APPENDIX D
Discussion of Noise and Its Effect on the Environment

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This appendix discusses sound and noise and their potential effects on the human and natural environment. Section D.1 provides an overview of the basics of sound and noise. Section D.2 defines and describes the different metrics used to describe noise. The largest section, Section D.3, reviews the potential effects of noise, focusing on effects on humans but also addressing effects on property values, terrain, structures, and animals. Section D.4 presents noise modeling methodology and assumptions. Section D.5 contains the list of references cited.

D.1 Basics of Sound

Section D.1.1 describes sound waves and decibels. Section D.1.2 review sounds levels and types of sounds.

D.1.1 Sound Waves and Decibels

Sound consists of minute vibrations in the air that travel through the air and are sensed by the human ear. Figure D-1 is a sketch of sound waves from a tuning fork. The waves move outward as a series of crests where the air is compressed and troughs where the air is expanded. The height of the crests and the depth of the troughs are the amplitude or sound pressure of the wave. The pressure determines its energy or intensity. The number of crests or troughs that pass a given point each second is called the frequency of the sound wave.

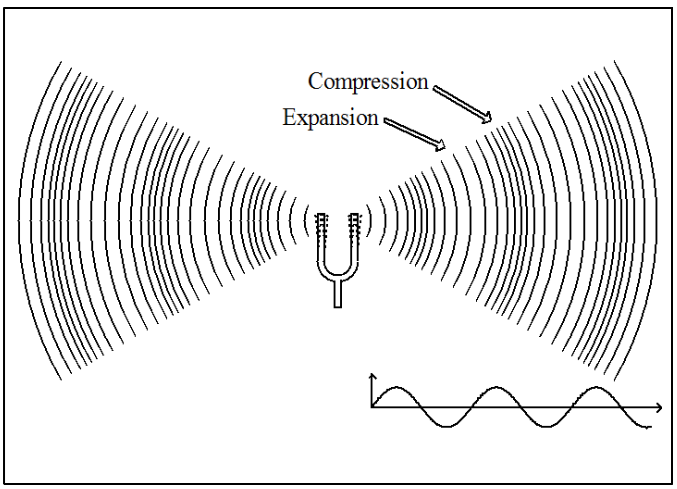


Figure D-1 Sound Waves from a Vibrating Tuning Fork

The measurement and human perception of sound involves three basic physical characteristics: intensity, frequency, and duration.

- Intensity is a measure of the acoustic energy of the sound and is related to sound pressure. The greater the sound pressure, the more energy carried by the sound and the louder the perception of that sound.
- Frequency determines how the pitch of the sound is perceived. Low-frequency sounds are characterized as rumbles or roars, while high-frequency sounds are typified by sirens or screeches.
- Duration or the length of time the sound can be detected.

The loudest sounds that can be comfortably heard by the human ear have intensities a trillion times higher than those of sounds barely heard. Because of this vast range, it is unwieldy to use a linear scale to represent the intensity of sound. As a result, a logarithmic unit known as the decibel (abbreviated dB) is used to represent the intensity of a sound. Such a representation is called a sound level. A sound level of 0 dB is approximately the threshold of human hearing and is barely audible under extremely quiet listening conditions. Normal speech has a sound level of approximately 60 dB. Sound levels above 120 dB begin to be felt inside the human ear as discomfort. Sound levels between 130 and 140 dB are felt as pain (Berglund and Lindvall 1995).

As shown in Figure D-1, the sound from a tuning fork spreads out uniformly as it travels from the source. The spreading causes the sound's intensity to decrease with increasing distance from the source. For a source such as an aircraft in flight, the sound level will decrease by about 6 dB for every doubling of the distance. For a busy highway, the sound level will decrease by 3-4.5 dB for every doubling of distance.

As sound travels from the source it also gets absorbed by the air. The amount of absorption depends on the frequency composition of the sound, the temperature, and the humidity conditions. Sound with high-frequency content gets absorbed by the air more than sound with low-frequency content. More sound is absorbed in colder and drier conditions than in hot and wet conditions. Sound is also affected by wind and temperature gradients, terrain (elevation and ground cover) and structures.

Because of the logarithmic nature of the decibel unit, sound levels cannot simply be added or subtracted and are somewhat cumbersome to handle mathematically. However, some simple rules are useful in dealing with sound levels. First, if a sound's intensity is doubled, the sound level increases by 3 dB, regardless of the initial sound level. For example:

60 dB + 60 dB = 63 dB, and

80 dB + 80 dB = 83 dB.

Second, the total sound level produced by two sounds of different levels is usually only slightly more than the higher of the two. For example:

60.0 dB + 70.0 dB = 70.4 dB.

Because the addition of sound levels is different than that of ordinary numbers, this process is often referred to as "decibel addition."

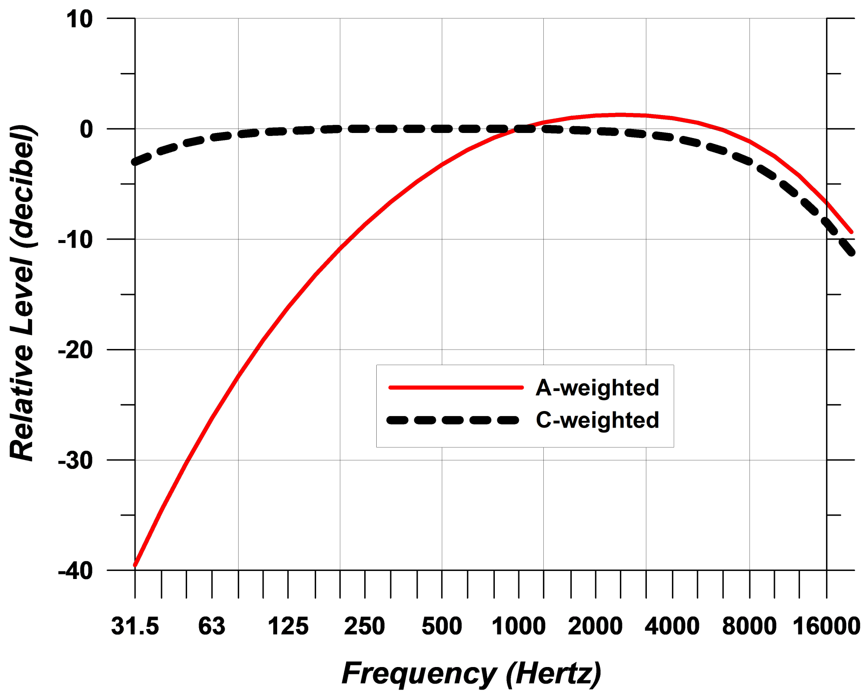
The minimum change in the sound level of individual events that an average human ear can detect is about 3 dB. On average, a person perceives a change in sound level of about 10 dB as a doubling (or halving) of the sound's loudness. This relation holds true for loud and quiet sounds. A decrease in sound level of 10 dB actually represents a 90% decrease in sound intensity but only a 50% decrease in perceived loudness because the human ear does not respond linearly.

Sound frequency is measured in terms of cycles per second or hertz (Hz). The normal ear of a young person can detect sounds that range in frequency from about 20 Hz to 20,000 Hz. As we get older, we lose the ability to hear high-frequency sounds. Not all sounds in this wide range of frequencies are heard equally. Human hearing is most sensitive to frequencies in the 1,000 to 4,000 Hz range. The notes on a piano range from just over 27 Hz to 4,186 Hz, with middle C equal to 261.6 Hz. Most sounds (including a single note on a piano) are not simple pure tones like the tuning fork in Figure D-1, but contain a mix, or spectrum, of many frequencies.

Sounds with different spectra are perceived differently even if the sound levels are the same. Weighting curves have been developed to correspond to the sensitivity and perception of different types of sound.

A-weighting and C-weighting are the two most common weightings. These two curves, shown in Figure D-2, are adequate to quantify most environmental noises. A-weighting puts emphasis on the 1,000 to 4,000 Hz range.

Very loud or impulsive sounds, such as explosions or sonic booms, can sometimes be felt, and can cause secondary effects, such as shaking of a structure or rattling of windows. These types of sounds can add to annoyance, and are best measured by C-weighted sound levels, denoted dBC. C-weighting is nearly flat throughout the audible frequency range, and includes low frequencies that may not be heard but cause shaking or rattling. C-weighting approximates the human ear's sensitivity to higher intensity sounds.



Source: ANSI S1.4A -1985 "Specification of Sound Level Meters"

Figure D-2 Frequency Characteristics of A- and C-Weighting

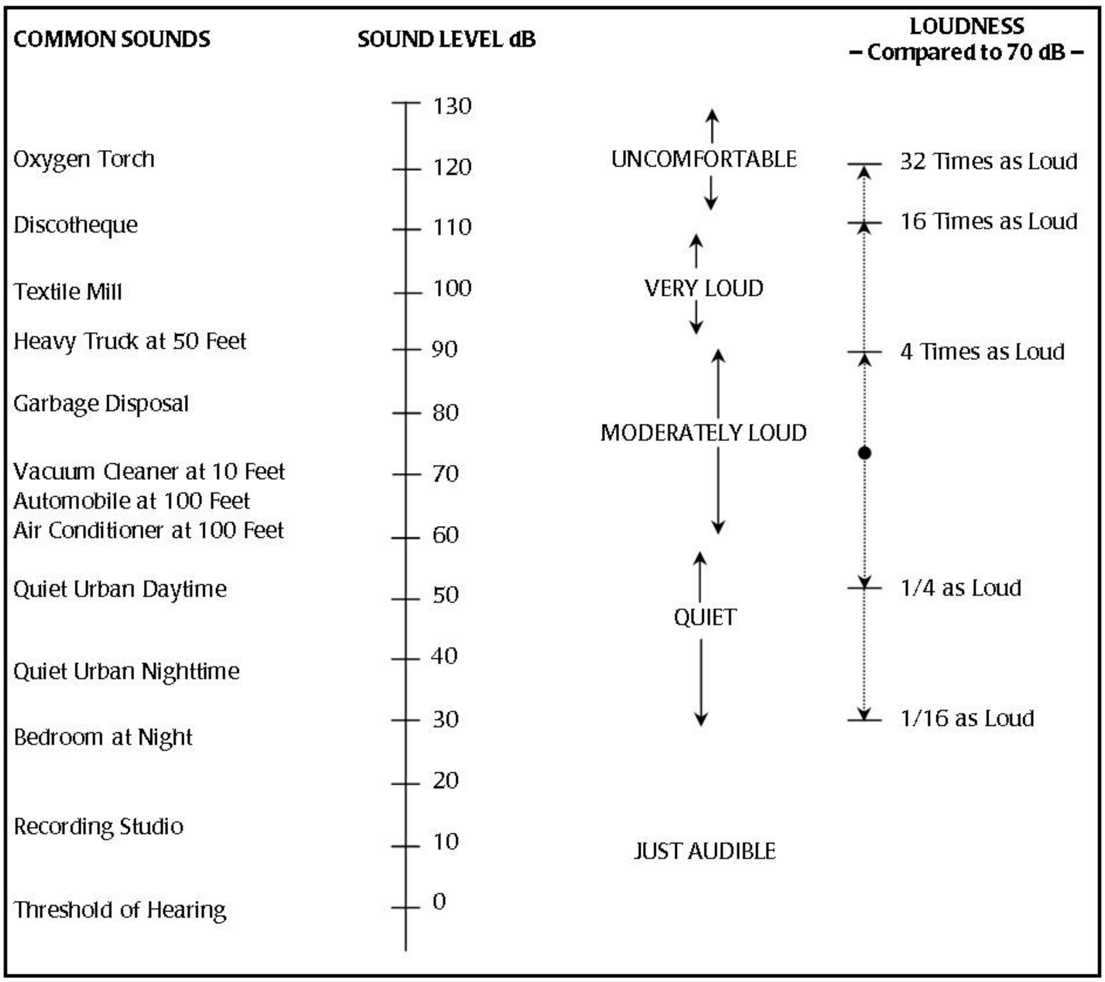
D.1.2 Sound Levels and Types of Sounds

Most environmental sounds are measured using A-weighting. They're called A-weighted sound levels, and sometimes use the unit dBA or dB(A) rather than dB. When the use of A-weighting is understood, the term "A-weighted" is often omitted and the unit dB is used. Unless otherwise stated, dB units refer to A-weighted sound levels.

Sound becomes noise when it is unwelcome and interferes with normal activities, such as sleep or conversation. Noise is unwanted sound. Noise can become an issue when its level exceeds the ambient or background sound level. Ambient noise in urban areas typically varies from 60 to 70 dB, but can be as high as 80 dB in the center of a large city. Quiet suburban neighborhoods experience ambient noise levels around 45-50 dB (U.S. Environmental Protection Agency (USEPA) 1978).

Figure D-3 is a chart of A-weighted sound levels from common sources. Some sources, like the air conditioner and vacuum cleaner, are continuous sounds whose levels are constant for some time. Some sources, like the automobile and heavy truck, are the maximum sound during an intermittent event like a vehicle pass-by. Some sources like "urban daytime" and "urban nighttime" are averages over extended periods. A variety of noise metrics have been developed to describe noise over different time periods. These are discussed in detail in Section D.2.

Impulsive noises are generally short, loud events. Their single-event duration is usually less than 1 second. Examples of impulsive noises are small-arms gunfire, hammering, pile driving, metal impacts during rail-yard shunting operations, and riveting. Examples of high-energy impulsive sounds are quarry/mining explosions, sonic booms, demolition, and industrial processes that use high explosives, military ordnance (e.g., armor, artillery and mortar fire, and bombs), explosive ignition of rockets and missiles, and any other explosive source where the equivalent mass of dynamite exceeds 25 grams (American National Standards Institute [ANSI] 1996).



Source: Harris 1979.

Figure D-3 Typical A-weighted Sound Levels of Common Sounds

D.2 Noise Metrics

Noise metrics quantify sounds so they can be compared with each other, and with their effects, in a standard way. The simplest metric is the A-weighted level, which is appropriate by itself for constant noise such as an air conditioner. Other types of noise, such as an aircraft overflight, vary with time. During an aircraft overflight, noise starts at the background level, rises to a maximum level as the aircraft flies close to the observer, then returns to the background as the aircraft recedes into the distance. This is sketched in Figure D-4, which also indicates two metrics (L_{max} and SEL) that are described in Sections A.2.1 and A.2.3 below.

There are a number of metrics that can be used to describe a range of situations, from a particular individual event to the cumulative effect of all noise events over a long time. This section describes the metrics relevant to environmental noise analysis.

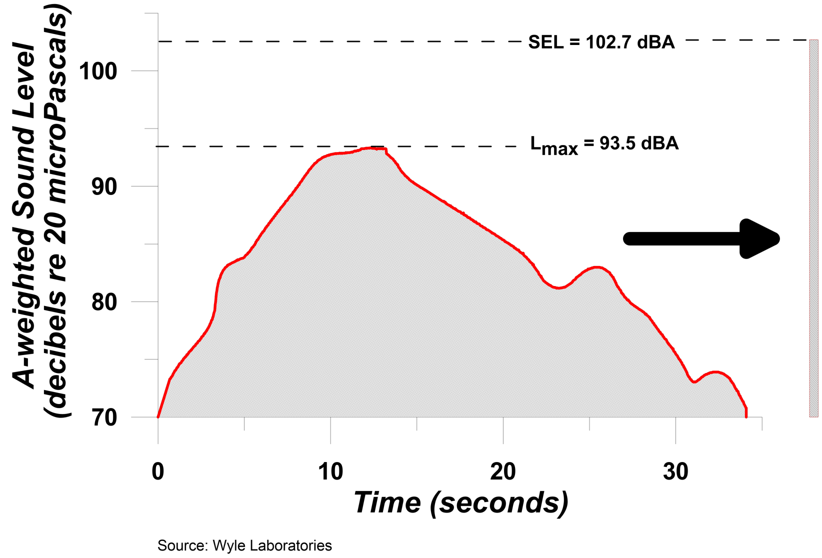


Figure D-4 Example Time History of Aircraft Noise Flyover

D.2.1 Single Events

D.2.1.1 Maximum Sound Level (L_{max})

The highest A-weighted sound level measured during a single event in which the sound changes with time is called the maximum A-weighted sound level or Maximum Sound Level and is abbreviated L_{max}. The L_{max} is depicted for a sample event in Figure D-4.

L_{max} is the maximum level that occurs over a fraction of a second. For aircraft noise, the “fraction of a second” is one-eighth of a second, denoted as “fast” response on a sound level measuring meter (ANSI 1988). Slowly varying or steady sounds are generally measured over 1 second, denoted “slow” response. L_{max} is important in judging if a noise event will interfere with conversation, TV or radio listening, or other common activities. Although it provides some measure of the event, it does not fully describe the noise, because it does not account for how long the sound is heard.

D.2.1.2 Peak Sound Pressure Level (L_{pk})

The Peak Sound Pressure Level is the highest instantaneous level measured by a sound level measurement meter. L_{pk} is typically measured every 20 microseconds, and usually based on unweighted or linear response of the meter. It is used to describe individual impulsive events such as blast noise. Because blast noise varies from shot to shot and varies with meteorological (weather) conditions, the U.S. Department of Defense (DOD) usually characterizes L_{pk} by the metric PK 15(met), which is the L_{pk} exceeded 15% of the time. The "met" notation refers to the metric accounting for varied meteorological or weather conditions.

D.2.1.3 Sound Exposure Level (SEL)

Sound Exposure Level combines both the intensity of a sound and its duration. For an aircraft flyover, SEL includes the maximum and all lower noise levels produced as part of the overflight, together with how long each part lasts. It represents the total sound energy in the event. Figure D-4 indicates the SEL for an example event, representing it as if all the sound energy were contained within 1 second.

Because aircraft noise events last more than a few seconds, the SEL value is larger than L_{max}. It does not directly represent the sound level heard at any given time, but rather the entire event. SEL provides a much better measure of aircraft flyover noise exposure than L_{max} alone.

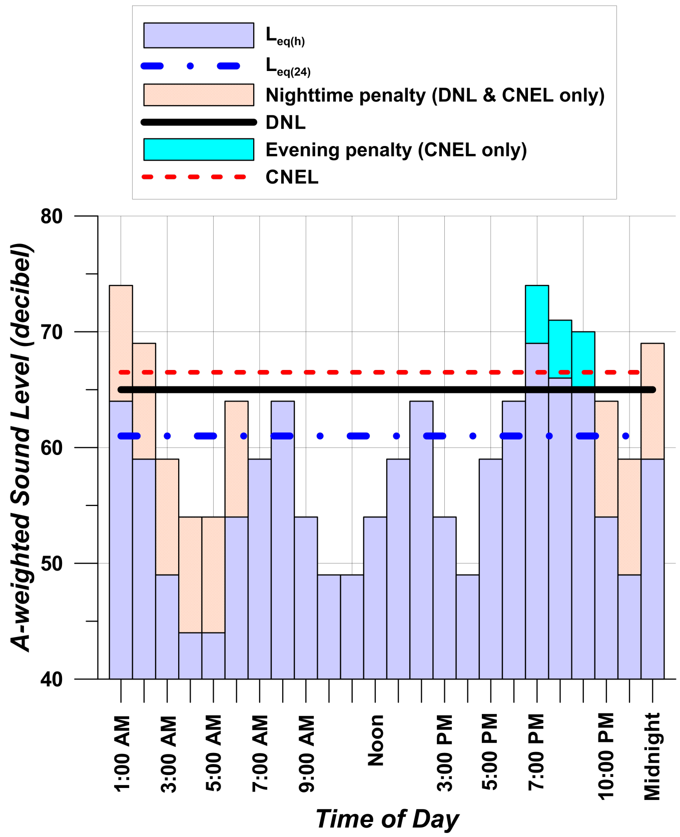
D.2.2 Cumulative Events

D.2.2.1 Equivalent Sound Level (L_{eq})

Equivalent Sound Level is a "cumulative" metric that combines a series of noise events over a period of time. L_{eq} is the sound level that represents the decibel average SEL of all sounds in the time period. Just as SEL has proven to be a good measure of a single event, L_{eq} has proven to be a good measure of series of events during a given time period.

The time period of an L_{eq} measurement is usually related to some activity, and is given along with the value. The time period is often shown in parenthesis (e.g., $L_{eq(24)}$ for 24 hours). The L_{eq} from 7 a.m. to 3 p.m. may give exposure of noise for a school day.

Figure D-5 gives an example of $L_{eq(24)}$ using notional hourly average noise levels ($L_{eq(h)}$) for each hour of the day as an example. The $L_{eq(24)}$ for this example is 61 dB.



Source: Wyle Laboratories

Figure D-5 Example of $L_{eq(24)}$, DNL and CNEL Computed from Hourly Equivalent Sound Levels

D.2.2.2 Day-Night Average Sound Level (DNL or L_{dn}) and Community Noise Equivalent Level (CNEL)

Day-Night Average Sound Level is a cumulative metric that accounts for all noise events in a 24-hour period. However, unlike $L_{eq(24)}$, DNL contains a nighttime noise penalty. To account for our increased sensitivity to noise at night, DNL applies a 10 dB penalty to events during the nighttime period, defined as 10:00 p.m. to 7:00 a.m. The notations DNL and L_{dn} are both used for Day-Night Average Sound Level and are equivalent.

CNEL is a variation of DNL specified by law in California (California Code of Regulations Title 21, *Public Works*) (Wyle Laboratories 1970). CNEL has the 10 dB nighttime penalty for events between 10:00 p.m. and 7:00 a.m. but also includes a 4.8 dB penalty for events during the evening period of 7:00 p.m. to 10:00 p.m. The evening penalty in CNEL accounts for the added intrusiveness of sounds during that period.

For airports and military airfields, DNL and CNEL represent the average sound level for annual average daily aircraft events.

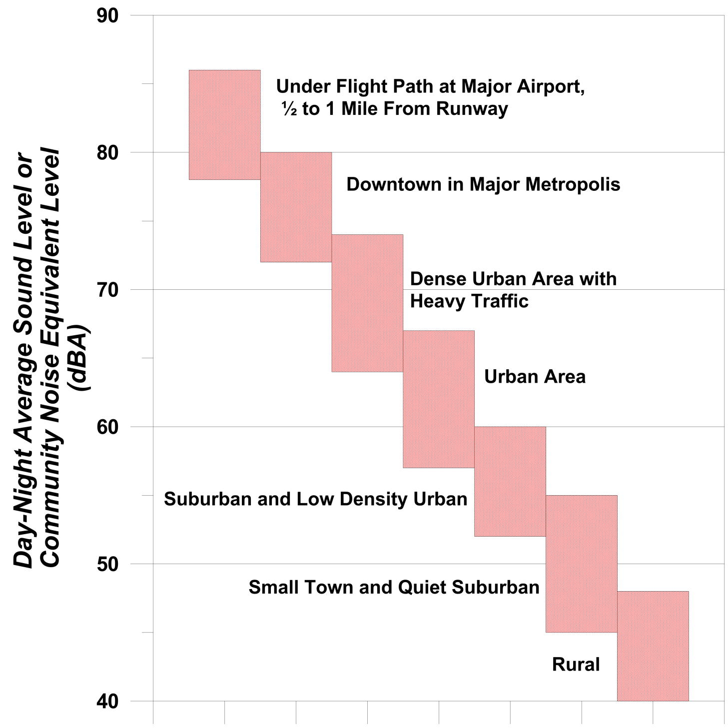
Figure D-5 gives an example of DNL and CNEL using notional hourly average noise levels ($L_{eq(h)}$) for each hour of the day as an example. Note the $L_{eq(h)}$ for the hours between 10 p.m. and 7 a.m. have a 10 dB penalty assigned. For CNEL the hours between 7p.m. and 10 p.m. have a 4.8 dB penalty assigned. The DNL for this example is 65 dB. The CNEL for this example is 66 dB.

Figure D-6 shows the ranges of DNL or CNEL that occur in various types of communities. Under a flight path at a major airport the DNL may exceed 80 dB, while rural areas may experience DNL less than 45 dB.

The decibel summation nature of these metrics causes the noise levels of the loudest events to control the 24-hour average. As a simple example, consider a case in which only one aircraft overflight occurs during the daytime over a 24-hour period, creating a sound level of 100 dB for 30 seconds. During the remaining 23 hours, 59 minutes, and 30 seconds of the day, the ambient sound level is 50 dB. The DNL for this 24-hour period is 65.9 dB. Assume, as a second example, that 10 such 30-second overflights occur during daytime hours during the next 24-hour period, with the same ambient sound level of 50 dB during the remaining 23 hours and 55 minutes of the day. The DNL for this 24-hour period is 75.5 dB. Clearly, the averaging of noise over a 24-hour period does not ignore the louder single events and tends to emphasize both the sound levels and number of those events.

A feature of the DNL metric is that a given DNL value could result from a very few noisy events or a large number of quieter events. For example, 1 overflight at 90 dB creates the same DNL as 10 overflights at 80 dB.

DNL or CNEL do not represent a level heard at any given time, but represent long-term exposure. Scientific studies have found good correlation between the percentages of groups of people highly annoyed and the level of average noise exposure measured in DNL (Schultz 1978; USEPA 1978).



Source: DOD 1978.

Figure D-6 Typical DNL or CNEL Ranges in Various Types of Communities

D.3 Noise Effects

Noise is of concern because of potential adverse effects. The following subsections describe how noise can affect communities and the environment, and how those effects are quantified. The specific topics discussed are:

- Annoyance,
- Speech interference,
- Sleep disturbance,
- Noise-induced hearing impairment
- Non-auditory health effects,
- Performance effects,
- Noise effects on children,
- Property values,
- Noise-induced vibration effects on structures and humans,
- Noise effects on terrain,
- Noise effects on historical and archaeological sites, and
- Effects on domestic animals and wildlife.

D.3.1 Annoyance

With the introduction of jet aircraft in the 1950s, it became clear that aircraft noise annoyed people and was a significant problem around airports. Early studies, such as those of Rosenblith et al. (1953) and Stevens et al. (1953) showed that effects depended on the quality of the sound, its level, and the number of flights. Over the next 20 years considerable research was performed refining this understanding and setting guidelines for noise exposure. In the early 1970s, the USEPA published its “Levels Document” (USEPA 1974) that reviewed the factors that affected communities. DNL (still known as L_{dn} at the time) was identified as an appropriate noise metric, and threshold criteria were recommended.

Threshold criteria for annoyance were identified from social surveys, where people exposed to noise were asked how noise affects them. Surveys provide direct real-world data on how noise affects actual residents.

Surveys in the early years had a range of designs and formats, and needed some interpretation to find common ground. In 1978, Schultz showed that the common ground was the number of people “highly annoyed,” defined as the upper 28% range of whatever response scale a survey used (Schultz 1978). With that definition, he was able to show a remarkable consistency among the majority of the surveys for which data were available. Figure D-7 shows the result of his study relating DNL to individual annoyance measured by percent highly annoyed (%HA).

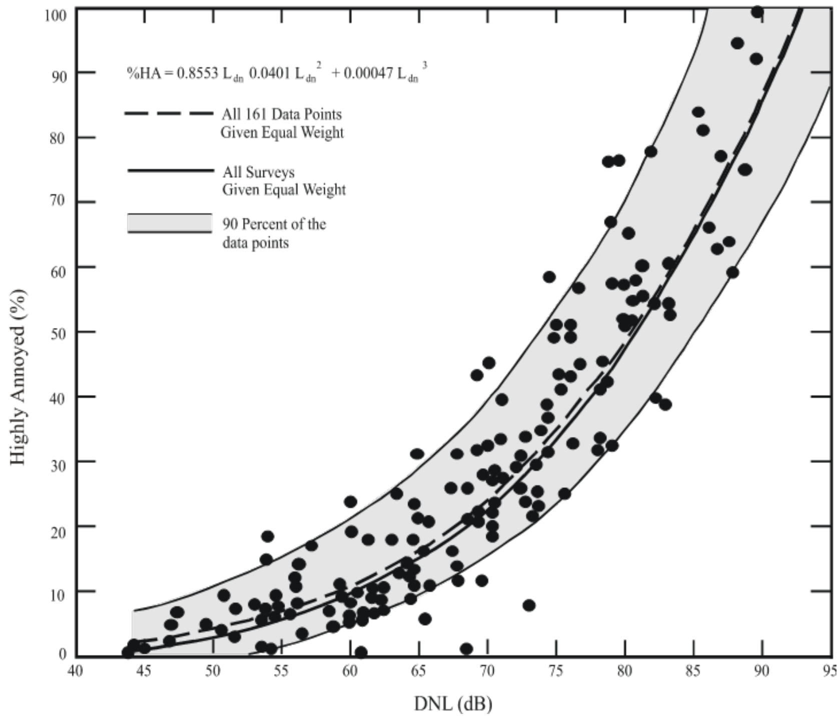


Figure D-7 Schultz Curve Relating Noise Annoyance to DNL (Schultz 1978)

Schultz's original synthesis included 161 data points. Figure D-8 compares revised fits of the Schultz data set with an expanded set of 400 data points collected through 1989 (Finegold et al. 1994). The new form is the preferred form in the US, endorsed by the Federal Interagency Committee on Aviation Noise (FICAN 1997). Other forms have been proposed, such as that of Fidell and Silvati (2004), but have not gained widespread acceptance.

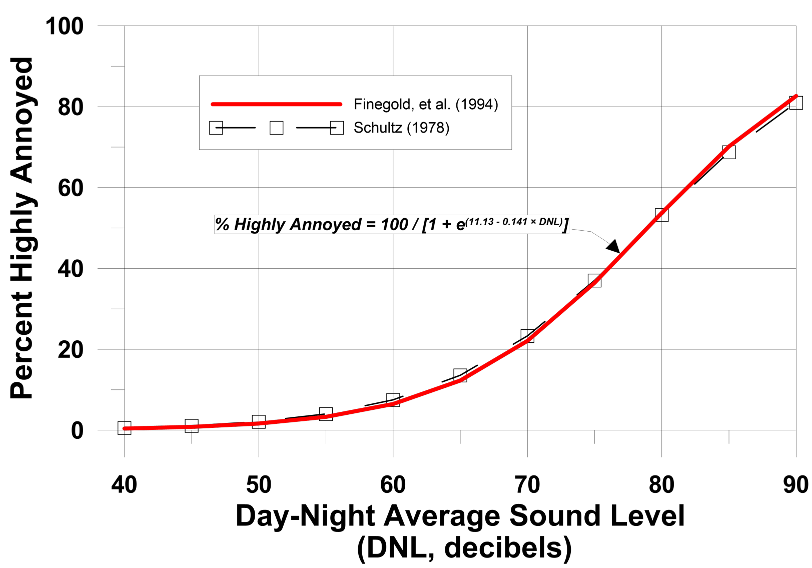


Figure D-8 Response of Communities to Noise; Comparison of Original Schultz (1978) with Finegold et al. (1994)

When the goodness of fit of the Schultz curve is examined, the correlation between groups of people is high, in the range of 85-90%. However, the correlation between individuals is much lower, at 50% or less. This is not surprising, given the personal differences between individuals. The surveys underlying the Schultz curve include results that show that annoyance to noise is also affected by non-acoustical factors. Newman and Beattie (1985) divided the non-acoustic factors into the emotional and physical variables shown in Table D-1.

Table D-1 Non-Acoustic Variables Influencing Aircraft Noise Annoyance

Emotional Variables	*Physical Variables*
Feeling about the necessity or preventability of the noise;	Type of neighborhood;
Judgement of the importance and value of the activity that is producing the noise;	Time of day;
Activity at the time an individual hears the noise;	Season;
Attitude about the environment;	Predictability of the noise;
General sensitivity to noise;	Control over the noise source; and
Belief about the effect of noise on health; and	Length of time individual is exposed to a noise.
Feeling of fear associated with noise.	-

Schreckenberg and Schuemer (2010) and Laszlo (2012) recently examined the importance of some of these factors on short term annoyance. Attitudinal factors were identified as having an effect on annoyance. In formal regression analysis, however, sound level (L_{eq}) was found to be more important than attitude. A series of studies at three European airports showed that less than 20 percent of the variance in annoyance can be explained by noise alone (M?rki 2013).

A recent study by Plotkin et al. (2011) examined updating DNL to account for these factors. It was concluded that the data requirements for a general analysis were much greater than are available from most existing studies. It was noted that the most significant issue with DNL is that it is not readily understood by the public, and that supplemental metrics such as TA and NA were valuable in addressing attitude when communicating noise analysis to communities (DOD 2009a).

A factor that is partially non-acoustical is the source of the noise. Miedema and Vos (1998) presented synthesis curves for the relationship between DNL and percentage “Annoyed” and percentage “Highly Annoyed” for three transportation noise sources. Different curves were found for aircraft, road traffic, and railway noise. Table D-2 summarizes their results. Comparing the updated Schultz curve suggests that the percentage of people highly annoyed by aircraft noise may be higher than previously thought. Miedema and Oudshoorn (2001) authors supplemented that investigation with further derivation of percent of population highly annoyed as a function of either DNL or DENL along with the corresponding 95 percent confidence intervals with similar results.

Table D-2 Percent Highly Annoyed for Different Transportation Noise Sources

DNL (dB)	*Percent Highly Annoyed (%HA)*			
	Miedema and Vos			*Schultz Combined*
	Air	*Road*	*Rail*	
55	12	7	4	3
60	19	12	7	6
65	28	18	11	12
70	37	29	16	22
75	48	40	22	36

Source: Miedema and Vos 1998.

As noted by the World Health Organization (WHO), however, even though aircraft noise seems to produce a stronger annoyance response than road traffic, caution should be exercised when interpreting synthesized data from different studies (WHO 1999).

Figure D-9 depicts the Federal Interagency Committee on Noise (FICON 1992) curve fit of DNL versus percent of the population highly annoyed, referred to as the 'Shultz Curve', compared to the International Organization for Standardization recommended relationship (ISO 1996-1). Consistent with WHO's recommendations, the FICON 1992 curve fit is considered to be the best source of dose information to predict community response to noise, but further research is recommended to investigate the differences in perception of noise from different sources.

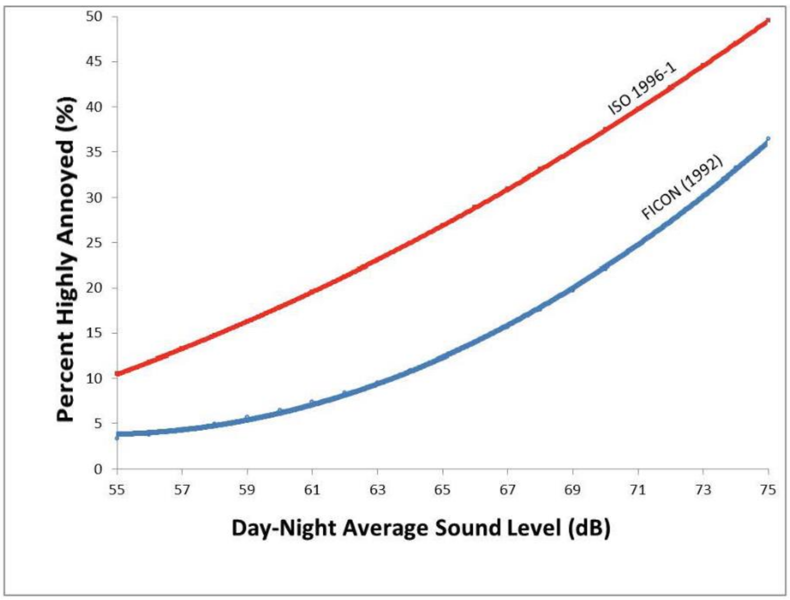


Figure D-9 Percent Highly Annoyed Comparison of ISO 1996-1 to FICON 1992

D.3.2 Speech Interference

Speech interference from noise is a primary cause of annoyance for communities. Disruption of routine activities such as radio or television listening, telephone use, or conversation leads to frustration and annoyance. The quality of speech communication is important in classrooms and offices. In the workplace, speech interference from noise can cause fatigue and vocal strain in those who attempt to talk over the noise. In schools it can impair learning.

There are two measures of speech comprehension:

1. *Word Intelligibility* - the percent of words spoken and understood. This might be important for students in the lower grades who are learning the English language, and particularly for students who have English as a Second Language.
2. *Sentence Intelligibility* – the percent of sentences spoken and understood. This might be important for high school students and adults who are familiar with the language, and who do not necessarily have to understand each word in order to understand sentences.

D.3.2.1 U.S. Federal Criteria for Interior Noise

In 1974, the USEPA identified a goal of an indoor $L_{eq(24)}$ of 45 dB to minimize speech interference based on sentence intelligibility and the presence of steady noise (USEPA 1974). Figure D-10 shows the effect of steady indoor background sound levels on sentence intelligibility. For an average adult with normal hearing and fluency in the language, steady background indoor sound levels of less than 45 dB L_{eq} are expected to allow 100% sentence intelligibility.

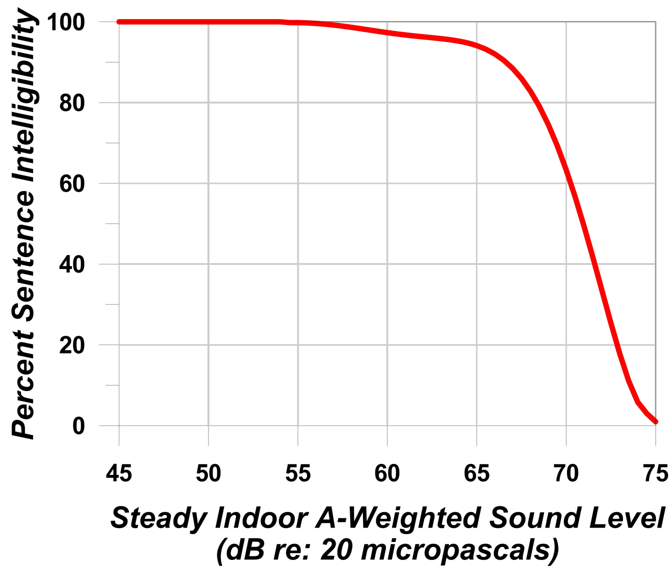


Figure D-10 Speech Intelligibility Curve (digitized from USEPA 1974)

The curve in Figure D-10 shows 99% intelligibility at L_{eq} below 54 dB, and less than 10% above 73 dB. Recalling that L_{eq} is dominated by louder noise events, the USEPA $L_{eq(24)}$ goal of 45 dB generally ensures that sentence intelligibility will be high most of the time.

D.3.2.2 Classroom Criteria

For teachers to be understood, their regular voice must be clear and uninterrupted. Background noise has to be below the teacher's voice level. Intermittent noise events that momentarily drown out the teacher's voice need to be kept to a minimum. It is therefore important to evaluate the steady background level, the level of voice communication, and the single-event level due to aircraft overflights that might interfere with speech.

Lazarus (1990) found that for listeners with normal hearing and fluency in the language, complete sentence intelligibility can be achieved when the signal-to-noise ratio (i.e., a comparison of the level of the sound to the level of background noise) is in the range of 15 to 18 dB. The initial ANSI classroom noise standard (ANSI 2002) and American Speech-Language-Hearing Association (ASLHA 2005) guidelines concur, recommending at least a 15 dB signal-to-noise ratio in classrooms. If the teacher's voice level is at least 50 dB, the background noise level must not exceed an average of 35 dB. The National Research Council of Canada (Bradley 1993) and WHO (1999) agree with this criterion for background noise.

For eligibility for noise insulation funding, the Federal Aviation Administration (FAA) guidelines state that the design objective for a classroom environment is 45 dB L_{eq} during normal school hours (FAA 1985).

Most aircraft noise is not continuous. It consists of individual events like the one sketched in Figure D-4. Since speech interference in the presence of aircraft noise is caused by individual aircraft flyover events, a time-averaged metric alone, such as L_{eq}, is not necessarily appropriate. In addition to the background level criteria described above, single-event criteria that account for those noisy events are also needed.

A 1984 study by Wyle for the Port Authority of New York and New Jersey recommended using Speech Interference Level (SIL) for classroom noise criteria (Sharp and Plotkin 1984). SIL is based on the maximum sound levels in the frequency range that most affects speech communication (500-2,000 Hz). The study identified an SIL of 45 dB as the goal. This would provide 90% word intelligibility for the short time periods during aircraft overflights. While SIL is technically the best metric for speech interference, it can be approximated by an L_{max} value. An SIL of 45 dB is equivalent to an A-weighted L_{max} of 50 dB for aircraft noise (Wesler 1986).

Lind et al. (1998) also concluded that an L_{max} criterion of 50 dB would result in 90% word intelligibility. Bradley (1985) recommends SEL as a better indicator. His work indicates that 95% word intelligibility would be achieved when indoor SEL did not exceed 60 dB. For typical flyover noise this corresponds to an Lmax of 50 dB. While WHO (1999) only specifies a background Lmax criterion, they also note the SIL frequencies and that interference can begin at around 50 dB.

The United Kingdom Department for Education and Skills (UKDfES) established in its classroom acoustics guide a 30-minute time-averaged metric of $L_{eq(30min)}$ for background levels and the metric of $L_{A1,30min}$ for intermittent noises, at thresholds of 30-35 dB and 55 dB, respectively. $L_{A1,30min}$ represents the A-weighted sound level that is exceeded 1% of the time (in this case, during a 30-minute teaching session) and is generally equivalent to the L_{max} metric (UKDfES 2003).

Table D-3 summarizes the criteria discussed. Other than the FAA (1985) 45 dB L_{max} criterion, they are consistent with a limit on indoor background noise of 35-40 dB L_{eq} and a single event limit of 50 dB L_{max}. It should be noted that these limits were set based on students with normal hearing and no special needs. At-risk students may be adversely affected at lower sound levels.

Table D-3 Indoor Noise Level Criteria Based on Speech Intelligibility

Source	***Metric/Level (dB)***	***Effects and Notes***
FAA (1985)	$L_{eq\ (during\ school\ hours)}$ = 45 dB	Federal assistance criteria for school sound insulation; supplemental single-event criteria may be used
Lind et al. (1998), Sharp and Plotkin (1984), Wesler (1986)	L_{max} = 50 dB	Single event level permissible in the classroom
WHO (1999)	L_{eq} = 35 dB L_{max} = 50 dB	Assumes average speech level of 50 dB and recommends signal to noise ratio of 15 dB.
ANSI (2010)	L_{eq} = 35 dB, based on Room Volume (e.g., cubic feet)	Acceptable background level for continuous and intermittent noise.
DfES (2003)	$L_{eq(30\ min)}$ = 30-35 dB L_{max} = 55 dB	Minimum acceptable in classroom and most other learning environs.

D.3.3 Sleep Disturbance

Sleep disturbance is a major concern for communities exposed to aircraft noise at night. A large amount of research developed in the laboratory during the past 30 years has produced variable results suggesting a complex interaction of factors, including the noise characteristics and individual sensitivity, rather than a clear dose-effect relationship (Muzet 2007). Sleep disorders may cause negative health effects such as cardiovascular problems, neuroendocrine abnormalities and changes in cognition, mood and memory. The causal relationships between noise exposure, effects on sleep, and contribution to health disturbances, both behavioral and physical, are not yet firmly established (Zaharna 2010). A number of studies have attempted to quantify the effects of noise on sleep. This section provides an overview of the major noise-induced sleep disturbance studies. Emphasis is on studies that have influenced U.S. federal noise policy. The studies have been separated into two groups:

1. Initial studies performed in the 1960s and 1970s, where the research was focused on sleep observations performed under laboratory conditions.
2. Later studies performed in the 1990s up to the present, where the research was focused on field observations.

D.3.3.1 Initial Studies

The relation between noise and sleep disturbance is complex and not fully understood. The disturbance depends not only on the depth of sleep and the noise level, but also on the non-acoustic factors cited for annoyance. The easiest effect to measure is the number of arousals or awakenings from noise events. Much of the literature has therefore focused on predicting the percentage of the population that will be awakened at various noise levels.

FICON's 1992 review of airport noise issues (FICON 1992) included an overview of relevant research conducted through the 1970s. Literature reviews and analyses were conducted from 1978 through 1989 using existing data (Griefahn 1978; Griefahn and Muzet 1978; Lukas 1978; Pearsons et al. 1989). Because of large variability in the data, FICON did not endorse the reliability of those results.

FICON did, however, recommend an interim dose-response curve, awaiting future research. That curve predicted the percent of the population expected to be awakened as a function of the exposure to SEL. This curve was based on research conducted for the U.S. Air Force (Finegold 1994). The data included most of the research performed up to that point, and predicted a 10% probability of awakening when exposed to an interior SEL of 58 dB. The data used to derive this curve were primarily from controlled laboratory studies.

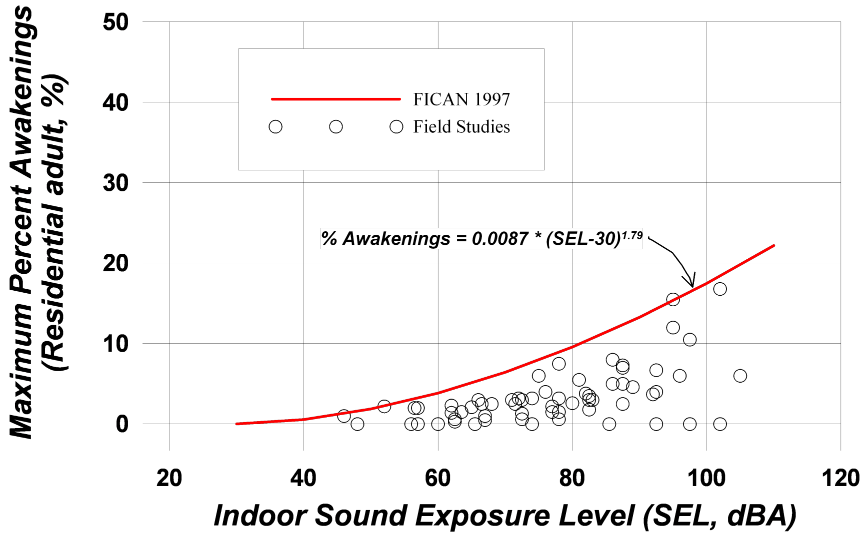
D.3.3.2 Recent Sleep Disturbance Research – Field and Laboratory Studies

It was noted that early sleep laboratory studies did not account for some important factors. These included habituation to the laboratory, previous exposure to noise, and awakenings from noise other than aircraft. In the early 1990s, field studies in people's homes were conducted to validate the earlier laboratory work conducted in the 1960s and 1970s. The field studies of the 1990s (e.g., Horne 1994) found that 80-90% of sleep disturbances were not related to outdoor noise events, but rather to indoor noises and non-noise factors. The results showed that, in real life conditions, there was less of an effect of noise on sleep than had been previously reported from laboratory studies. Laboratory sleep studies tend to show more sleep disturbance than field studies because people who sleep in their own homes are used to their environment and, therefore, do not wake up as easily (FICAN 1997).

D.3.3.3 FICAN

Based on this new information, in 1997 FICAN recommended a dose-response curve to use instead of the earlier 1992 FICON curve (FICAN 1997). Figure D-11 shows FICAN's curve, the red line, which is based on the results of three field studies shown in the figure (Ollerhead et al. 1992; Fidell et al. 1994; Fidell et al. 1995a, 1995b), along with the data from six previous field studies.

The 1997 FICAN curve represents the upper envelope of the latest field data. It predicts the maximum percent awakened for a given residential population. According to this curve, a maximum of 3% of people would be awakened at an indoor SEL of 58 dB. An indoor SEL of 58 dB is equivalent to an outdoor SEL of about 83 dB, with the windows closed (73 dB with windows open).



Source: FICAN 1997

Figure D-11 FICAN 1997 Recommended Sleep Disturbance Dose-Response Relationship

D.3.3.4 Number of Events and Awakenings

It is reasonable to expect that sleep disturbance is affected by the number of events. The German Aerospace Center (DLR Laboratory) conducted an extensive study focused on the effects of nighttime aircraft noise on sleep and related factors (Basner et al. 2004). The DLR study was one of the largest studies to examine the link between aircraft noise and sleep disturbance. It involved both laboratory and in-home field research phases. The DLR investigators developed a dose-response curve that predicts the number of aircraft events at various values of L_{max} expected to produce one additional awakening over the course of a night. The dose-effect curve was based on the relationships found in the field studies.

Later studies by DLR conducted in the laboratory comparing the probability of awakenings from different modes of transportation showed that aircraft noise lead to significantly lower awakening probabilities than either road or rail noise (Basner et al. 2011). Furthermore, it was noted that the probability of awakening, per noise event, decreased as the number of noise events increased. The authors concluded that by far the majority of awakenings from noise events merely replaced awakenings that would have occurred spontaneously anyway.

A different approach was taken by an ANSI standards committee (ANSI 2008). The committee used the average of the data shown in Figure D-11, rather than the upper envelope (shown as the red line), to predict average awakening from one event. Probability theory is then used to project the awakening from multiple noise events.

Currently, there are no established criteria for evaluating sleep disturbance from aircraft noise, although recent studies have suggested a benchmark of an outdoor SEL of 90 dB as an appropriate tentative criterion when comparing the effects of different operational alternatives. The corresponding indoor SEL would be approximately 25 dB lower (at 65 dB) with doors and windows closed, and approximately 15 dB lower (at 75 dB) with doors or windows open. According to the ANSI (2008) standard, the probability of awakening from a single aircraft event at this level is between 1 and 2% for people habituated to the noise sleeping in bedrooms with windows closed, and 2-3% with windows open. The probability of the exposed population awakening at least once from multiple aircraft events at noise levels of 90 dB SEL is shown in Table D-4. As of July 2018, the ANSI and ASA have withdrawn the 2008 standard, which formed the basis of much of the DNWG 2009 guidance (ANSI/ASA 2018).

The decision of Working Group S12/WG 15 to withdraw ANSI/ASA S12.9-2008/Part 6 implies that the method for calculating "at least one behavioral awakening per night" contained in the former Standard should no longer be relied upon for environmental impact assessment purposes. The Working Group believes that continued reliance on the 2008 Standard would lead to unreliable and difficult-to-interpret predictions of transportation-noise-induced sleep disturbance (ANSI/ASA 2018).

Table D-4 Probability of Awakening from NA90SEL

Number of Aircraft Events at 90 dB SEL for Average 9-hour Night	***Minimum Probability of Awakening at Least Once***	
	Windows Closed	***Windows Open***
1	1%	2%
3	4%	6%
5	7%	10%
9 (1 per hour)	12%	18%
18 (2 per hour)	22%	33%
27 (3 per hour)	32%	45%

Source: DOD 2009b.

A recent study further examined the relationship between self-reported sleep insufficiency and airport noise using the United States Behavioral Risk Factor Surveillance System (BRFSS) data and DNL contours generated by the FAA's INM software for 95 airports (Holt et al. 2015). The BRFSS data comprises random-digit-dialed telephone survey of non-institutionalized US civilians 18 years old or older covering all 50 states. Responses that included sleep insufficiency questions were included in this study totaling more than 700,000 respondents for 2008 and 2009 year data set. The authors found that, once controlled for individual sociodemographic characteristics and ZIP Code-level socioeconomic status, there were no significant associations between airport noise exposure levels and self-reported sleep insufficiency. These results are consistent with a study with a study which found that that aircraft noise-induced awakening are more reasonably predicted from relative rather than absolute sound exposure levels (Fidel et al. 2013). A response relationship between aircraft noise and sleep quality was found in a community-based cross-sectional study when controlling for mental health condition (Kim et al. 2014).

The WHO recommends the use of the A-weighted long-term average sound level L_{night}, measured outside the home, for sleep disturbance and related effects with interim target of 55 dB $L_{night, outside}$ and a night noise guideline of 40 dB (WHO 2009).

The choice of a noise metric for policy-making purposes depends on both the particular type of noise source and the particular effect being studies. Even for sleep disturbance due to aircraft noise, there is no single noise exposure metric or measurement approach which is generally agreed upon (Finegold 2010).

D.3.3.5 Summary

Sleep disturbance research still lacks the details to accurately estimate the population awakened for a given noise exposure. With the withdrawal of the ANSI 2008 guideline no current procedure to calculate the probability of awakening has been scientifically validated so any methods should be considered approximate at best.

D.3.4 Noise-Induced Hearing Impairment

Residents in surrounding communities express concerns regarding the effects of aircraft noise on hearing. This section provides a brief overview of hearing loss caused by noise exposure. The goal is to provide a sense of perspective as to how aircraft noise (as experienced on the ground) compares to other activities that are often linked with hearing loss.

D.3.4.1 Hearing Threshold Shifts

Hearing loss is generally interpreted as a decrease in the ear’s sensitivity or acuity to perceive sound (i.e., a shift in the hearing threshold to a higher level). This change can either be a Temporary Threshold Shift (TTS) or a Permanent Threshold Shift (PTS) (Berger et al. 1995).

TTS can result from exposure to loud noise over a given amount of time. An example of TTS might be a person attending a loud music concert. After the concert is over, there can be a threshold shift that may last several hours. While experiencing TTS, the person becomes less sensitive to low-level sounds, particularly at certain frequencies in the speech range (typically near 4,000 Hz). Normal hearing eventually returns, as long as the person has enough time to recover within a relatively quiet environment.

PTS usually results from repeated exposure to high noise levels, where the ears are not given adequate time to recover. A common example of PTS is the result of regularly working in a loud factory. A TTS can eventually become a PTS over time with repeated exposure to high noise levels. Even if the ear is given time to recover from TTS, repeated occurrence of TTS may eventually lead to permanent hearing loss. The point at which a TTS results in a PTS is difficult to identify and varies with a person’s sensitivity. NIOSH assumed the audiogram the standard functional test and therefore that an exposure that causes only a TTS to be considered benign. However, recent work has shown that noise-induced neuropathy can exist independent of PTS but would likely affect more complex auditory tasks such as speech discrimination in noise (Liberman 2016).

In the USA and Europe, 26 percent of adults have a bilateral hearing disorder that impairs their ability to hear clearly in noisy environments and an additional 2 percent have substantial unilateral hearing issues (Basner et al. 2014).

A few studies have examined hearing loss from exposure to aircraft noise. Noise-induced hearing loss for children who attended a school located under a flight path near a Taiwan airport was greater than for children at another school far away (Chen et al. 1997). Another study reported that hearing ability was reduced significantly in individuals who lived near an airport and were frequently exposed to aircraft noise (Chen and Chen 1993). In that study, noise exposure near the airport was greater than 75 dB DNL and L_{max} were about 87 dB during overflights. Conversely, several other studies reported no difference in hearing ability between children exposed to high levels of airport noise and children located in quieter areas (Andrus et al. 1975; Fisch 1977; Wu et al. 1995). It is not clear from those results whether children are at higher risk than adults, but the levels involved are higher than those desirable for learning and quality of life.

Ludlow and Sixsmith (1999) conducted a cross-sectional pilot study to examine the hypothesis that military jet noise exposure early in life is associated with raised hearing thresholds. The authors concluded that there were no significant differences in audiometric test results between military personnel who as children had lived in or near stations where fast jet operations were based, and a similar group who had no such exposure as children.

D.3.4.2 Criteria for Permanent Hearing Loss

It has been well established that continuous exposure to high noise levels will damage human hearing (USEPA 1978). A large amount of data on hearing loss have been collected, largely for workers in manufacturing industries, and analyzed by the scientific/medical community. The Occupational Safety and Health Administration (OSHA) regulation of 1971 places the limit on workplace noise exposure at an average level of 90 dB over an 8-hour work period or 85 dB over a 16-hour period (U.S. Department of Labor 1971). Some hearing loss is still expected at those levels. The most protective criterion, with no measurable hearing loss after 40 years of exposure, is an average sound level of 70 dB over a 24-hour period.

The USEPA established 75 dB $L_{eq(8)}$ and 70 dB $L_{eq(24)}$ as the average noise level standard needed to protect 96% of the population from greater than a 5 dB PTS (USEPA 1978). The National Academy of Sciences Committee on Hearing, Bioacoustics, and Biomechanics (CHABA) identified 75 dB as the lowest level at which hearing loss may occur (CHABA 1977). WHO concluded that environmental and leisure-time noise below an $L_{eq(24)}$ value of 70 dB "will not cause hearing loss in the large majority of the population, even after a lifetime of exposure" (WHO 1999).

D.3.4.3 Tinnitus

Tinnitus is the perception of sound in the absence of acoustic stimulus affecting approximately 10 percent of the adult population, which increases with age. Tinnitus is a symptom of a variety of diseases most commonly associated with hearing loss. Many people experience transient tinnitus lasting seconds or minutes after exposure to loud noise typically described as ringing or hissings most often at high pitched tones above 3,000 Hz (Davis and Rafaie 2000).

D.3.4.4 Summary

Aviation noise levels or temporary construction noise levels to non-participatory individuals are not comparable to the occupational noise levels associated with hearing loss of workers in manufacturing industries. There is little chance of hearing loss at levels less than 75 dB DNL. Noise levels equal to or greater than 75 dB DNL can occur near military airbases, and DOD policy specifies that NIPTS be evaluated when exposure exceeds 80 dB $L_{eq(24)}$ (DOD 2009c). There is some concern about L_{max} exceeding 115 dB in low altitude military airspace, but no research results to date have definitely related permanent hearing impairment to aviation noise or other temporary sources of noise at modestly elevated levels.

D.3.5 Non-auditory Health Effects

The potential for aircraft noise to impair one's health deserves special attention and accordingly has been the subject of numerous epidemiological studies and meta-analyses of the gathered data. The basic premise is that noise can cause annoyance, annoyance can cause stress, and prolonged stress is known to be a contributor to a number of health disorders, such as hypertension, myocardial infarction (heart attack), cardiovascular disease, and stroke. According to Kryter and Poza (1980) "It is more likely that noise-related general ill-health effects are due to the psychological annoyance from the noise interfering with normal everyday behavior, than it is from the noise eliciting, because of its intensity, reflexive response in the autonomic or other physiological systems of the body."

An early study by Cantrell (1974) confirmed that noise can provoke stress, but noted that results on its effect on cardiovascular health were contradictory. Some studies in the 1990s found a connection between aircraft noise and increased blood pressure (Michalak et al. 1990; Ising 1990; Rosenlund et al. 2001), while others did not (Pulles et al. 1990). This inconsistency in results led the WHO in 2000 to conclude that there was only a weak association between long-term noise exposure and hypertension and cardiovascular effects, and that a dose-response relationship could not be established (WHO 2000). Later, van Kempen concluded that "Whereas noise exposure can contribute to the prevalence of cardiovascular disease, the evidence for a relation between noise exposure and ischemic heart disease is still inconclusive" (van Kempen et al. 2002)

More recently, major studies have been conducted in an attempt to identify an association between noise and health effects, develop a dose-response relationship, and identify a threshold below which the effects are minimal. The most important of these are briefly described below. In these studies researchers usually present their results in terms of the Odds Ratio, or, which is the ratio of the odds that health will be impaired by an increase in noise level of 10 dB to the odds that health would be impaired without any noise exposure. An OR of 1.25 means that there is a 25 percent increase in likelihood that noise will impair health. To put the OR number in context, an OR of 1.5 would be considered a weak relationship between noise and health; 3.5 would be a moderate relationship; 9.0 would be a strong relationship; and 32 a very strong relationship (Cohen 1981a). The OR for the relationship between obesity and hypertension is 3.4 (Pikilidou et al. 2013), and that between smoking and coronary heart disease is 4.4 (Rosengren et al. 1992).

- A carefully designed study, Hypertension and Exposure to Noise near Airports (HYENA), was conducted around six European airports from 2002 through 2006 (Jarup et al. 2005, 2007, 2008, Babisch et al. 2008). There were 4,861 subjects, aged between 45 and 70. Blood pressure was measured and questionnaires administered for health, socioeconomic and lifestyle factors, including diet and physical exercise. Noise from aircraft and highways was predicted from models.

  HYENA results showed an OR less than 1 for the association between daytime aircraft noise and hypertension which was not statistically significant[1], indicating no positive association. The OR for the relationship between nighttime aircraft noise and hypertension was 1.14 – a result that was marginally statistically significant. For daytime road traffic noise, the OR was 1.1 and marginally significant. The measured effects were small, and not necessarily distinct from other events. A close review of the data for nighttime aircraft noise raised some questions about the data and the methods employed (ACRP 2008). Using data from the HYENA study Haralabidis et al. (2008) reported an increase in systolic blood pressure of 6.2 millimeters of mercury (mmHg)

[1] In many of the studies reported above the researchers use the word "significant" to describe a relationship between noise and health, conjuring up the idea that the relationship is strong and that the effect is large. But this is an inappropriate and misleading use of the word in statistical analysis. What the researchers really mean is that the relationship is "statistically significant" in that they are sure that it is real. It does not mean that the effect is large or important, or that it has any decision-making utility. A relationship can be statistically significant, i.e., real, while being weak, or small and insignificant.

for aircraft noise events (about 6 (about 5 percent) percent), and an increase of 7.4 mmHg (about 7 percent) for other indoor noises, such as snoring - a snoring partner and road traffic had similar impact on blood pressure.

- Ancona et al. (2010) reports a study on a randomly selected sample of subjects aged 45–70 years who had lived in the study area for at least 5 years. Personal data was collected via interview and blood pressure measurements were taken for a study population of 578 subjects. No statistically significant association was found between aircraft noise levels and hypertension for noise levels above 75 dB Leq(24) compared to levels below 65 dB. However, there was an increase in nocturnal systolic pressure of 5.4 mmHg (about 5 percent), for subjects in the highest exposure category (greater than or equal to 75 dB).
- Huss (2010) examined the risk of mortality from myocardial infarction (heart attack) resulting from exposure to aircraft noise using the Swiss National database of mortality records for the period 2000 to 2005. The analysis was conducted on a total of 4.6 million people with 15,500 deaths from acute myocardial infarction. The results showed that the risk of death from all circulatory diseases combined was not associated with aircraft noise, nor was there any association between noise and the risk of death from stroke. The overall risk of death from myocardial infarction alone was 1.07 and not statistically significant, but higher (OR = 1.3 and not statistically significant) in people exposed to aircraft noise of 60 dB DNL or greater for 15 years or more. The risk of death from myocardial infarction was also higher (OR = 1.10), and statistically significant, for those living near a major road. Cardiovascular risk factors, such as smoking, were not directly taken into account in this study.
- Floud (2013) used the HYENA data to examine the relationship between noise levels and self-reported heart disease and stroke. There was no association for daytime noise, and no statistically significant association for nighttime noise. However, for those exposed to nighttime aircraft noise for more than 20 years, the OR was 1.25 per 10 dB increase in noise (Lnight) and marginally significant.
- Correia et al. (2013) evaluated the risk of hospitalization for cardiovascular diseases in older people (≥65 years) residing in areas exposed to DNL of at least 45 dB around US airports. Health insurance data from 2009 Medicare records were examined for approximately 6 million people living in neighborhoods around 89 airports in the United States. The potential confounding effect of socioeconomic status was extracted from several zip code-level variables from the 2000 US census. No controls were included for smoking or diet, both of which are strong risk factors for cardiovascular disease. Noise levels were calculated at census block centroids. Taking into account the potential effects of air pollution, they report an OR of 1.035 that was marginally statistically significant. While the overall results show a link between increased noise and increased health risk, some of the individual airport data show a decreased health risk with increased aircraft noise exposure.
- Hansell et al. (2013) investigated the association of aircraft noise with risk of hospital admission for, and mortality from, stroke, coronary heart disease, and cardiovascular disease in neighborhoods around London’s Heathrow airport exposed to Leq(16) of at least 50 dB. The data were adjusted for age, sex, ethnicity, deprivation, and a smoking proxy (lung cancer mortality) at the census area level, but not at the individual level. It was important to consider the effect of ethnicity (in particular South Asian ethnicity, which is itself strongly associated with risk of coronary heart disease). The reported OR for stroke, heart disease, and cardiovascular disease were 1.24, 1.21, and 1.14 respectively. Similar results were reported for mortality.

- The results suggest a higher risk of mortality from coronary heart disease than cardiovascular disease, which seems counter intuitive given that cardiovascular disease encompasses all the diseases of the heart and circulation, including coronary heart disease and stroke along with heart failure and congenital heart disease (ERCD 2014).
- Evrard et al. (2015) studied mortality rates for 1.9 million residents living in 161 communes near three major French airports (Paris-Charles de Gaulle, Lyon Saint-Exupéry, and Toulouse-Blagnac) for the period 2007 to 2010. Noise levels in the communes ranged from 42 to 64 dB L_{den} (European standard for day–evening–night noise level similar to DNL). Lung cancer mortality at the commune level was used as a proxy measure for smoking because data on individual smoking or smoking prevalence were not available. Noise exposure was expressed in terms of a population weighted level for each commune. After adjustment for concentration of nitrogen dioxide (NO_2), Risk Ratios (similar to Odds Ratios) per 10 dB increase in noise were found to be 1.18 for mortality from cardiovascular disease, 1.23 for mortality from coronary heart disease, and 1.31 for mortality from myocardial infarction. There was no association between mortality from stroke and aircraft noise. As the author notes, results at the commune level may not be applicable to the individual level.
- Schmidt et al. (2015) studied nighttime aircraft noise effects on endothelial function and found flow-mediated dilation was significantly reduced (from 9.6 ± 4.3 to 7.9 ± 3.7 %; $p < 0.001$) and systolic blood pressure was increased (from 129.5 ± 16.5 to 133.6 ± 17.9 mmHg; $p = 0.030$) by nighttime aircraft noise.
- Seidler et al. (2016a and 2016b) found a statistically significant linear exposure-risk relationship with heart failure or hypertensive heart disease for aircraft traffic noise (1.6% risk increase per 10 dB increase in the 24-h continuous noise level; 95% CI 0.3–3.0%), road traffic noise (2.4% per 10 dB; 95% CI 1.6–3.2%), and railway noise (3.1% per 10 dB; 95% CI 2.2–4.1%). For individuals with 24-h continuous aircraft noise levels <40 dB and nightly maximum aircraft noise levels exceeding 50 dB six or more times, a significantly increased risk was observed. In general, risks of hypertensive heart disease were considerably higher than the risks of heart failure.
- Eriksson et al. 2007 found that for subjects exposed to energy-averaged levels above 50 dB(A) the adjusted relative risk for hypertension was 1.19 (95% CI = 1.03-1.37). Maximum aircraft noise levels presented similar results, with a relative risk of 1.20 (1.03-1.40) for those exposed above 70 dB(A). Stronger associations were suggested among older subjects, those with a normal glucose tolerance, nonsmokers, and subjects not annoyed by noise from other sources. Study comprised a cohort of 2754 men in 4 municipalities around Stockholm Arlanda airport was followed between 1992-1994 and 2002-2004.
- Matsui et al. (2008) reported higher OR for noise levels greater than L_{den} 70 dB, but not altogether statistically significant, for hypertension from the effects of military aircraft noise at Kadena Air Base in Okinawa. The study was conducted in 1995-1996 but used older noise data that was not necessarily appropriate for the same time period.
- A study of Noise-Related Annoyance, Cognition and Health (NORAH) designed to identify transportation noise effects in communities around German airports has reported results of self-monitoring of blood pressure of approximately 2,000 residents near Frankfurt airport exposed to aircraft Leq(24) in the range of 40 to 65 dB over the period 2012 to 2014 after the opening of a new runway (Schreckenberg 2015). The results showed small positive effects of noise on blood pressure without statistical significance. No statistically significant effect was determined between aircraft noise and hypertension as defined by WHO.

The NORAH study also included an examination of the effect of aircraft noise on cardiovascular disease (heart attack and stroke) based on examination of health insurance data between 2006 and 2010 for approximately 1 million people over the age of 40 exposed to aircraft $L_{eq(24)}$ in the range of 40 to 65 dB. A questionnaire was used to obtain information on confounding factors. The results showed non-statistically significant increase in risk for heart attack and stroke, and there was no apparent linear relationship between noise level and either effect. There was however a marginally significant but small increase in risk for heart failure (OR of 1.016). The risk of cardiovascular disease was found to be greater for road and rail noise than for aircraft noise.

The risk for unipolar depression was found to increase with exposure to aircraft noise (OR of 1.09), but the relationship was not linear - the risk decreasing at the higher noise levels, so this result was not considered reliable.

- A study investigating effects of aircraft noise on sleep disturbance among residences near a civilian airport in Seoul Korea found higher rates of insomnia and daytime hypersomnia in residents exposed to aircraft noise. The study utilized WECPNL data provided by the Seoul Regional Aviation Administration from five years earlier than the time of the questionnaires rather than direct noise measurements.
- A study of the effect of aircraft noise around a large international airport, Schiphol airport near Amsterdam, found an association between the use of non-prescribed sleep medication or sedatives with aircraft noise during the late evening (10-11 p.m.). However, the correlation between L_{den} and L_{eq}(10-11 p.m.) to sleep aids (OR 1.25 and 1.26, respectively) were not statistically significant (Franssen et al. 2004).

In many of the studies reported above the researchers use the word “significant” to describe a relationship between noise and health, conjuring up the idea that the relationship is strong and that the effect is large. But this is an inappropriate and misleading use of the word in statistical analysis. What the researchers really mean is that the relationship is “statistically significant” in that they are sure that it is real. It does not mean that the effect is large or important, or that it has any decision-making utility. A relationship can be statistically significant, i.e., real, while being weak, or small and insignificant.

In decision-making one would hardly rely on the results of a single study. Rather, one would like to see consistent results among studies and derive effect estimates from the different studies for a quantitative risk assessment (Babisch 2013). This has led to meta-analyses of the pooled results from field studies.

- Babisch and Kamp (2009) and Babisch (2013). The focus in this meta-analysis is on epidemiological studies or surveys directly related to associations between aircraft noise and cardiovascular disease (CVD) outcomes. Considering studies at 10 airports covering over 45,000 people, the pooled effect estimate of the relative risk for hypertension was 1.13 per 10 dB(A) and only marginally significant (WHO 2011). One of the studies included in the analysis was for military aircraft noise at Okinawa (see Matsui et al. 2008) for which the OR was 1.27 but not statistically significant. The authors conclude that “No single, generalized and empirically supported exposure-response relationship can be established yet for the association between aircraft noise and cardiovascular risk due to methodological differences between studies.” The pooled results show different slopes from different studies with different noise level ranges and methods being used.
- Huang et al. (2015) examined four research studies comprising a total of 16,784 residents. The overall OR for hypertension in residents with aircraft noise exposure was 1.36 for men and

statistically significant, and 1.31 and not statistically significant for women. No account was taken for any confounding factors. The meta-analysis suggests that aircraft noise could contribute to the prevalence of hypertension, but the evidence for a relationship between aircraft noise exposure and hypertension is still inconclusive because of limitations in study populations, exposure characterization, and adjustment for important confounders.

The four studies in Huang's analysis include one by Black et al. (2007) that purports to show relatively high OR values for self-reported hypertension, but these results only applied to a select subset of those surveyed that reported high noise stress. When this data set is excluded, Huang's meta-analysis yields results similar to those obtained in the HYENA and NORAH studies. Furthermore, the longitudinal study included in the analysis that followed 4721 people for 8 years (Eriksson et al. 2010) reported an OR of 1.02 that was not statistically significant.

- A review of published studies on incident cases of ischemic heart disease (IHD) was transformed into risk estimates per 10 dB increase in exposure by Vienneau et al. (2013). Pooled relative risk for IHD was 1.06 (1.03-1.09) per 10 dB increase in noise exposure with the linear exposure-response starting at 50 dB.
- Passchier-Vermeer reviewed studies on noise exposure and health effects and found sufficient evidence to support observation thresholds for hearing impairment, hypertension, IHD, annoyance, performance, and sleep disturbance due to noise exposure (Passchier-Vermeer 2020).

The connection from annoyance to stress to health issues requires careful experimental design because of the large number of confounding issues, such as heredity, medical history, smoking, diet, lack of exercise, air pollution, etc. Some highly publicized reports on health effects have, in fact, been rooted in poor science. Meecham and Shaw (1979) apparently found a relation between noise levels and mortality rates in neighborhoods under the approach path to Los Angeles International Airport. When the same data were analyzed by others (Frerichs et al. 1980) no relationship was found. Jones and Tauscher (1978) found a high rate of birth defects for the same neighborhood. But when the Centers for Disease Control performed a more thorough study near Atlanta's Hartsfield International Airport, no relationships were found for DNL greater than 65 dB (Edmonds et al. 1979).

The following additional studies have been conducted to further investigate the potential association between environmental noise exposure and health effects:

- Rhee et al. 2008 found that subjects exposed to helicopter noise had a significantly higher prevalence of hypertension than the unexposed control group. Although a source-specific difference in the risk of cardiovascular disease by environmental noise exposure is suggested, no other study has evaluated whether or not exposure to noise from helicopters differs from exposure to that from fighter jets in their influence on the prevalence of hypertension.
- Hwang et al. 2012 conducted a 20-year prospective cohort study of 1301 aviation workers in Taiwan to follow AGT genotypes (TT, TM and MM) across four exposure categories according to the levels of noise representing high (>80 dBA), medium (80-65 dBA), low exposure (64-50 dBA) and the reference level (49-40 dBA). AGT (TT vs. MM adjusted incidence rate ratio (IRR) 1.77, 95% CI 1.24 to 2.51) and noise exposure (high and medium combined) during 3-15 years (adjusted IRR 2.35, 95% CI 1.42 to 3.88) were independent determinants of hypertension. Furthermore, the risk of hypertension increased with noise exposure (adjusted IRR 3.73, 95% CI 1.84 to 7.56) among TT homozygotes but not among those with at least one M allele (Rothman synergy index=1.05).

- Siedler et al. 2016 studied myocardial infarction risk due to aircraft, rail, and road noise by investigating patients of the Rhine-Main region of Germany who were diagnosed with myocardial infarction in the years 2006-2010. The linear model revealed a statistically significant risk increase due to road noise (2.8% per 10 dB rise, 95% confidence interval [1.2; 4.5]) and railroad noise (2.3% per 10 dB rise [0.5; 4.2]), but not airplane noise. Airplane noise levels of 60 dB and above were associated with a higher risk of myocardial infarction (OR 1.42 [0.62; 3.25]). This higher risk is statistically significant if the analysis is restricted to patients who had died of myocardial infarction by 2014/2015 (OR 2.70 [1.08; 6.74]). In this subgroup, the risk estimators for all three types of traffic noise were of comparable magnitude (3.2% to 3.9% per 10 dB rise in noise level).
- Floud et al. 2011 examined the health effects of aircraft and road traffic noise exposure and the association with medication use. The cross-sectional study measured the use of prescribed antihypertensives, antacids, anxiolytics, hypnotics, antidepressants and antasthmatics in 4,861 persons living near seven airports in six European countries. Differences were found between countries in the effect of aircraft noise on antihypertensive use; for nighttime aircraft noise, a 10 dB increase in exposure was associated with ORs of 1.34 (95% CI 1.14 to 1.57) for the UK and 1.19 (1.02 to 1.38) for the Netherlands but no significant associations were found for other countries. For daytime aircraft noise, excess risks were found for the UK (OR 1.35; CI: 1.13 to 1.60) but a risk deficit for Italy (OR 0.82; CI: 0.71 to 0.96). There was an excess risk of taking anxiolytic medication in relation to aircraft noise (OR 1.28; CI: 1.04 to 1.57 for daytime and OR 1.27; CI: 1.01 to 1.59 for nighttime), which held across countries. The authors also found an association between exposure to 24-hour road traffic noise and the use of antacids by men (OR 1.39; CI 1.11 to 1.74).
- Haralabidis et al. 2011 studied the association between exposure to transportation noise and blood pressure reduction during nighttime sleep utilizing 24-hour ambulatory blood pressure measurements at 15-minute intervals carried out on 149 persons living near four major European airports. Although road traffic noise exposure was found to decrease blood pressure dipping in diastolic blood pressure, no associated decrease in dipping was found for aircraft noise.

Moreover, the public's understanding of the possible effects of aircraft noise has been hindered by the publication of overly sensational and misleading articles in the popular press, such as "Death by Aircraft Noise is a Real Concern for People Living Under the Flight Path" (Deutsche Welle 2013). Similarly, statements by reputed scientists have proved less than useful in the debate on the effects of aircraft noise on health ("It's quite clear that living near an airport is very dangerous for your health," says Eberhard Greiser, an emeritus professor of epidemiology at Bremen University. "Jet noise is more dangerous than any other kind of road traffic noise or rail noise because it is especially acute and sharp and it induces stress hormones") (Time 2009). Such conclusions have been firmly criticized by other German researchers as lacking in rigor by not considering other known factors that cause health problems, and for analyzing only a selection of the available data (ANR 2010).

D.3.5.1 Summary

Research studies seem to indicate that aircraft noise may contribute to the risk of health disorders, along with other factors such as heredity, medical history, smoking, alcohol use, diet, lack of exercise, air pollution, etc., but that the measured effect is small compared to these other factors, and often not statistically significant, i.e., not necessarily real. Despite some sensational articles purporting otherwise, and the intuitive feeling that noise in some way must impair health, there are no studies that definitively show a causal and significant relationship between aircraft noise and health. Such studies are notoriously difficult to conduct and interpret because of the large number of confounding factors that have to be considered for their effects to be excluded from the analysis. The WHO notes that there is still considerable variation among studies (WHO 2011). And, almost without exception, research studies conclude that additional research is needed to determine if such a causal relationship exists. The European Network on Noise and Health (ENNAH 2013) in its summary report of 2013 concludes that "…..while the literature on non-auditory health effects of environmental noise is extensive, the scientific evidence of the relationship between noise and non-auditory effects is still contradictory."

As a result, it is not possible to state that there is sound scientific evidence that aircraft noise is a significant contributor to health disorders.

D.3.6 Performance Effects

The effect of noise on the performance of activities or tasks has been the subject of many studies. Some of these studies have found links between continuous high noise levels and performance loss. Noise-induced performance losses are most frequently reported in studies where noise levels are above 85 dB. Moderate noise levels appear to act as a stressor for more sensitive individuals performing a difficult psychomotor task. Little change has typically been found in low-noise cases, however, cognitive learning differences were measured in subjects exposed to noise of passing aircraft with peak amplitudes of 48 dBA, presented once per minute, while performing text learning compared to a control group exposed to 35 dBA (Trimmel 2012). The findings suggest that background noise below 50 dBA, results in impaired and changed structures of learning, as indicated by reproduction scores because test persons are less able to switch between strategies.

While the results of research on the general effect of periodic aircraft noise on performance have yet to yield definitive criteria, several general trends have been noted including:

- A periodic intermittent noise is more likely to disrupt performance than a steady-state continuous noise of the same level. Flyover noise, due to its intermittent nature, might be more likely to disrupt performance than a steady-state noise of equal level.
- Noise is more inclined to affect the quality than the quantity of work.
- Noise is more likely to impair the performance of tasks that place extreme demands on workers.

D.3.7 Noise Effects on Children

Recent studies on school children indicate a potential link between aircraft noise and both reading comprehension and learning motivation. The effects may be small but may be of particular concern for children who are already scholastically challenged.

D.3.7.1 Effects on Learning and Cognitive Abilities

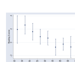
Early studies in several countries (Cohen et al. 1973, 1980, 1981b; Bronzaft and McCarthy 1975; Green et al. 1982; Evans et al. 1998; Haines et al. 2002; Lercher et al. 2003) showed lower reading scores for children living or attending school in noisy areas than for children away from those areas. In some studies noise-exposed children were less likely to solve difficult puzzles or more likely to give up.

A longitudinal study reported by Evans et al. (1998) conducted prior to relocation of the old Munich airport in 1992, reported that high noise exposure was associated with deficits in long-term memory and reading comprehension in children with a mean age of 10.8 years. Two years after the closure of the airport, these deficits disappeared, indicating that noise effects on cognition may be reversible if exposure to the noise ceases. Most convincing was the finding that deficits in memory and reading comprehension developed over the two year follow-up for children who became newly noise exposed near the new airport: deficits were also observed in speech perception for the newly noise-exposed children.

More recently, the Road Traffic and Aircraft Noise Exposure and Children's Cognition and Health (RANCH) study (Stansfeld et al. 2005; Clark et al. 2005) compared the effect of aircraft and road traffic noise on more than 2,000 children in three countries. This was the first study to derive exposure-effect associations for a range of cognitive and health effects, and was the first to compare effects across countries.

The study found a linear relation between chronic aircraft noise exposure and impaired reading comprehension and recognition memory. No associations were found between chronic road traffic noise exposure and cognition. Conceptual recall and information recall surprisingly showed better performance in high road traffic noise areas. Neither aircraft noise nor road traffic noise affected attention or working memory (Stansfeld et al. 2005; Clark et al. 2005).

Figure D-12 shows RANCH's result relating noise to reading comprehension. It shows that reading falls below average (a z-score of 0) at L_{eq} greater than 55 dB. Because the relationship is linear, reducing exposure at any level should lead to improvements in reading comprehension.



Sources: Stansfeld et al. 2005; Clark et al. 2005

Figure D-12 RANCH Study Reading Scores Varying with L_{eq}

An observation of the RANCH study was that children may be exposed to aircraft noise for many of their childhood years and the consequences of long-term noise exposure were unknown. A follow-up study of the children in the RANCH project is being analyzed to examine the long-term effects on children's reading comprehension (Clark et al. 2009). Preliminary analysis indicated a trend for reading comprehension to be poorer at 15-16 years of age for children who attended noise-exposed primary schools. An additional study utilizing the same data set (Clark et al. 2012) investigated the effects of traffic-related air pollution and found little evidence that air pollution moderated the association of noise exposure on children's cognition.

There was also a trend for reading comprehension to be poorer in aircraft-noise-exposed secondary schools. Significant differences in reading scores were found between primary school children in the two different classrooms at the same school (Bronzaft and McCarthy 1975). One classroom was exposed to high levels of railway noise while the other classroom was quiet. The mean reading age of the noise-exposed children was 3–4 months behind that of the control children. Studies suggest that the evidence of the effects of noise on children's cognition has grown stronger over recent years, (Stansfeld and Clark 2015), but further analysis adjusting for confounding factors is ongoing, and is needed to confirm these initial conclusions.

Studies identified a range of linguistic and cognitive factors to be responsible for children´s unique difficulties with speech perception in noise. Children have lower stored phonological knowledge to reconstruct degraded speech reducing the probability of successfully matching incomplete speech input when compared with adults. Additionally, young children are less able than older children and adults to make use of contextual cues to reconstruct noise-masked words presented in sentential context (Klatte and Bergstrom 2013).

FICAN funded a pilot study to assess the relationship between aircraft noise reduction and standardized test scores (Eagan et al. 2004; FICAN 2007). The study evaluated whether abrupt aircraft noise reduction within classrooms, from either airport closure or sound insulation, was associated with improvements in test scores. Data were collected in 35 public schools near three airports in Illinois and Texas. The study used several noise metrics. These were, however, all computed indoor levels, which makes it hard to compare with the outdoor levels used in most other studies.

The FICAN study found a significant association between noise reduction and a decrease in failure rates for high school students, but not middle or elementary school students. There were some weaker associations between noise reduction and an increase in failure rates for middle and elementary schools. Overall, the study found that the associations observed were similar for children with or without learning difficulties, and between verbal and math/science tests. As a pilot study, it was not expected to obtain final answers, but provided useful indications (FICAN 2007).

A recent study of the effect of aircraft noise on student learning (Sharp et al. 2013) examined student test scores at a total of 6,198 US elementary schools, 917 of which were exposed to aircraft noise at 46 airports with noise exposures exceeding 55 dB DNL. The study found small but statistically significant associations between airport noise and student mathematics and reading test scores, after taking demographic and school factors into account. Associations were also observed for ambient noise and total noise on student mathematics and reading test scores, suggesting that noise levels per se, as well as from aircraft, might play a role in student achievement. Recent evidence suggests that potential negative effects on classroom performance can be due to chronic ambient noise exposure. A study of French eight and nine year old children found a significant association between ambient noise levels in urban environments due primarily to road noise (Pujol et al. 2014). The study estimated noise levels at children's bedrooms (L_{den}) and found a modest effect of lower scores on French tests associated with higher L_{den} at children's homes. Once adjusted for classroom $L_{Aeq,day}$, the association between L_{den} and math test scores became borderline significant.

As part of the NORAH study conducted at Frankfurt airport, reading tests were conducted on 1,209 school children at 29 primary schools. It was found that there was a small decrease in reading performance that corresponded to a one-month reading delay. However, a recent study observing children at 11 schools surrounding Los Angeles International Airport found that the majority of distractions to elementary age students were other students followed by themselves, which includes playing with various items and daydreaming. Less than 1 percent of distractions were caused by traffic noise (National Academy of Sciences, Engineering, and Medicine 2017).

While there are many factors that can contribute to learning deficits in school-aged children, there is increasing awareness that chronic exposure to high aircraft noise levels may impair learning. This awareness has led WHO and a North Atlantic Treaty Organization (NATO) working group to conclude that daycare centers and schools should not be located near major sources of noise, such as highways, airports, and industrial sites (NATO 2000; WHO 1999). The awareness has also led to the classroom noise standard discussed earlier (ANSI 2002).

D.3.7.2 Health Effects on Children

A number of studies, including some of the cognitive studies discussed above, have examined the potential for effects on children's health. Health effects include annoyance, psychological health, coronary risk, stress hormones, sleep disturbance and hearing loss.

Annoyance. Chronic noise exposure causes annoyance in children (Bronzaft and McCarthy 1975; Evans et al. 1995). Annoyance among children tends to be higher than for adults, and there is little habituation (Haines et al. 2001a). The RANCH study found annoyance may play a role in how noise affects reading comprehension (Clark et al. 2005).

Psychological Health. Lercher et al. (2002) found an association between noise and teacher ratings of psychological health, but only for children with biological risk defined by low birth weight and/or premature birth. Haines et al. (2001b) found that children exposed to aircraft noise had higher levels of psychological distress and hyperactivity. Stansfeld et al. (2009) replicated the hyperactivity result, but not distress. Crombie et al. (2011) found similar hyperactivity results but found no significant associations between aircraft noise at school and later mental health issues in children at risk at birth, i.e., low birth weight.

As with studies of adults, the evidence suggests that chronic noise exposure is probably not associated with serious psychological illness, but there may be effects on well-being and quality of life. Further research is needed, particularly on whether hyperactive children are more susceptible to stressors such as aircraft noise.

Coronary Risk. The HYENA study discussed earlier indicated a possible relation between noise and hypertension in older adults. Cohen et al. (1980, 1981a) found some increase in blood pressure among school children, but within the normal range and not indicating hypertension. Hygge et al. (2002) found mixed effects. The RANCH study found some effect for children at home and at night, but not at school (van Kempen 2006). In the Munich study (Evans et al., 1998), chronic noise exposure was found to be associated with both baseline systolic blood pressure and lower reactivity of systolic blood pressure to a cognitive task presented under acute noise. After the new airport opened, a significant increase in systolic blood pressure was observed providing evidence for a causal link between chronic noise exposure and raised blood pressure. No association was found between noise and diastolic blood pressure or reactivity (Stansfeld and Crombie 2011; Stansfeld 2015).

However, the relationship between aircraft noise and blood pressure was not fully consistent between surveys in different countries. These findings, taken together with those from previous studies, suggest that no univocal conclusions can be drawn about the association between aircraft noise exposure and blood pressure. Overall, the evidence for noise effects on children's blood pressure is mixed, and less certain than for older adults.

Stress Hormones. Some studies investigated hormonal levels between groups of children exposed to aircraft noise compared to those in a control group. Two studies analyzed cortisol and urinary catecholamine levels in school children as measurements of stress response to aircraft noise (Haines et al. 2001a, 2001b, 2001c). In both instances, there were no differences between the aircraft-noise-exposed children and the control groups. Davies (2012) discusses a study in France among 10-year-old schoolchildren showed that school noise exposure was associated with higher cortisol levels indicative of a stress reaction these finding are supported by a Swedish study who found increased prevalence of reduced diurnal cortisol variability in relation with classroom L_{eq} during school day levels between 59 and 87 dBa.

Sleep Disturbance. A sub-study of RANCH in a Swedish sample used sleep logs and the monitoring of rest/activity cycles to compare the effect of road traffic noise on child and parent sleep (Öhrström et al. 2006). An exposure-response relationship was found for sleep quality and daytime sleepiness for children. While this suggests effects of noise on children's sleep disturbance, it is difficult to generalize from one study.

D.4 Noise Modeling Methodology and Assumptions

D.4.1 Existing Noise Levels

The existing Leq at representative points of interest in the vicinity of Washington Navy Yard are estimated to be either 60 to 65 dB or 65 to 70 dB based up noise measurements collected at two other sites (USDOT 2014) and prior 2017 Navy calculated traffic noise levels along two nearby streets. The assumed existing Leq were selected on the conservative side (numerically smaller numbers), which results in potentially larger reported increase due to action alternatives.

D.4.1.1 Roadway Construction Noise Model (RCNM)

The RCNM software allows the calculation of noise levels at user-entered distances from various types of construction equipment for sound propagation paths over flat ground. The first step involves identifying the potential construction equipment and their usage. RCNM contains default usage factors defined as the percentage of time during a construction noise operation that a piece of construction equipment is operating at full power and the usage factor term only affects the computation of Leq and L10. For instance, if a jackhammer is modeled to operate for 1 hour then the 20 percent usage factor would equate to 12 minutes generating the full power L_{max}. All equipment modeled in this EIS utilized the default usage factors.

The next step requires determining the distances between proposed construction sites to the nearest noise-sensitive receptors and the ground type under each primary sound propagation path (i.e., over land, over water, or a combination of both). All paths are over land except the path to Anacostia Park (REC-3 on EIS Table 3.7-2 and Figure 3.7-2). Although either vibratory or impact pile driving equipment could be utilized, this analysis considers the greater noise level of the impact pile driving noise source of 101.3 dB L_{max} measured at 50 feet (15 meters) for noise analysis. Impact pile driving would represent the greatest noise source levels of the proposed action. The RCNM software does not include the ability to directly calculate noise levels propagated over water; therefore, an adjustment, as described in ISO 9613-2, was required to account for the decreased attenuation over water, amounting to sound levels 6 dB greater for propagation completely over water and 3 dB greater for the combination of part water and part land propagation paths when compared with all over land.

RCNM provides noise outputs for L_{max} and L_{eq} where Lmax is determined by the LmaxCalc term in equation (1) and Leq by equation (2):

LmaxCalc = selected_Lmax – 20log(D/50) - shielding (1)

> Where selected_Lmax is the "Spec" or "Actual" maximum A-weighted sound level at 50 ft., listed the RCNM manual for all pieces of equipment, in dBA; D is the distance between the equipment and the receptor, in feet; and shielding is the insertion loss of any barriers or mitigation, in dBA.

Shielding loss due buildings, terrain, or any barriers was set to 0 dBA. Because obstructions present in the vicinity of Washington Navy Yard were considered in this analysis the resulting noise levels presented for noise-sensitive receptors could be overstated.

Leq = LmaxCalc + 10log(U.F.%/100) (2)

> Where U.F.% is the time-averaging equipment usage factor, in percent

Because construction activity is assumed to only occur during the DNL daytime period (7 a.m. to 10 p.m.) the use of a cumulative metric, such as DNL, would not be necessary or appropriate.

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