1969 scale. The onset and progress of noise-induced permanent hearing loss is slow and insidious. The exposed individual is unlikely to notice it. Total hearing loss from noise exposure has not been observed.

Acoustic Trauma. The outer and middle ear rarely are damaged by intense noise. However, explosive sounds can rupture the tympanic membrane or dislocate the ossicular chain. The permanent hearing loss that results from very brief exposure to a very loud noise is termed **acoustic trauma** [5]. Damage to the outer and middle ear may or may not accompany acoustic trauma.

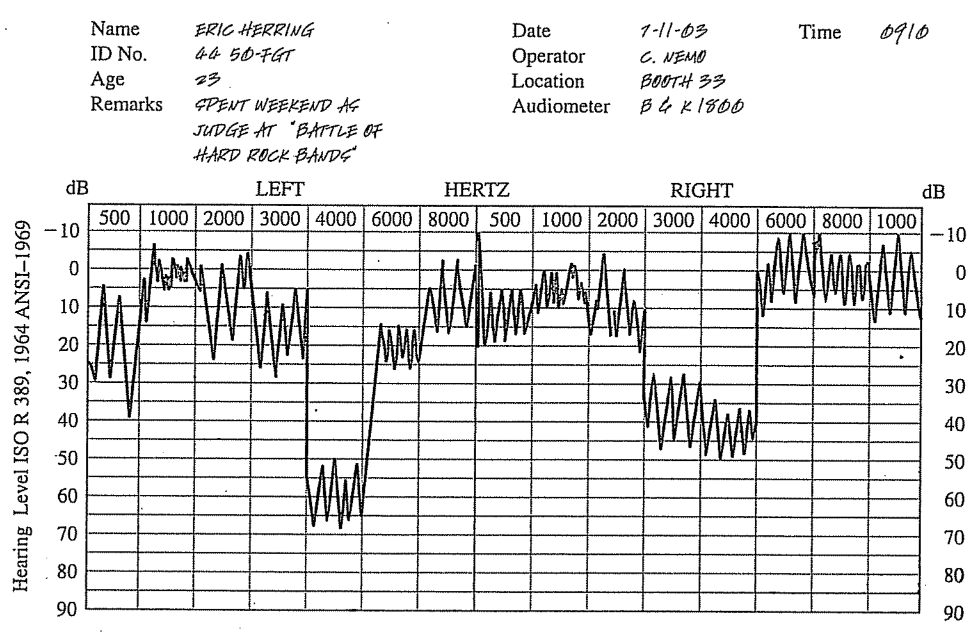


FIGURE 15–16

An audiogram illustrating hearing loss at the high-frequency notch.

Protective Mechanisms. Although the extent and mechanisms are unclear, it appears that the structures of the middle ear offer some protection to the delicate sensory organs of the inner ear [6]. One mechanism of protection is a change in the mode of vibration of the stapes. As noted earlier, there is some evidence that the muscles of the middle ear contract reflexively in response to loud noise. This contraction results in a reduction in the amplification that this series of levers normally produces. Changes in transmission may be on the order of 5 to 10 dB. However, the reaction time of the muscle–bone structure is on the order of 10 ms. Thus, this protection is not effective against steep acoustic wave fronts that are characteristic of impact or impulsive noise.

Damage-Risk Criteria

A **damage-risk criterion** specifies the maximum allowable exposure to which a person may be exposed if risk of hearing impairment is to be avoided. The American Academy of Ophthalmology and Otolaryngology has defined **hearing impairment** as an average HTL in excess of 25 dB (ANSI-1969) at 500, 1000, and 2000 Hz. This is called the **low fence. Total impairment** is said to occur when the average HTL exceeds 92 dB. Presbycusis is included in setting the 25-dB ANSI low fence. Two criteria have been set to provide conditions under which nearly all workers may be repeatedly exposed without adversely affecting their ability to hear and understand normal speech.

Continuous or Intermittent Exposure. The National Institute for Occupational Safety and Health (NIOSH) has recommended that occupational noise exposure be controlled so that no worker is exposed in excess of the limits defined by line B in Figure 15–17. In addition, NIOSH recommends that new installations be designed to hold noise exposure below the limits defined by line A in Figure 15–17. The Walsh–Healey Act, which was enacted by Congress in 1969 to protect workers, used a damage-risk criterion equivalent to the line A criterion.

Speech Interference

As we all know, noise can interfere with our ability to communicate. Many noises that are not intense enough to cause hearing impairment can interfere with speech communication. The interference, or **masking,** effect is a complicated function of the distance between the speaker and listener and the frequency components of the spoken words. The speech interference level (SIL) was

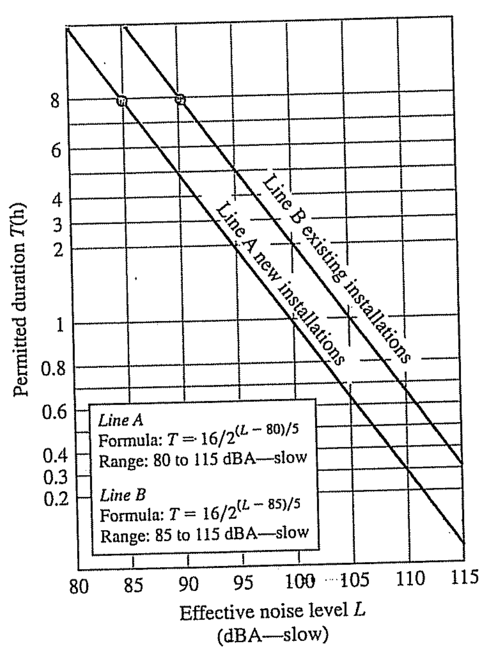


FIGURE 15–17

NIOSH occupational noise exposure limits for continuous or intermittent noise exposure.

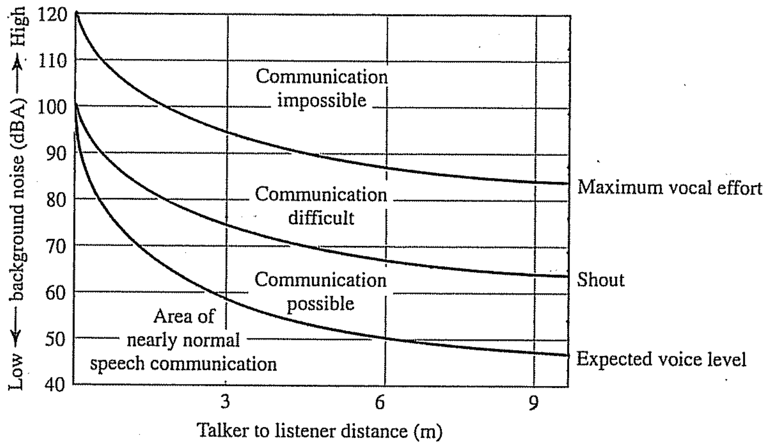


FIGURE 15–18

Quality of speech communication as a function of sound level and distance. [*Source:* James D. Miller, *Effects of Noise on People* (U.S. Environmental Protection Agency Publication No. NTID 300.7), Washington, DC: U.S. Government Printing Office, 1971.]

developed as a measure of the difficulty in communication that could be expected with different background noise levels [7]. It is now more convenient to talk in terms of A-weighted background noise levels and the quality of speech communication (Figure 15–18).

EXAMPLE 15–5 Consider the problem of a speaker in a quiet zone who wishes to speak to a listener operating a 4.5-Mg truck 6.0 m away. The sound level in the truck cab is about 73 dBA.

Solution Using Figure 15–18, we can see that she is going to have to shout very loudly to be heard. However, if she moved to within about 1.0 m, she would be able to use her "expected" voice level, that is, the unconscious slight rise in voice level that one would normally use in a noisy situation.

It can be seen that at distances not uncommon in living rooms or classrooms (4.5–6.0 m), the A-weighted background level must be below about 50 dB for normal conversation.

Annoyance

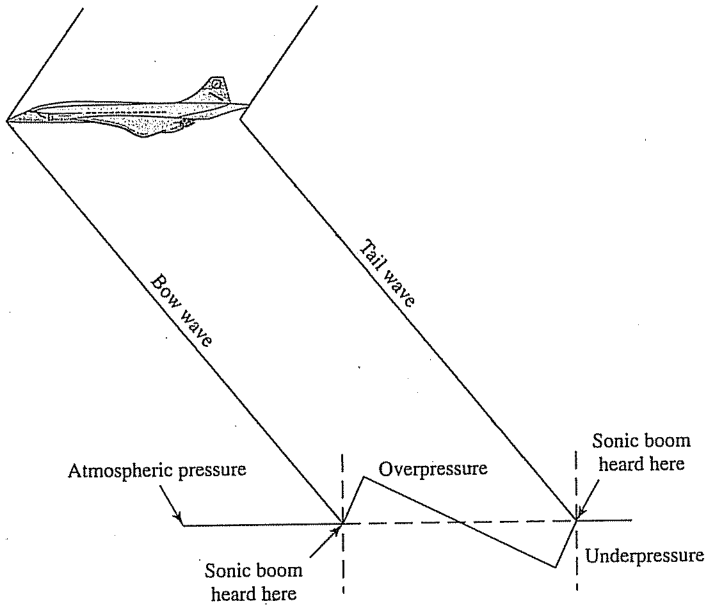
Annoyance by noise is a response to auditory experience. Annoyance has its base in the unpleasant nature of some sounds, in the activities that are disturbed or disrupted by noise, in the physiological reactions to noise, and in the responses to the meaning of "messages" carried by the noise [8]. For example, a sound heard at night may be more annoying than one heard by day, just as one that fluctuates may be more annoying than one that does not. A sound that resembles another sound that we already dislike and that perhaps threatens us may be especially annoying. A sound that we know is mindlessly inflicted and will not be removed soon may be more annoying than one that is temporarily and regretfully inflicted. A sound, the source of which is visible, may be more annoying than one with an invisible source. A sound that is new may be less annoying. A sound that is locally a political issue may have a particularly high or low annoyance [9].

The degree of annoyance and whether that annoyance leads to complaints, product rejection, or action against an existing or anticipated noise source depend on many factors. Some of these factors have been identified, and their relative importance has been assessed. Responses to aircraft noise have received the greatest attention. There is less information available concerning responses to other noises, however, such as those of surface transportation and industry, and those from recreational activities [8]. Many of the noise-rating or forecasting systems now in existence were developed in an effort to predict annoyance reactions.

Sonic Booms. One noise of special interest with respect to annoyance is called **sonic boom** or, more correctly as we shall see, sonic booms.

FIGURE 15–19

Sonic booms resulting from bow wave and tail wave set in motion by supersonic flight.



The flow of air around an aircraft or other object whose speed exceeds the speed of sound (supersonic) is characterized by the existence of discontinuities in the air known as **shock wave.** These discontinuities result from the sudden encounter of an impenetrable body with air. At subsonic speeds, the air seems to be forewarned; thus, it begins its outward flow before the arrival of the leading edge. At supersonic speeds, however, the air in front of the aircraft is undisturbed, and the sudden impulse at the leading edge creates a region of overpressure (Figure 15–19) where the pressure is higher than atmospheric pressure. This overpressure region travels outward with the speed of sound, creating a conically shaped shock wave called the **bow wave** that changes the direction of airflow. A second shock wave, the **tail wave,** is produced by the tail of the aircraft and is associated with a region where the pressure is lower than normal. This underpressure discontinuity causes the air behind the aircraft to move sideways.

Major pressure changes are experienced at the ear as the bow and tail shock waves reach an observer. Each of these pressure deviations produces the sensation of an explosive sound [10]. Note that the pressure wave and, hence, the sonic boom exist whenever the aircraft is at supersonic speed and not "just when it breaks the sound barrier."

Both the loudness of the noise and the startling effect of the impulse (it makes us "jump") are found to be very annoying. Apparently we can never get used to this kind of noise. Supersonic flight by commercial aircraft is forbidden in the airspace above the United States. Supersonic flight by military aircraft is restricted to sparsely inhabited areas.

Sleep Interference

Sleep interference is a special category of annoyance that has received a great deal of attention and study [11]. Almost all of us have been wakened or kept from falling asleep by loud, strange, frightening, or annoying sounds. It is commonplace to be wakened by an alarm clock or clock radio. But it also appears that one can get used to sounds and sleep through them. Possibly, environmental sounds only disturb sleep when they are unfamiliar. If so, disturbance of sleep would depend only on the frequency of unusual or novel sounds. Everyday experience also suggests that sound can help to induce sleep and, perhaps, to maintain it. The soothing lullaby, the steady hum of a fan, or the rhythmic sound of the surf, can serve to induce relaxation. Certain steady sounds can serve as an acoustical shade and mask disturbing transient sounds.

Common anecdotes about sleep disturbance suggest an even greater complexity. A rural person may have difficulty sleeping in a noisy urban area. An urban person may be disturbed by

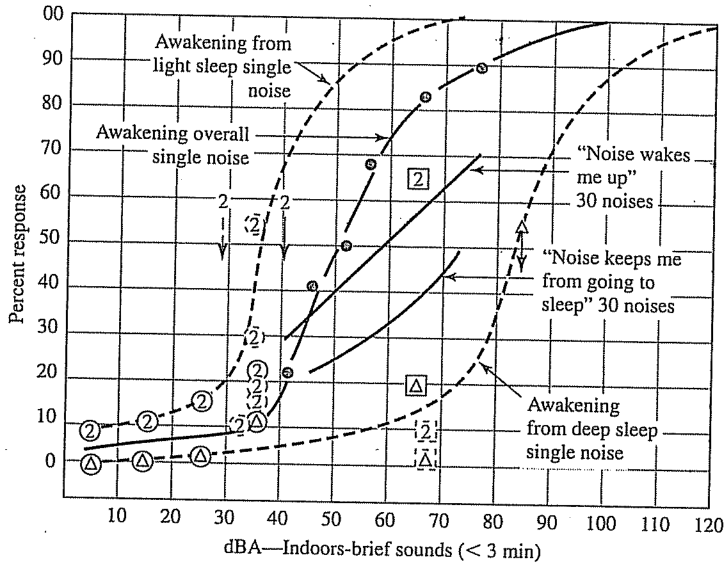


FIGURE 15–20

Effects of brief noise on sleep. [*Source:* J. D. Miller (U.S. Environmental Protection Agency Publication No. NTID 300.7), Washington, DC: U.S. Government Printing Office, 1971.]

the quiet when sleeping in a rural area. And how is it that a parent may wake to a slight stirring of his or her child, yet sleep through a thunderstorm? These observations all suggest that the relations between exposure to sound and the quality of a night's sleep are complicated.

The effects of relatively brief noises (about 3 min or less) on a person sleeping in a quiet environment have been studied the most thoroughly. Typically, presentations of the sounds are widely spaced throughout a sleep period of 5 to 7 h. A summary of some of these observations is presented in Figure 15–20. The dashed lines are hypothetical curves that represent the percent of awakenings under conditions in which the subject is a normally rested young adult male who has been adapted for several nights to the procedures of a quiet sleep laboratory. He has been instructed to press an easily reached button to indicate that he has awakened, and had been moderately motivated to awake and respond to the noise.

While in light sleep, subjects can awake to sounds that are about 30–40 dB above the level at which they can be detected when subjects are conscious, alert, and attentive. While in deep sleep, the stimulus may have to be 50–80 dB above the level at which they can be detected by conscious, alert, attentive subjects before they will awaken the sleeping subject.

The solid lines in Figure 15–20 are data from questionnaire studies of persons who live near airports. The percentage of respondents who claim that flyovers wake them or keep them from falling asleep is plotted against the A-weighted sound level of a single flyover. These curves are for the case of approximately 30 flyovers spaced over the normal sleep period of 6 to 8 h. The filled circles represent the percentage of sleepers that awake to a 3-min sound at each A-weighted sound level (dBA) or lower. This curve is based on data from 350 persons, each tested in his or her own bedroom. These measures were made between 2:00 and 7:00 A.M. It is reasonable to assume that most of the subjects were roused from a light sleep.

Effects on Performance

When a task requires the use of auditory signals, speech or nonspeech, then noise at any intensity level sufficient to mask or interfere with the perception of these signals will interfere with the performance of the task.

Where mental or motor tasks do not involve auditory signals, the effects of noise on their performance have been difficult to assess. Human behavior is complicated, and it has been difficult to discover exactly how different kinds of noises might influence different kinds of people doing different kinds of tasks. Nonetheless, the following general conclusions have emerged. Steady noises without special meaning do not seem to interfere with human performance unless the A-weighted noise level exceeds about 90 dB. Irregular bursts of noise (intrusive noise) are more disruptive than steady noises. Even when the A-weighted sound levels of irregular bursts are below 90 dB, they may sometimes interfere with performance of a task. High-frequency components of noise, above about 1000–2000 Hz, may produce more interference with performance than low-frequency components of noise. Noise does not seem to influence the overall rate of work, but high levels of noise may increase the variability of the rate of work. "Noise pauses" may occur followed by compensating increases in work rate. Noise is more likely to reduce the accuracy of work than to reduce the total quantity of work. Complex tasks are more likely to be adversely influenced by noise than are simple tasks.

Acoustic Privacy

Without opportunity for privacy, either everyone must conform strictly to an elaborate social code or everyone must adopt highly permissive attitudes. Opportunity for privacy avoids the necessity for either extreme. In particular, without opportunity for acoustical privacy, one may experience all of the effects of noise previously described, and, in addition, one is constrained because one's own activities may disturb others. Without acoustical privacy, sound, like a faulty telephone exchange, reaches the "wrong number." The result disturbs both the sender and the receiver.

15–3 RATING SYSTEMS

Goals of a Noise-Rating System

An ideal noise-rating system is one that allows measurements by sound level meters or analyzers to be summarized succinctly and yet represent noise exposure in a meaningful way. In our previous discussions on loudness and annoyance, we noted that our response to sound is strongly dependent on the frequency of the sound. Furthermore, we noted that the type of noise (continuous, intermittent, or impulsive) and the time of day that it occurred (night being worse than day) were significant factors in annoyance.

Thus, the ideal system must take frequency into account. It should differentiate between daytime and nighttime noise. And, finally, it must be capable of describing the cumulative noise exposure. A statistical system can satisfy these requirements.

The practical difficulty with a statistical rating system is that it would yield a large set of parameters for each measuring location. A much larger array of numbers would be required to characterize a neighborhood. It is literally impossible for such an array of numbers to be used effectively in enforcement. Thus, considerable effort has been made to define a single number measure of noise exposure. The following paragraphs describe one of the systems now being used.

The L_N Concept

The parameter L_N is a statistical measure that indicates how frequently a particular sound level is exceeded [12]. If, for example, we write $L_{30} = 67$ dBA, then we know that 72 dB(A) was exceeded for 30% of the measuring time. A plot of L_N against N where $N = 1\%, 2\%, 3\%$, and so forth, would look like the cumulative distribution curve shown in Figure 15–21.

Allied to the cumulative distribution curve is the probability distribution curve. A plot of this will show how often the noise levels fall into certain class intervals. In Figure 15–22 we can see that 35% of the time the measured noise levels ranged between 65 and 67 dBA; for 15% of the time they ranged between 67 and 69 dBA; and so on. The relationship between this picture and the one for L_N is really quite simple. By adding the percentages given in successive class intervals from right to left, we can arrive at a corresponding L_N, where N is the sum of the percentages and L is the lower limit of the left-most class interval added, thus, L_{30}

$$L(1 + 2 + 12 + 15) = 67 \text{ dBA}$$

FIGURE 15-21

Cumulative distribution curve.

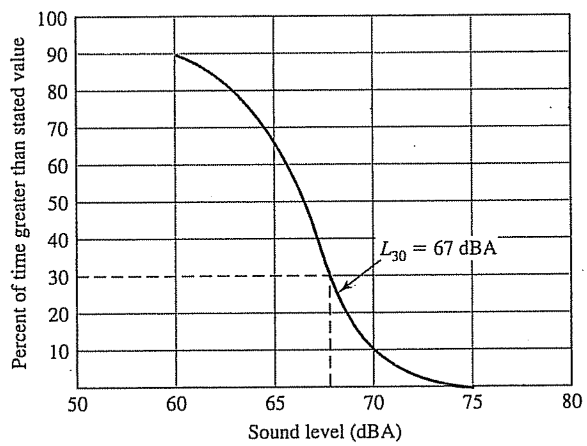
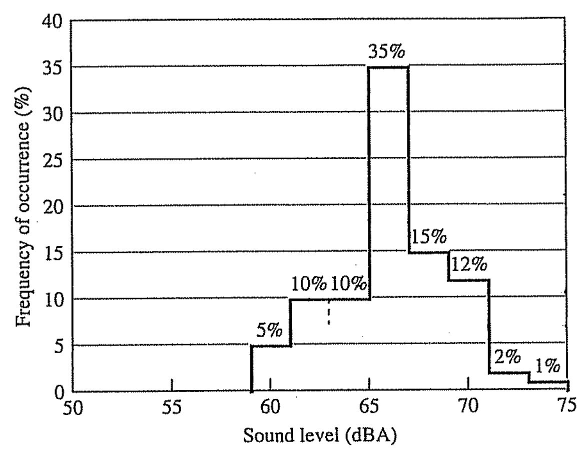


FIGURE 15-22

Probability distribution plot.



The L_{eq} Concept

The equivalent continuous equal energy level (L_{eq}) can be applied to any fluctuating noise level [12]. It is that constant noise level that, over a given time, expends the same amount of energy as the fluctuating level over the same period. It is expressed as follows.

$$L_{eq} = 10 \log \frac{1}{t} \int_0^t 10^{L(t)/10}\, dt \qquad (15\text{–}14)$$

where t = the time over which L_{eq} is determined
$L(t)$ = the time varying noise level in dBA

Generally speaking, there is no well-defined relationship between $L(t)$ and time, so a series of discrete samples of $L(t)$ have to be taken. This modifies the expression to

$$L_{eq} = 10 \log \sum_{i=1}^{i=n} 10^{L_i/10}\, t_i \qquad (15\text{–}15)$$

where n = the total number of samples taken
L_i = the noise level in dBA of the ith sample
t_i = fraction of total sample time

EXAMPLE 15-6 Consider the case where a noise level of 90 dBA exists for 10 min and is followed by a reduced noise level of 70 dBA for 30 min. What is the equivalent continuous equal energy level for the 40-min period? Assume a 5-min sampling interval.

Solution If the sampling interval is 5 min, then the total number of samples (n) is 8, and the fraction of total sample time (t_i) for each sample is 1/8 = 0.125. With these preliminary calculations, we may now compute the sum.

$$\sum_{t=1}^{2} = (10^{90/10})(0.250) + (10^{70/10})(0.750)$$

$$= (2.50 \times 10^8) + (7.50 \times 10^6) = 2.58 \times 10^8$$

And finally, we take the log to find

$$L_{eq} = 10 \log(2.58 \times 10^8) = 84.11, \text{ or } 84 \text{ dBA}$$

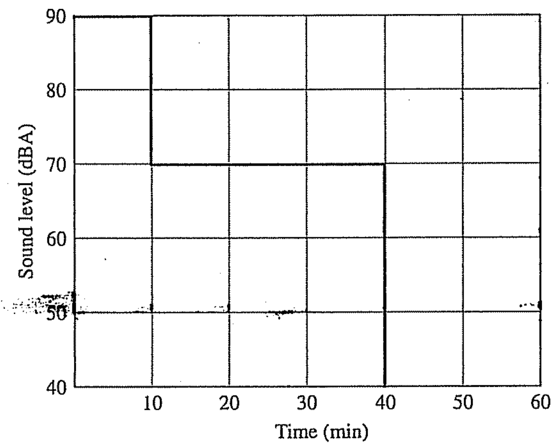


FIGURE 15–23

Graphical illustration of L_{eq} computation given in Example 15–6.

The example calculation is depicted graphically in Figure 15–23. From this you may note that great emphasis is put on occasional high noise levels.

The equivalent noise level was introduced in 1965 in Germany as a rating specifically to evaluate the effect of aircraft noise on the neighbors of airports [13]. It was almost immediately recognized in Austria as appropriate for evaluating the effect of street traffic noise in dwellings and schoolrooms. It has been embodied in the national test standards of Germany for rating the subjective effects of fluctuating noises of all kinds, such as from street and road traffic, rail traffic, canal and river ship traffic, aircraft, industrial operations (including the noise from individual machines), sports stadiums, playgrounds, and the like.

15–4 COMMUNITY NOISE SOURCES AND CRITERIA

It is not our intent to provide a detailed discussion of the noise characteristics of all community noise sources. Likewise, we have not attempted to provide a comprehensive list of noise criteria. Rather, we have selected a few examples to provide you with a feeling for the magnitude and range of the numbers.

Transportation Noise

Aircraft Noise. The noise spectra of a wide body fan jet (e.g., the Boeing 747) reveal that sound pressure levels are higher on takeoff than during the approach to land. This is typical of all aircraft. With the notable exception of the turbo jets, smaller aircraft have lower sound pressure levels.

The annoyance criteria for aircraft operations are based on extensive field measurements and opinion surveys. The results of annoyance surveys at nine airports in the United States and Great Britain are summarized in Figure 15–24. L_{dn} is the L_{eq} for a 24-h period with a 10-dB penalty added to the sound levels that occur during the night which is defined as 10 P.M. to 7 A.M.

Highway Vehicle Noise. For most automobiles, exhaust noise constitutes the predominant source for normal operation below about 55 km · h^{-1} (Figure 15–25). Although tire noise is much less of a problem in automobiles than in trucks, it is the dominant noise source at speeds above 80 km · h^{-1}. Although not as noisy as trucks, the total contribution of automobiles to the noise environment is significant because of the very large number in operation.

Diesel trucks are 8–10 dB noisier than gasoline-powered ones. At speeds above 80 km · h^{-1}, tire noise often becomes the dominant noise source on the truck. The "crossbar" tread is the noisiest.

Motorcycle noise is highly dependent on the speed of the vehicle. The primary source of noise is the exhaust. The noise spectra of two-cycle and four-cycle engines are of somewhat different character. The two-cycle engines exhibit more high-frequency spectra energy content.

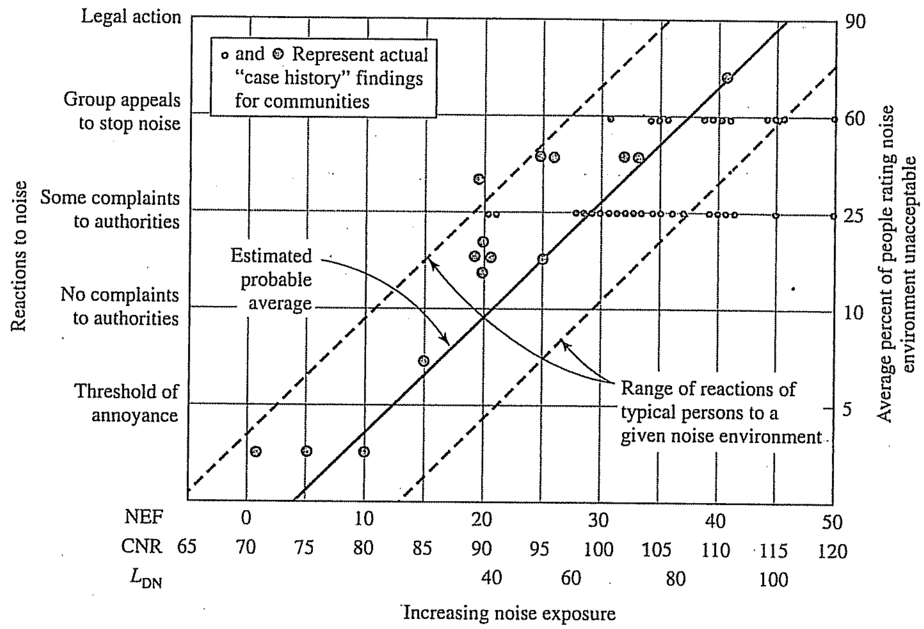
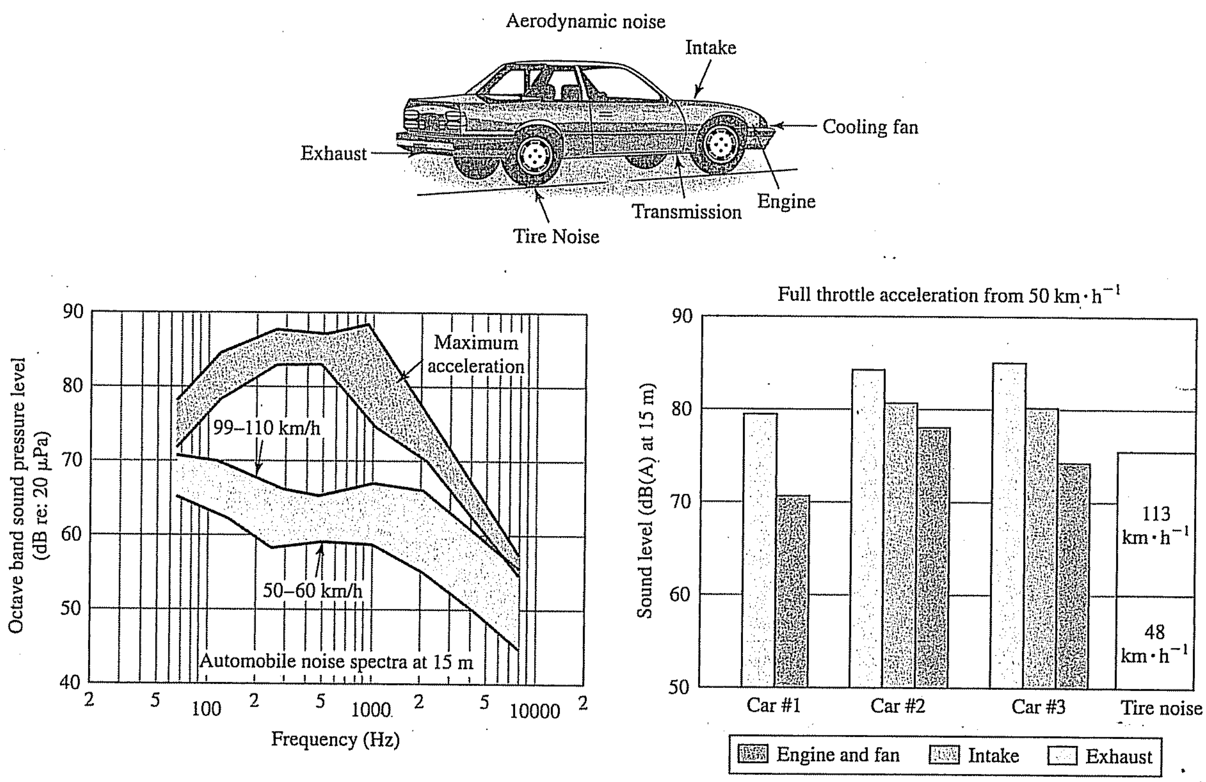


FIGURE 15–24

Relationship between exposure to aircraft noise and annoyance. (*Source:* K. D. Kryter, G. Jansen, D. Parker, et al., *Non-Auditory Effects of Noise.* Report of WG-63, National Academy of Science–National Research Council Committee on Hearing, Bioacoustics, and Biomechanics, Washington, DC: U.S. GPO, 1971.)

FIGURE 15–25

Typical noise spectra of automobiles. (*Source:* U.S. Environmental Protection Agency, *Transportation Noise,* Washington, DC: U.S. Government Printing Office, 1971.)



The U.S. Federal Highway Administration has developed the traffic noise standards shown in Table 15–3. The levels are above those that would be expected to yield no problems but are below those of many existing highways.

Other Internal Combustion Engines

Because of their ubiquitous nature and the general interest they stimulate, the combustion engines listed in Table 15–4 are included at this point. "In general, these devices are not significant

TABLE 15–3 FHA Noise Standards for New Construction

Land Use Category	Exterior Design Noise Level[a] (dBA) L_{eq}	L_{10}	Description of Land Use Category
A	57	60	Tracts of lands in 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. For example, such areas could include amphitheaters, particular parks or portions of parks, or open spaces, which are dedicated or recognized by appropriate local officials for activities requiring special qualities of serenity and quiet.
B	67	70	Residences, motels, hotels, public meeting rooms, schools, churches, libraries, hospitals, picnic areas, recreation areas, playgrounds active sports areas, and parks.
C	72	75	Developed lands, properties or activities not included in categories A and B.
D	Unlimited	Unlimited	Undeveloped lands.
E	52 (interior)	55 (interior)	Public meeting rooms, schools, churches, libraries, hospitals, and other such public buildings.

[a]Either L_{eq} or L_{10} may be used, but not both. The levels are to be based on a 1-h sample.

TABLE 15–4 Summary of Noise Characteristics of Internal Combustion Engines

Source	A-Weighted Noise Energy[a] ($kW \cdot h \cdot day^{-1}$)	Typical A-Weighted Noise Level at 15.2 m (dBA)	8-h Exposure Level[b] (dBA) Average	Maximum	Typical Exposure Time (h)
Lawn mowers	63	74	74	82	1.5
Garden tractors	63	78	N/A	N/A	N/A
Chain saws	40	82	85	95	1
Snow blowers	40	84	61	75	1
Lawn edgers	16	78	67	75	0.5
Model aircraft	12	78	70[c]	79[c]	0.25
Leaf blowers	3.2	76	67	75	0.25
Generators	0.8	71	—	—	—
Tillers	0.4	70	72	80	1

[a]Based on estimates of the total number of units in operation per day.
[b]Equivalent level for evaluation of relative hearing damage risk.
[c]During engine trimming operation.
Source: U.S. Environmental Protection Agency, *Transportation Noise and Noise from Equipment Powered by Internal Combustion Engines*, EPA Pub. No. NTID 300.13, Government Printing Office, Washington, D.C., 1971.

contributors to average residential noise levels in urban areas. However, the relative annoyance of most of the equipment tends to be high [14]." The 8-h exposure level is in reference to the equipment operator.

Construction Noise

The range of sound levels found for 19 common types of construction equipment is shown in Figure 15–26. Although the sample was limited, the data appear to be reasonably accurate. The noise produced by the interaction of the machine and the material on which it acts often contributes greatly to the sound level.

FIGURE 15–26

Range of sound levels from various types of construction equipment (based on limited available data samples). (*Source: Report to the President and Congress on Noise*, 1972.)

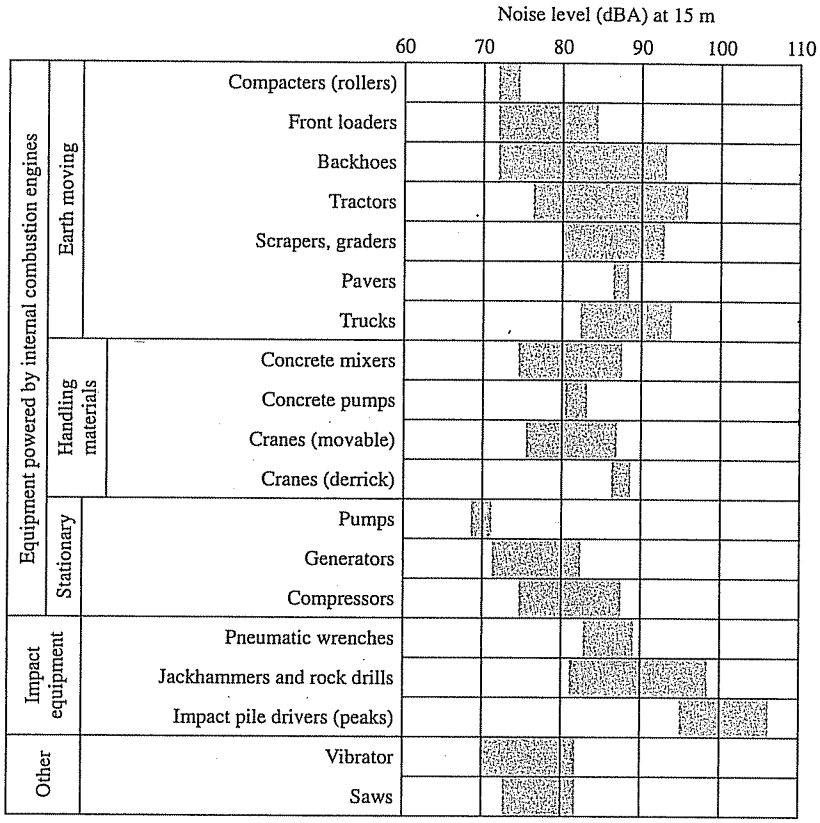


TABLE 15–5 HUD Noise Assessment Criteria for New Residential Construction

General External Exposures	Assessment
Exceeds 89 dBA 60 min per 24 hours Exceeds 75 dBA 8 hours per 24 hours CNR zone 3, NEF zone C (airport environs) $L_{NP} > 88$ dB (NP) (exterior)	Unacceptable
Exceeds 65 dBA 8 hours per 24 hours Loud repetitive sounds on site CNR zone 2, NEF zone B (airport environs) L_{NP} 74–88 dB (NP) (exterior)	Discretionary: normally unacceptable
Does not exceed 65 dBA more than 8 hours per 24 hours L_{NP} 62–74 dB (NP) (exterior)	Discretionary: normally acceptable
Does not exceed 45 dBA more than 30 min per 24 hours CNR zone I, NEF zone A (airport environs) $L_{NP} < 62$ dB (NP) (exterior)	Acceptable

It is difficult, at best, to quantify the annoyance that results from construction noise. The following generalizations appear to hold.

1. Single-house construction in suburban communities will generate sporadic complaints if the boundary line 8-h L_{eq} exceeds 70 dBA.
2. Major excavation and construction in a normal suburban community will generate threats of legal action if the boundary line 8-h L_{eq} exceeds 85 dBA.

Zoning and Siting Considerations

The U.S. Department of Housing and Urban Development (HUD) set out guideline criteria for noise exposure at residential sites for new construction (Table 15–5). The Federal Aviation

Administration (FAA) has also specified noise levels for land use compatibility. These guidelines, and those given earlier for traffic noise (see Table 15–3), if followed in zoning and siting, will minimize annoyance and complaints.

Levels to Protect Health and Welfare

In accordance with the directive from Congress, the EPA published noise criteria levels that it deemed necessary to protect the health and welfare of U.S. citizens (Table 15–6) [15]. The EPA maintained that a quiet residential environment is necessary in both urban and rural areas to prevent activity interference and annoyance and to permit the hearing mechanism an opportunity to recuperate if it is exposed to high levels during the day. The L_{dn} of 45 provides a fair margin of safety.

15–5 TRANSMISSION OF SOUND OUTDOORS

Inverse Square Law

If a sphere of radius δ vibrates with a uniform radial expansion and contraction, sound waves radiate uniformly from its surface. If the sphere is placed such that no sound waves are reflected back in the direction of the source, and if the product $\kappa\delta$, where κ is the wave number,* is much less than 1, then the sound intensity at any radial distance r from the sphere is inversely proportional to the square of distance, that is,

$$I = \frac{W}{4\pi r^2} \quad (15\text{–}16)$$

where I = sound intensity (in $W \cdot m^{-2}$)
W = sound power of source (in W)

This is the **inverse square law.** It explains that portion of the reduction of sound intensity with distance that is due to wave divergence (Figure 15–27). For a line source such as a roadway or a railroad, the reduction of sound intensity is inversely proportional to r rather than r^2. From a practical standpoint it is difficult if not impossible to measure the sound power of the source. In such instances we measure the sound pressure level at some known distance from the source and then use the inverse square law or radial dependence relationships to estimate the sound pressure level at some other distance. For example, using the inverse square law, the sound pressure level, L_{p2}, at a distance r_2 from the source may be determined if the sound pressure level, L_{p1}, at some closer point, r_1, is known:

$$L_{p2} = L_{p1} - 10\log\left(\frac{r_2}{r_1}\right)^2 \quad (15\text{–}17)$$

For a line source, the sound pressure level, L_{p2}, at a distance r_2 from the source may be determined at some closer point, r_1 by a similar equation.

$$L_{p2} = L_{p1} - 10\log\left(\frac{r_2}{r_1}\right) \quad (15\text{–}18)$$

*$\kappa = 2\pi/\lambda$, where λ wavelength, κ has units of reciprocal length, m^{-1}.

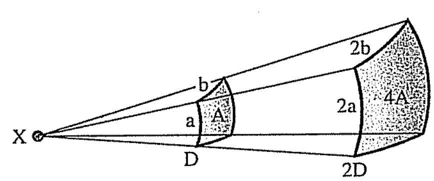


FIGURE 15–27

Illustration of inverse square law.

TABLE 15-6 Yearly Energy Average L_{eq} Identified as Requisite to Protect the Public Health and Welfare with an Adequate Margin of Safety

		Indoor			Outdoor		
	Measure	**Activity Interference**	**Hearing Loss Consideration**	**To Protect Against Both Effects[b]**	**Activity Interference**	**Hearing Loss Consideration**	**To Protect Against Both Effects[b]**
Residential with outside space and farm residences	L_{dn}	45		45	55		55
	$L_{eq(24)}$		70			70	
Residential with no outside space	L_{dn}	45		45			
	$L_{eq(24)}$		70				
Commercial	$L_{eq(24)}$	a	70	70[c]	a	70	70[c]
Inside transportation	$L_{eq(24)}$	a	70	a			
Industrial	$L_{eq(24)}$[d]	a	70	70[c]	a	70	70[c]
Hospitals	L_{dn}	45		45	55		55
	$L_{eq(24)}$		70			70	
Educational	$L_{eq(24)}$	45		45	55		55
	$L_{eq(24)}$[d]		70			70	
Recreational areas	$L_{eq(24)}$	a	70	70[c]	a	70	70[c]
Farm land and general unpopulated land	$L_{eq(24)}$				a	70	70[c]

[a]Because different types of activities appear to be associated with different levels, identification of a maximum level for activity interference may be difficult except when speech communication is a critical activity.

[b]Based on lowest level.

[c]Based only on hearing loss.

[d]An $L_{eq(8)}$ of 75 dB may be identified in these situations so long as the exposure over the remaining 16 h per day is low enough to result in negligible contribution to the 24-h average, that is, no greater than an L_{eq} of 60 dB.

Note: Explanation of identified level for hearing loss: The exposure period that results in hearing loss at the identified level is a period of 40 years.

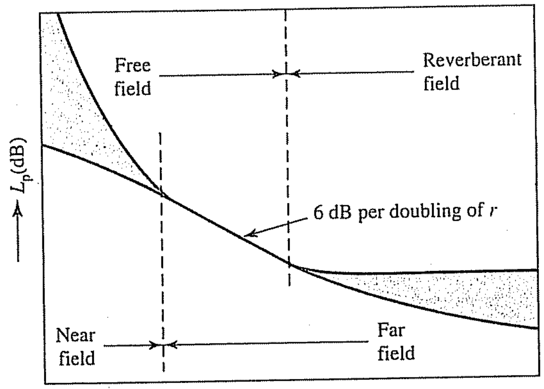


FIGURE 15–28

Variation of sound-pressure level in an enclosure along radius r from a noise source. (*Source:* L. L. Beranek, *Noise and Vibration Control*, McGraw-Hill, New York, 1971. Reprinted by permission.)

Radiation Fields of a Sound Source

The character of the wave radiation from a noise source will vary with distance from the source (Figure 15–28). At locations close to the source, the **near field,** the particle velocity is not in phase with the sound pressure. In this area, L_p fluctuates with distance and does not follow the inverse square law. When the particle velocity and sound pressure are in phase, the location of the sound measurement is said to be in the **far field.** If the sound source is in free space, that is, there are no reflecting surfaces, then measurements in the far field are also **free field measurements**. If the sound source is in a highly reflective space, for example, a room with steel walls, ceiling and floor, then measurements in the far field are also **reverberant field measurements.** The shaded area in the far field of Figure 15–28 shows that L_p does not follow the inverse square law in the reverberant field.

Directivity

Most real sources do not radiate sound uniformly in all directions. If you were to measure the sound pressure level in a given frequency band at a fixed distance from a real source, you would find different levels for different directions. If you plotted these data in polar coordinates, you would obtain the directivity pattern of the source.

The **directivity factor** is the numerical measure of the directivity of a sound source. In logarithmic form the directivity factor is called the **directivity index.** For a spherical source it is defined as follows:

$$DI_\theta = L_{p\theta} - L_{ps} \qquad (15\text{–}19)$$

where $L_{p\theta}$ = sound pressure level measured at distance r' and angle θ from a directive source radiating power W into an echo-free (**anechoic**) space (in dB)

L_{ps} = sound pressure level measured at distance r' from a nondirective source radiating power W into anechoic space (in dB). This is the same source as the directive source, but acting in the ideal fashion that we assumed in developing the inverse square law.

For a source located on or near a hard, flat surface, the directivity index takes the following form:

$$DI_\theta = L_{p\theta} - L_{ps} + 3 \qquad (15\text{–}20)$$

The 3-dB addition is made because the measurement is made over a hemisphere instead of a sphere. That is, the intensity at a radius, r, is twice as large if a source radiates into a hemisphere rather than the ideal sphere we have used up to this point. Each directivity index is applicable only to the angle at which L_p was measured and only for the frequency at which it was measured.

We assume that the directivity pattern does not change its shape regardless of the distance from the source. This allows us to apply the inverse square law to directive sources simply by measuring the sound pressure level at a distance r_1, along the directive angle of interest.

Airborne Transmission

Effects of Atmospheric Conditions. Sound energy is absorbed in quiet isotropic air by molecular excitation and relaxation of oxygen molecules and, at very low temperatures, by heat conduction and viscosity in the air. Molecular excitation is a complex function of the frequency of noise, humidity, and temperature. In general, we may say that as the humidity decreases, sound absorption increases. As the temperature increases to about 10–20°C (depending on the noise frequency), absorption increases. Above 25°C, absorption decreases. Sound absorption is higher at higher frequencies.

The vertical temperature profile greatly alters the propagation paths of sound. If a superadiabatic lapse rate exists, sound rays bend upward and noise shadow zones are formed. If an inversion exists, sound rays are bent back toward the ground. This results in an increase in the sound level. These effects are negligible for short distances but may exceed 10 dB at distances over 800 m.

In a similar fashion, wind speed gradients alter the way noise propagates. Sound traveling with the wind is bent down, while sound traveling against the wind is bent upward. When sound waves are bent down, there is little or no increase in sound levels. But when sound waves are bent upward, sound levels can be noticeably reduced.

Basic Point Source Model. A point source is one for which $\kappa\delta \ll 1$ and for which Equation 15–16 holds. According to Magrab,

> In practice most noise sources cannot be classified as simple point sources. However, the sound field of a complicated sound source will look as if it were a point source if the following two conditions are met: (1) $r/\delta \gg 1$ that is, the distance from the source is large compared to its characteristic dimension, and (2) $\delta/\lambda \ll r/\delta$, that is, the ratio of the size of the source to the wavelength of sound in the medium is small compared to the ratio of the distance from the source to its characteristic dimension. Recall that $r/\delta \gg 1$ from the first condition. A value of $r/\delta > 3$ is a sufficient approximation; therefore, $\delta\lambda \ll 3$ [16].

The basic point source equation is

$$L_{p2} = L_{p1} - 10\log\left(\frac{r_2}{r_1}\right)^2 - A_e \quad (15\text{–}21)$$

where L_{p2} = the desired SPL at angle θ and distance r_2 from source (in dB)
L_{p1} = the measured SPL at angle θ and distance r_1 from source (in dB)
r_1, r_2 = distance from source to measurement L_{p1} and L_{p2}, respectively
A_e = attenuation for the distance $r_2 - r_1$ (in dB)

With the exception of the last term (A_e), it is the inverse square law. The A_e term is the excess attenuation beyond wave divergence. It is caused by environmental conditions and has units of decibels.

The A_e term may be further divided into six terms as follows [17]:

A_{e1} = effect of the difference in value of ρc from 400 rayls when the ambient temperature and barometric pressure differ appreciably from values that make $\rho c = 400$, for example, 38.9°C and 101.325 kPa. Units are decibels. (1 rayl = 1 $N \cdot s \cdot m^{-3}$)
A_{e2} = attenuation by absorption in the air (in dB)
A_{e3} = attenuation by rain, sleet, snow, or fog (in dB)
A_{e4} = attenuation by barriers (in dB)
A_{e5} = attenuation by grass, shrubbery, and trees (in dB)
A_{e6} = attenuation and fluctuation owing to wind and temperature gradients, to atmospheric turbulence, and to the characteristics of the ground (in dB)

The effect of the difference in ρc from 400 rayls can be calculated by first computing the change in density (ρ) due to temperature and pressure changes (see "Gas Laws" in Chapter 2).

The effect of temperature changes on the speed of sound (c) can be calculated using Equation 15–6. The total attenuation, A_{e1}, is then computed as follows:

$$A_{e1} = 10 \log \frac{\rho c}{400} \tag{15–22}$$

The sign of A_{e1} is +. Thus, positive values of the right side of Equation 15–22 serve to reduce L_{p2} and negative values increase it.

Results of laboratory tests of the effects of temperature and humidity on attenuation of sound, A_{e2}, in the frequency range of 1.25 to 12,500 Hz, for temperatures between −10 and 30°C, and for relative humidities between 10 and 90% have been published by the Society of Automotive Engineers [18]. For a temperature of 20°C, the following formula may be used [19]:

$$A_{e2} = 7.4 \times 10^{-8} \frac{f^2 r}{\phi} \tag{15–23}$$

where f = geometric mean frequency of band (in Hz)
r = distance between source and receiver (in m)
ϕ = relative humidity (%)

For other temperatures (20 ± 10°C), an approximate solution may be used.

$$A'_{e2} = \frac{A_{e2}}{1 + (\beta)(\Delta T)(f)} \tag{15–24}$$

where A'_{e2} = attenuation at 20°C and ϕ = 50% from Equation 15–23 (in dB)
$\beta = 4 \times 10^{-6}$ for T (in °C)
$\Delta T = T - 20$°C
T = temperature (in °C)

The excess attenuation due to rain, mist, fog, hail, sleet, and snow have not been studied extensively. A_{e3} is on the order of 0.5×10^{-3} dB · m^{-1} in fog and generally is taken to be zero for conservative estimates.

The attenuation due to barriers (A_{e4}) is a complex function of the path length and the wavelength of the sound. This topic is beyond the scope of this text.

The absorption data for grass, shrubbery, and trees (A_{e5}) are not easy to generalize. Attenuations range from 0 to 0.30 dB · m^{-1}. This analysis, too, is beyond the scope of this text.

The effects of wind and stability (A_{e6}) are treated separately for upwind and downwind receptors. For the downwind case, Figure 15–29 is used to calculate A_{e6}. For the upwind case,

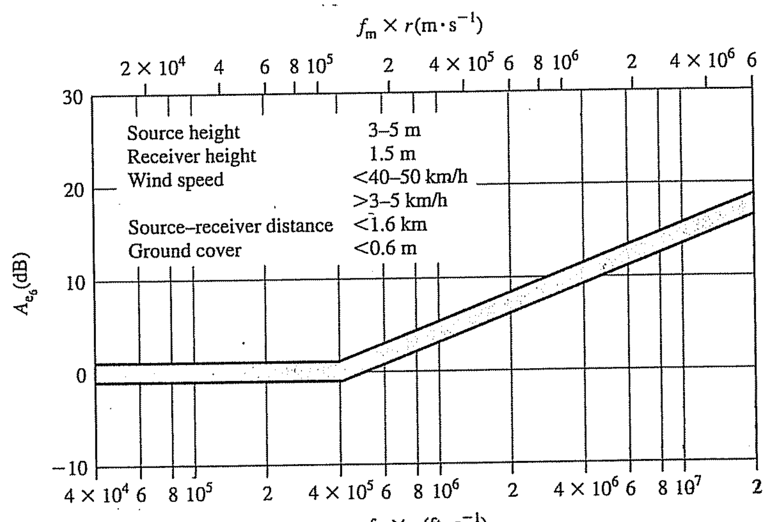


FIGURE 15–29

Downwind excess attenuation, A_{e6}. (*Source:* L. L. Beranek, *Noise and Vibration Control.* Reprinted by permission.)

TABLE 15–7 Estimates of X_0 Upwind, 300–5000 Hz ($\phi = 0$)

Time		Sky		Temperature Profile			Wind speed	X_0
Day	Night	Clear	Overcast	Lapse	Neutral	Inversion	($m \cdot s^{-1}$)	(m)
x		x		x			4–8	75
x			x		x		4–7	120
	x	x				x	1–2	600

FIGURE 15–30

Definition of the "shadow zone" for upwind excess attenuation.
Code:
x_0 Distance from source to shadow zone
ϕ Angle between wind and sound
ϕ_c Critical angle
(*Source:* L. L. Beranek, *Noise and Vibration Control.* Reprinted by permission.)

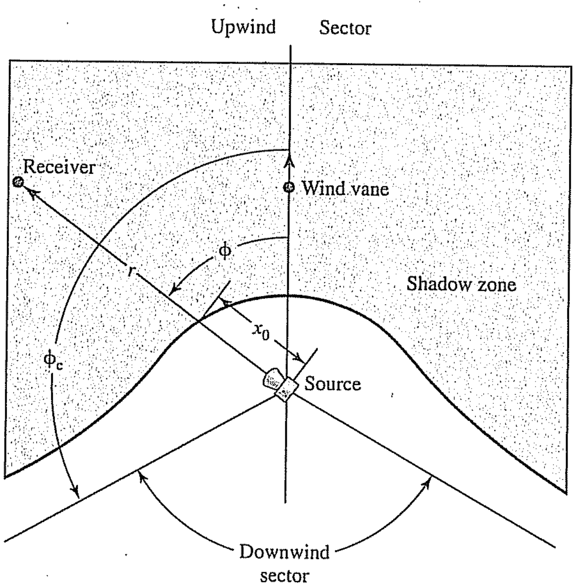
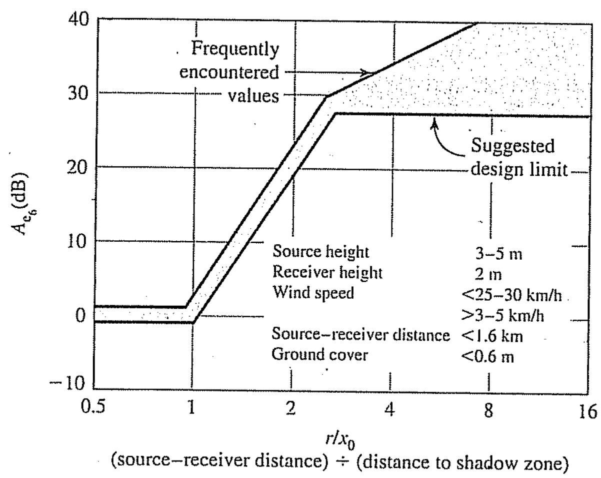


FIGURE 15–31

Upwind excess attenuation. (*Source:* L. L. Beranek, *Noise and Vibration Control.* Reprinted by permission.)



one nighttime and two daytime conditions are considered (Table 15–7). The quantity X_0 is the estimated distance from the noise source to the edge of the shadow zone (Figure 15–30). This is where the wind and temperature deflection of the sound waves begins to come into play. Once the value of X_0 is determined, Figure 15–31 can be used to select the attenuation value.

EXAMPLE 15–7 The sound pressure level (SPL) measured 50 m from a compressor is 90 dB at 1000 Hz. Determine the SPL 200 m upwind and downwind on a clear summer afternoon if the wind speed is $5\ m \cdot s^{-1}$, the temperature is 20°C, the relative humidity is 50%, and the barometric pressure is 100.325 kPa.

Solution We begin by computing the A_e terms. We assume that the L_{p1} measurement was taken at the same temperature and pressure at which the L_{p2} estimate is to be made. Thus, the value of A_{e1} at r_2 is the same as the value at r_1, and the attenuation for the distance $r_2 - r_1$ is zero, that is, $A_{e1} = 0.0$.

The attenuation by air absorption is calculated directly from Equation 15–23 with the $r_2 - r_1$ distance being 200 − 50 = 150 m.

$$A_{e2} = 7.4 \times 10^{-8} \frac{(1000)^2(150)}{50}$$

$$= 0.22 \text{ dB}$$

We assume that A_{e3}, A_{e4}, and A_{e5} all equal zero for the reasons noted in the text. The attenuation, A_{e6}, for downwind may be determined from Figure 15–29 after we have computed the abscissa quantity. Note that we assume that the 50-m measurement was taken under the same conditions as for the prediction at 200 m.

For r_1,

$$f_m \times r = (1000 \text{ Hz})(50 \text{ m}) = 5.0 \times 10^4 \text{ m} \cdot \text{s}^{-1}$$

and from Figure 15–29 we find A_{e6} is 0 dB.

For r_2,

$$f_m \times r = (1000 \text{ Hz})(200 \text{ m}) = 2.00 \times 10^5 \text{ m} \cdot \text{s}^{-1}$$

and $A_{e6} = 2$ dB from Figure 15–29. The resultant value for $r_2 - r_1$ is then

$$A_{e6} = 2 - 0 = 2 \text{ dB}$$

For the upwind case we must start with Table 15–7. From the problem statement, we find it is a clear summer afternoon. From this we can assume a lapse temperature profile, and because $5 \text{ m} \cdot \text{s}^{-1}$ is within the limits of the table, $X_0 = 75$ m. At lower wind speeds the shadow zone is removed to quite a large distance and probably can be ignored for all practical purposes. At higher wind speeds the howl of the wind quickly moves X_0 toward the source.

With $X_0 = 75$, we calculate r/X_0 for r_1 and r_2, separately, and take the difference in A_{e6} values.

For r_1,

$$\frac{r}{X_0} = \frac{50}{75} = 0.67$$

and from Figure 15–31, $A_{e6} = 0$. For r_2,

$$\frac{r}{X_0} = \frac{200}{75} = 2.67$$

and $A_{e6} = 25$ dB from Figure 15–31. The resultant value is

$$A_{e6} = 25 - 0 = 25 \text{ dB}$$

The total downwind attenuation is then

$$\sum = 0 + 0.22 + 0 + 0 + 0 + 2$$

$$= 2.22 \text{ dB}$$

The total upwind attenuation is then

$$\sum = 0 + 0.22 + 0 + 0 + 0 + 25$$

$$= 25.22 \text{ dB}.$$

Using Equation 15–21, the downwind SPL is

$$L_{p2} = 90 - 10 \log\left(\frac{200}{50}\right)^2 - 2.22$$

$$= 75.74, \text{ or } 76 \text{ dB at } 1000 \text{ Hz}$$

The upwind SPL is

$$L_{p2} = 90 - 10\log\left(\frac{200}{50}\right)^2 - 25.22$$

$$= 52.74, \text{ or } 53 \text{ dB at } 1000 \text{ Hz}$$

Obviously, it is much better to be upwind. Note that if you wished to estimate L_{eq}, L_{dn}, L_A, and so on, the value of L_{p2} would have to be calculated at each octave band geometric mean frequency and then summed by decibel addition.

15–6 TRAFFIC NOISE PREDICTION

L_{eq} Prediction

The Ontario Ministry of Transportation and Communications developed a traffic noise prediction equation based on the L_{eq} concept [20]. The empirical equation they developed is as follows:

$$L_{eq} = 42.3 + 10.2\log(V_c + 6V_t) - 13.9\log D + 0.13S \quad (15\text{–}25)$$

where L_{eq} = energy equivalent sound level during 1 h (in dBA)
V_c = volume of automobiles (four tires only) (in vehicles $\cdot$ h^{-1})
V_t = volume of trucks (six or more tires) (in vehicles $\cdot$ h^{-1})
D = distance from edge of pavement to receiver (in m)
S = average speed of traffic flow during 1 h (in km $\cdot$ h^{-1})

This equation does not account for barriers. A nomograph is available to take barriers into account.

L_{dn} Prediction

The Ontario method is a direct extension of the L_{eq} methodology that enables the calculation of L_{dn}. The modified model has the following form:

$$L_{dn} = 31.0 + 10.2\log[\text{ADDT} + \%T\,\text{ADDT}/20] - 13.9\log D + 0.13S \quad (15\text{–}26)$$

where L_{dn} = equivalent A-weighted sound level during 24-h period with 10-dBA weighting applied to 2200 – 0700 h (in dBA)
ADDT = annual average daily traffic (in vehicles $\cdot$ day^{-1})
$\%T$ = average percentage of trucks during a typical day (%)

This equation, like Equation 15–25, does not take into account barriers.

15–7 NOISE CONTROL

Source-Path-Receiver Concept

If you have a noise problem and want to solve it, you have to find out something about what the noise is doing, where it comes from, how it travels, and what can be done about it. A straightforward approach is to examine the problem in terms of its three basic elements: that is, sound arises from a source, travels over a path, and affects a receiver or listener [21].

The source may be one or any number of mechanical devices that radiate noise or vibratory energy. Such a situation occurs when several appliances or machines are in operation at a given time in a home or office.

The most obvious transmission path by which noise travels is simply a direct line-of-sight air path between the source and the listener. For example, aircraft flyover noise reaches an observer on the ground by the direct line-of-sight air path. Noise also travels along structural paths. Noise can travel from one point to another via any one path or a combination of several paths. Noise from a washing machine operating in one apartment may be transmitted to another apartment along air passages such as open windows, doorways, corridors, or duct work. Direct physical contact of the washing machine with the floor or walls sets these building components into vibration. This vibration is transmitted structurally throughout the building, causing walls in other areas to vibrate and to radiate noise.

The receiver may be, for example, a single person, a classroom of students, or a suburban community.

Solution of a given noise problem might require alteration or modification of any or all of these three basic elements:

1. Modifying the source to reduce its noise output
2. Altering or controlling the transmission path and the environment to reduce the noise level reaching the listener
3. Providing the receiver with personal protective equipment

Control of Noise Source by Design

Reduce Impact Forces. Many machines and items of equipment are designed with parts that strike forcefully against other parts, producing noise. Often, this striking action or impact is essential to the machine's function. Several steps can be taken to reduce noise from impact forces. The particular remedy to be applied will be determined by the nature of the machine in question.

A few of the more obvious design modifications are

1. Reduce the weight, size, or height of fall of the impacting mass.
2. Cushion the impact by inserting a layer of shock-absorbing material between the impacting surfaces. In some situations, you could insert a layer of shock-absorbing material behind each of the impacting heads or objects to reduce the transmission of impact energy to other parts of the machine.
3. Whenever practical, one of the impact heads or surfaces should be made of nonmetallic material to reduce resonance (ringing) of the heads.
4. Substitute the application of a small impact force over a long period for a large force over a short period to achieve the same result.

Reduce Speeds and Pressures. Reducing the speed of rotating and moving parts in machines and mechanical systems results in smoother operation and lower noise output. Likewise, reducing pressure and flow velocities in air, gas, and liquid circulation systems lessens turbulence, resulting in decreased noise radiation. Some specific suggestions that may be incorporated in design are discussed the following sections.

Reduce Frictional Resistance. Reducing friction between rotating, sliding, or moving parts in mechanical systems frequently results in smoother operation and lower noise output. Similarly, reducing flow resistance in fluid distribution systems results in less noise radiation. Four of the more important factors that should be checked to reduce frictional resistance in moving parts are alignment, polish, balance, and eccentricity (out-of-roundness).

Reduce Radiating Area. Generally speaking, the larger the vibrating part or surface, the greater the noise output. The rule of thumb for quiet machine design is to minimize the effective radiating surface areas of the parts without impairing their operation or structural strength. This can be done by making parts smaller, removing excess material, or by cutting openings, slots, or perforations in the parts. For example, replacing a large, vibrating sheet-metal safety guard on a machine with a guard made of wire mesh or metal webbing might result in a substantial reduction in noise because of the drastic reduction in surface area of the part.

Reduce Noise Leakage. In many cases, machine cabinets can be made into rather effective soundproof enclosures through simple design changes and the application of some sound-absorbing treatment. Substantial reductions in noise output may be achieved by adopting some of the following recommendations:

1. All unnecessary holes or cracks, particularly at joints, should be caulked.
2. All electrical or plumbing penetrations of the housing or cabinet should be sealed with rubber gaskets or a suitable nonsetting caulk.
3. If practical, all other functional or required openings or ports that radiate noise should be covered with lids or shields edged with soft rubber gaskets to achieve an airtight seal.
4. Other openings required for exhaust, cooling, or ventilation purposes should be equipped with mufflers or acoustically lined ducts.
5. Openings should be directed away from the operator and other people.

Isolate and Dampen Vibrating Elements. In all but the simplest machines, the vibrational energy from a specific moving part is transmitted through the machine structure, forcing other component parts and surfaces to vibrate and radiate sound—often with greater intensity than that generated by the originating source itself.

Generally, vibration problems can be considered in two parts. First, we must prevent energy transmission between the source and surfaces that radiate the energy. Second, we must dissipate or attenuate the energy somewhere in the structure. The first part of the problem is solved by isolation. The second part is solved by damping.

The most effective method of vibration isolation involves the resilient mounting of the vibrating component on the most massive and structurally rigid part of the machine. Damping material or structures are those that have some viscous properties. They tend to bend or distort slightly, thus consuming part of the noise energy in molecular motion. The use of spring mounts on motors and laminated galvanized steel and plastic in air-conditioning ducts are two examples.

Provide Mufflers or Other Silencers. There is no real distinction between mufflers and silencers. They are often used interchangeably. They are, in effect, acoustical filters and are used when fluid flow noise is to be reduced. The devices can be classified into two fundamental groups: absorptive and reactive mufflers. An **absorptive muffler** is one whose noise reduction is determined mainly by the presence of fibrous or porous materials, which absorb the sound. A **reactive muffler** is one whose noise reduction is determined mainly by geometry. It is shaped to reflect or expand the sound waves with resultant self-destruction.

Although several terms are used to describe the performance of mufflers, the most frequently used appears to be insertion loss (IL). **Insertion loss** is the difference between two sound pressure levels that are measured at the same point in space before and after a muffler has been inserted. Because each muffler IL is highly dependent on the manufacturer's selection of materials and configuration, we will not present general IL prediction equations.

Noise Control in the Transmission Path

After you have tried all possible ways of controlling the noise at the source, your next line of defense is to set up devices in the transmission path to block or reduce the flow of sound energy before it reaches your ears. This can be done in several ways: (1) absorb the sound along the path, (2) deflect the sound in some other direction by placing a reflecting barrier in its path, or (3) contain the sound by placing the source inside a sound-insulating box or enclosure.

Selection of the most effective technique will depend on various factors, such as the size and type of source, intensity and frequency range of the noise, and the nature and type of environment.

Separation. We can make use of the absorptive capacity of the atmosphere, as well as divergence, as a simple, economical method of reducing the noise level. Air absorbs high-frequency sounds more effectively than low-frequency sounds. However, if enough distance is available, even low-frequency sounds will be absorbed appreciably.

If you can double your distance from a point source, you will have succeeded in lowering the sound pressure level by 6 dB. It takes about a 10-dB drop to halve the loudness. If you have to contend with a line source such as a railroad train, the noise level drops by only 3 dB for each doubling of distance from the source. The main reason for this lower rate of attenuation is that line sources radiate sound waves that are cylindrical in shape. The surface area of such waves only increases twofold for each doubling of distance from the source. However, when the distance from the train becomes comparable to its length, the noise level will begin to drop at a rate of 6 dB for each subsequent doubling of distance.

Indoors, the noise level generally drops only from 3 to 5 dB for each doubling of distance in the near vicinity of the source. However, farther from the source, reductions of only 1 or 2 dB occur for each doubling of distance due to the reflections of sound off hard walls and ceiling surfaces.

Absorbing Materials. Noise, like light, will bounce from one hard surface to another. In noise control work, this is called **reverberation.** If a soft, spongy material is placed on the walls, floors, and ceiling, the reflected sound will be diffused and soaked up (absorbed).

Sound-absorbing materials such as acoustical tile, carpets, and drapes placed on ceiling, floor, or wall surfaces can reduce the noise level in most rooms by about 5–10 dB for high-frequency sounds, but only 2–3 dB for low-frequency sounds. Unfortunately, such treatment provides no protection to an operator of a noisy machine who is in the midst of the direct noise field. For greatest effectiveness, sound-absorbing materials should be installed as close to the noise source as possible.

Because of their light weight and porous nature, acoustical materials are ineffectual in preventing the transmission of either airborne or structure-borne sound from one room to another. In other words, if you can hear people walking or talking in the room or apartment above, installing acoustical tile on your ceiling will not reduce the noise transmission.

Acoustical Lining. Noise transmitted through ducts, pipe chases, or electrical channels can be reduced effectively by lining the inside surfaces of such passageways with sound-absorbing materials. In typical duct installations, noise reductions on the order of 10 dB $\cdot$ m^{-1} for an acoustical lining 2.5 cm thick are well within reason for high-frequency noise. A comparable degree of noise reduction for the lower frequency sounds is considerably more difficult to achieve because it usually requires at least a doubling of the thickness or the length of acoustical treatment.

Barriers and Panels. Placing barriers, screens, or deflectors in the noise path can be an effective way of reducing noise transmission, provided that the barriers are large enough in size, and depending on whether the noise is high or low frequency. High-frequency noise is reduced more effectively than low frequency.

The effectiveness of a barrier depends on its location, its height, and its length. Referring to Figure 15–32, we can see that the noise can follow four different paths.

First, the noise follows a direct path to receivers who can see the source well over the top of the barrier. The barrier does not block their line of sight and therefore provides no attenuation. No matter how absorptive the barrier is, it cannot pull the sound downward and absorb it.

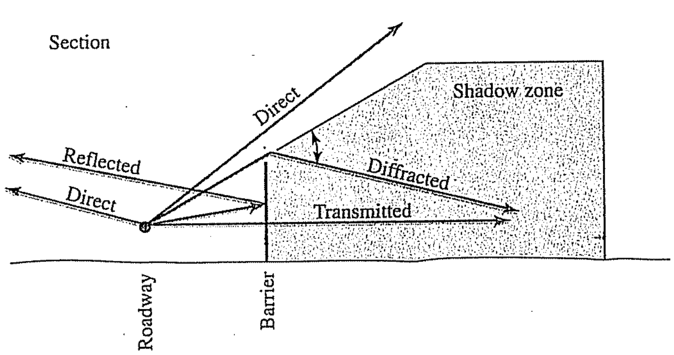


FIGURE 15–32

Noise paths from a source to a receiver. (*Source: National Cooperative Highway Research Program 174, 1976.*)

Second, the noise follows a diffracted path to receivers in the shadow zone of the barrier. The noise that passes just over the top edge of the barrier is diffracted (bent) down into the apparent shadow zone in the figure. The larger the angle of diffraction, the more the barrier attenuates the noise in this shadow zone. In other words, less energy is diffracted through large angles than through smaller ones.

Third, in the shadow zone, the noise transmitted directly through the barrier may be significant in some cases. For example, with extremely large angles of diffraction, the diffracted noise may be less than the transmitted noise. In this case, the transmitted noise compromises the performance of the barrier. It can be reduced by constructing a heavier barrier. The allowable amount of transmitted noise depends on the total barrier attenuation desired. More is said about this transmitted noise later.

The fourth path shown in Figure 15–32 is the reflected path. After reflection, the noise is of concern only to a receiver on the opposite side of the source. For this reason, acoustical absorption on the face of the barrier may sometimes be considered to reduce this reflected noise; however, this treatment will not benefit any receivers in the shadow zone. It should be noted that in most practical cases the reflected noise does not play an important role in barrier design. If the source of noise is represented by a line of noise, another short-circuit path is possible. Part of the source may be unshielded by the barrier. For example, the receiver might see the source beyond the ends of the barrier if the barrier is not long enough. This noise from around the ends may compromise, or short-circuit, barrier attenuation. The required barrier length depends on the total net attenuation desired. When 10–15-dB attenuation is desired, barriers must, in general, be very long. Therefore, to be effective, barriers must not only break the line of sight to the nearest section of the source but also to the source far up and down the line.

Of these four paths, the noise diffracted over the barrier into the shadow zone represents the most important parameter from the barrier design point of view. Generally, the determination of barrier attenuation or barrier noise reduction involves only calculation of the amount of energy diffracted into the shadow zone.

Enclosures. Sometimes it is much more practical and economical to enclose a noisy machine in a separate room or box than to quiet it by altering its design, operation, or component parts. The walls of the enclosure should be massive and airtight to contain the sound. Absorbent lining on the interior surfaces of the enclosure will reduce the reverberant buildup of noise within it. Structural contact between the noise source and the enclosure must be avoided, so that the source vibration is not transmitted to the enclosure walls, thus short-circuiting the isolation.

Control of Noise Source by Redress

The best way to solve noise problems is to design them out of the source. However, we are frequently faced with an existing source that, either because of age, abuse, or poor design, is a noise problem. The result is that we must redress, or correct, the problem as it currently exists. The following identify some measures that might apply if you are allowed to tinker with the source: balance rotating parts; reduce frictional resistance; apply damping materials; seal noise leaks; and perform routine maintenance to repair mufflers, rough road surfaces, and so forth.

Protect the Receiver

When All Else Fails. When exposure to intense noise fields is required and none of the measures discussed so far is practical, as, for example, for the operator of a chain saw or pavement breaker, then measures must be taken to protect the receiver. The following two techniques are commonly employed.

Alter Work Schedule. Limit the amount of continuous exposure to high noise levels. In terms of hearing protection, it is preferable to schedule an intensely noisy operation for a short interval of time each day over a period of several days rather than a continuous 8-h run for a day or two.

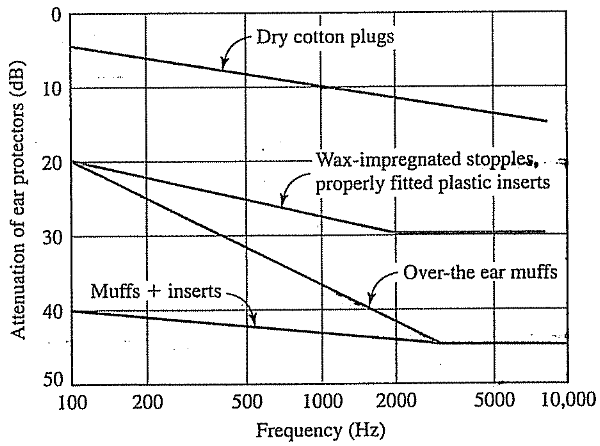


FIGURE 15–33

Attenuation of ear protectors at various frequencies. (*Source: National Bureau of Standards Handbook*, p. 119, 1976.)

In industrial or construction operations, an intermittent work schedule would benefit not only the operator of the noisy equipment, but also other workers in the vicinity. If an intermittent schedule is not possible, then workers should be given relief time during the day. They should take their relief time at a low-noise-level location and should be discouraged from trading relief time for dollars, paid vacation, or an "early out" at the end of the day!

Inherently noisy operations, such as street repair, municipal trash collection, factory operation, and aircraft traffic, should be curtailed at night and early morning to avoid disturbing the sleep of the community. Remember: operations between 10 P.M. and 7 A.M. are effectively 10 dBA higher than the measured value.

Ear Protection. Molded and pliable earplugs, cup-type protectors, and helmets are commercially available as hearing protectors. Such devices may provide noise reductions ranging from 15 to 35 dB (Figure 15–33). Earplugs are effective only if they are properly fitted by medical personnel. As shown in Figure 15–33, maximum protection can be obtained when both plugs and muffs are employed. Only muffs that have a certification stipulating the attenuation should be used.

These devices should be used only as a last resort, after all other methods have failed to lower the noise level to acceptable limits. Ear protection devices should be used while operating lawn mowers, mulchers, and chippers, and while firing weapons at target ranges. It should be noted that protective ear devices do interfere with speech communication and can be a hazard in some situations where warning calls may be a routine part of the operation (e.g., TIMBERRRR!). A modern ear-destructive device is a portable miniradio–recorder that uses earphones. In this "reverse" muff, high noise levels are directed at the ear without attenuation. If you can hear someone else's radio–recorder, that person is subjecting himself to noise levels in excess of 90–95 dBA!

CHAPTER REVIEW

When you have completed studying this chapter; you should be able to do the following without the aid of your textbook or notes:

1. Define frequency, based on a sketch of a harmonic wave you have drawn, and state its units of measure (namely, hertz, Hz).
2. State the basic unit of measure used in measuring sound energy (namely, the decibel, dB) and explain why it is used.
3. Define sound pressure level in mathematical terms, that is,

$$\text{SPL} = 20 \log \frac{P_{\text{rms}}}{(P_{\text{rms}})_0}$$

4. Explain why a weighting network is used in a sound level meter.

5. List the three common weighting networks and sketch their relative frequency response curves. (Label frequencies, that is, 20, 1000, and 10,000 Hz; and relative response, that is, 0, −5, −20, and −45 dB, as in Figure 15–6.)
6. Differentiate between a mid/high-frequency noise source and a low-frequency source on the basis of A, B, and C scale readings.
7. Explain the purpose of octave band analysis.
8. Differentiate among continuous, intermittent, and impulsive noise.
9. Sketch the curves and label the axes of the two typical types of impulsive noise.
10. Sketch a Fletcher–Munson curve, label the axes, and explain what the curve depicts.
11. Define *phon*.
12. Explain the mechanism by which hearing damage occurs.
13. Explain what hearing threshold level (HTL) is.
14. Define *presbycusis* and explain why it occurs.
15. Distinguish between temporary threshold shift (TTS), permanent threshold shift (PTS), and acoustic trauma with respect to cause of hearing loss, duration of exposure, and potential for recovery.
16. Explain why impulsive noise is more dangerous than steady-state noise.
17. Explain the relationship between the allowable duration of noise exposure and the allowable level for hearing protection, that is, damage-risk criteria.
18. List five effects of noise other than hearing damage.
19. List the three basic elements that might require alteration or modification to solve a noise problem.

With the aid of this text, you should be able to do the following:

1. Calculate the resultant sound pressure level from a combination of two or more sound pressure levels.
2. Determine the A-, B-, and C-weighted sound levels from octave band readings.
3. Compute the mean sound level from a series of sound level readings.
4. Compute the following noise statistics if you are provided the appropriate data: L_p or L_{eq}.
5. Determine whether or not a noise level will be acceptable given a series of measurements and the criteria listed in Tables 15–3, 15–5, and 15–6.
6. Calculate the sound level at a receptor site after transmission through the atmosphere.
7. Estimate the noise level (L_{eq} or L_{dn}) that might be expected for a given roadway configuration and traffic pattern.

PROBLEMS

15–1 A building located near a road is 6.92 m high. How high is the building in terms of wavelengths of a 50.0-Hz sound? Assume that the speed of sound is 346.12 m · s^{-1}.

Answer: One wavelength

15–2 Repeat Problem 15–1 for a 500-Hz sound if the temperature is 25.0°C.

15–3 Determine the sum of the following sound levels (all in decibels): 68, 82, 76, 68, 74, and 81.

Answer: 85.5, or 86 dB

15–4 A motorcyclist is warming up his racing cycle at a racetrack approximately 200 m from a sound level meter. The meter reading is 56 dBA. What meter reading would you expect if 15 of the motorcyclist's friends join him with motorcycles having exactly the same sound emission characteristics? You may assume that the sources may be treated as ideal point sources located at the same point.

15–5 A law enforcement officer has taken the following readings with her sound level meter. Is the noise source a predominantly low- or middle-frequency emitter? Readings: 80 dBA, 84 dBB, and 90 dBC.

Answer: Predominantly low frequency

15–6 The following readings have been made outside the open stage door of the opera house: 109 dBA, 110 dBB, and 111 dBC. Is the singer a bass or a soprano? Explain how you arrived at your answer.

15–7 Convert the following octave band measurements to an equivalent A-weighted level.

Band Center Frequency (Hz)	Band Level (dB)	Band Center Frequency (Hz)	Band Level (dB)
31.5	78	1000	80
63	76	2000	80
125	78	4000	73
250	82	8000	65
500	81		

Answer: 85.5, or 86 dBA

15–8 Using the typical noise spectrum for automobiles traveling at 50–60 km · h^{-1} (see Figure 15–25), determine the equivalent A-weighted level using the following octave band geometric mean center frequencies (all in hertz): 63, 125, 250, 500, 1000, 2000, 4000, and 8000.

15–9 Compute the average sound pressure level of the following readings by simple arithmetic averaging and by logarithmic averaging (see Equation 15–13) (all readings in decibels): 42, 50, 65, 71, and 47. Does arithmetic averaging underestimate or overestimate the sound pressure level?

Answers: $\bar{x} = 55.00$, or 55 dB $\bar{L}_p = 61.57$, or 62 dB

15–10 Repeat Problem 15–9 for the following data (all in decibels): 76, 59, 35, 69, and 72.

15–11 The following noise record was obtained in the front yard of a home. Is this a relatively quiet or a relatively noisy neighborhood? Determine the equivalent continuous equal energy level.

Time (h)	Sound Level (dBa)	Time (h)	Sound Level (dBa)
0000–0600	42	1500–1700	50
0600–0800	45	1700–1800	47
0800–0900	50	1800–0000	45
0900–1500	47		

Answers: It is a quiet neighborhood. $L_{eq} = 46.2$, or 46 dBA

15–12 A developer has proposed putting a small shopping mall next to a very quiet residential area in Nontroppo, Michigan. Based on the measurements shown in the following table, which were taken at a similar size mall in a similar setting, should the developer expect complaints or legal action? Calculate L_{eq}.

Time (h)	Sound Level (dBA)	Time (h)	Sound Level (dBA)
0000–0600	42	1000–2000	70
0600–0800	55	2000–2200	68
0800–1000	65	2200–0000	57

15–13 Two oil-fired boilers for a 600-MW (megawatt) power plant produce an 83-dB noise level at 31.5 Hz, 180.0 m from the induced draft fans. Determine the sound pressure level 488.0 m upwind on an overcast day when the wind speed is 4.50 m · s^{-1}, the temperature is 20.0°C, the relative humidity is 30.0%, and the barometric pressure is 106.0 kPa.

Answer: SPL at 488.0 m = 56 dB at 31.5 Hz

15–14 The sound pressure level from a jet engine test cell is 90 dB at 125 Hz, and at 1000 Hz at a distance of 400 m. What are the sound pressure levels at 125 and 1000 Hz, 1200 m downwind on a clear evening when the wind speed is $1.50 \text{ m} \cdot \text{s}^{-1}$, the temperature is 20.0°C, the relative humidity is 50.0%, and the barometric pressure is 103.2 kPa?

15–15 Consider an ideal single lane of road that carries 1200 vehicles per hour uniformly spaced along the road and determine the following:

(a) The average center-to-center spacing of the vehicles for an average traffic speed of $40.0 \text{ km} \cdot \text{h}^{-1}$.
(b) The number of vehicles in a 1-km length of the lane when the average speed is $40.0 \text{ km} \cdot \text{h}^{-1}$.
(c) The sound level (dBA) 60.0 m from a 1-km length of this roadway with automobiles emitting 71 dBA at the edge of an 8.0-m wide roadway. Assume that the autos travel at a speed of $40.0 \text{ km} \cdot \text{h}^{-1}$, that the sound radiates ideally from a hemisphere, and that contributions of less than 0.3 dBA may be ignored.

Answers: **(a)** Average center-to-center spacing = 33.3 m
(b) Number of vehicles in a kilometer length = $30 \text{ vehicles} \cdot \text{km}^{-1}$
(c) = 47.47, or 48 dBA

15–16 Repeat Problem 15–15 if the vehicle speed is increased to $80.0 \text{ km} \cdot \text{h}^{-1}$ and the spacing is decreased or increased appropriately to maintain $1200 \text{ vehicles} \cdot \text{h}^{-1}$.

15–17 In preparation for a public hearing on a proposed interstate bypass at Nontroppo, Michigan, the county road commission has requested that you prepare an estimate of the potential for violation of residential FHA noise standards 75 m from the centerline of the interstate. The edge of the pavement is 28.65 m from the centerline.

Data for I-481 at Pianissimo Avenue
Estimated traffic
Automobiles: 7800 per hour at $88.5 \text{ km} \cdot \text{h}^{-1}$
Heavy trucks: 650 per hour at $88.5 \text{ km} \cdot \text{h}^{-1}$

Compute the unattenuated L_{eq}, at the receiver for autos only.

Answer: $L_{eq} = 70$ dBA

15–18 Determine the potential for violation of FHA noise standards at the north side of Fermata School 123.17 m from the edge of the interstate highway.

Data for I-481 at Fermata School
Estimated traffic: Same as at Pianissimo Avenue (Problem 15–17)

Compute the unattenuated L_{eq} at the school for the combined traffic flow.

DISCUSSION QUESTIONS

15–1 Classify each of the following noise sources by type, that is, continuous, intermittent, or impulse. (Not all sources fit these three classifications.)

(a) Electric saw (b) Air conditioner (c) Alarm clock (bell type) (d) Punch press

15–2 Is the following statement true or false? If it is false, correct it in a nontrivial manner.

"A sonic boom occurs when an aircraft breaks the sound barrier."

15–3 Is the following statement true or false? If it is false, correct it in a nontrivial manner.

"Excessive continuous noise causes hearing damage by breaking the stapes."

15–4 As the safety officer of your company, you have been asked to determine the feasibility of reducing exposure time as a method of reducing hearing damage for the following situation:

> The worker is operating a high-speed grinder on steel girders for a high-rise building. The effective noise level at the operator's ear is 100 dBA. She cannot wear protective ear devices because she must communicate with others.

What amount of exposure time would you set as the limit?

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