APPENDIX E

Sound Basics

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FIGURES

TABLES

E.1 SOUND BASICS

E.1.1 Properties of Sound

E.1.1.1 Sound Wave Properties

To gain an understanding of the principles applied to the analysis of sound effects, it may first be beneficial to examine the characteristics of "sound" and how it relates to "noise." The definitions of sound and noise are bound up in human perceptions of each. Sound is a complex vibration transmitted through the air that, upon reaching the ears, may be perceived as desirable or unwanted. Noise can be defined simply as unwanted sound or, more specifically, as any sound that is undesirable because it interferes with speech and hearing, is intense enough to damage hearing, or is otherwise annoying (USEPA 1976).

Sound can be defined as an auditory sensation evoked by an oscillation (vibratory disturbance) in the pressure and density of a fluid, such as air, or in the elastic strain of a solid, with the frequency in the approximate range of 20 to 20,000 Hz. In air, sound propagation occurs as momentum is transferred through molecular displacement from the displaced molecule to an adjacent one. An object's vibrations stimulate the air surrounding it, and cause a series of compression and rarefaction cycles as it moves outward and inward. The number of times per second the wave passes from a period of compression, through a period of rarefaction, and back to the start of another compression is referred to as the *frequency* of the wave and is expressed in cycles per second, or hertz (Hz). The distance traveled by the wave through one complete cycle is referred to as the *wavelength*. The higher the frequency, the shorter the wavelength and vice versa.

E.1.1.2 Sound Intensity and Loudness

As sound propagates from a single source, it radiates more or less uniformly in all directions, forming a sphere of acoustic energy. Although the total amount of acoustic energy remains constant as the spherical wave expands, the intensity of the energy [amount of energy per unit of area on the surface of the sphere, normally expressed in watts per square meter (watts/m^2)] decreases in proportion to the square of the distance (because the same amount of energy must be distributed over the surface area of the sphere which increases in proportion to the square of the distance from the source).

The intensity of the acoustic energy cannot be measured conveniently; however, as the sound waves propagate through the air, they create changes in pressure which can be measured conveniently and provide a meaningful measure of the acoustic power intensity (loudness). The sound intensity is proportional to the square of the fluctuations of the pressure above and below normal atmospheric pressure. Measurements of sound pressure (defined as the root mean square of the fluctuations in pressure relative to atmospheric pressure) are the most common measure of the strength of sound or noise.

E.1.1.3 The Decibel

The faintest sound audible to the normal human ear has an intensity of approximately 10^{-12} watts/m^2. In contrast, the sound intensity produced by a Saturn rocket at liftoff is approximately 10^8 watts/m^2. The ratio of these two sound intensities is 10^{20} (1 followed by 20 zeros), a range that is difficult to comprehend or use.

To permit comparison of values which vary so greatly in magnitude, it is most convenient to express them in terms of their logarithms - the power to which 10 must be raised to equal the number. The logarithms of the sound intensities indicated above would vary from -12 to 8, a range of 20 units. To avoid the use of negative numbers, it is convenient to express the values in terms of the logarithm of their ratio to a standardized reference value, most frequently the lowest value expected to be encountered. On this logarithmic scale, an increase of 1 unit represents a ten-fold increase in the ratio. On this scale, the values for the sound intensities would vary from 0 to 20.

The unit of measurement on a logarithmic scale is the *Bel*, named in honor of Alexander Graham Bell. The bel is a rather large unit and since each unit represents a 10-fold increase relative to the previous value, it is convenient to divide each unit into 10 subunits known as decibels and abbreviated as *dB*. Using the decibel scale, our range of intensity ratios now expands to 0.0 to 200.0 rather than 0 to 20. The decibel scale is commonly used for the measurement of values which vary over extremely large ranges. Because the values are the logarithms of ratios, they are dimensionless (have no units of measurement such as length, mass or time) and are normally referred to as *levels*. By definition:

$$L = 10\,log\left(\frac{MeasuredQuantity}{ReferencedQuantity}\right)$$ **(Eq. E.1-1)**

Because decibels are logarithmic, they are not arithmetically additive. If two similar sound sources produce the same amount of sound (for example 100 dB each), the total sound level will be 103 dB, not 200 dB. The greater the difference between the two sound levels, the less impact the smaller number will have on the larger. As an example, if 70 dB and 50 dB are logarithmically added, the result is less than 0.05 of a decibel increase, to 70.04 dB. Likewise, when summing multiple events of the same magnitude, the heaviest penalty is paid for the first two or three events, with each successive event having a lesser impact. For example, if five 100 dB events are added, the result is approximately 107 dB. Sound levels can be added using the following equation:

$$10\,log\left[\sum_{i=1}^{n} 10^{\frac{x_i}{10}}\right]$$ (Eq.E.1-2)

E.1.1.4 Measurement of Sound Intensity

As stated previously, sound pressure can be measured more conveniently and accurately than sound intensity (although measurement techniques are available for measuring sound intensity directly). The sound intensity (power per unit area) varies in proportion to the square of the sound pressure. For example in a plane progressive wave in air, the sound intensity (I) is defined by the equation:

$$I = \frac{P^2}{dC} \qquad \textbf{(Eq.E.1-3)}$$

Where: d=Density of the air

C=Velocity of sound in air

The change in sound intensity can be measured in terms of the change in *sound pressure level (SPL)* expressed in decibels:

$$SPL = 10\,log\left[\frac{SP^2_{Meas}}{SP^2_{Ref}}\right] \qquad \textbf{(Eq.E.1-4)}$$

Where: SP_{Meas} *= Measured sound pressure*

SP_{Ref} *= Reference pressure (20* μ*P)*

E.1.1.5 Sound Propagation and Attenuation

As stated previously, sound intensity decreases with increasing distance from the source due to the dissipation of the sound energy over an increasing area. The sound intensity varies inversely with the square of distance from the source. For each time the distance from the source doubles, the sound pressure is reduced by a factor of two, and the sound level, which is proportional to the square of the pressure, is reduced by a factor of 4. As illustrated by the equation below (Eq. E.1-5), this is equivalent to a decrease of approximately 6 dB in the sound pressure level for each doubling of distance.

$$L = 10\,log\left(\frac{(0.5P^2}{P^2_{Ref}}\right) = 10\,log(0.5^2) + 10\,log\left(\frac{P^2}{P^2_{Ref}}\right) = -6 + 10\,log\left(\frac{P^2}{P^2_{Ref}}\right) \qquad \textbf{(Eq.E.1-5)}$$

In addition to the decrease in sound leve,l which results from the spreading of the sound waves and distribution of the sound energy over an increasingly large area, interaction with the molecules of the atmosphere results in absorption of some of the sound energy. The amount of energy absorbed is dependent on the atmospheric conditions (temperature and humidity) and on the frequency characteristics of the sound. Figure E.1–1 illustrates the effect of frequency on the absorption of sound under typical weather conditions of 60° F and 49% relative humidity.

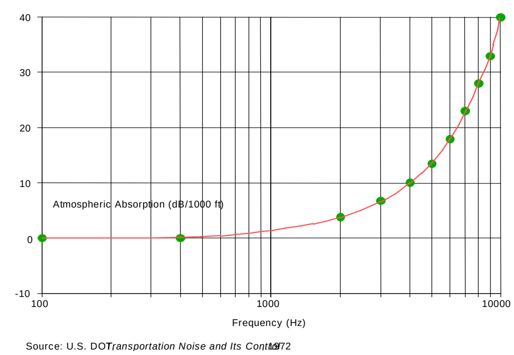


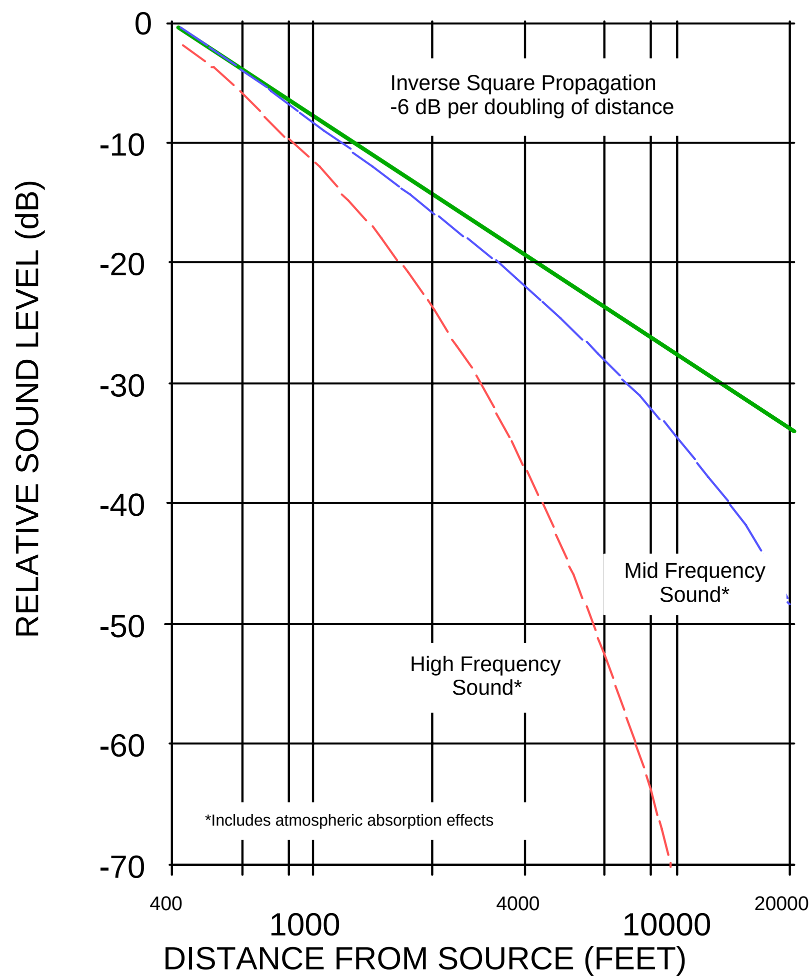
Figure E.1–1 Typical Effect of Frequency on Atmospheric Absorption of Sound

As shown in Figure E.1-1, atmospheric absorption can have a significant influence on the attenuation of sounds with a high frequency. For complex noise signals with a significant high frequency component, such as aircraft noise, atmospheric attenuation can result in significant reduction in sound levels as the distance from the source increases. Figure E.1-2 illustrates typical noise level variation as a function of distance *with* and *without* atmospheric absorption effects. As shown in Figure E.1-1, the effect of atmospheric attenuation is significant for high frequency sound (1,000 Hz and above) at essentially all distance, and becomes significant for mid-frequency sound (around 500 Hz) at large distances.

In addition to molecular absorption, there are a variety of atmospheric phenomena, such as wind and temperature gradients, which affect the propagation of sound through the air. Sound propagating from sources on or near the ground (such as aircraft ground runups and flight at low altitudes) is also influenced by terrain, vegetation, and structures which may either absorb or reflect sound, depending upon their characteristics and location and orientation relative to the source.

E.1.1.6 Sound Energy Dose Response

Observations that attempt to describe the environmental consequences of discrete events must weigh the characteristics of the individual sound events by the number of those events. These measurements describe an empirical dosage-effect relationship, and are one of the few quantitative tools available for predicting sound-induced annoyance. These metrics are often referred to as dose-response metrics, and will be discussed later in this appendix.



Source: U.S. DoD, *Planning in the Noise Environment* 1978

Figure E.1-2 Typical Attenuation of Sound with Distance from a Point Source

E.1.2 Human Hearing

E.1.2.1.1 How the Human Ear Works

Sound waves entering the ear are enhanced by the resonant characteristics of the auditory canal. Sound waves travel up the ear canal and set up vibrations in the eardrum. Behind the eardrum is a cavity called the middle ear. The middle ear functions as an impedance matcher. It is comprised of three tiny bones that provide frictional resistance, mass, and stiffness, and thus act in opposition to the incoming sound wave and transmit vibrations to the inner ear. More specifically, sound pressure from waves traveling through the air (low impedance) is amplified about 21 times so that it may efficiently travel into the high impedance fluid medium in the inner ear. This is accomplished by the leverage action of the three middle ear bones. The footplate of the stapes, the bone closest to the inner ear, in turn moves in and out of the oval window in the inner ear. The movement of the oval window sets up motion in the fluid that fills the inner ear. The movement of this fluid causes the hairs immersed in the fluid to move. The movement of these hairs stimulates the cells attached to them to send impulses along the fibers of the auditory nerve to the brain. The brain translates these impulses into the sensation of *sound*.

E.1.2.2 Human Response to Sounds

E.1.2.2.1 Human Hearing Thresholds

Laboratory experiments have found that the "absolute" threshold of hearing in young adults corresponds to a pressure of about 0.0002 dyne/centimeter^2 (cm^2) or 0.00002 Pascal. This reference level was determined in a quiet noise environment and at the most acute frequency range of human hearing, between 1,000 and 4,000 Hz. The general range of human hearing is usually defined as being between 20 and 20,000 Hz. Frequencies below 20 Hz are called infrasonic, while those above 20,000 Hz are called ultrasonic. Frequencies in the range of 20 to 20,000 Hz are called sonic, and are referred to as the audible frequency area.

E.1.2.2.2 Loudness

On the decibel scale, an increase in Sound Pressure Level (SPL) of 3 dB represents a doubling of sound energy, but an increase in SPL on the order of 10 dB represents a subjective doubling of "loudness" (U.S. DoD 1978). Table E.1-1 depicts the relative loudness of typical noises encountered in the indoor and outdoor environments.

Table E.1–1 Decibel Levels (dB) and Relative Loudness of Typical Noise Sources in Indoor and Outdoor Environments

dB(A)	Overall level	Community Noise Levels (Outdoor)	Home and Industry Noise Levels (Indoor)	Subjective Loudness (Relative to 70 dB)
120	Uncomfortably loud	Military jet aircraft take-off from aircraft carrier with afterburner at 50 ft .... 130 dB	Oxygen torch...................121 dB	32 times as loud
110		Turbo-fan aircraft at takeoff power at 200 ft .... 118 dB	Riveting machine.............110 dB Rock band .... 108-114 dB	16 times as loud
100	Very loud	Boeing 707 or DC-8 aircraft at 1 nautical mile (6080 ft) before landing .... 106 dB Jet flyover at 1000 ft.......... 103 dB Bell J-2A helicopter at 100 ft100 dB		8 times as loud
90		Boeing 737 or DC-9 aircraft at 1 nautical mile (6080 ft) before landing .... 97 dB Power mower .... 96 dB Motorcycle at 25 ft............... 90 dB	Newspaper press ....97 dB	4 times as loud
80		Car wash at 20 ft................. 89 dB Propeller plane flyover at 1000 ft .... 88 dB Diesel truck 40 mph at 50 ft 84 dB Diesel train 45 mph at 100 ft83 dB	Food blender. . . . . 88 dB Milling machine ....85 dB Garbage disposal..............80 dB	2 times as loud
70	Moderately loud	High urban ambient sound.. 80 dB Passenger car 65 mph at 25 ft77 dB Freeway at 50 ft from pavement edge at 10 a.m. .... 76 dB	Living room music ....76 dB Radio or TV-audio, vacuum cleaner.................70 dB	70 dB(A)
60		Air conditioning unit at 100 ft .... 60 dB	Cash register at 10 ft... 65-70 dB Electric typewriter at 10 ft..64 dB Dishwasher (Rinse) at 10 ft60 dB Conversation.....................60 dB	1/2 as loud
50	Quiet	Large transformers at 100 ft .... 50 dB		1/4 as loud
40		Bird calls............................. 44 dB Lowest limit of urban ambient sound .... 40 dB		
dB Scale Interrupted				
10	Just audible			
0	Threshold of Hearing			

Source: M.C. Branch, et al. 1970.

The loudness of sound (sensation) depends on its intensity, and on the frequency of the sound and the characteristics of the human ear. The intensity of sound is a purely physical property, whereas the loudness depends also upon the characteristics of the receptor ear. In other words, the intensity of a given sound striking the ear of a normal hearing person and of a hard-of-hearing person might be the same, but the perceived loudness would be quite different.

E.1.2.2.3 Effects of Frequency on Loudness

The response of the human ear to frequency and intensity is *not* linear, but varies with sensation level. Figure E.1-3 depicts this response characteristic. The equal loudness levels depicted in the figure were defined as the intensity required to make a given test tone seem equally as loud as the reference tone of 1,000 Hz. The unit of loudness level that is used to plot the data is called the *phon*. Thus, the loudness level in phons of any sound is equal to the intensity level in decibels of a 1,000 Hz tone which is perceived as equal in loudness to the sound under evaluation.

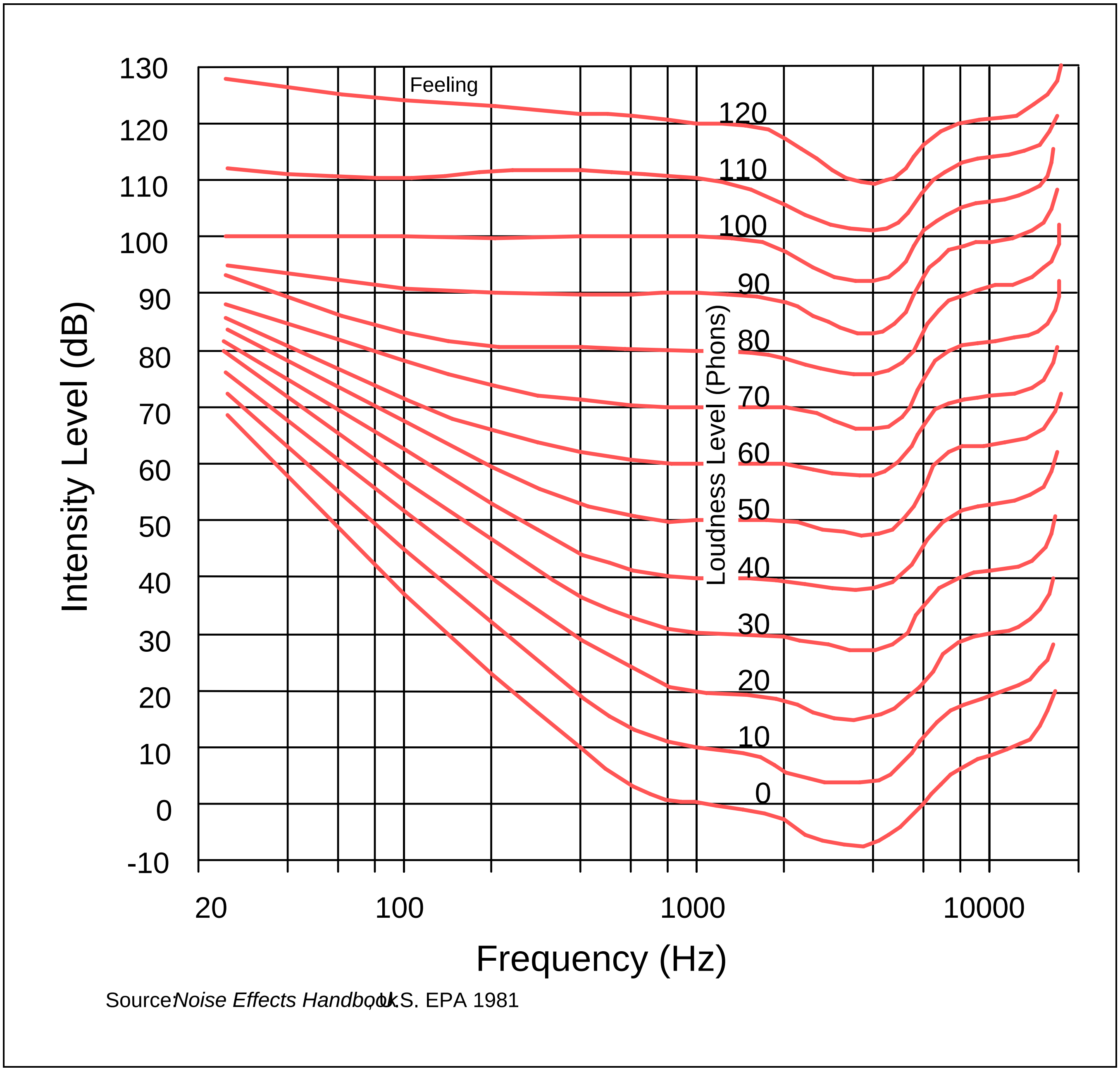


Figure E.1–3 Equal Loudness Contours

The data in Figure E.1-3 can be used to illustrate the effects of both frequency and energy level on the sensation of loudness. The effect of frequency on the perceived loudness is most pronounced at frequencies below 1000 Hz and low sound levels. Although 100 Hz and 1000 Hz tones with intensity levels of approximately 37 dB and 0 dB, respectively, are perceived as equally loud (i.e., barely detectable-0 phons), the 100 Hz tone has 5000 times the sound energy of the 1000 Hz tone. In contrast, 100 Hz and 1000 Hz tones with intensities of 100 dB would sound equally loud-approximately 100 phons. The relationship between frequency, intensity, and loudness is quite complex. However, humans do have a sense of relative loudness, and a fair measure of agreement can be reached on when a sound is one-third as loud as another, one-half as loud, etc.

E.1.2.2.4 Frequency Weighted Sound Levels

Because the human ear does not respond to sounds of varying frequency and intensity in a linear fashion, various "weighting" factors are applied to noise measurements in an effort to produce results which correspond to human response. These weighting factors are applied to the levels of sound in specific frequency intervals and added or subtracted based on the average human response to sounds in that frequency range; the resultant values are then summed to determine the overall "weighted" level. The most commonly used weighting systems are the "A" and "C" scales.

The A-scale de-emphasizes the low- and high-frequency portions of the sound spectrum. This weighting provides a good approximation of the response of the average human ear and correlates well with the average person's judgment of the relative loudness of a noise event. In contrast, the C-weighting scale gives nearly equal emphasis to sounds of all frequencies and approximates the actual (unweighted) sound level. The C-weighted sound level is used for large amplitude impulse sounds such as sonic booms, explosions, and weapons noise in which the total amount of energy is an important factor. Figure E.1-4 shows how A-weighting and C-weighting in a sound meter are applied to sounds of various frequencies.

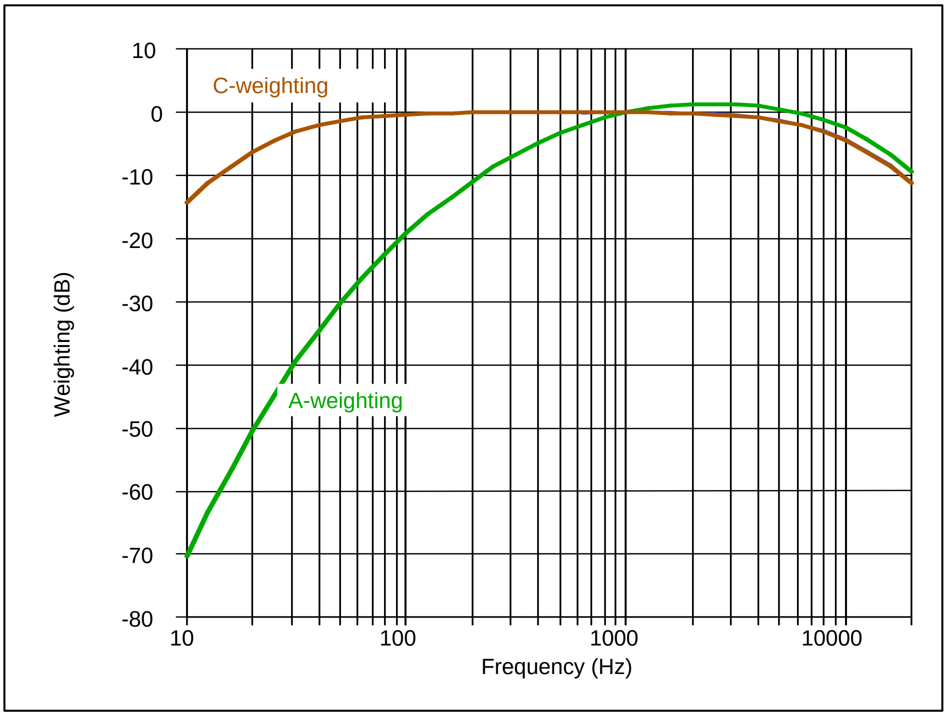


Figure E.1–4 Frequency Responses for Sound Level Weighting Characteristics

E.1.2.2.5 Supersonic Aircraft and Sonic Booms

An aircraft in supersonic flight (faster than the speed of sound) creates a wave of compressed air out in front of the aircraft. This wave is known as a "sonic boom" and is heard, and felt, as a sudden, loud impulse noise. A sonic boom may be defined as "an acoustic phenomenon heard when an object exceeds the speed of sound" (U.S. DoD AF 1986a). Individuals on the ground experiencing a sonic boom actually hear the change in pressure when air molecules are first compressed and then returned to a more normal state. This pressure differential across the shock wave is relatively large and is very sudden. The human ear perceives this rapid change in pressure as an impulsive sound not unlike a firecracker, a rifle shot, or the crack of a whip.

Supersonic aircraft create two categories of sonic booms: the carpet boom and the focused (or super) boom. An aircraft traveling straight and level at supersonic speeds would create a continuous boom that can be likened to a moving carpet across the ground. Focused booms, on the other hand, are a result of maneuvering flight and most often occur during rapid acceleration, tight turns, and pushover operations with a small curvature or arc of the flight track. The surface area affected by focused booms is usually substantially smaller than that impacted by a carpet boom. The intensity and overpressures created by a focused boom may be two to five times higher, while the duration would be about the same.

Not all booms created by aircraft are heard at ground level. Variations in atmospheric temperature (decreasing temperature gradients as altitude increases) tend to bend the sound waves upward. Depending on the altitude and Mach number1 of an aircraft, the paths of many sonic booms are deflected upward and never reach the earth. Likewise, the width of the area impacted by a sonic boom can also be decreased. Of those sonic booms that reach the surface, the intensity of the sound overpressure is largely dependent on the aircraft altitude, airspeed, size (length), and attitude (straight and level, turning, climbing, diving, etc.). This peak sound overpressure is expressed in terms of dBC (C-weighted decibel) or pounds per square foot (psf) of pressure. Maximum peak overpressure (L_{pk}) normally occurs directly under the flight track of the aircraft and decreases laterally at a rate proportional to -(3/4) power of the slant range between the aircraft and the observer. As an example, if an F-16 aircraft flying at supersonic speed and at 15,000 feet above the ground produced a sonic boom that generated an overpressure of 2.4 psf directly beneath the aircraft, the overpressure would decay laterally from the flight path. At 1 mile laterally, L_{pk} would equal 2.30 psf; at 2 miles, L_{pk} would equal 2.06 psf, at 3 miles, L_{pk} would equal 1.81 psf, and by about 4.25 miles, L_{pk} would equal 0.50 psf.

[1] Mach Number is defined as the ratio the speed of a moving object to the speed of sound in the medium through which it travels.

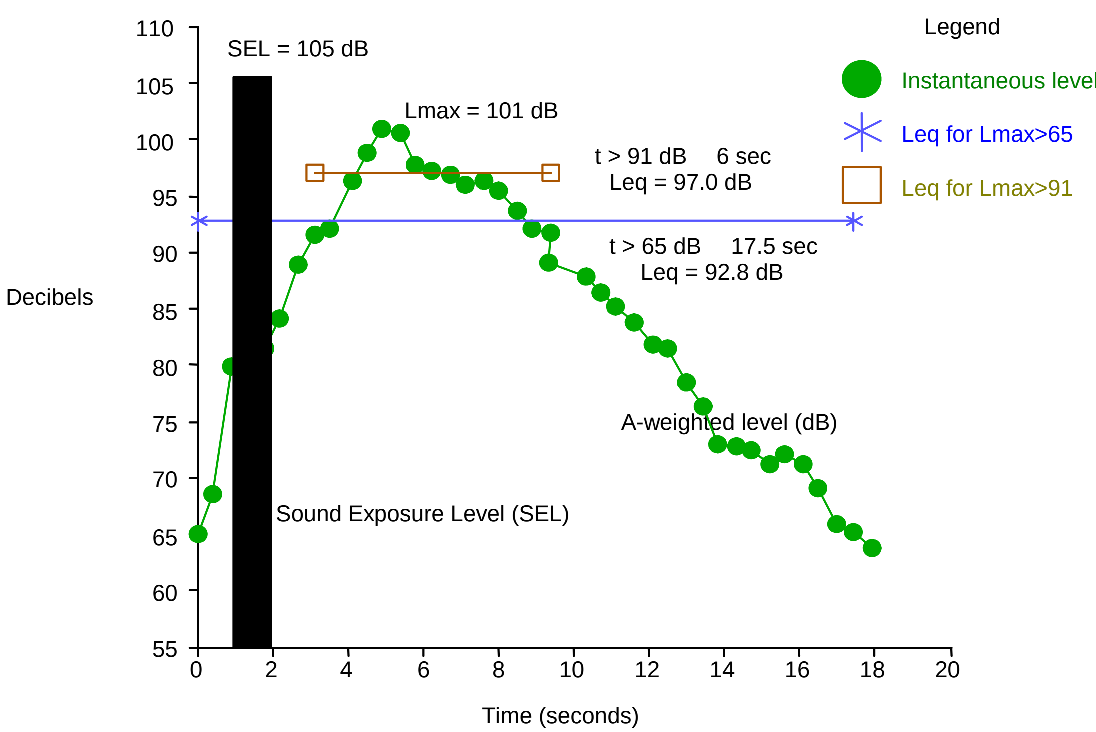
E.1.2.3 Sound Metrics

To assess the impacts of sound on a diverse spectrum of receptors, a variety of metrics may be used. Depending on the specific situation, appropriate metrics may include instantaneous levels, single event, or cumulative metrics. Single event metrics are used to assess the potential impacts of sound on structures and animals, and may be employed for informational purposes in the assessment of some human effects. Cumulative metrics are most useful in characterizing the overall noise environment and are the primary metrics used in development of community (exposed population) dose-response relationships.

E.1.2.4 Single Event Metrics

Metrics used to characterize a single sound event include the instantaneous sound level as a function of time, the maximum sound level, the equivalent (average) level, and the Sound Exposure Level (SEL), a single number metric which incorporates both level and duration. The relationship between these metrics is illustrated in Figure E.1-5.

Figure E.1-5 Relationship Between Single Event Sound Metrics



E.1.2.4.1 Single Event Instantaneous Sound Levels

The Sound Pressure Level (SPL) and the A-weighted sound level, both expressed in decibels (dB), may be used to characterize single event maximum sound levels for general audible noise. Figure E.1-5 indicates the variation in the A-weighted sound level (L) for the time during a typical aircraft flyover event when the level exceeds 65 dB. For this event (which is representative of a flyover by a military fighter aircraft at a distance of approximately 1,000 feet and a speed of 350 knots), the sound level increases rapidly to a level of approximately 101 dB in approximately 5.5 seconds and then decreases back to less than 65 dB in a period of approximately 12 seconds.

E.1.2.4.2 Single Event Maximum Sound Level (L_{max})

The single event maximum value is the most easily understood descriptor for a noise event, it provides no information concerning either the duration of the event or the amount of sound energy. This metric is currently used for noise certification of small propeller-driven aircraft and to assess potential effects on animals.

E.1.2.4.3 Duration

The "duration" of a sound event can be determined in terms of the total time during which the sound level exceeds some specified threshold value. In the example in Figure E.1-5, the level exceeds 65 dB for approximately 17.5 seconds. A major limitation on the usefulness of this metric is the absence of a standardized threshold value and the inability to quantify the amount of sound energy associated with the event.

Equivalent Level (L_{eq})

For any specified period, the equivalent sound level, i.e., the level of a steady tone which provides an equivalent amount of sound energy may be calculated using the relationship:

$$L_{eq(T)} = 10\,log\left[\frac{1}{T}\int_0^T 10^{\frac{L_A(t)}{10}}\,dt\right] \qquad \textbf{(Eq. E.1-6)}$$

Where: $L_{eq(T)}$ is the equivalent sound level for the period T
T is the length of the time interval during which the average is taken, and
$L_A(t)$ is the time varying value of the A-weighted sound level in the interval 0 to T.

Although the equivalent sound level metric includes all of the sound energy during an event, the absence of a standardized averaging period makes it difficult to compare data for events of different duration. In the example in Figure E.1-5, the equivalent level for the 17.5 second duration of the event above 65 dB (Leq(17.5sec)) is approximately 92.8 dB; if the Leq is calculated for the approximately 6 seconds during which the sound level exceeds 90 dB, the result is approximately 97.0 dB.

E.1.2.4.4 Single Event Energy (Sound Exposure Level)

Subjective tests indicate that human response to noise is a function not only of the maximum level, but also of the duration of the event and its variation with respect to time. Evidence indicates that two noise events with equal sound energy will produce the same response. For example, a noise with a constant level of SPL 85 dB lasting for 10 seconds would be judged to be equally as annoying as a noise event with an SPL 82 dB and a duration of 20 seconds. (i.e., one-half the energy lasting twice as long). This is known as the "equal energy principle." The Sound Exposure Level (SEL) is a measure of the physical energy of the noise event which takes into account both intensity and duration. The SEL is based on the integral of the A-weighted sound level during the period it is above a specified threshold (that is at least 10 dB below the maximum value measured during the noise event) with reference to a standardized duration of 1 second. Thus, the SEL is the level of a constant sound with a duration of 1 second which would provide an amount of sound energy equal to the energy of the event under consideration. It may be calculated using the equation for the equivalent level Eq. E.1-6 with the duration (T) replaced by the referenced time (Tref) of 1 second.

$$SEL = 10\log\left[\frac{1}{T_{Ref}}\int_{t_1}^{t_2} 10^{\frac{L_A(t)}{10}}dt\right] = 10\log\left[\int_{t_1}^{t_2} 10^{\frac{L_A(t)}{10}}dt\right] \qquad \textbf{(Eq. E.1-7)}$$

Where: TRef is equal to 1 second
t1 is the time at which the level exceeds 10 dB below the maximum value; and
t2 is the time at which the level drops below 10 dB below the maximum value.

In the example in Equation E.1-7, the SEL is approximately 105 dB. The value of considering both total energy and duration is illustrated by comparison of the calculated SEL values based on the time above 65 dB and the time above 91 dB (10 dB less than the maximum recorded value of 101 dB). The SEL calculated on the basis of the levels during the approximately 17.5 seconds when the sound level is above 65 dB is 105.3 dB; based on the approximately 6 seconds when the level exceeds 91 dB, the calculated SEL is 105.0 dB, a difference of only 0.3 dB. By comparison, the L_{eq} values for the same periods were 92.8 and 97.0 dB, respectively, a difference of 4.2 dB. This comparison illustrates the value of SEL as a single number metric which considers both total energy and duration.

Table E.1-2 and Table E.1-3 provide SEL and L_{max} values for military and commercial aircraft operating at takeoff thrust and airspeed, and measured at a slant distance of 1000 feet. By definition, SEL values are referenced to a duration of 1 second and should not be confused with either the average or maximum noise levels associated with a specific event. As noted in equation E.1-7, the SEL value for the flyover event was approximately 105 dB while the equivalent level based on a duration of approximately 17 seconds was 92.8, a difference of 12.2 dB. By definition, noise levels that exceed the SEL value must have durations of less than one second. For aircraft overflights, maximum noise levels would typically be 5 to 10 dB below the SEL value.

Table E.1–2 Sound Exposure Level (SEL) and Maximum A-Weighted Level (L_{max}) Data for Military Aircraft

Aircraft Type	Sound Exposure Level (SEL)[a]	Maximum Sound Level (L_{max})
Jet Bomber/Tanker/Transport		
B-1B	123.5	118.3
B-52G	121.5	113.9
B-52H	112.2	105.2
C-17	100.0	94.5
C-5	113.5	106.3
C-135B	106.6	101.9
C-141	105.8	99.7
KC-135A	117.8	109.1
KC-135R	92.2	87.1
Other Jet Aircraft with Afterburners		
F-4	115.7	109.7
F-14	109.7	106.4
F-15	112.0	104.3
F-16	106.7	101.0
F-18	116.9	108.0
FB-111	108.1	102.3
T-38	105.5	98.3
Other Jet Aircraft without Afterburners		
A-6	112.5	108.3
A-7	111.3	107.7
A-10	96.9	93.2
C-21	91.1	84.6
T-1A	99.4	90.3
T-37	97.7	91.0
T-39	103.3	96.8
T-43	100.8	94.1
Propeller Aircraft		
C-12	79.3	73.2
C-130	90.5	83.7
P-3	96.8	91.0

[a] At nominal takeoff thrust and airspeed and at a slant distance of 1,000 ft from the aircraft.

Source: U.S. Air Force, AL/OEBN 1992.

Table E.1–3 Sound Exposure Level (SEL) and Maximum A-Weighted Level (L_{max}) Data for Civilian Airdraft

Aircraft Type	Sound Exposure Level (SEL)[a]	Maximum Sound Level (L_{max})
Civil Jet Aircraft		
707, DC-8	113.5	104.4
727	112.5	106.5
737, DC-9	110.0	104.0
747	102.5	96.3
757	97.0	91.5
767	96.7	91.2
DC-10, L-1011	100.0	92.3
Learjet	97.1	89.4

[a] At nominal takeoff thrust and airspeed and at a slant distance of 1,000 ft from the aircraft.

Source: U.S. Air Force, AL/OEBN 1992.

SEL is a measure of the total energy associated with a single noise event, and is useful for making calculations involving aircraft flyovers. The frequency characteristics, sound level, and duration of aircraft flyover noise events vary according to aircraft type and model (engine type), aircraft configuration (i.e., flaps, landing gear, etc.), engine power setting, aircraft speed, and the distance between the observer and the aircraft flight track. SEL versus slant range values are derived from noise measurements made according to a source noise data acquisition plan developed by Bolt, Beranek, and Newman, Inc., in conjunction with the U.S. Air Force's Armstrong Laboratory[2] (AL) and carried out by AL. Extensive noise data were collected for various types of aircraft/engines at different power settings and phases of flight. This extensive database of aircraft noise data provides the basis for calculating average individual-event sound descriptors for specific aircraft operations at any location under varying meteorological conditions. These reference values are adjusted to a location by correcting for temperature, humidity, altitude, and variations from standard aircraft operating conditions (power settings and speed).

[2] The U.S. Air Force Armstrong Laboratory was formerly known as the Armstrong Aerospace Medical Research Laboratory (AAMRL) and the majority of the work discussed in this section was conducted under that designation.

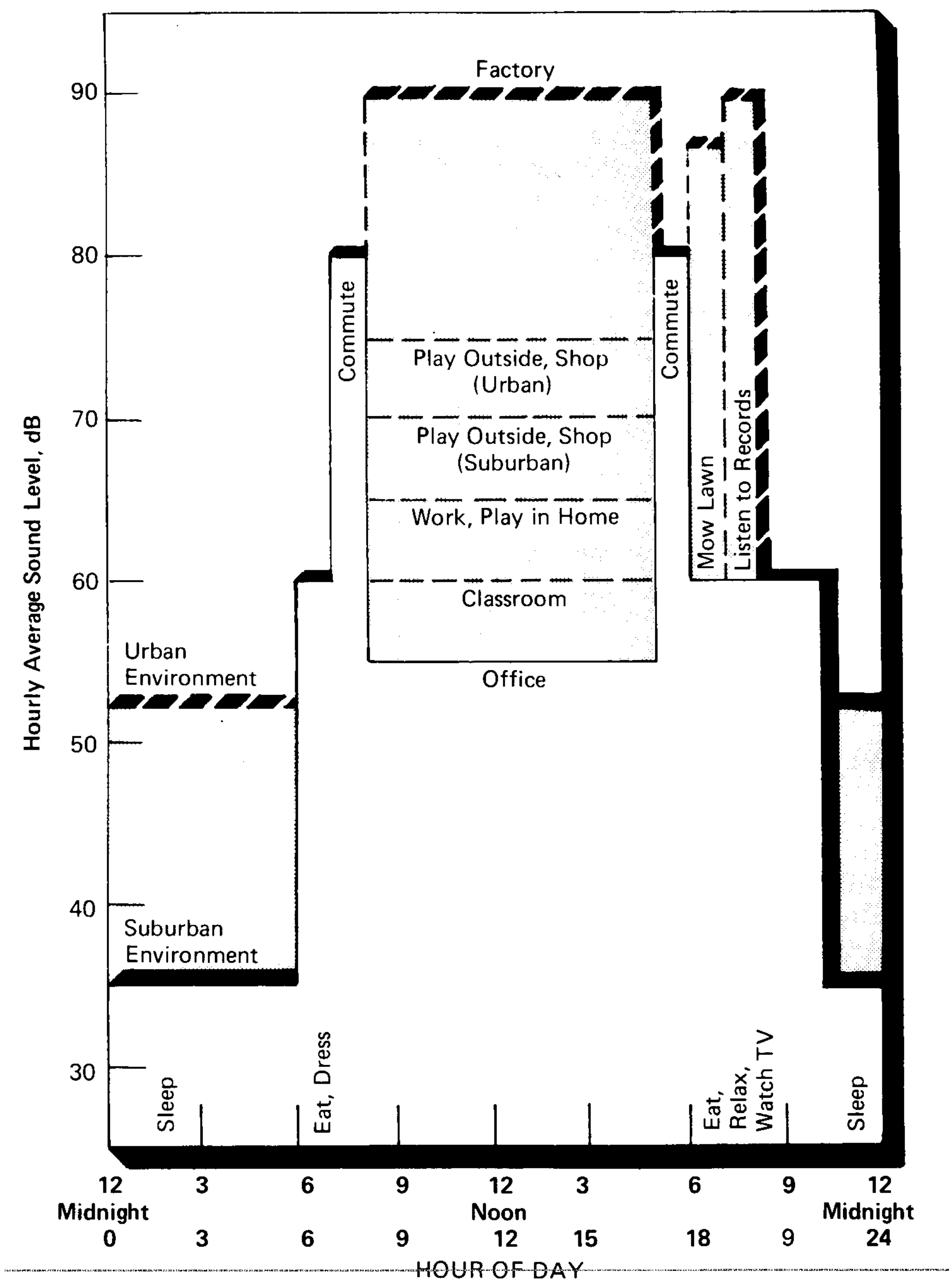
E.1.2.5 Application of Single Event Metrics

Single event analysis is sometimes conducted to evaluate sleep disturbances at nighttime and, less frequently, some speech interference issues, primarily at locations where the cumulative, A-weighted sound is below DNL 65 dB. However, there is no accepted methodology for aggregating effects into some form of cumulative impact metric; and single event metrics do not describe the overall noise environment. As described below, the day-night cumulative methodology includes a 10 dB nighttime penalty that reflects the potential for added annoyance due to sleep disturbance, speech interference, and other effects (U.S. Air Force, AAMRL 1991).

Single event prediction methods have limited application to land use planning. One should not infer that an area is simultaneously exposed to a given noise level, since sound decays with increasing distance from the flight track. The databases used in noise models are based on the average of numerous SEL values collected under carefully controlled conditions and normalized to standard acoustic conditions and aircraft operating parameters. Although these values may be adjusted to reflect specific meteorological conditions (temperature and humidity) and aircraft operating parameters (power setting and speed), they represent average values for that type of aircraft operating under the specified conditions. However, for a variety of reasons including daily/seasonal weather changes, wind speed and direction, variations in aircraft power settings and speed due to weight or weather conditions, etc., SEL values measured for specific events under field conditions may vary significantly from the average values predicted on the basis of the standardized values. Consequently, the single event metric has limited use in evaluating sound impacts. When SEL is used to supplement cumulative metrics, it serves only to provide additional information. SEL has been used to evaluate sleep interference, but does not predict long-term human health effects. Sleep interference evaluation using SEL does not presently account for human habituation.

E.1.2.6 Cumulative Energy Average Metrics

Urban traffic is by far the most pervasive outdoor residential sound source, although aircraft sound is a significant source as well. Over 96 million persons are estimated to be exposed, in and around their homes, to high traffic noise levels. Figure E.1-6 depicts the typical daily sound exposure found in various settings. Cumulative energy average metrics correlate well with aggregate community response to the sound environment. They may be derived from single event sound levels or computed from measured data. Although they were not designed as single event measures, they use single event data averaged over a specified time period. Thus single event measures or cumulative measures can relate to speech and sleep disturbance, although the relationship with sleep disturbance is not clearly established (Dean 1992).



Source: *Noise Effects Handbook* , U.S. EPA 1981

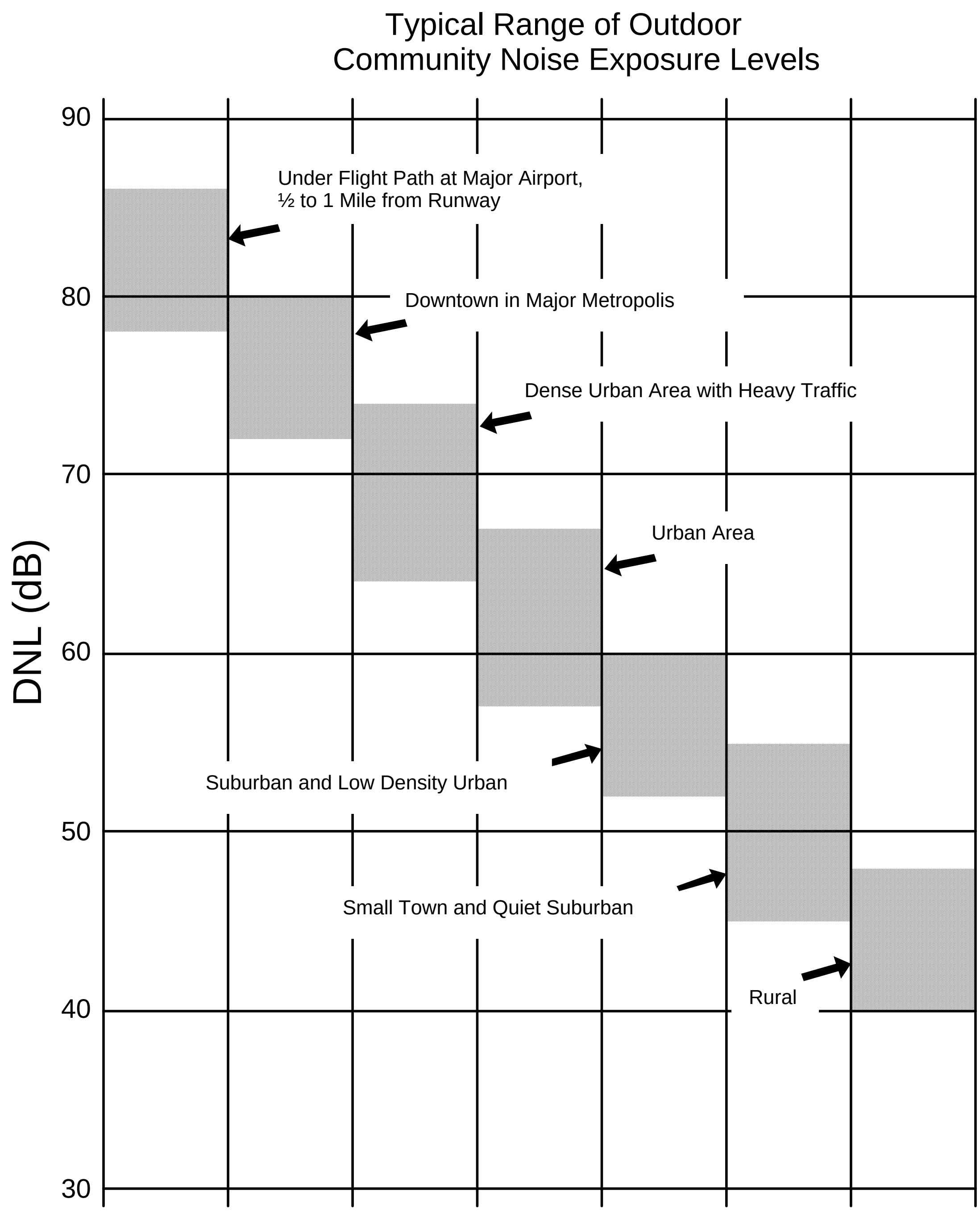
Figure E.1-6 Hypothesized Life Style Sound Exposure Patterns

E.1.2.6.1 Equivalent Sound Level

The Equivalent Sound Level (L_{eq}) is the Energy-Averaged Sound Level (usually A-weighted) integrated over a specified time period. The term "equivalent" indicates that the total acoustical energy associated with a varying sound (measured during the specified period) is equal to the acoustical energy of a steady state level of L_{eq} for the same period of time. The purpose of the L_{eq} is to provide a single number measure of sound averaged over a specified time period (Newman and Beattie 1985).

E.1.2.6.2 Day-Night Average Sound Level

The Day-Night Average Sound Level (DNL) is the Energy-Averaged Sound Level (L_{eq}) measured over a period of 24 hours, with a 10 dB penalty applied to nighttime (10 p.m. to 7 a.m.) sound levels to account for increased annoyance by sound during the night hours. The annual average DNL (DNL y-avg.) is the value specified in the FAA Federal Aviation Regulation (FAR) Part 150 noise compatibility planning process, and provides the basis for the land use compatibility planning guidelines in the Air Force Air Installation Compatible Use Zone (AICUZ) program (Newman and Beattie 1985; U.S. Air Force 1984). The typical range of outdoor DNL levels is illustrated in Figure E.1-7.



Source: DoD 1978

Figure E.1-7Typical Range of Outdoor Community Day-Night Average Noise Levels (DNL)

E.1.2.7 Basis for Use of DNL as the Single Environmental Descriptor

DNL (L_{eq} with a 10 dB penalty for nighttime exposure) was selected by EPA as the uniform descriptor of cumulative sound exposure to correlate with health and welfare effects (U.S. EPA 1974, 1982). Subsequently, all Federal agencies adopted YDNL (L_{dny}) as the basis for describing community noise exposure. DNL methodology has given consistent results in the national and international literature under a wide range of noise conditions (including loud and soft noise levels, and frequent and infrequent numbers of discrete aircraft events). Although seasonal corrections are not included in the definition of the DNL metric, the methodology does not preclude its use in any analysis of a special, well-defined noise exposure scenario.

Sound predictions are less reliable at lower levels (as low as 2 events per day) and at increasing distances from the airport, where the ability to determine the contribution of different sound sources is diminished. Since public health and welfare effects have not been established at these lower levels, there are problems in interpreting predictions below DNL 60 dB (DNL 55 dB plus a 5 dB margin of safety). Much of the criticism of the use of YDNL for community annoyance and land use compatibility around airports may stem from a failure to understand the metric. Another factor may be that some persons exposed to aircraft noise do not accept DNL 65 dB as the appropriate lower limit of noise exposure for noise impact. However, an average sound metric such as DNL takes into account the sound levels of all individual events that occur during a 24-hour period, and the number of times those events occur. The averaging of sound over a 24-hour period does not ignore the louder single events, but actually tends to emphasize both the sound level and number of those events. This is the basic concept of a time-averaged sound metric, and specifically DNL. The logarithmic nature of the dB unit causes sound levels of the loudest events to control the 24-hour average.

E.1.2.8 Day-Night Average Sound Level (C-Weighted)

While peak sound pressure level may be satisfactory for assessing impulses in a restricted range of peak pressures and durations, it is not sufficient as a general descriptor for use in measurement or prediction of the combined environmental effects of impulses having different pressure-time characteristics (U.S. Air Force 1984). The noise measures recommended for assessing these impulsive sound events is the C-Weighted Day-Night Average Sound Level, symbolized L_{cdn}. C-weighting does not discount the low frequency components of the sound event which are a major part of impulsive noise. Further, estimates of impulsive noise magnitude conform to magnitude estimates of other noises when the high-energy impulsive noise is measured by C-weighting. L_{cdn} is computed in the same manner as L_{dn}, except the Energy Averaged Sound Level used would be referenced to the C-weighting scale rather than the A-weighting. L_{cdn} has been found to correlate well with average human responses to impulsive noise and is the acoustical measure recommended by the National Research Council and the Environmental Protection Agency for assessing the environmental impacts of impulsive noise (U.S. Air Force 1984).

E.1.2.9 Onset Rate Adjusted Monthly Day-Night Average A-Weighted Sound Level (L_{dnmr})

Aircraft operations along low-altitude military training routes (MTRs) create noise effects that are not described well using the metrics that have been identified so far in this appendix. Most MTRs are used intermittently, from five to ten times per day along the most heavily traveled routes to less than ten times per one or two weeks. Average usage is in the range of two to five times per day. MTRs are typically several miles wide and aircraft can use any portion of the route, thus even points under the centerline of the route will probably not be directly flown over by each sortie. Use of MTRs results in noise exposure that is "well below threshold limits for hearing damage or other physiological effects" (U.S. Air Force, AAMRL 1987). However, aircraft flying at maneuvering speeds and at a minimum of 500 feet above ground level generate high-level, short-duration noise events that tend to create annoyance due to a startling effect on people flown over by these aircraft. L_{dnmr} modifies the DNL metric with a penalty for the onset rate of an aircraft, based on its airspeed, altitude, and number and type of engines. The penalty is a logarithmic ratio of onset rates with the following equation:

Onset Penalty = 16.6 log [Onset Rate (dB/sec)/ (15 dB/sec)]

The onset penalty is applied to DNL values computed for low-altitude flight operations. This metric applies for onset rates from 15 dB per second to 30 dB per second. Onset rates below the threshold of 15 dB do not require adjustments to the DNL, while onset rates greater than 30 dB per second are assigned a maximum penalty of a 5 dB increase to the computed DNL.

E.1.2.10 Supplemental Sound Metrics

DNL is sometimes supplemented by other metrics to characterize specific effects. These analyses are accomplished on a case-by-case basis, as required, and may include L_{eq} (Equivalent Sound Level), composite one-third octave band SPL (Sound Pressure Level), SEL (Sound Exposure Level), and L_{max} (Maximum Sound Level). Sound pressure levels are the starting points for all other metrics. Composite one-third octave band SPL is used to analyze sound impacts on structures; L_{max} is used to assess impacts on animals. SPL and L_{max} are expressed in units of decibels (dB).

E.1.3 Sound Analysis Methodology

E.1.3.1 NOISEMAP Computer Program

The NOISEMAP program is actually a group of computer programs developed by the U.S. Air Force to predict noise exposures in the vicinity of an air base due to aircraft flight, maintenance, and ground run-up operations. These programs can also be used for noise exposure prediction at civilian or joint-use (military-civilian) airfields if appropriate noise reference files are available. The NOISEMAP programs utilize a database of aircraft noise emission characteristics (NOISEFILE) that is accessed by the OMEGA10 and OMEGA11 subprograms to produce SEL versus slant range values specific to the aircraft operating parameters and meteorological conditions.

Data describing flight tracks, flight profiles, power settings, flight paths and profile utilization, and ground run-up information by type of aircraft/engine are assembled and processed for input into a central computer. The NOISEMAP program uses this information to calculate DNL values at points on a regularly spaced 100x100 grid surrounding the airfield. This information is then input to another subprogram that generates contour lines connecting points of equal DNL values in a manner similar to elevation contours shown on topographic maps. Contours are normally generated at 5 dB intervals beginning at a lower limit of DNL 65 dB, the maximum level considered acceptable for unrestricted residential use.

E.1.3.2 MRNMAP Computer Program

MRNAMP is a noise model used to calculate distributed aircraft operations under Military Operations Areas (MOAs), along Military Training Routes (MTRs), and Ranges. The program begins by calculating a table of SEL values versus ground distance based on the aircraft operating at an equivalent acoustical altitude. Then the distance separating noise contours is multiplied by time spent in the airspace and the actual speed of the aircraft. The result is the area of noise contours swept out under the airspace. The energy-average is calculated by normalizing this area with respect to the total airspace area and summing over all contours. The model is based on measurements made in actual MOAs and aircraft trajectory data collected from aircraft training in MOAs and on ranges.

MRNMAP can generate several metrics including L_{eq}, L_{dn}, and L_{dnmr}. The L_{dnmr} calculations are accomplished using the validated Air Force algorithm. All the raster files created by MRNMAP can be displayed on a standard VGA computer screen, output to an ASCII file containing a grid of equally spaced numbers, and output to a Geographic Information System compatible raster file.

E.1.3.3 ROUTEMAP Computer Program

ROUTEMAP calculates ground level noise exposure along an MTR corridor. ROUTEMAP treats an individual flight track as a point source moving along a line, which, when time-averaged, becomes a line source. Vertical plane dispersion is modeled by using an equivalent acoustical altitude that is determined from an altitude distribution of time spent at selected altitude ranges. Algorithms used in ROUTEMAP are either the same as or closely resembling those used by NOISEMAP, with the difference being ROUTEMAP's adaptation for low-altitude, high-speed flyovers (Cook n.d.). ROUTEMAP generates its adjusted SEL values from the ROUTEFILE dataset, OMEGA10R. Input variables required are aircraft type, number of day and night operations per month, airspeed, power setting, altitude, and whether the flight is VFR or IFR. L_{dnmr} is computed for ground positions within 13 miles of the route centerline. ROUTEMAP can also compute L_{eq}, the monthly A-weighted noise level without onset or night penalty and the population expected to be highly annoyed as a function of L_{dnmr} (Cook n.d.).

E.1.3.4 Integrated Noise Model (INM) Computer Program

The INM program was initially released in January 1978 by the Federal Aviation Administration (FAA). The model has been substantially updated since that time, and is the recommended tool for site analysis for Airport Noise Control and Land Use Compatibility (ANCLUC) planning studies. INM contains computer models for determining the impact of aircraft noise in and around airports. This noise impact can be given in terms of contours of equal noise exposure for Noise Exposure Forecast (NEF), Equivalent Sound Level (L_{eq}), Day-Night Average Sound Level (DNL), and Time Above a specified threshold of A-weighted sound (TA).

The contours are presented in the form of a printout of the contour coordinates and area impacted, and as a plot of the contours. In addition, a printout report of populations within the contour areas may be produced. The model also allows for the calculation of several noise measures at specific points (grid) in the airport vicinity. The output from this type of calculation is a printout report. The model also produces a number of supporting reports.

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E.2 EFFECTS OF SOUNDS ON HUMANS

Undesired sound may interfere with a broad range of human activities, degrading public health and welfare. Affected activities may include speech, sleep, learning, relaxation, listening, and other human endeavors. The level of sound that interferes with human activity depends on the activity and its contextual frame of reference. The effect of activity interference is often described in terms of annoyance. However, various other factors, such as attitude towards the sound source and local conditions, may influence an individual's reaction to activity interferences (U.S. EPA, Office of Noise Abatement and Control 1974).

E.2.1 Annoyance

Annoyance is a summary measure of the general adverse reaction of people to noise that produces speech interference; sleep disturbance; induces a desire for a tranquil environment; or interferes with the ability to use the telephone, radio or television satisfactorily. The measure of this adverse reaction is the percentage of area population that feels highly annoyed by sound of a specified level.

Sound can be defined as an auditory sensation evoked by an oscillation (vibratory disturbance) in the pressure and density of a fluid (including air), or in the elastic strain in a solid, with frequency in the approximate range of 20 to 20,000 Hz. Noise can be defined simply as any unwanted sound; or, more specifically, as any sound that is undesirable because it interferes with speech and hearing, is intense enough to damage hearing, or is otherwise annoying (U.S. EPA, Office of Noise Assessment and Control 1976). In practice, the definitions of sound and noise are bound up in the subjective human perceptions of each. Annoyance is a psychological response to a given noise exposure. It may result from speech or sleep interference, but it can arise in a variety of other circumstances. The perceived unpleasantness of the noise is a factor of annoyance, as is any anxiety or apprehension that the noise may cause (Frankel 1986). Community response is a term used to describe the annoyance of groups of people exposed to environmental noise in residential settings.

The preponderance of case histories and social surveys indicate that the response of a community to aircraft noise is affected not only by how loud the sound is, but also by how often sound events occur (e.g., the total sound exposure in a specified time period). This is consistent with the results of psychoacoustic laboratory experiments that show that the magnitude of sound and its duration are exchanges on an energy summation basis. On the assumption that community response is related to the total sound energy in a specified time period, events of equal magnitude are summed on the basis of 10 Log N where N is the number of events. Recent studies have shown that 10 Log N can be used to accurately predict community annoyance for sound events as low as 2 per day; other studies had previously shown that 10 Log N worked well for cumulative sound exposure of several hundred events per day (Schomer 1981, Fields and Powell 1987).

The effect of noise on people derives from complex relationships between numerous factors; and separating the effects of these often confounding factors is impractical, if not impossible. The variability in the way individuals react to sound makes it impossible to accurately predict how any one individual will respond to a given sound. However, when the community is considered as a whole, trends emerge which relate noise to annoyance. DNL alone provides an adequate indicator of community annoyance to aircraft noise. EPA's "Levels" document states "This formula of equivalent level [DNL] is used here to relate noise in residential environments to chronic annoyance by speech interference and in some part by sleep and activity interference" (U.S. EPA, Office of Noise Abatement and Control 1974).

In 1978, Schultz synthesized a relationship between transportation noise exposure and the prevalence of annoyance in communities from the findings of a number of social surveys. These assessments have become the model for assessing the effects of long-term sound exposure on communities. Schultz developed methods for converting sound exposures measured in different units to a common set of units (DNL) and devised ways of comparing annoyance judgments measured on very different response scales. The independent variable Schultz chose for the dosage-effect relationship was a cumulative measure of the time integral of sound intensity to which the communities are exposed. The dependent variable was a measure of the upper portion of the distribution of self-reported annoyance. The resulting metric, "Percent Highly Annoyed," is symbolically illustrated as (%HA). The logistic fits by Armstrong Laboratory to Schultz (161 points) and an update of 400 data points are expressed by the following relationship:

Fit to 400 points: $\%HA = 100/[1 + EXP(11.13 - .141\ LDN)]$

Schultz Fit: $\%HA = 100/[1 + EXP(10.43 - .132\ LDN)]$

This approximation was adopted in preference to a third order polynomial least squares fit as recommended by Fidell and Green (1989) to ensure the dose-response relationship predicts no annoyance at an exposure level of DNL 45 dB, and conforms with the EPA Levels document. Results derived from a recent analysis by Armstrong Laboratory of the update of 400 data points to the Schultz curve validate the continued accuracy of the Schultz relationship between DNL and %HA. Further, %HA remains the best approach since the updated curve differs less than one percent in the DNL range of 45 dB to 75 dB from the original logistics fit. Finally, the review also concluded that the DNL-%HA relationship is valid for all types of transportation noise. The new curve is shown in Figure E.2–1.

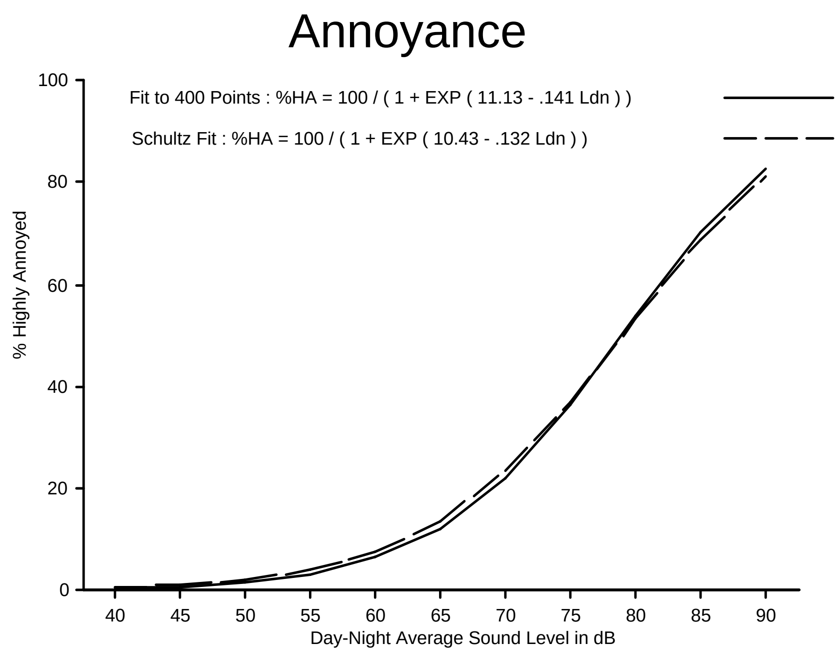

Figure E.2–1 Comparison of Logistic Fits for Prediction of Percent Highly Annoyed-- Schultz Data (161 points) and Update of 400 Data Points

Thus, the "Schultz Curve" is the best available source of empirical dosage-effect information for predicting community response to transportation noise; and annoyance is the characterization of the community response. On the other hand, complaints are not a measure of community impact. An analysis of complaints by Luz, Raspet and Schomer (1985) supports noise abatement (reduction) policies based on an assessment of the level of annoyance rather than the number of complaints. Annoyance can exist without complaints and, conversely, complaints may exist without adverse sound levels. The current body of evidence indicates that complaints are an inadequate indicator of the full extent of noise effects on a population (Fields and Hall 1987). The estimates of annoyance presented in this document are based on the average Percent Highly Annoyed for each DNL interval indicated in Table E.2-1.

Table E.2–1 Average Percent Highly Annoyed (%HA) by DNL Level

DNL	% Highly Annoyed	DNL	% Highly Annoyed	DNL	% Highly Annoyed
50	1.6626	64	10.8515	78	46.7048
51	1.9096	65	12.2927	79	50.225
52	2.1924	66	13.8955	80	53.743
53	2.516	67	15.6699	81	57.2241
54	2.886	68	17.6245	82	60.6351
55	3.3086	69	19.7657	83	63.9455
56	3.7906	70	22.0974	84	67.1284
57	4.3397	71	24.6197	85	70.1615
58	4.9642	72	27.3289	86	73.0271
59	5.6733	73	30.2167	87	75.7128
60	6.4767	74	33.27	88	78.2109
61	7.385	75	36.4705	89	80.5182
62	8.4092	76	39.7953	90	82.6353
63	9.5609	77	43.2171		

Note: Fit to 400 data points.

E.2.2 Speech Interference

Speech interference associated with aircraft noise is a primary source of annoyance to individuals on the ground. The disruption of leisure activities (such as listening to the radio, television, and music), and conversation gives rise to frustration and irritation. Quality speech communication is obviously also important in the classroom, office, and industrial settings. Researchers have found that aircraft noise at the 75 dB level annoyed the highest percentage of the population when it interfered with television sound, with eighty percent of the test population reporting annoyance. Also high on the list of annoyances for the surveyed population was flickering of the television picture and interference with casual conversation by aircraft noise (Newman and Beattie 1985).

Noise levels that interfere with listening to a desired sound such as speech or music can be defined in terms of the level of interfering sound required to mask the desired sound. Such levels have been quantified for speech communication by directly measuring the interference with speech intelligibility as a function of the level of the intruding sound relative to the level of speech sounds (U.S. EPA, Office of Noise Abatement and Control 1974). In general, it was found that intelligibility is related to the amount by which the levels of speech signals exceed steady state noise levels. The difference between speech and noise levels is usually referred to as the speech-to-noise ratio. However, since no quantitative relationship has been established between speech interference and learning, no additional criteria have been developed for determining speech interference effects on learning.

E.2.3 Hearing Loss

Hearing loss can be either temporary or permanent. A noise-induced temporary threshold shift is a temporary loss of hearing experienced after a relatively short exposure to excessive noise. A Noise-Induced Temporary Threshold Shift (NITTS) means that the detection level of sound has been increased. Recovery is fairly rapid after cessation of the noise. A Noise-Induced Permanent Threshold Shift (NIPTS) is an irreversible loss of hearing caused by prolonged exposure to excessive noise. This loss is essentially indistinguishable from the normal hearing loss associated with aging. Permanent hearing loss is generally associated with destruction of the hair cells of the inner ear. Based on EPA criteria, hearing loss is not expected for people living in areas with DNL < 75 dB. Further, as stated in the EPA Levels document, changes in hearing levels of 5 dB are generally not considered noticeable or significant (U.S. EPA, Office of Noise Abatement and Control 1974).

An outdoor DNL of 75 dB is considered the threshold above which the risk of hearing loss is evaluated. Following guidelines recommended by the Committee on Hearing, Bioacoustics, and Biomechanics, the average change in the threshold of hearing for people exposed to DNL ≥ 75 dB was evaluated (National Research Council 1977). Results indicated that an average of 1 dB hearing loss could be expected for people exposed to DNL ≥ 75 dB. For the most sensitive 10% of the exposed population, the maximum anticipated hearing loss would be 4 dB. These hearing loss projections must be considered high as the calculations are based on an average daily outdoor exposure of 16 hr (7:00 a.m. to 10:00 p.m.) over a 40 year period. It is doubtful that any individual would spend this amount of time outdoors within the DNL ≥ 75 dB contours.

E.2.4 Sleep Disturbance

The effects of noise on sleep have long been a concern of parties interested in assessing residential noise environments. Early studies, conducted mainly in the 1970s, measured noise levels in bedrooms in which sleep was apparently undisturbed by noise. Tests were conducted mainly in laboratory environments in which sleep disturbance was measured in a variety of ways. Most frequently, awakening was measured either by a verbal response, or a button push; in some instances, sleep disturbance, as well as awakening, was determined by electroencephalograph (EEG) recordings of brain activity which indicated stages of sleep and awakening. Various types of noise were presented to the sleeping subjects throughout the night. These noises consisted primarily of transportation noises, including those produced by aircraft, trucks, cars and trains. The aircraft noises included both subsonic aircraft flyover noises as well as sonic booms. Synthetic noises, including laboratory-generated sounds consisting of shaped noises and tones, were also studied.

Reviews by Lukas (1975), Griefahn and Muzet (1978), and Pearsons et al. (1989) provide an overview of data available in the 1970s on the effects of different levels of noise on sleep-state changes and waking. Various A-weighted levels between 25 and 50 dB were observed to be associated with an absence of sleep disturbance. Because of the large variability of the data in these reviews, there is some question as to the reliability of the results. Consequently, the dose-response curve developed by Lukas, which plots the probability of awakening as a function of SEL, provides a guide only to the most extreme limits of the potential effects of noise on sleep.

The 10-dB nighttime "penalty" added to noise levels for the period from 10 PM to 7 AM in computing DNL is intended to account for the intrusiveness of noise at night, partly due to the lower nighttime ambient, and therefore tends to reflect to some extent the potential for wakeups. However, some agencies believe that if there are an unusual number of nighttime noise events, supplemental analysis to indicate sleep disturbance semi-quantitatively, in terms of the putative number of wakeups, is desirable. Such an analysis is generally based on a "single-event" parameter, such as SEL or L_{max}.

Based on the literature reviewed in a recent Air Force-sponsored study of sleep disturbance (Pearsons et al. 1989), no specific adverse health effects have been clearly associated with sleep disturbance, either awakening or sleep-state changes. Nevertheless, sleep disturbance, particularly awakening, is generally considered undesirable, and may be considered an impact caused by noise exposure (consequently, awakening has been selected as the parameter recommended for evaluating the effects of noise on sleep). The U.S. Air Force plans to conduct a field study of sleep disturbance, using awakening as the dependent variable, in the near future (1993/1995) (Finegold et al. 1990).

As reported in the 1989 study by Pearsons et al, the effort to develop a sleep disturbance prediction curve identified the need for substantially more research in this area. Of concern were:

- large discrepancies between laboratory and field studies;
- highly variable and incomplete data bases;
- lack of appropriate field studies;
- the study's methodologies;
- the need to consider non-acoustic effects; and
- the role of habituation.

In cases where supplemental analysis of potential sleep disturbance is considered necessary, the USAF has developed an <u>interim</u> dose-response curve to predict the percent of exposed population expected to be awakened (% awakening) as a function of exposure to single event noise levels expressed as SEL (Finegold et al. 1992). This interim prediction curve is based on statistical adjustment of the most recent, inclusive analysis of published sleep disturbance studies conducted by Pearson et al. (1989). The recommended dose-response relationship is expressed by the equation:

$$\%Awaking = (7.079x\ 10^{-}6)x\ SEL^{3.496}$$

This recommended interim dose-response relationship is shown by the curve in Figure E.2-2, and the individual points shown in the figure represent groupings of recorded data.

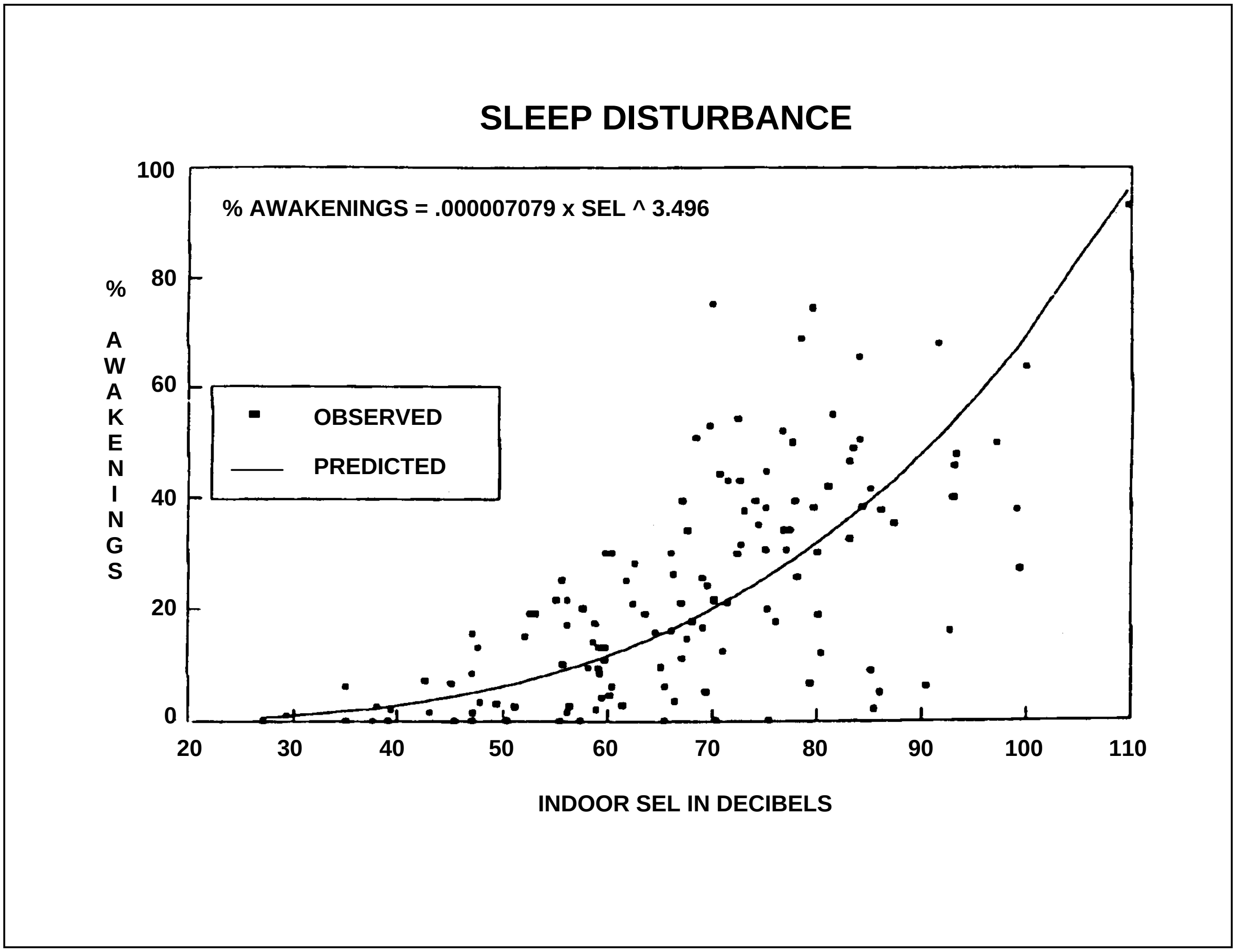

Figure E.2–2 Sleep Disturbance as a Function of Single Event Noise Exposure (Finegold et al. 1992)

In December 1992, the first report of a comprehensive field study conducted by the Civil Aviation Authority of the British Department of Transport was released (Ollerhead et al, 1992). This study was conducted under carefully controlled field conditions and used devices known as actimeters to measure fine limb movements, usually of the wrist, which are indicative of sleep disturbance. Field work was conducted during the summer of 1991 at locations surrounding major British airports. In all, 400 subjects were monitored for a total of 5,742 subject-nights resulting in a total of some 40,000 subject-hours of sleep data which were subsequently analyzed and broken down into more than 4.5 million 30-second epochs. A total of 4,823 aircraft noise events were logged during the 120 measurement nights and outdoor noise levels ranged from 60 dBA to more than 100 dBA L_{max}. Actimetry data were correlated with sleep-EEG records for 178 subject nights and showed good agreement between actimetrically determined arousals and EEG determined awakenings.

The mean arousal rate (i.e., the proportion of epochs with movement arousals) for all subjects, all causes, all nights and all epochs was 5.3 percent. For the average sleeping period of 7.25 hours, this is equivalent to about 45 arousals per night. Of these, some 40 percent (i.e., about 18±4) were considered likely to be awakenings of 10-15 seconds or more, the remainder being considered minor perturbations.

Based on the data obtained during this study, the authors reached the following conclusions concerning the effects of aircraft noise on sleep:

- All subjective reactions vary greatly from person to person and from time to time and sleep disturbance is no exception; deviations from the average can be very large. Even so, this study indicates that, once asleep, very few people living near airports are at risk of any substantial sleep disturbance due to aircraft noise, even at the highest event noise levels.

- At outdoor event levels below 90 dBA (80 dBA L_{max}), average sleep disturbance rates are unlikely to be affected by aircraft noise. At higher levels, and most of the events upon which these conclusions are based were in the range 90 to 100 dBA SEL (90 to 95 dBA L_{max}), the chance of the average person being awakened is about 1 in 75 [1.33 percent]. Compared to the overall average of about 18 nightly awakenings, this probability indicates that even large numbers of noisy nighttime aircraft movements will cause very little increase in the average person's nightly awakenings. Therefore, based on expert opinion on the consequences of sleep disturbance, the results of this study provide no evidence to suggest that aircraft noise is likely to cause harmful after effects.

- At the same time, it must be emphasized that these are estimates of *average* effects; clearly, more susceptible people exist. At one extreme, 2-3 percent of people are over 60 percent more sensitive than average; some maybe twice as sensitive to noise disturbance. There may also be particular times of the night, perhaps during periods of sleep lightening, when individuals could be

> more sensitive to noise. Although the relationship cannot be verified statistically, the data do indicate that aircraft events with noise levels greater than 100 dBA SEL (95 dBA L_{max}) out of doors, will have a greater chance of disturbing sleep. The most sensitive people may also react to aircraft noise events with levels below 90 dBA SEL (80 dBA L_{max}), approximating to 95 EPNdB on the noise scale used internationally for the noise certification of aircraft.

The results of this study are consistent with the results of the laboratory studies reviewed by Pearsons et al (1989) which indicated much lower levels of sleep disturbance under field conditions than under laboratory conditions. As noted above, Ollerhead concludes that sleep disturbance rates are unlikely to affected by aircraft noise below 90 dB SEL and that for events with SELs in the range of 90 to 100 dB, the chance of an average persons being awakened are about 1 in 75 (about 1.33 percent). Although the authors concluded that events with SEL > 100 dB are more likely to result in sleep disturbance, no specific dose-response relationship between SEL and percent awaking was suggested. To provide an estimate of the percent awaking for SELs between 100 and 110 dB data on unadjusted arousal rates (i.e., not adjusted for the varying sensitivity of individuals) were used. For this analysis, 50 percent of the actimetrically measured arousals were assumed to result in awaking. Table 1-5 provides a comparison of the predicted percent awaking based on the Air Force interim model and the data in Ollerhead et al (1992). This document provides comparisons of predicted awaking based on both the Air Force interim model and the data in Ollerhead et al. (1992)[3].

Table E.2–2 Comparison of Predicted Awakening Based on Air Force Interim Model and Data from Ollerhead et al. (1992)

Outdoor SEL (dB)	Predicted Awaking (percent)	
	Air Force Interim Model	Ollerhead et.al. (1992)
> 110	41.0	Not Estimated
105-110	33.3	2.8
100-105	26.6	2.1
95-100	21.0	1.3
90-95	16.3	1.1
85-90	12.3	0

There should be continued research into community reactions to aircraft noise, including both sleep disturbance and non-auditory health effects of noise.

[3] Since the data in Ollerhead et al. (1992) does not include SEL > 110 dB, the predicted awaking based on the Air Force interim model for SEL > 95 was used in both estimates.

E.2.5 Non-auditory Health Effects

Based on summaries of previous research in the field, (Thompson 1981; Thompson et al. 1989; CHABA 1981; CHABA 1982; Hattis et al. 1980; and U.S. EPA 1981) predictions of non-auditory health effects as a result of exposure to aircraft noise (both subsonic and supersonic) in a residential environment have not been conclusively demonstrated. One of the earliest of these projects (CHABA 1981) reported that, while the available evidence was suggestive, it did not provide definitive answers to the question of health effects of long-term exposure to noise, other than to the auditory system. The committee recommended that, in the absence of adequate knowledge as to whether or not noise can produce effects upon health, other than damage to the auditory system, an attempt should be made to obtain more critical evidence. A valid predictive procedure requires: (1) evidence for a causal relationship between aircraft noise exposure and adverse non-auditory health consequences, and (2) knowledge of a quantitative (dose-response) relationship between the amount of noise exposure and specific health effects. Because the results of studies of aircraft noise on health are highly equivocal, there is currently no scientific basis for making valid risk assessments.

Alleged non-auditory health consequences of aircraft noise exposure which have been studied include birth defects, low birth weight, mental problems, cancer, stroke, hypertension, sudden cardiac death, myocardial infarction, and cardiac arrhythmias. Of these, hypertension is the most biologically plausible effect of noise exposure. Noise appears to elicit many of the same biochemical and physiological reactions, including temporary elevation of blood pressure, as do many other everyday stressors. These temporary increases in blood pressure are believed to lead to a gradual resetting of the body's blood pressure control system. Over a period of years, some researchers hypothesize that permanent hypertension may develop (e.g. Peterson et al., 1984).

One mechanism hypothesized is that continuous stimulation of the central nervous system by noise induces changes in cardiac function and peripheral vascular resistance, which in turn raises blood pressure and gradually resets the baro-receptor (blood pressure) control system. Although inconclusive, studies of the prevalence of elevated blood pressure in noise-exposed populations suggest that long-term exposure to high levels of occupational noise may be associated with an increase in hypertension in the later decades of life. These studies, coupled with increases in flight operations around civilian airports and military airbases plus an increase in low altitude overflights in military training areas, have increased public concern about potential health hazards of aircraft noise exposure in recent years.

Studies in residential areas exposed to aircraft noise have produced contradictory results that are difficult to interpret. Early investigations indicated that incidence of hypertension was from two to four times higher in areas near airports than in areas away from airports (Karagodina et al., 1969). Although Meechan and Shaw (1988) continue to report excessive cardiovascular mortality among individuals, 75 years or older, living near the Los Angles

International Airport, their findings cannot be replicated (Frerichs et al., 1980). In fact, noise exposure increased over the years while there was a decline in all cause, age-adjusted death rates and inconsistent changes in age-adjusted cardiovascular, hypertension, and cerebrovascular disease rates. Some European research (Ising et al., 1991; Ising and Spreng 1988) has shown more positive association between exposure to aircraft noise and adverse health effects, including a result that showed more pronounced effects in females than males. The adequacy of the methodology and the consistency of the conclusions, however are still being debated. The major problem that requires further consideration is that the methodology of these studies does not lend itself to conclusive proof of significant non-auditory health effects in residential areas exposed to aircraft noise.

Most studies which have been controlled for multiple factors have shown no, or a very weak association between noise exposure and non-auditory health effects. This observation holds for studies of occupational and traffic noise as well as for aircraft noise exposure. In contrast to the reports of two- to six-fold increases in incidence of hypertension due to high industrial noise (see review by Thompson et al., 1989), the more rigorously controlled studies (Talbott et al., 1985; and van Dijk et al. 1987) showed equivocal associations between hypertension and prolonged exposure to high levels of occupational noise. In the Talbott et al. (1985) study, a significant relationship was shown between noise-induced hearing loss and high blood pressure in the 56 plus age group.

The critical question is whether observed positive associations are causal ones. In the aggregate, studies indicated that the association between street traffic noise and blood pressure or other cardiovascular changes are arguable. Two large prospective collaborative studies (Babish and Gallacher 1990) of heart disease are of particular interest. To date, cross-sectional data from these cohorts offer contradictory results. Data from one cohort show a slight increase in mean systolic blood pressure [2.4 millimeters of mercury (mmHg)] in the noisiest, compared to the quietest area; while data from the second cohort show the lowest mean systolic blood pressure and highest high-density lipoprotein cholesterol (lipoprotein protective of heart disease) for men in the noisiest area. These effects of traffic noise on blood pressure and blood lipids were more pronounced in men who were also exposed to high levels of noise at work.

More rigorous epidemiologic study designs for investigating causal and dose-response relationships depend upon assignment of noise dose and health status to individuals. The best established environmental noise descriptor, yearly DNL, is inherently place-oriented and may bear little specifiable relationship to personal exposure. Because health consequences of environmental noise exposure are unlikely to appear in less than five to ten years, individual dosimetry may not be practicable. There are three problems with using dosimetry in epidemiologic studies wearing may be: (1) burdensome, (2) irritating, and (3) tedious to the participants.

It is clear from the foregoing that the current state of technical knowledge cannot support inference of a causal or consistent relationship, or a quantitative dose-response model, between residential aircraft noise exposure and health consequences. Thus, no technical means are available for predicting extra-auditory health effects of noise exposure. This conclusion cannot be construed as evidence of no effect of residential aircraft noise exposure on non-auditory health. Current findings, taken in sum, indicate that further rigorous studies, such as an appropriately designed prospective epidemiologic study, are urgently needed.

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E.3 Effects of Sound on Structures

The structural effects of sound generated by industrial activities and ground transportation have been a concern of civil engineers for many years. In the 1960s, the need for reliable statistical models to predict the effects of sonic booms produced a body of knowledge on how sound energy from aircraft affects structures. The potential effects of sound vibrations on buildings from subsonic aircraft overflights did not become a concern until the advent of larger planes. During the 1970s, extensive research prompted by development of the Concorde aircraft probed the effects of sound vibrations on a variety of modern and historic structures. Increased environmental awareness in the 1980s has further spurred research to investigate potential damage to structures from overflights by smaller aircraft and by helicopters.

Potential damage to a structure from aircraft overflights is the result of increased air pressure on the structure and from vibrations transmitted in the structure. As a jet aircraft flies at subsonic speeds, it generates (1) pressure from the airflow in the vicinity of the engines and airframe; (2) a lift pulse pressure field, or momentary pressure increase on the ground from air flow over the wings; and (3) wake and trailing vortex pressure fields.

The effect of engine noise is a function of the type of engine, the speed or power condition, the sound frequency, and the slant distance. For a given aircraft, the speed or power condition and slant distance are variables that may be manipulated to mitigate potential effects on structures.

Lift pulse pressure field varies with gross weight of the aircraft, the height of the aircraft above the ground, the slant range (a function of height and horizontal distances along the flight path and at right angles to the flight path), and time (Bedard and Cook 1987). Peak pressure increases with increasing weight of the aircraft and its proximity to the ground, and is reduced by the cube of the slant range. Thus the area of greatest potential pressure lies directly under the flight track of large planes at low altitudes; however, measurements and calculations have shown that for realistic operational scenarios these pressures are relatively low compared to those occurring naturally (e.g. winds of 10-20 mph). Since the pressure load attenuates rapidly with increased distance from the center of the flight track, even the very small potential for damage to structures can be mitigated by lateral adjustment of the flight track. For most jet aircraft these pressures are less than 1 PSF. For heavy helicopters at very low altitudes (50 feet AGL), the pressures can be an order of magnitude higher.

The dynamic pressures on a structure from the wake and trailing vortices shed by the air flow over the aircraft increase with the plane's speed and wing area, and decrease with the slant range. Again, adjusting the slant range, especially through lateral displacement of the flight track, is a mitigation option.

All structures are subjected to many sources of stress or pressure. Inherent natural stresses include those from changes in temperature and humidity, wind pressure, thunder, snow load, and seismic disturbances. Human activities that induce stress include blasting, operating heavy machinery, and passing ground transportation vehicles. On a smaller scale, normal household activities such as the use of vacuum cleaners and washing machines, and the slamming of doors generate vibrations. Buildings are designed to withstand these natural environmental stresses and normal uses. In addition, buildings may have special design modifications to accommodate expected stresses from industrial uses or unusual environmental conditions, such as snow load or high winds.

Some building materials are more sensitive than others to external pressures and induced vibrations. Windows with large panes of glass are most vulnerable. Plaster walls in frame buildings are susceptible to cracking. Components that are least likely to experience damage are masonry walls of stone, concrete block, adobe, or brick. In addition, the design of some buildings provides greater damping of induced vibrations than others. Research data have not categorically proven old buildings to be more vulnerable to vibrations than newer buildings, but prudence dictates that unique structures of historic significance be given special consideration.

In order to assess the potential for possible damage to structures from flight operations, the Air Force has historically reviewed existing literature, conducted experiments, and employed statistical models. A common procedure is to evaluate the potential effect of a "worst case" scenario for subsonic flight activity. If the effects of the worst case are negligible, time and money are not spent in evaluating cases of lesser magnitude. In the case of low altitude operations, such as along a military training route (MTR), the potential effects to sites directly under the track of bombers at 200 feet above ground level (AGL) have been measured. Bombers, along with the C-5, have been chosen as "worst case" models because of their large size.

However, peak overpressures caused by subsonic flight tend to be of a relative low magnitude when compared to the overpressures created by flight in the supersonic regime. As discussed previously in Appendix A, page 13, for those sonic booms that reach the surface, the intensity of the sound overpressure is largely dependent on the aircraft altitude, airspeed, size, and attitude. These peak overpressures occur directly under the aircraft and diminish laterally. Worthy of mention, is a 1977 test on an adobe house in southern Arizona. The house was instrumented and exposed to supersonic training overhead. The evaluation concluded that the adobe structure reacted similarly to a conventional style structure---there was no difference in the probability of damage to an adobe structure as compared to a conventional structure. It is estimated that the "probability of a structure being hit by a 6 psf carpet boom is less than one in 20,000 chances; for an 11 psf carpet boom the probability is beyond four standard deviations of the mean boom strength and is considered to be below any level of significance" (U.S. DoD AF 1984). For focus booms greater than twice the nominal carpet boom pressure, the probability of a structure being hit is less than the range of one in 3,400 chances; and a superboom is less than one in 16,700 chances. With this low probability, the chances of a boom causing structural damage are very small.

By far, the largest percentage of sonic boom damage claims stem from broken or cracked glass. Further tests have shown that glass that has been sandblasted, scratched, or nicked will not exhibit the same strength as a new, properly installed pane of glass. By using a data base of unpublished static results provided by Libbey-Owens-Ford Company, a statistical analysis was performed to determine the probability of glass breakage for various overpressures. If an aircraft were to approach head-on or perpendicular to the plane of the window the probabilities of breakage would be as depicted below in Table E.3-1.

Table E.3–1 Probability of Glass Breakage from Sonic Booms

Estimate of the Impacts of Sonic Boom Overpressures on Glass Window Panes	
Overpressures (psf)	**Broken Panes per Million**
1	23
2	75
3	300
4	1,200
5	2,300
6	4,000
7	6,500
8	10,000
9	14,000
10	20,000
11	26,000
12	33,000
13	40,000
14	49,000
15	59,000

Source: U.S. DoT FAA 1973.

In summary, subsonic aircraft operations generate dynamic pressures that are much lower than those normally experienced by surface structures. Supersonic flight has the potential to create substantially greater overpressures than those generated by subsonic flight; however, the chance of those small areas of sonic boom impacts affecting a structure are quite remote. The magnitude of the pressures experienced by surface structures is determined by characteristics of the aircraft and the nature of the operation being performed by the aircraft. Three highly influential factors are the size of the aircraft, its height above the surface, and the proximity of the structure to the center of the flight path. The magnitude of the pressures exerted on buildings from overflight by aircraft has been found to be less than the pressure from natural events, such as wind, and less than the design load for most buildings. Table E.3-2 summarizes the predicted effects of sound, expressed in one-third octave band sound pressure levels, on structures.

Table E.3–2 Effects of Sounds on Structures

Noise Effects on Structures			
Peak Overpressure		Effects Summary	
dB	PSF[1]		
0-127	0-1	**Typical Community Exposures (Generally Below 2 PSF**	No Damage to structures No Significant Reaction
127-131	1.0-1.5		Rare Minor Damage Some Public Reaction
131-140	1.5-4.0	Window damage possible, increasing public reaction, particularly at night	
140-146	4.0-8.0[2]	Incipient damage to structures	
146-171	8.0-144	Measured booms at minimum altitudes experienced by humans: no injury	
185	720	Estimated threshold for eardrum rupture (maximum overpressure)	
194	2160	Estimated threshold for lung damage (maximum overpressure)	

Notes: [1] PSF = Pounds per Square Foot
[2] With the exception of window glass breakage, booms less than 11 psf should not damage "building structures in good repair." B.L. Clarkson and W.H. Mayes,"Sonic Boom Building Structure Responses Including Damages," J. Acoust. Soc. 51, 742-757, 1972.

Source: Speakman 1992.

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