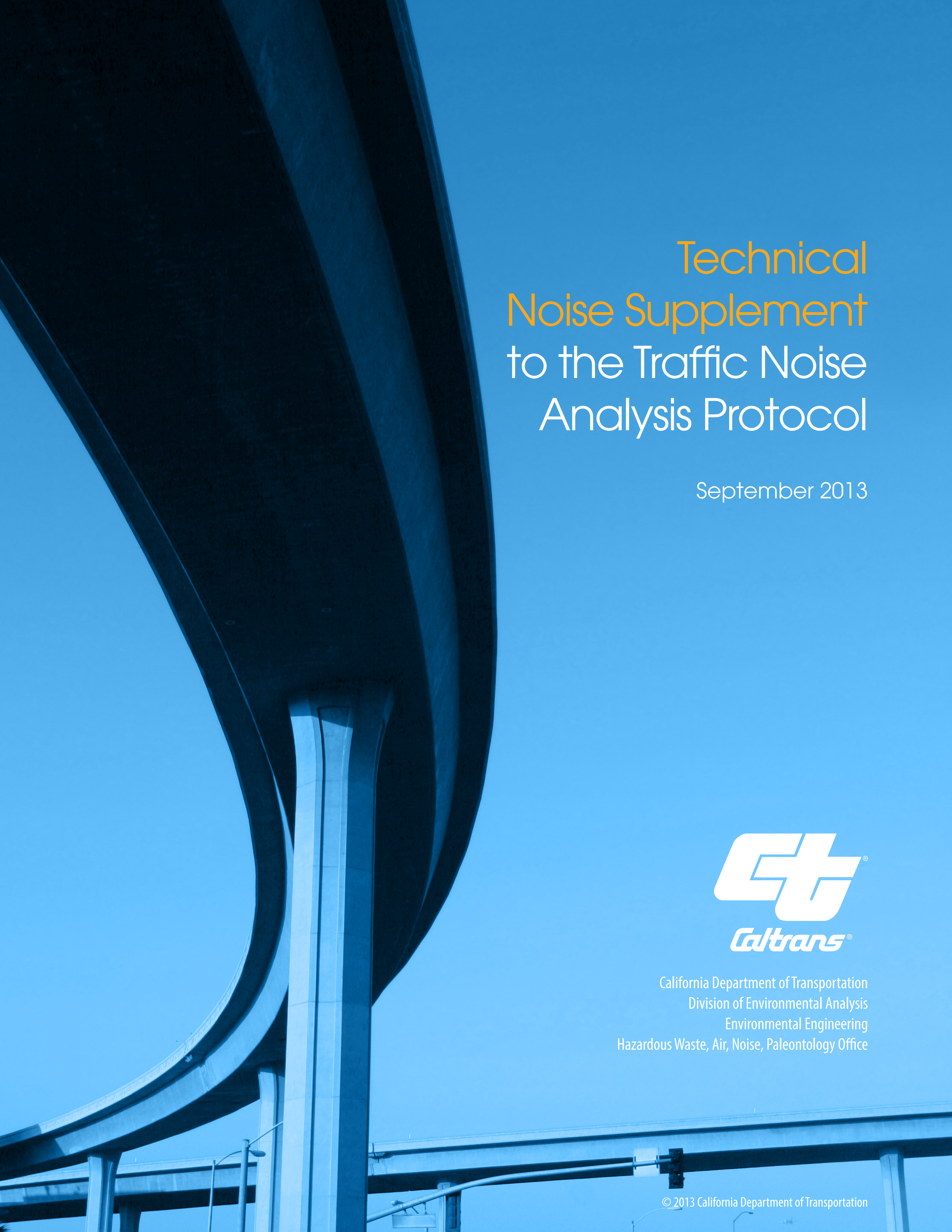

Technical Noise Supplement to the Traffic Noise Analysis Protocol

September 2013

Caltrans

California Department of Transportation
Division of Environmental Analysis
Environmental Engineering
Hazardous Waste, Air, Noise, Paleontology Office

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15. Abstract

This manual contains Caltrans noise analysis procedures, practices, and other useful technical background information related to the analysis and reporting of highway and construction noise impacts and abatement. It supplements and expands on concepts and procedures referred to in the *Traffic Noise Analysis Protocol*, which in turn is required by federal regulations in 23CFR772. *The contents of this document are not official policy, standard, or regulation*, and are for informational purposes—*unless they are referenced in the Protocol.* Except for some Caltrans-specific methods and procedures, most methods and procedures recommended in this document are in conformance with industry standards and practices. This document can be used as a stand-alone guide for highway noise training purposes or as a reference for technical concepts, methodology, and terminology needed to acquire a basic understanding of highway noise and construction noise-related issues.

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Technical Noise Supplement to the Caltrans Traffic Noise Analysis Protocol

A Guide for Measuring, Modeling, and Abating Highway Operation and Construction Noise Impacts

California Department of Transportation
Division of Environmental Analysis
Environmental Engineering
Hazardous Waste, Air, Noise, Paleontology Office
1120 N Street, Room 4301 MS27
Sacramento, CA 95814
Contact: Bruce Rymer
916/653-6073

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Acronyms and Abbreviations

Δ	change
°F	degrees Farenheit
AASHTO	American Association of State Highway and Transportation Officials
AC	asphalt concrete
ADT	average daily traffic
ANSI	American National Institute of Standards
B	bels
Caltrans	California Department of Transportation
CFR	Code of Federal Regulations
CNEL	community noise equivalent level
cps	cycles per second
dB	decibels
dB/s	decibels per second
dBA	A-weighted decibels
DGAC	dense-graded asphalt concrete
EWNR	Exterior Wall Noise Rating
FHWA	Federal Highway Administration
ft/s	feet per second
GPS	global positioning system
Guidance Manual	Technical Guidance Manual on the Effects on the Assessment and Mitigation of Hydroacoustic Effects of Pile Driving Sound on Fish
Hz	hertz
I-	Interstate
kHz	kilohertz
km/hr	kilometers per hour
kVA	kilovolt-amperes
L_{dn}	day-night noise level
L_{eq}	equivalent noise level
L_{max}	maximum noise level

m/s	meters per second
mph	miles per hour
N	Newton
N/m^2	Newton per square meter
NAC	noise abatement criteria
NADR	Noise Abatement Decision Report
NIST	National Institute of Standards and Technology
Nm	Newton meter
NRC	noise reduction coefficient
OBSI	on-board sound intensity
OGAC	open-graded aspalt concrete
OSHA	Occupational Safety and Health Administration
PCC	Portland concrete cement
PLD	path length difference
Protocol	Traffic Noise Analysis Protocol
psi	pounds per square inch
pW	picowatt
REMEL	Reference Energy Mean Emission Level
rms	root mean square
SPL	sound pressure level
SR	State Route
STC	Sound Transmission Class
TeNS	Technical Noise Supplement
TL	transmission loss
TNM	Traffic Noise Model
VNTSC	Volpe National Transportation Systems Center
vph	vehicles per hour
W	watts
W/m^2	watts per square meter
$\mu N/m^2$	microNewtons per square meter
µPa	micro Pascals

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- Jim Andrews (California Department of Transportation)—technical reviewer
- Dave Buehler (ICF International)—technical editor

Dedication:

This edition of the Technical Noise Supplement is dedicated to Rudy Hendriks whose early work substantially contributed to the science of highway acoustics.

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Section 1
Introduction and Overview

1.1 Introduction

This 2013 Technical Noise Supplement (TeNS) to the California Department of Transportation (Caltrans) *Traffic Noise Analysis Protocol for New Highway Construction, Reconstruction, and Retrofit Barrier Projects* (Protocol) (California Department of Transportation 2011) is an updated version of the 2009 TeNS. This version of the TeNS is compatible with applicable sections of the 2011 Protocol that were prepared in response to changes to Title 23 Part 772 of the Code of Federal Regulations (CFR) which were published in July 2010. The current Protocol was approved by the Federal Highway Administration (FHWA) and became effective on July 13, 2011. Be sure to check for updates to the Protocol.

The purpose of this document is to provide technical background information on transportation-related noise in general and highway traffic noise in particular. It is designed to elaborate on technical concepts and procedures referred to in the Protocol. The contents of the TeNS are for informational purposes; *unless they are referenced in the Protocol, the contents of this document are not official policy, standard, or regulation*. Except for some Caltrans-specific methods and procedures, most methods and procedures recommended in TeNS are in conformance with industry standards and practices.

This document can be used as a stand-alone document for training purposes or as a reference for technical concepts, methodology, and terminology needed to acquire a basic understanding of transportation noise with emphasis on highway traffic noise.

Revisions to this document are listed below.

- Removal of references and discussion relating to traffic noise models that preceded the current FHWA Traffic Noise Model (TNM).

- Abbreviated discussions of several topics such as bioacoustics and quieter pavement that are now covered in more detail in newer technical references.

- Elimination of metric units in accordance with Caltrans current standards. The exception to this is units of pressure that are traditionally expressed in metric units such as micro-pascals.

- Removal of the traffic noise analysis screening procedure which was removed from the Protocol.

- Removal of obsolete information.

The 2009 version of TeNS will remain available on the Caltrans website as a reference for information that has been removed from this edition. The 2009 version of TeNS contains a number of measurement procedures for non-routine noise studies.

1.2 Overview

The TeNS consists of eight sections. Except for Section 1, each covers a specific subject of highway noise. A brief description of the subjects follows.

- Section 1, *Introduction and Overview*, summarizes the subjects covered in the TeNS.
- Section 2, *Basics of Highway Noise*, covers the physics of sound as it pertains to characteristics and propagation of highway noise, effects of noise on humans, and ways of describing noise.
- Section 3, *Measurements and Instrumentation*, provides background information on noise measurements, and discusses various noise-measuring instruments and operating procedures.
- Section 4, *Detailed Analysis for Traffic Noise Impacts*, provides guidance for conducting detailed traffic noise impact analysis studies. This section includes identifying land use, selecting receptors, determining existing noise levels, predicting future noise levels, and determining impacts.
- Section 5, *Detailed Analysis for Noise Barrier Design Considerations*, outlines the major aspects that affect the acoustical design of noise barriers, including the dimensions, location, and material; optimization of noise barriers; possible noise reflections; acoustical design of overlapping noise barriers (to provide maintenance access to areas

behind barriers); and drainage openings in noise barriers. Challenges and cautions associated with noise barrier design are also discussed.

- Section 6, *Noise Study Reports*, discusses the contents of noise study reports.
- Section 7, *Non-Routine Considerations and Issues*, covers non-routine situations involving the effects of noise on distant receptors, use of sound intensity and sound power as tools in characterizing sound sources, pavement noise, noise monitoring for insulating facilities, construction noise, earthborne vibrations, California Occupational Safety and Health Administration (OSHA) noise standards, and effects and abatement of transportation-related noise on marine and wildlife.
- Section 8, *Glossary*, provides terminology and definitions common in transportation noise.
- Appendix A, *References Cited*, provides a listing of literature directly cited or used for reference in the TeNS.

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Section 2
Basics of Highway Noise

The following sections introduce the fundamentals of sound and provide sufficient detail to understand the terminology and basic factors involved in highway traffic noise prediction and analysis. Those who are actively involved in noise analysis are encouraged to seek out more detailed textbooks and reference books to acquire a deeper understanding of the subject.

2.1 Physics of Sound

2.1.1 Sound, Noise, and Acoustics

Sound is a vibratory disturbance created by a moving or vibrating source in the pressure and density of a gaseous or liquid medium or in the elastic strain of a solid that is capable of being detected by the hearing organs. Sound may be thought of as the mechanical energy of a vibrating object transmitted by pressure waves through a medium to human (or animal) ears. The medium of primary concern is air. In absence of any other qualifying statements, sound is considered airborne sound, as opposed to structure- or earthborne sound, for example.

Noise is defined as sound that is loud, unpleasant, unexpected, or undesired. It therefore may be classified as a more specific group of sounds. Although the terms *sound* and *noise* are often used synonymously, perceptions of sound and noise are highly subjective.

Sound is actually a process that consists of three components: source, path, and receiver. All three components must be present for sound to exist. Without a source, no sound pressure waves would be produced. Similarly, without a medium, sound pressure waves would not be transmitted. Finally, sound must be received—a hearing organ, sensor, or other object must be present to perceive, register, or be affected by sound. In most situations, there are many different sound sources, paths, and receivers.

In the context of an analysis pursuant to 23 CFR 772 the term *receptor* means a single dwelling unit or the equivalent of a single dwelling unit. A *receiver* is a single point that can represent one receptor or multiple receptors. As an example it is common when modeling traffic noise to use a single receiver in the model to represent multiple receptors. Acoustics is the field of science that deals with the production, propagation, reception, effects, and control of sound. The field is very broad, and transportation-related noise and abatement addresses only a small, specialized part of acoustics.

2.1.2 Speed of Sound

When the surface of an object vibrates in air, it compresses a layer of air as the surface moves outward and produces a rarefied zone as the surface moves inward. This results in a series of high and low air pressure waves (relative to the steady ambient atmospheric pressure) alternating in sympathy with the vibrations. These pressure waves, not the air itself, move away from the source at the speed of sound, approximately 1,126 feet per second (ft/s) in air with a temperature of 68 degrees Fahrenheit (°F). The speed of sound can be calculated from the following formula:

$$c = \sqrt{1.401\left(\frac{P}{\rho}\right)} \tag{2-1}$$

Where:

c = speed of sound at a given temperature, in ft/s

P = air pressure in pounds per square foot (pounds/ft^2)

ρ = air density in slugs per cubic foot (slugs/ft^3)

1.401 = ratio of the specific heat of air under constant pressure to that of air in a constant volume

For a given air temperature and relative humidity, the ratio P/ρ tends to remain constant in the atmosphere because the density of air will reduce or increase proportionally with changes in pressure. Therefore, the speed of sound in the atmosphere is independent of air pressure. When air temperature changes, ρ changes, but *P* does not. Therefore, the speed of sound is temperature-dependent, as well as somewhat humidity-dependent because humidity affects the density of air. The effects of the latter with regard to the speed of sound, however, can be ignored for the purposes of the TeNS. The fact that the speed of sound changes with altitude has nothing to do with the change in air pressure and is only caused by the change in temperature.

For dry air of 32ºF, ρ is 0.002509 slugs/ft^3. At a standard air pressure of 29.92 inches Hg, pressure is 14.7 pounds per square inch (psi) or 2,118 pounds/ft^2. Using Equation 2-1, the speed of sound for standard pressure and temperature can be calculated as follows:

$$\mathbf{c} = \sqrt{(1.401)\left(\frac{2{,}118}{0.002509}\right)} = 1{,}087 \text{ ft/s.}$$

From this base value, the variation with temperature is described by the following equation:

$$c = 1051.3\sqrt{1+\frac{T_f}{459.7}} \text{ ft/s} \qquad \textbf{(2-2)}$$

Where:

c = speed of sound

T_f = temperature in degrees Fahrenheit (include minus sign for less than 0ºF)

The above equations show that the speed of sound increases or decreases as the air temperature increases or decreases, respectively. This phenomenon plays an important role in the atmospheric effects on noise propagation, specifically through the process of refraction, which is discussed in Section 2.1.4.3.

2.1.3 Sound Characteristics

In its most basic form, a continuous sound can be described by its frequency or wavelength (pitch) and amplitude (loudness).

2.1.3.1 Frequency, Wavelength, and Hertz

For a given single pitch, the sound pressure waves are characterized by a sinusoidal periodic (i.e., recurring with regular intervals) wave, as shown in Figure 2-1. The upper curve shows how sound pressure varies above and below the ambient atmospheric pressure with distance at a given time. The lower curve shows how particle velocity varies above 0 (molecules moving right) and below 0 (molecules moving left). Please note that when the pressure fluctuation is at 0, the particle velocity is at its maximum, either in the positive or negative direction; when the pressure is at its positive or negative peak, the particle velocity is at 0. Particle velocity describes the motion of the air molecules in response to the pressure waves. It does not refer to the velocity of the waves, otherwise known as the speed of sound. The distance (λ) between crests of both curves is the wavelength of the sound.

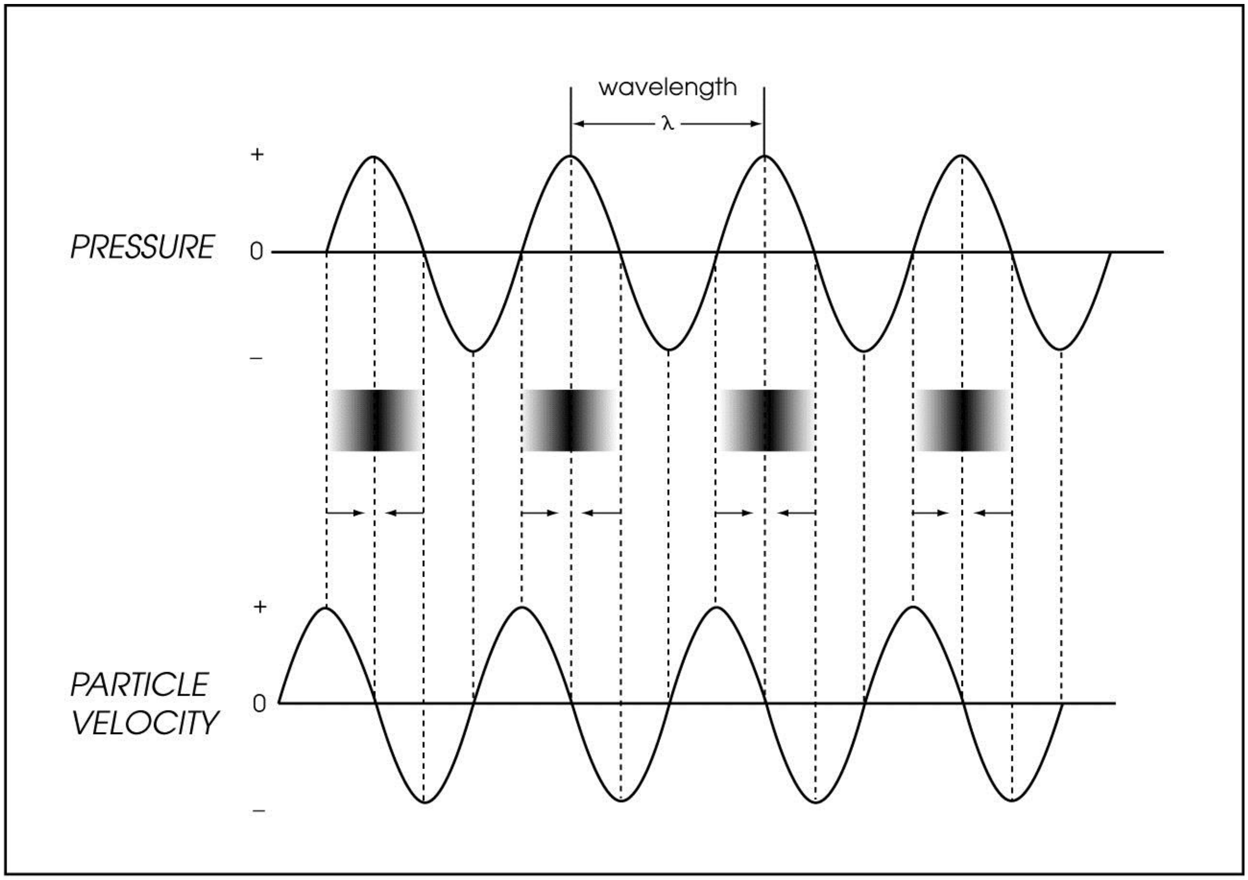

Figure 2-1. Sound Pressure vs. Particle Velocity

The number of times per second that the wave passes from a period of compression through a period of rarefaction and starts another period of compression is referred to as the frequency of the wave (Figure 2-2). Frequency is expressed in cycles per second, or hertz (Hz): 1 Hz equals one cycle per second. High frequencies are sometimes more conveniently expressed in units of kilohertz (kHz) or thousands of hertz. The extreme range of frequencies that can be heard by the healthiest human ears spans from 16 to 20 Hz on the low end to about 20,000 Hz (20 kHz) on the high end. Frequencies are heard as the pitch or tone of sound. High-pitched sounds produce high frequencies, and low-pitched sounds produce low frequencies. Very-low-frequency airborne sound of sufficient amplitude may be felt before it can be heard and is often confused with earthborne vibrations. Sound less than 16 Hz is referred to as infrasound, while high frequency sound above 20,000 Hz is called ultrasound. Both infrasound and ultrasound are not audible to humans, but many animals can hear or sense frequencies extending well into one or both of these regions.

Ultrasound also has various applications in industrial and medical processes, specifically cleaning, imaging, and drilling.

The distance traveled by a sound pressure wave through one complete cycle is referred to as the wavelength. The duration of one cycle is called the period. The period is the inverse of the frequency. For example, the frequency of a series of waves with periods of 0.05 (1/20) second is 20 Hz; a period of 0.001 (1/1000) second is 1,000 Hz or 1 kHz. Although low frequency earthborne vibrations (e.g., earthquakes and swaying of bridges or other structures) often are referred to by period, the term rarely is used in expressing airborne sound characteristics.

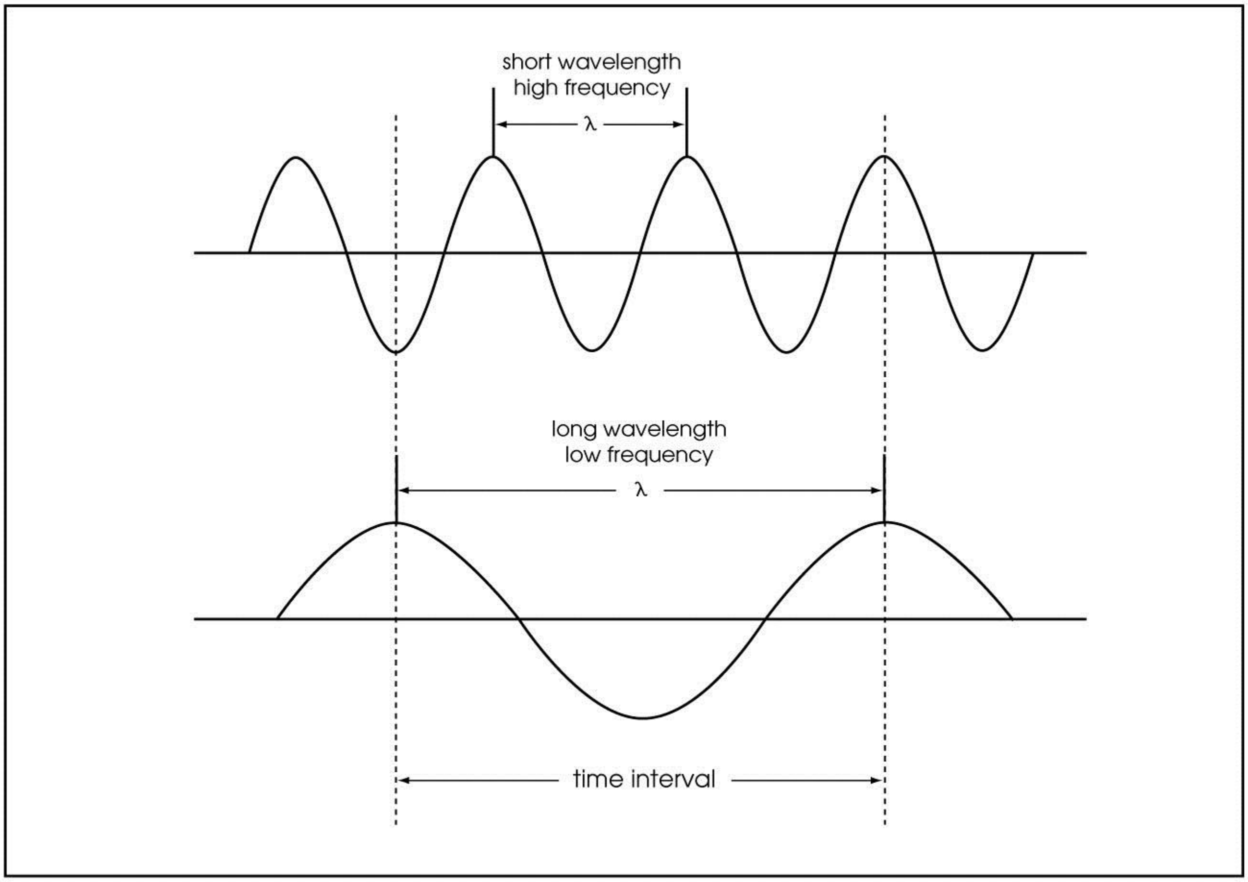

Figure 2-2. Frequency and Wavelength

Figure 2-2 shows that as the frequency of a sound pressure wave increases, its wavelength decreases, and vice versa. The relationship between frequency and wavelength is linked by the speed of sound, as shown in the following equations:

$$\lambda = \frac{c}{f} \quad \textbf{(2-3)}$$

$$f = \frac{c}{\lambda} \quad \textbf{(2-4)}$$

$$c = f\lambda \quad \textbf{(2-5)}$$

Where:

λ = wavelength (feet)

c = speed of sound (1,126.5 ft/s at 68ºF)

f = frequency (Hz)

In these equations, care must be taken to use the same units (distance units in feet and time units in seconds) for wavelength and speed of sound. Although the speed of sound is usually thought of as a constant, it has been shown that it actually varies with temperature. These mathematical relationships hold true for any value of the speed of sound. Frequency normally is generated by mechanical processes at the source (e.g., wheel rotation, back and forth movement of pistons) and therefore is not affected by air temperature. As a result, wavelength usually varies inversely with the speed of sound as the latter varies with temperature.

The relationships between frequency, wavelength, and speed of sound can be visualized easily by using the analogy of a train traveling at a given constant speed. Individual boxcars can be thought of as the sound pressure waves. The speed of the train (and individual boxcars) is analogous to the speed of sound, while the length of each boxcar is the wavelength. The number of boxcars passing a stationary observer each second depicts the frequency (*f*). If the value of the latter is 2, and the speed of the train (*c*) is 68 miles per hour (mph), or 100 ft/s, the length of each boxcar (λ) must be: $c/f = 100/2 = 50$ feet.

Using Equation 2-3, a table can be developed showing frequency and associated wavelength. Table 2-1 shows the frequency and wavelength relationship at an air temperature of 68ºF.

Table 2-1. Wavelength of Various Frequencies

Frequency (Hz)	Wavelength at 68ºF (Feet)
16	70
31.5	36
63	18
125	9
250	4.5
500	2.3

Frequency (Hz)	Wavelength at 68ºF (Feet)
1,000	1.1
2,000	0.56
4,000	0.28
8,000	0.14
16,000	0.07

The validity of Table 2-1 can be checked by multiplying each frequency by its wavelength, which should equal the speed of sound. Please notice that because of rounding, multiplying frequency and wavelength gives varying results for the speed of sound in air, which for 68ºF should be constant at 1,126.5 ft/s.

Frequency is an important component of noise analysis. Virtually all acoustical phenomena are frequency-dependent, and knowledge of frequency content is essential. Sections 2.1.3.6 and 2.1.3.7 discuss how frequency is considered in sound level measurements and sound analysis.

2.1.3.2 Sound Pressure Levels and Decibels

As indicated in Figure 2-1, the pressures of sound waves continuously change with time or distance and within certain ranges. The ranges of these pressure fluctuations (actually deviations from the ambient air pressure) are referred to as the amplitude of the pressure waves. Whereas the frequency of the sound waves is responsible for the pitch or tone of a sound, the amplitude determines the loudness of the sound. Loudness of sound increases and decreases with the amplitude.

Sound pressures can be measured in units of microNewtons per square meter ($\mu N/m^2$), also called micro Pascals (μPa): 1 μPa is approximately one-hundred-billionth (1/100,000,000,000) of the normal atmospheric pressure. The pressure of a very loud sound may be 200 million μPa, or 10 million times the pressure of the weakest audible sound (20 μPa). Expressing sound levels in terms of μPa would be very cumbersome because of this wide range. Sound pressure levels (SPLs) are described in logarithmic units of ratios of actual sound pressures to a reference pressure squared called bels. To provide a finer resolution, a bel is divided into tenths, or decibels (dB). In its simplest form, SPL in decibels is expressed as follows:

$$\text{Sound pressure level (SPL)} = 10\log_{10}\left(\frac{p_1}{p_0}\right)^2 \text{ dB} \qquad \textbf{(2-6)}$$

Where:

P_1 = sound pressure

P_0 = reference pressure, standardized as 20 μPa

The standardized reference pressure, P_0, of 20 μPa corresponds to the threshold of human hearing. When the actual sound pressure is equal to the reference pressure, the expression results in a sound level of 0 dB:

$$10\log_{10}\left(\frac{p_1}{p_0}\right)^2 = 10\log_{10}(1) = 0 \text{ dB}$$

Please note that 0 dB does not represent an absence of any sound pressure. Instead, it is an extreme value that only those with the most sensitive ears can detect. Therefore, it is possible to refer to sounds as less than 0 dB (negative dB) for sound pressures that are weaker than the threshold of human hearing. For most people, the threshold of hearing is probably close to 10 dB.

2.1.3.3 Root Mean Square and Relative Energy

Figure 2-1 depicted a sinusoidal curve of pressure waves. The values of the pressure waves were constantly changing, increasing to a maximum value above normal air pressure, then decreasing to a minimum value below normal air pressure, in a repetitive fashion. This sinusoidal curve is associated with a single frequency sound, also called a pure tone. Each successive sound pressure wave has the same characteristics as the previous wave. The amplitude characteristics of such a series of simple waves then can be described in various ways, all of which are simply related to each other. The two most common ways to describe the amplitude of the waves is in terms of peak SPL and root mean square (rms) SPL.

Peak SPL simply uses the maximum or peak amplitude (pressure deviation) for the value of P_1 in Equation 2-6. Therefore, peak SPL only uses one value (absolute value of peak pressure deviation) of the continuously changing amplitudes. The rms value of the wave amplitudes (pressure deviations) uses all positive and negative instantaneous amplitudes, not just the peaks. It is derived by squaring the positive and negative instantaneous pressure deviations, adding these together, and dividing the sum by the number of pressure deviations. The result is called the mean square of the pressure deviations; the square root of this mean value is the rms value. Figure 2-3 shows the peak and rms relationship for sinusoidal or single-frequency waves. The rms is 0.707 times the peak value.

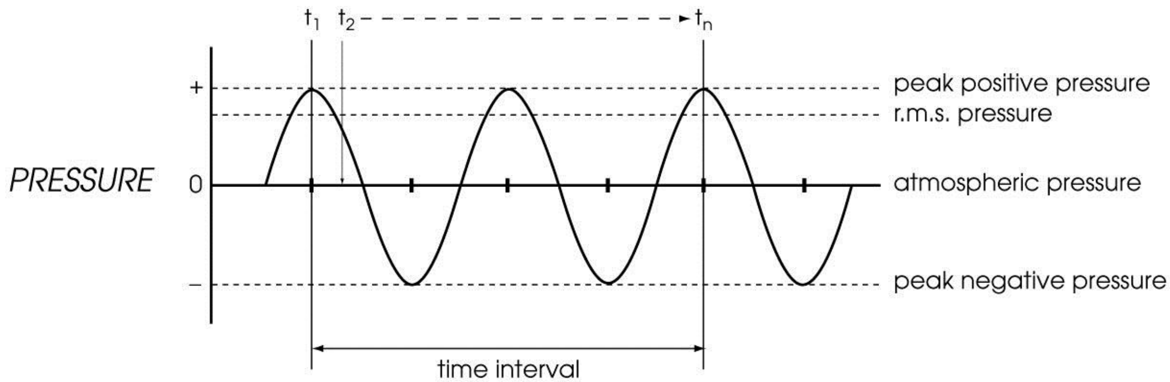

Figure 2-3. Peak and Root Mean Square Sound Pressure

In terms of discrete samples of the pressure deviations, the mathematical expression is as follows:

$$\text{rms} = \sqrt{\left({}_1\sum^n (t_1^2 + t_2^2 + \ldots t_n^2)/n\right)} \qquad \textbf{(2-7)}$$

Where:

$t_1, t_2, \ldots t_n$ = discrete pressure values at times t_1 through t_n above (positive) and below (negative) the local atmospheric pressure

Sound pressures expressed in rms are proportional to the energy contents of the waves and are therefore the most important and often used measure of amplitude. Unless indicated otherwise, all SPLs are expressed as rms values.

2.1.3.4 Relationship between Sound Pressure Level, Relative Energy, Relative Pressure, and Pressure

Table 2-2 shows the relationship between rms SPL, relative sound energy, relative sound pressure, and pressure. Please note that SPL, relative energy, and relative pressure are based on a reference pressure of 20 μPa and by definition are all referenced to 0 dB. The pressure values are the actual rms pressure deviations from local ambient atmospheric pressure.

The most useful relationship is that of SPL (dB) and relative energy. Relative energy is unitless. Table 2-2 shows that for each 10 dB increase in SPL the acoustic energy increases tenfold (e.g., an SPL increase from 60 to 70 dB increases the energy 10 times). Acoustic energy can be thought of as the energy intensity (energy per unit area) of a certain noise source, such as a heavy truck, at a certain distance. For example, if one heavy truck passing by an observer at a given speed and distance produces an SPL of 80 A-weighted decibels (dBA), the SPL of 10 heavy trucks identical to the single truck would be 90 dBA if they all could simultaneously occupy the same space and travel at the same speed and distance from the observer.

Because SPL is computed using $10\log_{10}(P_1/P_2)^2$, the acoustic energy is related to SPL as follows:

$$(P_1/P_2)^2 = 10^{SPL/10} \qquad \textbf{(2-8)}$$

Table 2-2. Relationship between Sound Pressure Level, Relative Energy, Relative Pressure, and Sound Pressure

Sound Pressure Level (dB) $10\log_{10}\left(\frac{p_1}{p_0}\right)^2$	Relative Energy $\left(\frac{p_1}{p_0}\right)^2$	Relative Pressure $\left(\frac{p_1}{p_0}\right)$	Sound Pressure (μPa) (P_1)
200	10^{20}	10^{10}	
154			10^{9} (1,000 Pa)
150	10^{15}		
140	10^{14}	10^{7}	
134			10^{8} (100 Pa)
130	10^{13}		
120	10^{12}	10^{6}	
114			10^{7} (10 Pa)
110	10^{11}		
100	10^{10}	10^{5}	
94			10^{6} (1 Pa)
90	10^{9}		
80	10^{8}	10^{4}	
74			10^{5} μPa
70	10^{7}		
60	10^{6}	10^{3}	
54			10^{4} μPa
50	10^{5}		
40	10^{4}	10^{2}	

Sound Pressure Level (dB) $10\log_{10}\left(\frac{P_1}{P_0}\right)^2$	Relative Energy $\left(\frac{P_1}{P_0}\right)^2$	Relative Pressure $\left(\frac{P_1}{P_0}\right)$	Sound Pressure (μPa) (P_1)
34			10^3 μPa
30	10^3		
20	10^2	10^1	
14			10^2 μPa
10	10^1		
0	**10^0 = 1 = Ref.**	**10^0 = 1 = Ref.**	**$P_1 = P_0 = 20$** μPa

2.1.3.5 Adding, Subtracting, and Averaging Sound Pressure Levels

Because decibels are logarithmic units, SPL cannot be added or subtracted by ordinary arithmetic means. For example, if one automobile produces an SPL of 70 dB when it passes an observer, two cars passing simultaneously would not produce 140 dB; they would combine to produce 73 dB. The following discussion provides additional explanation of this concept. The SPL from any source observed at a given distance from the source may be expressed as $10\log_{10}(P_1/P_0)^2$ (see Equation 2-6). Therefore, the SPL from two equal sources at the same distance would be calculated as follows:

$$SPL = 10\log_{10}[(P_1/P_0)^2+(P_1/P_0)^2] = 10\log_{10}[2(P_1/P_0)^2]$$

This can be simplified as $10\log_{10}(2) + 10\log_{10}(P_1/P_0)^2$. Because the logarithm of 2 is 0.301, and 10 times that would be 3.01, the sound of two equal sources is 3 dB more than the sound level of one source. The total SPL of the two automobiles therefore would be 70 + 3 = 73 dB.

Adding and Subtracting Equal Sound Pressure Levels

The previous example of adding the noise levels of two cars may be expanded to any number of sources. The previous section described the relationship between decibels and relative energy. The ratio $(P_1/P_0)^2$ is the relative (acoustic) energy portion of the expression SPL = $10\log_{10}(P_1/P_0)^2$, in this case the relative acoustic energy of one source. This must immediately be qualified with the statement that this is not the acoustic power output of the source. Instead, the expression is the relative acoustic energy per unit area received by the observer. It may be stated that *N* identical automobiles or other noise sources would yield an SPL calculated as follows:

$$SPL_{Total} = SPL_1 + 10\log_{10}(N) \qquad \textbf{(2-9)}$$

Where:

SPL_1 = SPL of one source

N = number of identical sources to be added (must be more than 0)

<u>Example</u>

If one noise source produces 63 dB at a given distance, what would be the noise level of 13 of the same source combined at the same distance?

<u>Solution</u>

$SPL_{Total} = 63 + 10\log_{10}(13) = 63 + 11.1 = 74.1$ dB

Equation 2-9 also may be rewritten as follows. This form is useful for subtracting equal SPLs:

$$SPL_1 = SPL_{Total} - 10\log_{10}(N) \qquad \textbf{(2-10)}$$

<u>Example</u>

The SPL of six equal sources combined is 68 dB at a given distance. What is the noise level produced by one source?

<u>Solution</u>

$SPL_1 = 68 \text{ dB} - 10\log_{10}(6) = 68 - 7.8 = 60.2$ dB

In these examples, adding equal sources actually constituted multiplying one source by the number of sources. Conversely, subtracting equal sources was performed by dividing the total. For the latter, Equation 2-9 could have been written as $SPL_1 = SPL_{Total} + 10\log_{10}(1/N)$. The logarithm of a fraction yields a negative result, so the answers would have been the same.

These exercises are very useful for estimating traffic noise impacts. For example, if one were to ask what the respective SPL increases would be along a highway if existing traffic were doubled, tripled, or quadrupled (assuming traffic mix, distribution, and speeds would not change), a reasonable prediction could be made using Equation 2-9. In this case, N would be the existing traffic (N = 1); N = 2 would be doubling, N = 3 would be tripling, and N = 4 would be quadrupling the existing traffic. Because $10\log_{10}(N)$ in Equation 2-9 represents the increase in SPL, the above values for N would yield +3, +4.8, and +6 dB, respectively.

Similarly, one might ask what the SPL decrease would be if traffic were reduced by a factor of 2, 3, or 4 (i.e., N = 1/2, N = 1/3, and N = 1/4, respectively). Applying $10\log_{10}(N)$ to these values would yield -3, -5, and -6 dB, respectively.

The same problem also may arise in a different form. For example, the traffic flow on a given facility is 5,000 vehicles per hour, and the SPL is 65 dB at a given location next to the facility. One might ask what the expected SPL would be if future traffic increased to 8,000 vehicles per hour. The solution would be:

$$65 + 10\log_{10}(8{,}000/5{,}000) = 65 + 2 = 67 \text{ dB.}$$

Therefore, *N* may represent an integer, fraction, or ratio. However, *N* always must be more than 0. Taking the logarithm of 0 or a negative value is not possible.

In Equations 2-9 and 2-10, $10\log_{10}(N)$ was the increase from SPL_1 to SPL_{Total} and equals the change in noise levels from an increase or decrease in equal noise sources. Letting the change in SPLs be referred to as ΔSPL, Equations 2-9 and 2-10 can be rewritten as follows:

$$\Delta SPL = 10\log_{10}(N) \qquad \textbf{(2-11)}$$

This equation is useful for calculating the number of equal source increments (N) that must be added or subtracted to change noise levels by ΔSPL. For example, if it is known that an increase in traffic volumes increases SPL by 7 dB, the factor change in traffic (assuming that traffic mix and speeds did not change) can be calculated as follows:

$7 \text{ dB} = 10\log_{10}(N)$

$0.7 \text{ dB} = \log_{10}(N)$

$10^{0.7} = N$

$N = 5.0$

Therefore, the traffic volume increased by a factor of 5.

Adding and Subtracting Unequal Sound Pressure Levels

If noise sources are not equal or equal noise sources are at different distances, $10\log_{10}(N)$ cannot be used. Instead, SPLs must be added or subtracted individually using the SPL and relative energy relationship in Equation 2-8. If the number of SPLs to be added is *N*, and SPL_1, SPL_2, and SPL_n represent the first, second, and *n*th SPL, respectively, the addition is accomplished as follows:

$$SPL_{Total} = 10\log_{10}[10^{SPL_1/10} + 10^{SPL_2/10} + \ldots 10^{SPL_n/10}] \quad \textbf{(2-12)}$$

The above equation is the general equation for adding SPLs. The equation also may be used for subtraction (simply change “+” to “–”). However, the result between the brackets must always be more than 0. For example, determining the total SPL of 82, 75, 88, 68, and 79 dB would use Equation 2-12 as follows:

$$SPL = 10\log_{10}(10^{68/10} + 10^{75/10} + 10^{79/10} + 10^{82/10} + 10^{88/10}) = 89.6 \text{ dB}$$

Adding Sound Pressure Levels Using a Simple Table

When combining sound levels, a table such as the following may be used as an approximation.

Table 2-3. Decibel Addition

When Two Decibel Values Differ by:	Add This Amount to the Higher Value:	Example:
0 or 1 dB	3 dB	70 + 69 = 73 dB
2 or 3 dB	2 dB	74 + 71 = 76 dB
4 to 9 dB	1 dB	66 + 60 = 67 dB
10 dB or more	0 dB	65 + 55 = 65 dB

This table yields results within about 1 dB of the mathematically exact value and can be memorized easily. The table can also be used to add more than two SPLs. First, the list of values should be sorted, from lowest to highest. Then, starting with the lowest values, the first two should be combined, the result should be added to the third value, and so on until only the answer remains. For example, to determine the sum of the sound levels used in the preceding example using Table 2-3, the first step would be to rank the values from low to high: 68, 75, 79, 82, and 88 dB.

Using Table 2-3, the first two noise levels then should be added. The result then would be added to the next noise level, etc., as follows:

68 + 75 = 76,

76 + 79 = 81,

81 + 82 = 85,

85 + 88 = 90 dB

For comparison, using Equation 2-12, total SPL was 89.6 dB.

Two decibel-addition rules are important. First, when adding a noise level to an approximately equal noise level, the total noise level increases 3 dB.

For example, doubling the traffic on a highway would result in an increase of 3 dB. Conversely, reducing traffic by one half would reduce the noise level by 3 dB. Second, when two noise levels are 10 dB or more apart, the lower value does not contribute significantly (less than 0.5 dB) to the total noise level. For example, 60 + 70 dB ≈ 70 dB. This means that if a noise level measured from a source is at least 70 dB, the background noise level (without the target source) must not be more than 60 dB to avoid risking contamination.

Averaging Sound Pressure Levels

There are two ways of averaging SPLs: arithmetic averaging and energy-averaging. Arithmetic averaging is simply averaging the decibel values. For example, the arithmetic average (mean) of 60 and 70 dB is:

$$(60 + 70)/2 = 65 \text{ dB}$$

Energy averaging is averaging of the energy values. Using the previous example, the energy average (mean) of 60 and 70 dB is:

$$10\log[(10^{6.0} + 10^{7.0})/2] = 67.4 \text{ dB}$$

Please notice that the energy average is always equal to or more than the arithmetic average. It is only equal to the arithmetic average if all values are the same. Averaging the values 60, 60, 60, and 60 dB yields equal results of 60 dB in both cases. The following discussion shows some examples of when each method is appropriate.

Energy Averaging

Energy averaging is the most widely used method of averaging noise levels. Sound energy relates directly to the sound source. For example, at a given distance the sound energy from six equal noise sources is three times that of two of the same sources at that same distance. To average the number of sources and calculate the associated noise level, energy averaging should be used. Examples of applications of energy averaging are provided below.

Example 1

To determine the average noise level at a specific receiver along a highway between 6 a.m. and 7 a.m., five 1-hour measurements were taken on random days during that hour. The energy-averaged measurement results were 68, 67, 71, 70, and 71 dB. What is a good estimate of the noise level at that receiver? Because the main reason for the fluctuations in noise levels is probably the differences in source strength (vehicle mix, volumes, and speeds), energy averaging is appropriate. Therefore, the result would be: $10\log[(10^{6.8} + 10^{6.7} + 10^{7.1} + 10^{7.0} + 10^{7.1})/5] = 69.6$ dB, or 70 dB.

Example 2

Another situation is where traffic volumes substantially change during a measurement period. Noise is measured at a location along a highway. Vehicles on that highway are distributed equally, are traveling at the same speed, and are of the same type (e.g., automobiles). Such traffic characteristics would produce a near steady-state noise level. The typical procedure would be to measure the traffic noise for an hour. After 15 minutes, the traffic volume suddenly increases sharply, but speeds remain the same and the vehicles, although closer together, are still equally distributed for the remaining 45 minutes. The noise level during the first 15 minutes was 70 dB and during the last 45 minutes was 75 dB. What was the energy-averaged noise level? Because the time periods were not the same, the energy average must be time-weighted by using the following equation:

$$\text{Energy-averaged noise level} = 10\log[(15 * 10^{7.0} + 45 * 10^{7.5})/60] = 74.2 \text{ dB}$$

In this example, the time was weighted in units of minutes. This also could have been accomplished using fractions of 1 hour, as follows:

$$\text{Energy-averaged noise level} = 10\log[(0.25 * 10^{7.0} + 0.75 * 10^{7.5})/1] = 74.2 \text{ dB}$$

Arithmetic Averaging

Arithmetic averaging is used less frequently, but it is used in situations such as the following. For example, the objective is to measure the noise of a machine with great accuracy. For simplicity, assume that the machine produces a steady noise level, which is expected to be constant, each time the machine is turned on. Because accuracy is of great importance, it is chosen to take repeat measurements with different sound level meters and to calculate the average noise level. In this case, it is appropriate to calculate the arithmetic mean by adding the measured decibel values and dividing by the number of measurements. Because the same source is measured repeatedly, any measured noise fluctuations are mainly from errors inherent in the instrumentation; method of measurement; environmental conditions; and, to a certain extent, source strength. Because the errors are distributed randomly, the expected value of the measurements is the arithmetic mean.

It is also appropriate to use arithmetic means for statistical comparisons of noise levels, or hypothesis testing, whether the noise levels were obtained by energy averaging or arithmetic means. Examples of applications of arithmetic averaging are provided below.

Example 1

In this example the objective is to compare the noise levels from Compressors A and B. It is decided to take five independent noise measurements at 25 feet from each compressor. Between each measurement, the compressors will be shut off and restarted. The following data are collected:

Compressor	Measured Noise Levels (dB)	Arithmetic Average (dB)
A	75, 76, 73, 74, 75	(75+76+73+74+75)/5 = 74.6
B	77, 75, 76, 78, 75	(77+75+76+78+75)/5 = 76.2

In addition, the hypothesis that Compressors A and B emit the same noise can be tested by calculating the standard deviations and using appropriate statistical tests assuming a certain level of significance. However, this is not the subject of discussion in this case.

Example 2

Residents A and B live next to the same highway. Resident A complains about the noise at night, while Resident B does not. One wishes to determine whether the nighttime noise level is higher at Residence A than Residence B. Four hours at night are randomly selected, and simultaneous energy-averaged noise measurements are taken at Residences A and B during the 4 hours. The measurement results are:

Hour	Residence A (dB)	Residence B (dB)
1	65	62
2	62	58
3	63	59
4	66	63
Arithmetic mean	64.0	60.5

The goal is a statistical comparison of noise levels at Residences A and B for the same randomly selected time periods, as well as the same traffic and environmental conditions. Although the 1-hour noise levels represent energy averages for each hour, arithmetic means should be calculated for the statistical comparison, as shown in the preceding measurement results.

The hypothesis that noise levels at Residence A equal noise levels at Residence B can be tested using the standard deviations, as well as the appropriate tests and significance levels. Please note, however, that statistical significance has no relationship to human significance. In this example, the noise level at Residence A is probably significantly higher statistically than at Residence B. In terms of human perception, however, the difference may be barely perceptible.

A good rule to remember is that whenever measurements or calculations must relate to the number of sources or source strength, energy averaging should be used. However, if improving accuracy in measurements or calculations of the same events or making statistical comparisons is the goal, the arithmetic mean is appropriate. Additional details about averaging and time-weighting are addressed in Section 2.2.2.

2.1.3.6 A-Weighting and Noise Levels

SPL alone is not a reliable indicator of loudness. Frequency or pitch also has a substantial effect on how humans respond. While the intensity (energy per unit area) of the sound is a purely physical quantity, loudness or human response depends on the characteristics of the human ear.

Human hearing is limited not only to the range of audible frequencies, but also in the way it perceives the SPL in that range. In general, the healthy human ear is most sensitive to sounds between 1,000 and 5,000 Hz and perceives both higher and lower frequency sounds of the same magnitude with less intensity. To approximate the frequency response of the human ear, a series of SPL adjustments is usually applied to the sound measured by a sound level meter. The adjustments, or weighting network, are frequency-dependent.

The A-scale approximates the frequency response of the average young ear when listening to most everyday sounds. When people make relative judgments of the loudness or annoyance of a sound, their judgments correlate well with the A-scale sound levels of those sounds. There are other weighting networks that have been devised to address high noise levels or other special problems (e.g., B-, C-, D-scales), but these scales rarely, if ever, are used in conjunction with highway traffic noise. Noise levels for traffic noise reports should be reported as dBA. In environmental noise studies, A-weighted SPLs commonly are referred to as noise levels.

Figure 2-4 shows the A-scale weighting network that is normally used to approximate human response. The 0-dB line represents a reference line; the curve represents frequency-dependent attenuations provided by the ear’s response. Table 2-4 shows the standardized values (American National Standards Institute 1983). The use of this weighting network is signified by appending an “A” to the SPL as dBA or dB(A).

The A-weighted curve was developed from averaging the statistics of many psychoacoustic tests involving large groups of people with normal hearing in the age group of 18 to 25 years. The internationally standardized curve is used worldwide to address environmental noise and is incorporated in virtually all environmental noise descriptors and standards. Section 2.2.2 addresses the most common descriptors applicable to transportation noise.

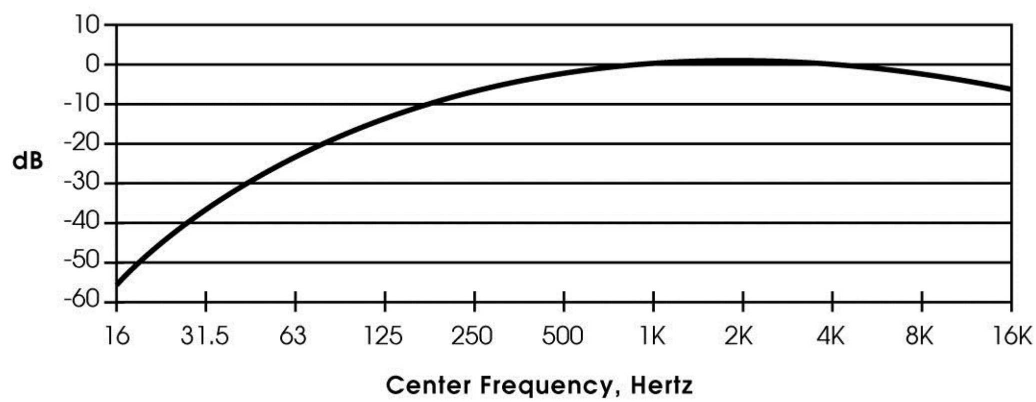

Figure 2-4. A-Weighting Network

Table 2-4. A-Weighting Adjustments for One-Third-Octave Center Frequencies

Frequency (Hz)	A-Weighting (dB)	Frequency (Hz)	A-Weighting (dB)	Frequency (Hz)	A-Weighting (dB)	Frequency (Hz)	A-Weighting (dB)
16	-56.7	100	-19.1	630	-1.9	4,000	+1.0
20	-50.5	125	-16.1	800	-0.8	5,000	+0.5
25	-44.7	160	-13.4	1,000	0	6,300	-0.1
31.5	-39.4	200	-10.9	1,250	+0.6	8,000	-1.1
40	-34.6	250	-8.6	1,600	+1.0	10,000	-2.5
50	-30.6	315	-6.6	2,000	+1.2	12,500	-4.3
63	-26.2	400	-4.8	2,500	+1.3	16,000	-6.6
80	-22.5	500	-3.2	3,150	+1.2	20,000	-9.3

Source: American National Standards Institute 1983.

Sound level meters used for measuring environmental noise have an A-weighting network built in for measuring A-weighted sound levels. This is accomplished through electronic filters, also called band pass filters. Each filter allows the passage of a selected range (band) of frequencies only and attenuates its SPL to modify the frequency response of the sound level meter to about that of the A-weighted curve and the human ear.

A range of noise levels associated with common indoor and outdoor activities is shown in Table 2-5. The decibel scale is open-ended. As discussed, 0 dB or 0 dBA should not be construed as the absence of sound. Instead, it is the generally accepted threshold of the best human hearing. SPLs in negative decibel ranges are inaudible to humans. On the other extreme, the decibel scale can go much higher than shown in Table 2-5. For example, gunshots, explosions, and rocket engines can reach 140 dBA or higher at close range. Noise levels approaching 140 dBA are nearing the threshold of pain. Higher levels can inflict physical damage on such things as structural members of air and spacecraft and related parts. Section 2.2.1.1 discusses the human response to changes in noise levels.

Table 2-5. Typical Noise Levels

Common Outdoor Activities	Noise Level (dBA)	**Common Indoor Activities**
	110	Rock band
Jet flyover at 1,000 feet		
	100	
Gas lawnmower at 3 feet		
	90	
Diesel truck at 50 feet at 50 mph		Food blender at 3 feet
	80	Garbage disposal at 3 feet
Noisy urban area, daytime		
Gas lawnmower, 100 feet	**70**	Vacuum cleaner at 10 feet
Commercial area		Normal speech at 3 feet
Heavy traffic at 300 feet	**60**	
		Large business office
Quiet urban daytime	**50**	Dishwasher in next room
Quiet urban nighttime	**40**	Theater, large conference room (background)
Quiet suburban nighttime		
	30	Library
Quiet rural nighttime		Bedroom at night, concert hall (background)
	20	
		Broadcast/recording studio
	10	
	0	

2.1.3.7 Octave and One-Third-Octave Bands and Frequency Spectra

Very few sounds are pure tones (i.e., consisting of a single frequency). To represent the complete characteristics of a sound properly, it is necessary to divide the total sound into its frequency components (i.e., determine how much sound [SPL] comes from each of the multiple frequencies that make up the sound). This representation of frequency vs. SPL is called a frequency spectrum. Spectra usually consist of 8- to 10-octave bands, more or less spanning the frequency range of human hearing (20 to 20,000 Hz). Just as with a piano keyboard, an octave represents the frequency interval between a given frequency and twice that frequency. Octave bands are internationally standardized and identified by their “center frequencies” (geometric means).

Because octave bands are rather broad, they are frequently subdivided into thirds to create one-third-octave bands. These are also standardized. For convenience, one-third-octave bands are sometimes numbered from 1 (1.25-Hz one-third-octave center frequency, which cannot be heard by humans) to 43 (20,000-Hz one-third-octave center frequency). Within the extreme range of human hearing there are 30 one-third-octave bands ranging from band 13 (20-Hz one-third-octave center frequency) to band 42 (16,000-Hz one-third-octave center frequency). Table 2-6 shows the ranges of the standardized octave and one-third-octave bands, as well as band numbers.

Frequency spectra are used in many aspects of sound analysis, from studying sound propagation to designing effective noise control measures. Sound is affected by many frequency-dependent physical and environmental factors. Atmospheric conditions, site characteristics, and materials and their dimensions used for sound reduction are some of the most important examples.

Sound propagating through the air is affected by air temperature, humidity, wind and temperature gradients, vicinity and type of ground surface, obstacles, and terrain features. These factors are all frequency-dependent.

The ability of a material to transmit noise depends on the type of material (concrete, wood, glass, etc.) and its thickness. Effectiveness of different materials at transmitting noise depends on the frequency of the noise. See Section 5.1.1 for a discussion of transmission loss and sound transmission class.

Wavelengths serve to determine the effectiveness of noise barriers. Low frequency noise, with its long wavelengths, passes easily around and over a noise barrier with little loss in intensity. For example, a 16-Hz noise with a wavelength of 70 feet will tend to pass over a 16-foot-high noise barrier. Fortunately, A-weighted traffic noise tends to dominate in the 250- to 2,000-Hz range with wavelengths in the range of about 0.6 to 4.5 feet. As discussed later, noise barriers are less effective at lower frequencies and more effective at higher ones.

Table 2-6. Standardized Band Numbers, Center Frequencies, One-Third-Octave and Octave Bands, and Octave Band Ranges

Band	Center Frequency (Hz)	One-Third-Octave Band Range (Hz)	Octave Band Range (Hz)
12	**16**	14.1–17.8	**11.2–22.4**
13	20	17.8–22.4	
14	25	22.4–28.2	
15	**31.5**	28.2–35.5	**22.4–44.7**
16	40	35.5–44.7	
17	50	44.7–56.2	
18	**63**	56.2–70.8	**44.7–89.1**
19	80	70.8–89.1	
20	100	89.1–112	
21	**125**	112–141	**89.1–178**
22	160	141–178	
23	200	178–224	
24	**250**	224–282	**178–355**
25	315	282–355	
26	400	355–447	
27	**500**	447–562	**355–708**
28	630	562–708	
29	800	708–891	
30	**1,000**	891–1,120	**708–1,410**
31	1,250	1,120–1,410	
32	1,600	1,410–1,780	
33	**2,000**	1,780–2,240	**1,410–2,820**
34	2,500	2,240–2,820	
35	3,150	2,820–3,550	
36	**4,000**	3,550–4,470	**2,820–5,620**
37	5,000	4,470–5,620	
38	6,300	5,620–7,080	
39	**8,000**	7,080–8,910	**5,620–11,200**
40	10,000	8,910–11,200	
41	12,500	11,200–14,100	
42	**16,000**	14,100–17,800	**11,200–22,400**

Band	Center Frequency (Hz)	One-Third-Octave Band Range (Hz)	Octave Band Range (Hz)
43	20,000	17,800–22,400	
Source: Harris 1979.			

Figure 2-5 shows a conventional graphical representation of a typical octave-band frequency spectrum. The octave bands are depicted as having the same width, although each successive band should increase by a factor of 2 when expressed linearly in terms of 1-Hz increments.

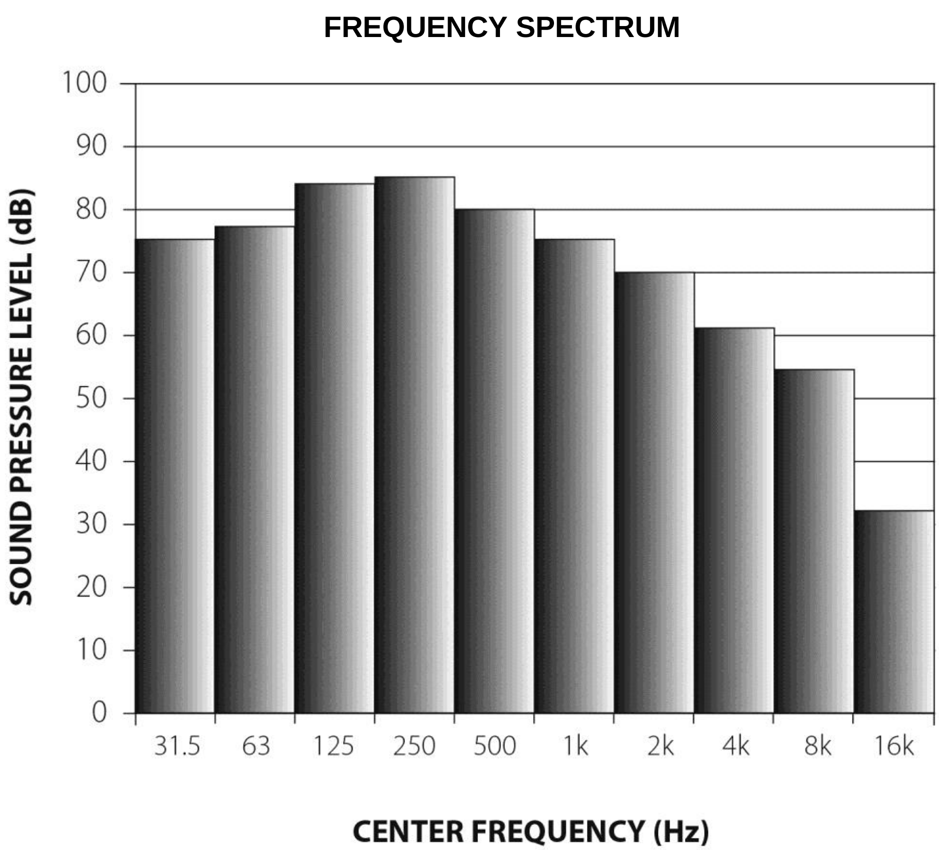

Figure 2-5. Typical Octave Band Frequency Spectrum

A frequency spectrum can also be presented in tabular form. For example, the data used to generate Figure 2-5 is illustrated in tabular form in Table 2-7.

Table 2-7. Tabular Form of Octave Band Spectrum

Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)
31.5	75
63	77
125	84
250	85
500	80
1,000	75
2,000	70
4,000	61
8,000	54
16,000	32
Total sound pressure level = 89 dB	

Often, one is interested in the total noise level, or the summation of all octave bands. Using the data shown in Table 2-8, one may simply add all the SPLs, as was explained in Section 2.1.3.5. The total noise level for the above octave band frequency spectrum is 89 dB.

The same sorts of charts and tables can be compiled from one-third-octave band information. For example, if more detailed one-third-octave information for the above spectrum is available, a one-third-octave band spectrum could be constructed as shown in Figure 2-6 and Table 2-8. Note that the total noise level does not change, and that each subdivision of three one-third-octave bands adds up to the total octave band shown in the previous example.

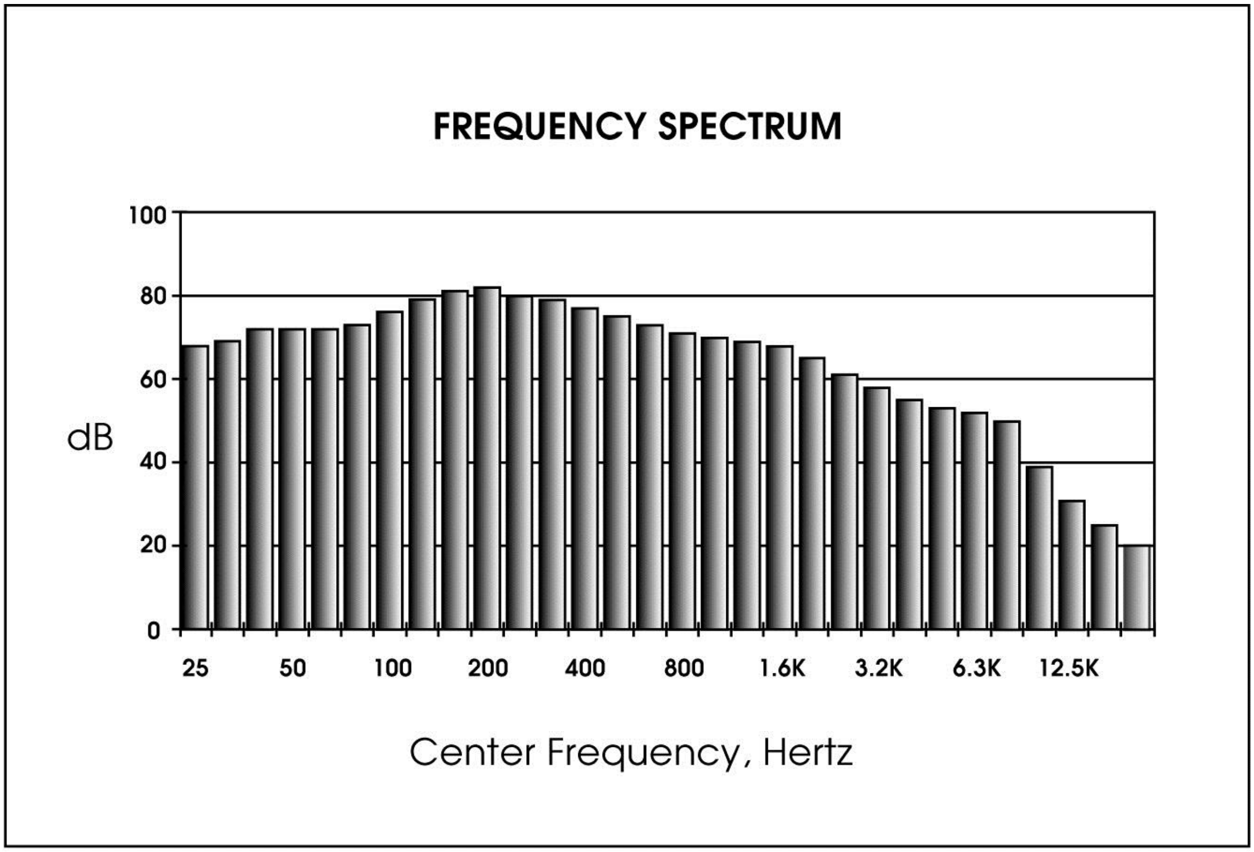

Figure 2-6. Typical One-Third-Octave Band Frequency Spectrum

Frequency spectrums are usually expressed in linear, unweighted SPLs (dB). However, they may also be A-weighted by applying the adjustments from Table 2-4. For example, the data in Table 2-8 can be A-weighted (rounded to nearest dB) as shown in Table 2-9.

Table 2-8. Tabular Form of One-Third Octave Band Spectrum

One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)	One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)	One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)
25	68	**250**	80	2,500	61
31.5	69	315	79	3,200	58
40	72	400	77	**4,000**	55
50	72	**500**	75	5,000	53
63	72	630	73	6,300	52
80	73	800	71	**8,000**	50
100	76	**1,000**	70	10,000	39
125	79	1,250	69	12,500	31
160	81	1,600	68	**16,000**	25

One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)	One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)	One-Third-Octave Band Center Frequency (Hz)	Sound Pressure Level (dB)
200	82	**2,000**	65	20,000	20
Total sound pressure level = 89 dB					

Table 2-9. Adjusting Linear Octave Band Spectrum to A-Weighted Spectrum

Octave Band Center Frequency (Hz)	Sound Pressure Level (dBA)
31.5	75 – 39 = 36
63	77 – 26 = 51
125	84 – 16 = 68
250	85 – 9 = 76
500	80 – 3 = 77
1,000	75 – 0 = 75
2,000	70 + 1 = 71
4,000	61 + 1 = 62
8,000	54 – 1 = 53
16,000	32 – 7 = 25
Total sound pressure level = 89 dB (linear) and 81.5 dBA	

The total A-weighted noise level is 81.5 dBA, compared with the linear noise level of 89 dB. In other words, the original linear frequency spectrum with a total noise level of 89 dB is perceived as a total A-weighted noise level of 81.5 dBA.

A linear noise level of 89 dB with a different frequency spectrum distribution, could have produced a different A-weighted noise level, either higher or lower. The reverse may also be true. Theoretically, an infinite number of frequency spectrums could produce either the same total linear noise level or the same A-weighted spectrum. This is an important concept because it can help explain a variety of phenomena dealing with noise perception. For example, some evidence suggests that changes in frequencies are sometimes perceived as changes in noise levels, although the total A-weighted noise levels do not change significantly. Section 7 addresses with some of these phenomena.

2.1.3.8 White and Pink Noise

White noise is noise with a special frequency spectrum that has the same amplitude (level) for each frequency interval over the entire audible frequency spectrum. It is often generated in laboratories for calibrating sound level measuring equipment, specifically its frequency response. One might expect that the octave or one-third-octave band spectrum of white noise would be a straight line, but this is not true. Beginning with the lowest audible octave, each subsequent octave spans twice as many frequencies than the previous ones, and therefore contains twice the energy. This corresponds with a 3-dB step increase for each octave band, and 1 dB for each one-third-octave band.

Pink noise, in contrast, is defined as having the same amplitude for each octave band (or one-third-octave band), rather than for each frequency interval. Its octave or one-third-octave band spectrum is truly a straight "level" line over the entire audible spectrum. Therefore, pink noise generators are conveniently used to calibrate octave or one-third-octave band analyzers.

Both white and pink noise sound somewhat like the static heard from a radio that is not tuned to a particular station.

2.1.4 Sound Propagation

From the source to receiver, noise changes both in level and frequency spectrum. The most obvious is the decrease in noise as the distance from the source increases. The manner in which noise reduces with distance depends on the following important factors.

- Geometric spreading from point and line sources.
- Ground absorption.
- Atmospheric effects and refraction.
- Shielding by natural and manmade features, noise barriers, diffraction, and reflection.

2.1.4.1 Geometric Spreading from Point and Line Sources

Sound from a small localized source (approximating a point source) radiates uniformly outward as it travels away from the source in a spherical pattern. The sound level attenuates or drops off at a rate of

6 dBA for each doubling of the distance (6 dBA/DD). This decrease, resulting from the geometric spreading of the energy over an ever-increasing area, is referred to as the inverse square law. Doubling the distance increases each unit area, represented by squares with sides “a” in Figure 2-7, from a^2 to $4a^2$.

Because the same amount of energy passes through both squares, the energy per unit area at 2D is reduced four times from that at distance D. Therefore, for a point source the energy per unit area is inversely proportional to the square of the distance. Taking $10\log_{10}(1/4)$ results in a 6-dBA/DD reduction. This is the point source attenuation rate for geometric spreading.

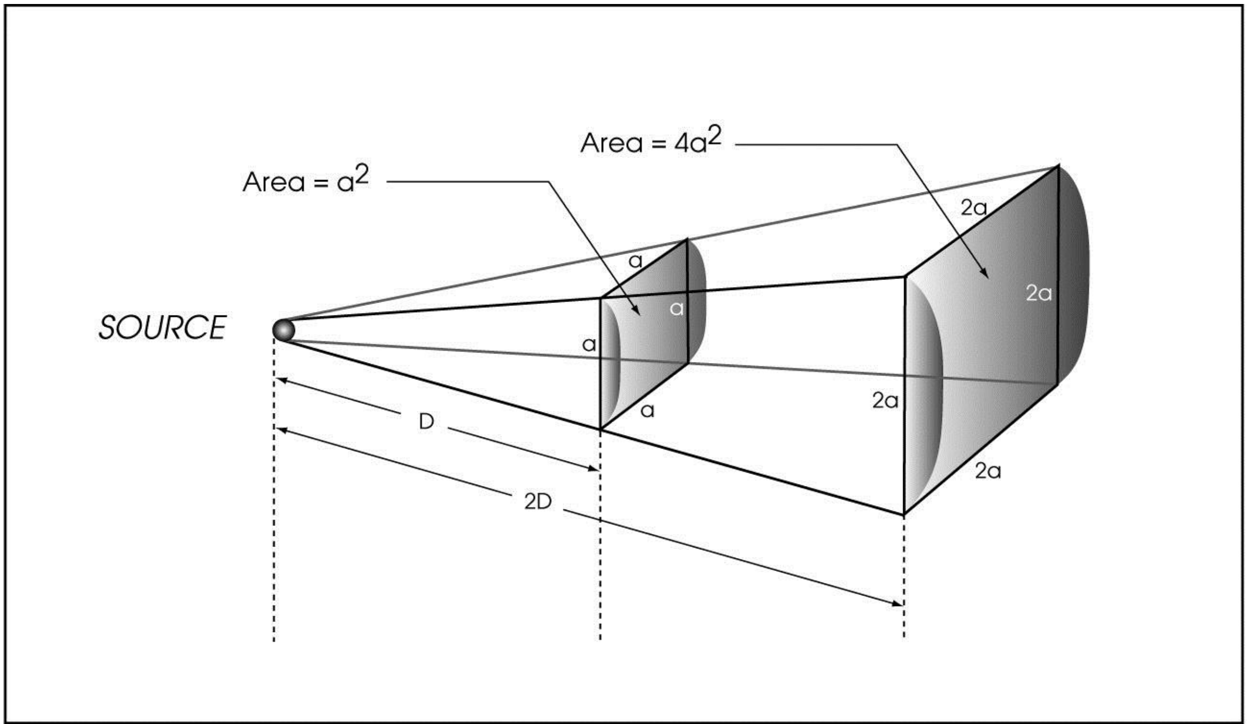

Figure 2-7. Point Source Propagation (Spherical Spreading)

As seen in Figure 2-8, based on the inverse square law the change in noise level between any two distances because of spherical spreading can be found using the following equation:

$$dBA_2 = dBA_1 + 10\log_{10}[(D_1/D_2)]^2 = dBA_1 + 20\log_{10}(D_1/D_2) \qquad \textbf{(2-13)}$$

Where:

dBA_1 = noise level at distance D_1

dBA_2 = noise level at distance D_2

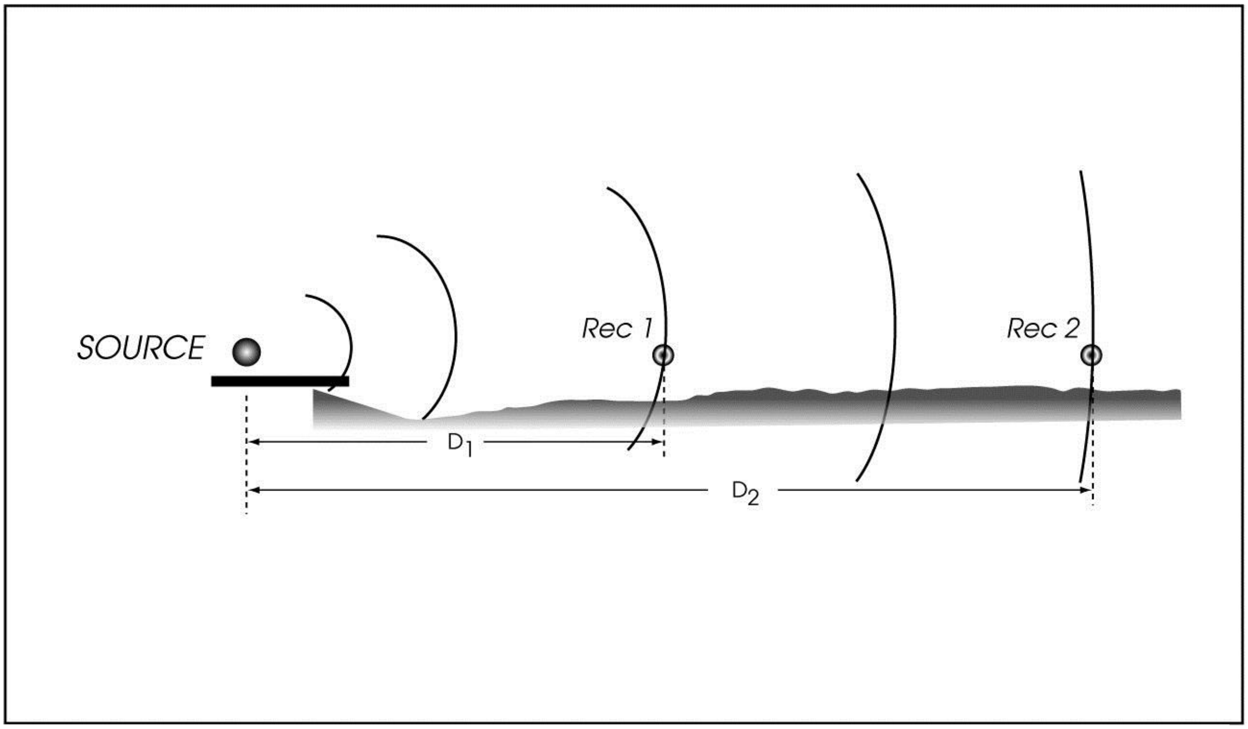

Figure 2-8. Change in Noise Level with Distance from Spherical Spreading

However, highway traffic noise is not a single, stationary point source. The movement of the vehicles makes the source of the sound appear to emanate from a line (line source) rather than a point when viewed over a time interval (Figure 2-9). This results in cylindrical spreading rather than spherical spreading. Because the change in surface area of a cylinder only increases by two times for each doubling of the radius instead of the four times associated with spheres, the change in sound level is 3 dBA/DD. The change in noise levels for a line source at any two different distances from cylindrical spreading is determined using the following equation:

$$dBA_2 = dBA_1 + 10\log_{10}(D_1/D_2) \qquad \textbf{(2-14)}$$

Where:

dBA_1 = noise level at distance D_1 and conventionally the known noise level

dBA_2 = noise level at distance D_2 and conventionally the unknown noise level

Note

The expression $10\log_{10}(D_1/D_2)$ is negative when D_2 is more than D_1 and positive when D_1 is more than D_2. Therefore, the equation automatically accounts for the receiver being farther or closer with respect to the source—$\log_{10}$ of a number less than 1 gives a negative result, $\log_{10}$ of a number more than 1 is positive, and $\log_{10}(1) = 0$.