Noise Levels Research Synthesis

Review and Updates to Findings in *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*

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This document synthesizes findings from major publications on the adverse effects of noise and sound levels to protect public health and welfare, and compares those findings to *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety* (published in 1974 by the Environmental Protection Agency). While hearing loss and speech interference were well understood in 1974, substantial research has been conducted over the past 45 years that improves understanding of how noise adversely affects annoyance, sleep, health, cognition, and housing cost. Knowledge gaps and research recommendations are provided for each of the topics reported.

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Executive Summary

This document synthesizes findings from major publications on the adverse effects of noise and sound levels to protect public health and welfare, and compares those findings to *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety* (published in 1974 by the Environmental Protection Agency and herein called the Levels Document). The primary goal of this work was to identify research that confirms, modifies, replaces, or fills in gaps in the Levels Document.

ANALYSIS OF ADVERSE EFFECTS

The table on the next page summarizes research findings in the Levels Document and recent research on adverse effects to noise from typical sources such as aviation, highway, and rail.

Hearing loss and activity interference (specifically speech interference) were the best-understood adverse effects of noise when the Levels Document was published. Little new research has been performed in those areas since 1974.

The Levels Document associated the noise levels provided for hearing loss or activity interference to other adverse effects of noise such as annoyance, sleep, health, and cognition. Substantial research has been conducted over the past 45 years that improves understanding of each of these adverse effects. In addition, this report includes findings on the financial impacts of noise on property values, which was not addressed in the Levels Document.

ANALYSIS OF SPECIAL NOISE SOURCES

This report includes an overview of impulse and stationary noise sources in a separate section, as they tend to have different noise characteristics than typical transportation noise sources.

The effect of impulse noise on hearing was well understood in the Levels Document and remains relevant today. Studies on annoyance to impulse noise from non-aircraft sources are limited. There is renewed interest in research on annoyance from supersonic aircraft, including developing aircraft designs that reduce sonic boom overpressures, as well as assessing community response.

Stationary sources described in this report include quarries, rail yards, industrial sites and temporary construction, wind turbines, and commercial space launch sites. The noise characteristics within and among these sites vary substantially in noise levels, sound quality, times of operation, and locations. The most effective method for reducing impacts of noise in communities surrounding stationary noise sources is effective land use planning.

Summary of Noise Levels Research Findings for Adverse Effects to Noise

	Effect	Levels Document	Levels Document Key Assumptions	Recent Research
Noise Effects Best Understood in Levels Document (1974)	Hearing Loss	$L_{Aeq(24)} \leq 70$ dB all areas	Protects nearly the entire population from hearing loss from 40 years of continuous exposure	Little new research on noise induced hearing loss. Occupational noise standards use different assumptions
	Activity interference	Residential Areas: $L_{dn} \leq 45$ dB indoors $L_{dn} \leq 55$ dB outdoors	Protects 95-100% speech intelligibility, with a margin of safety	Protective noise levels likely have not changed
Noise Effects Not Well Quantified when Levels Document was Published	Annoyance	Residential Areas: $L_{dn} \leq 45$ dB indoors $L_{dn} \leq 55$ dB outdoors	Assumed protection against speech interference protected against annoyance; Insufficient annoyance evidence	Percent highly annoyed can range from 10% to 70% at the same noise exposure level
	Sleep Impacts	$L_{dn} \leq 45$ dB indoors $L_{dn} \leq 55$ dB outdoors	Maintaining $L_{dn} \leq 55$ dB outdoors will provide $L_{dn} \leq 40$ dB indoors; nighttime portion of L_{dn} will be approximately 32 dB, which should protect against sleep interference in most cases	Across transportation noise sources, higher levels of noise associated with increased likelihood of being awakened and higher self-reported sleep disturbance.
	Health Effects	$L_{Aeq(24)} \leq 70$ dB all areas	Assumed protection against hearing loss protected against other health effects.	Noise levels lower than those necessary to cause hearing loss can lead to other negative health outcomes
	Cognitive Effects	$L_{Aeq(24)} \leq 45$ dB indoors $L_{Aeq(24)} \leq 55$ dB outdoors	Assumed protection against speech interference was the key consideration in educational areas	Increase in noise is associated with short and long-term memory issues, reduced reading comprehension, and lower test scores
	Financial Impacts	Not Addressed	Not Applicable	Increase in noise is associated with a decrease in property values; magnitude is inconclusive

Gap Analysis and Recommendations

Although many of the adverse effects to noise and special noise sources have been studied, consistent, conclusive results have not been obtained and questions remain. Recommendations for future research are listed below.

- Conduct longitudinal studies to improve understanding of the effects of cumulative noise exposure on **human hearing**.
- Improve understanding of the relationship between **activity interference** and annoyance, as interference with certain activities may cause more annoyance than other activities.
- Account for confounding factors in quantifying percent highly annoyed. Despite the wealth of **annoyance** survey data available, there are large discrepancies in correlations derived from different data sets. Study distributions of confounding variables to understand their overall effect. Develop systematic corrections for non-acoustic factors in order to reduce variance in study data, e.g., selection of study questions, rating scales of annoyance, and other study design elements should be repeated across studies.
- Assess **noise metrics** used to describe annoyance, sleep impacts, and health to capture the qualities of sound that most appropriately relate to the adverse effects.
- Understand and use new types of large-scale data collection to assess **sleep impacts**, such as actigraphy to measure sleep based on wrist movements.
- Substantiate the relationship between noise exposure and **health outcomes** through consistent, repeatable studies. Consider how the relationship between noise exposure and health may change across different demographic subgroups (e.g., age and socioeconomic status).
- Determine the relative impacts of different **interventions**. Encourage interventions that have a greater benefit for the same amount of noise reduction.
- Study how road, rail, and other noise sources affect **cognition** in both home and school environments.
- Account for differences in study factors (e.g., geography, housing types, and noise sources) to understand how much noise affects **property values**. Seek opportunities to study the financial impacts of noise before and after a change in noise exposure (i.e., natural experiment method).
- Conduct more repeatable studies on **annoyance to non-aircraft impulse noise** in order to improve understanding of the exposure-response relationship.
- Continue to build knowledge on **supersonic aircraft noise**.
- Support effective **land use planning** techniques.
- Build understanding on the possible effects of noise from **wind turbines** on humans.
- Continue to study and refine models and methods to assess noise and community impacts from **commercial space launches**.

Glossary of Terms

Ambient Noise/Sound

The noise level in an environment or an area from all sources. This can include nearby transportation sources, utilities in or outside of buildings, fans, music, and other sources.

Amplitude

The pressure differential between the peak pressure of a sound wave and the atmospheric pressure.

Amplitude Modulated Noise

A type of steady state noise in which the overall amplitude rises and falls in a regular, periodic pattern. This type of noise can be heard near wind turbines, where the sound of the vibrations of the blades gets louder and softer periodically as the turbine rotates.

A-weighting

Frequency-dependent weighting filter that is used to correct measured or calculated sound to approximate the human hearing system's sensitivity to different frequencies when the unweighted sound pressure level is approximately 40 dB.

Beta Coefficient Analysis

A type of statistical regression analysis used in situations that have multiple independent variables and a single dependent variable. The analysis is used to compare the relative strength of the effect of each independent variable considered in the analysis. The analysis computes a value of a beta coefficient for each independent variable. The higher the absolute value of an independent variable's beta coefficient, the stronger the effect of that independent variable.

Broadband Noise

Sound that has energy present over a wide range of frequencies.

C-weighting

Frequency-dependent weighting system that is used to correct measured or calculated sound to approximate the human hearing system's sensitivity to different frequencies when the unweighted sound pressure level is approximately 100 dB. C-weighting does not modify lower frequencies as much as A-weighting and is therefore sometimes used when the sound has substantial low frequency content.

Continuous Noise

Noise with negligibly small fluctuations of sound pressure level (SPL) within a specified period of observation.

Dose

The amount of actual noise exposure to which a person is subjected. This term is often used in the context of dose-response relationships and can be measured using various metrics.

Equal-Energy Principal/Hypothesis

The assumption that equal amounts of total sound energy will cause the same amount of harm to human recipients of that sound level, regardless of time duration, intermittency, or other qualities of the sound. That is, if a person is exposed to two different sounds with one being louder but having a shorter duration than the other, but both having the same total sound energy, the two will have the same overall effect.

Exposure-Response or Dose-Response

A measurable relationship describing an effect of noise on humans. The relationships input must be the noise level measured using a standard metric. The response can be any effect of noise on humans, including any of the adverse effects described in this report.

Fast Response

A time weighting that is used to integrate continuous measurements to reduce the temporal variation. A fast response applies an exponential window to the incoming data with a time constant of τ = 125 milliseconds. The output of this time weighting can still be a continuous signal (if applied using analog circuitry). Other time weightings include impulse (τ = 35 ms) and slow (τ =1 s). Of these three, the fast time weighting most closely approximates the human auditory systems time integration. Fast response noise measurements are usually notated in noise metric abbreviations with a subscripted "F," for example, L_{AFmax}.

Frequency

The physical characteristic that describes the number of repetitions per second of a sound in units of Hertz (Hz).

L_{dn}

Day-night average sound level. Calculated by averaging sound levels throughout a 24-hour period, with a 10 dB penalty added to nighttime noise levels. A-weighted metric. Also depicted as DNL.

L_{day}

The average, A-weighted sound level, with no penalties added, during daytime hours. Usually between 7 am and 10 pm.

L_{night}

The average, A-weighted sound level, with no penalties added, during nighttime hours. Usually between 10 pm and 7 am.

$L_{evening}$

The average, A-weighted sound level, with no penalties added, during evening hours. Usually between 7 pm and 10 pm.

$L_{Aeq(T)}$

Equivalent Continuous Sound Level. The average, A-weighted sound level over the time T. This value is equivalent to the continuous constant sound level that has the same total energy as the measured sound over the same defined period. Usually, the time T is 1 hour, 8 hours, 16 hours, 24 hours, or another period that is relevant to daily human activities.

L_{max}

Maximum sound level. The maximum time-weighted sound pressure level within a specified time response using, e.g. slow or fast response time.

L_{den}

Community Noise Level or Day-Evening Night Sound Level. 24-hour average sound level with 5 dB penalty applied for evening hours (7 pm to 10 pm), and 10 dB penalty applied to nighttime hours (10 pm to 7 am), with no penalty applied to daytime sound levels. Calculated similarly to L_{dn} or DNL. L_{den} is the metric used in California.

L_{peak}

The peak sound pressure measured within a specified time interval.

Noise-induced Permanent Threshold Shift (NIPTS)

Permanent damage to hearing from noise, most often due to damage of the hair cells inside the cochlea that translate acoustic vibrations into electrical signals transmitted by auditory nerves. Caused by over-exposure to noise, and in turn over-excitation of these hair cells. Permanent threshold shift is a medical condition with multiple negative impacts.

Noise-induced Temporary Threshold Shift (TTS)

TTS is a change in hearing threshold that recovers to pre-exposure levels (baseline) over time. The amount of time to recover to baseline may be relatively fast (minutes to hours) or slow (days to weeks). The TTS hypothesis suggests that TTS measured 2 minutes after 8-hour exposure to a certain level of noise is similar to the NIPTS caused after 10 to 20 years of exposure to the same level of noise.

Pitch

The perceived quality of a sound as it relates to high or low frequencies. In other words, the degree of highness or lowness of a tone.

Slow Response

A time weighting that is used to integrate continuous measurements to reduce the temporal variation. A slow response applies an exponential window to the incoming data with a time constant of $\tau = 1$ second. The output of this time weighting can still be a continuous signal (if applied using analog circuitry). Other time weightings include impulse ($\tau = 35$ ms) and fast ($\tau = 35$ ms). The historical purpose for using a slow time weighting was to slow the needle on analog meters down enough to be read by the technician. Of the three weightings mentioned, the slow time weighting will also produce the lowest sound level results. Slow response noise measurements are usually notated in noise metric abbreviations with a subscripted “S,” for example, L_{ASmax}.

Sound Exposure Level (SEL)

The sound level that has the same total sound energy in one second as a measured sound over a certain period. This is often used when measuring or describing single airplane flyovers or vehicle pass-bys because these events have easily definable start and end times. In these cases, the sound exposure level describes the total sound energy in a noise-generating event normalized to 1 second of time.

Sound Pressure Level (SPL)

The basic measure of sound as it relates to the reference sound pressure. Measured in decibels, it is calculated as 20 times the base 10 logarithm of the ratio of the sound pressure to the reference sound pressure of 20 micropascals.

Spectrum

A description of the multiple frequency components and their respective amplitudes that additively make up a full sound wave.

Tone

In contrast to broadband noise, a sound that has energy content at only discrete frequencies. Pure tones have a single component, complex tones have several components, often with frequencies at integer multiples of the lowest component’s frequency.

Wavelength

The physical distance between two peaks in a sound wave. Wavelength is equal to the speed of sound divided by the frequency of the sound. For example at standard atmospheric conditions, the speed of sound is approximately 1,125 ft/s. Thus, the sound of a pure tone at 1000 Hz would have a wavelength of 1.125 ft.

1 Introduction

The Environmental Protection Agency (EPA) *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety* (published in 1974 and herein called the Levels Document) and companion works also published in the 1970s (see next section) is foundational for the federal government's noise policies. The Levels Document considered multiple noise metrics, sources, adverse effects, and levels to protect public health and welfare.

This document synthesizes findings from major publications on noise and its impacts to public health and welfare on selected subject matter. The primary goal of the current research documented herein was to understand which elements of the Levels Document are still applicable today. Specifically, the Volpe Center identified research that either confirms, modifies, or replaces findings in the original document, or identified research that fills in gaps that were not included in the original document.

1.1 Background on the Levels Document

The Noise Control Act of 1972 established two related requirements to publish scientific information about the health and welfare effects of noise. In 1973, EPA published *Public Health and Welfare Criteria for Noise*. In 1974, EPA published the Levels Document. In 1978, EPA published a companion, *Protective Noise Levels: Condensed Version of EPA Levels Document*, which was intended to clarify the original 242-page document in a less technical, 25-page summary focused on the best-understood effects of noise on people.

The Levels Document provided information on the:

- maximum noise exposure levels to avoid significant adverse effects to hearing and activity interference,[1] which were well understood at the time of study,
- effects of special types of noises that were not as well understood at the time of the study, including infrasound, ultrasound, and impulse noise such as sonic boom,
- measurement of environmental noise exposure and "protective" levels of environmental noise in defined areas (i.e., indoor and outdoor land uses) that are requisite to protect the public health and welfare with an adequate margin of safety in terms of hearing loss and activity interference.

A summary of noise levels identified by the EPA as requisite to protect public health and welfare with an adequate margin of safety is provided in the Levels Document and presented below.

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[1] The Levels Document described activity interference and annoyance in the same section, as interference affects annoyance. However, the document also notes that annoyance due to other factors (background level, state of the human auditor, etc.) is complex and focus of "levels" was placed more on speech interference as a cause of annoyance than these other factors.

Table 1 Summary of Noise Levels Identified as Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety in 1974 Levels Document

Effect	**Level***	**Area**
Hearing Loss	$L_{Aeq(24)} \leq 70$ dB	All areas
Outdoor activity interference and annoyance	$L_{dn} \leq 55$ dB	Outdoors in residential areas and farms and other outdoor areas where people spend widely varying amounts of time and other places in which quiet is a basis for use.
	$L_{Aeq(24)} \leq 55$ dB	Outdoor areas where people spend limited amounts of time, such as school yards, playgrounds, etc.
Indoor activity interference and annoyance	$L_{dn} \leq 45$ dB	Indoor residential areas
	$L_{Aeq(24)} \leq 45$ dB	Other indoor areas with human activities such as schools, etc.

* Note: The Levels Document uses the notation L_{eq} for long-term equivalent A-weighted sound level. This table uses the notation L_{Aeq} instead of L_{eq} to clarify the use of A-weighting.

Protective levels were not intended to be noise limit criteria; rather they were intended to be a basis for setting standards along with other relevant factors including technical feasibility and economic reasonableness. The 1978 Condensed Version of the EPA Levels Document clarified, “they must not be viewed as standards, criteria, regulations, or goals. Rather, they should be viewed as levels below which there is no reason to suspect that the general population will be at risk from any of the identified effects of noise.”

1.2 Introduction to Noise

Noise is defined broadly as unwanted or undesirable sound. Sound is vibration in a fluid medium, usually air. When scientists study this phenomenon in humans, they usually refer specifically to vibrations with frequencies between 20 Hz and 20,000 Hz (or 20 kilohertz), the frequency range that can be heard by humans. Whether a sound is categorized as noise or not is subjective and depends on the listener and the context. Sound generally becomes unwanted because it produces a negative psychological or physiological response in humans. Usually these sounds are byproducts of human activities that are heard and experienced by uninvolved surrounding populations.

Noise is most easily analyzed within the “source, path, receiver” framework, illustrated in Figure 1. This framework asks the following three questions:

1) How is the sound produced?

   This is the **SOURCE** of the sound, and can be transportation noise like from a highway or a moving train or plane. Other sound sources are stationary like factories or quarries. The source of the sound also determines the physical properties of the sound that eventually influence how it affects the receiver.

2) How does the sound travel from the source to the receiver?

   This is the **PATH** of the sound. The path may be completely unobstructed through the air. Often, there are solid objects the sound reaches before reaching the receiver. This can be an earthen hill, a sound barrier, or the wall of a home. Sound can travel through some of these barriers. Windows are a good example that attenuate the sound somewhat, but still allow some sound waves to travel to the interior of a home. In other cases, the sound may travel around these obstacles. The ability to travel through or around the obstacles depends on the properties of the sound and the properties of the obstacle, e.g., how large and heavy it is.

3) Who or what experiences the sound?

   This is the **RECEIVER** of the sound. This includes the human who can hear the sound and the auditory system that allows them to hear it. Sometimes, the entire structure, like the residence, workplace, or school building, is used as an ersatz receiver of the sound.

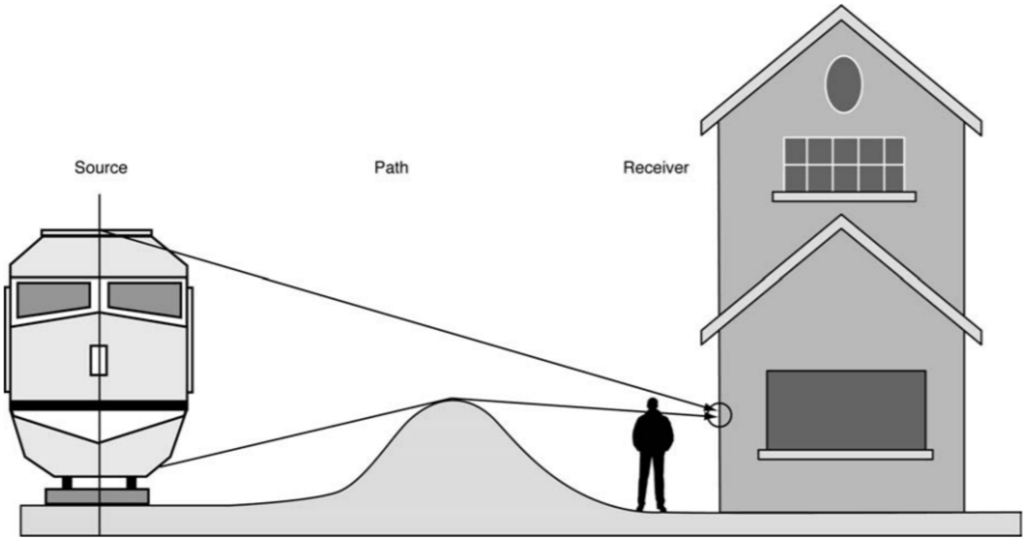

Figure 1 Source-Path-Receiver Framework (Source: FTA Noise and Vibration Impact Assessment Manual)

Sound can be studied separately at each of these three physical locations. Attenuation techniques are different in each case, and the sound itself may have different characteristics at the source, over the path, and at the receiver. It is important to understand how the: 1) sound is created and its properties at the point of creation; 2) sound may be reflected or absorbed while traversing the path; and 3) receiver reacts to the resulting sound.

1.2.1 Physical Properties of Noise at the Sound Source

Sound is a variation in the pressure of the air from normal atmospheric pressure. The variations are usually produced by the physical vibration of a solid object. The vibration of an object moves the air particles surrounding that object back and forth. The air around the object thus alternates between high and low pressure relative to atmospheric pressure. This alternating pattern propagates as a pressure wave through the air, and can travel far distances if it is not attenuated or reflected by another solid object. At normal atmospheric temperature and pressure, sound travels at a constant speed just over 1,000 feet per second.

Two important numerical values are used to describe the physical properties of the sound pressure wave. The first is **amplitude**. The amplitude of the wave is the size of the difference between the maximum pressure of the air in the sound wave and the regular atmospheric pressure of the air without a sound wave traveling through it. The larger the pressure variations, the larger the amplitude, and the louder it will be when experienced by the receiver. Amplitude can be described simply using the pressure metric Pascals. The human hearing system cannot detect pressure variations smaller than 20 micropascals. Therefore, sound waves below this absolute amplitude cannot be heard by humans. Additionally, the range of the amplitude of commonly occurring sound waves in nature and human society is very large; the loudest of these common sounds can be up to 200 Pascals, or 10 million times more pressure than the quietest sound that can be heard. Because of the absolute lower limit of the human hearing system and the large range of values for pressure differential, the amplitude of sound is often described using decibels, which typically describes the sound pressure logarithmically relative to 20 micropascals. Some common sounds and their approximate sound levels are shown in Figure 2 to the right.

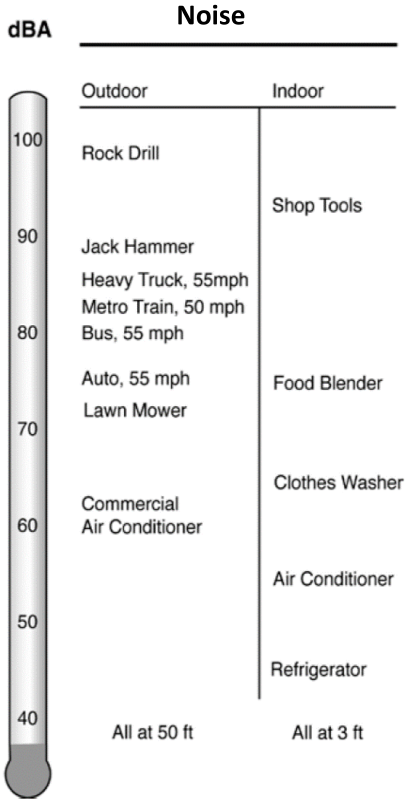

Figure 2. Sound levels from a variety of indoor and outdoor sources.

The second important property is **frequency**. The frequency of the sound describes how quickly the pressure variations in the wave go from high pressure to low pressure and back again. The faster the variations occur, the higher the frequency will be. The frequency of the sound determines the pitch of the sound as experienced by receivers. Thus, the higher the frequency, the higher the pitch that will be heard. The variation from high to low pressures in a sound wave in air happens many times per second. Therefore, frequencies are generally described using the metric “Hertz,” which means “cycles per second.”

Another important physical quality of sound is the **duration**. Sounds can be continuous and last for many hours, like the steady hum of a refrigerator in a household or the sound of cars on a busy highway near an urban area. Other sounds can last for minutes like construction equipment. Some sounds are impulsive; they last for very short amounts of time, often less than a second, and only include a small number of pressure variations, such as an explosion. Closely related to duration is the pattern of the sound. If it is not continuous, sounds may happen at a regular interval over the course of the day, or intermittently at certain times a day, or for a few hours randomly. It may cease completely during nighttime hours or continue through the night. Each of these qualities can have different effects once the sound reaches the relevant receiver.

While sound waves can have a regular pattern of high and low pressures with a constant frequency and amplitude (pure tone), almost all sounds contain a combination of different frequencies at different amplitudes that change the quality of the sound. Sometimes, there is a broad range of densely spaced frequency components at similar amplitudes. Sound that includes wide ranges of high and low frequencies at similar amplitudes is called “broadband” noise. Physical actions that create broadband noise include tires rolling on pavement, wind and rain, air conditioning and heating systems in buildings, and some engine noises.

Sounds can have “tones” or components at discrete frequencies that have much higher amplitudes than neighboring frequencies. A single tonal component is called a “pure-tone”. Multiple tonal components are called a “complex tone”. Sirens on police cars or ambulances create tones that change over time in a regular pattern. Many gasoline engines produce broadband noise that has some tonal content due to the periodic rotations of the components within them.

1.2.2 Sound Attenuation over the Path

Sound waves lose amplitude as they move further from the sound source. The most important reason for this attenuation is that sound energy is spread out over a larger volume of air at larger distances from the origin point of the sound. For point sources, this spreading translates to about a 6-decibel reduction every time the distance doubles. When the source of the sound is a line instead of a singular point, the sound energy spreads more slowly. This means the sound reduces by 3 decibels every doubling of distance.

Further attenuation is caused by sound absorption as the wave travels through the atmosphere. This phenomenon has to do with the complex interactions that occur between the gaseous molecules that make up the air, and includes energy dissipation from friction and mechanical movements of the gas particles. Humidity, temperature, pressure, and the mix of different gasses in the air all affect the rate of atmospheric absorption. The frequency of the sound also affects the rate of attenuation by absorption. The attenuation can range from .03 decibels to 60 decibels for every 1,000 feet depending on the frequency and the atmospheric conditions.

Absorption can also be caused by human made objects through which the sound travels. The method of energy dissipation usually utilizes friction to convert the acoustic energy into thermal energy. Examples include constrained layer damping, where a viscous layer between two metal plates converts the vibrations of the plates to heat; and the heating of air by pumping the air through constricted channels in open-cell foam insulation. Sound absorbing materials are often designed to reduce the amplitude of sound waves that impinge upon them. When designed adequately, attenuations of the overall sound levels may be approximately 25 decibels from one side of the sound absorbing barrier to the other, depending on the material and geometry of the site where the insulation is installed.

Environmental shielding, like earthen hills, sound barriers, and buildings block sound waves from directly propagating to receiving sites. This is called “shielding,” and it is an important consideration in assessing environmental noise levels produced by any source. Despite shielding effects, the sound is not usually fully blocked from reaching receivers. Diffraction allows part of the sound wave to “roll-over” the barrier. The effectiveness of the shielding depends on the frequency of the sound and the geometry of the object providing the shielding.

Finally, ground surfaces also reflect and attenuate sound waves. In addition to the sound waves that directly reach the receiver, additional waves reach the receiver after reflecting off ground surfaces. These reflected waves tend to increase the overall noise levels experienced by the receiver. However, reflected waves will have lower amplitudes than the waves that travel directly from the source to the receiver, because the ground absorbs some of the sound energy as the wave is being reflected. The amount of energy that the ground absorbs, and thus the degree to which the reflected wave is attenuated, changes based on the type of ground over which the sound wave travels. For example, hard pavement or concrete reflects sound well, and there is little attenuation of the reflected wave once it reaches the receiver. Grassy or vegetated ground surfaces absorb sound energy more readily, so the reflected wave is more attenuated when it reaches the receiver. The final sound experienced by the receiver is a combination of direct and reflected waves, as illustrated in Figure 3.

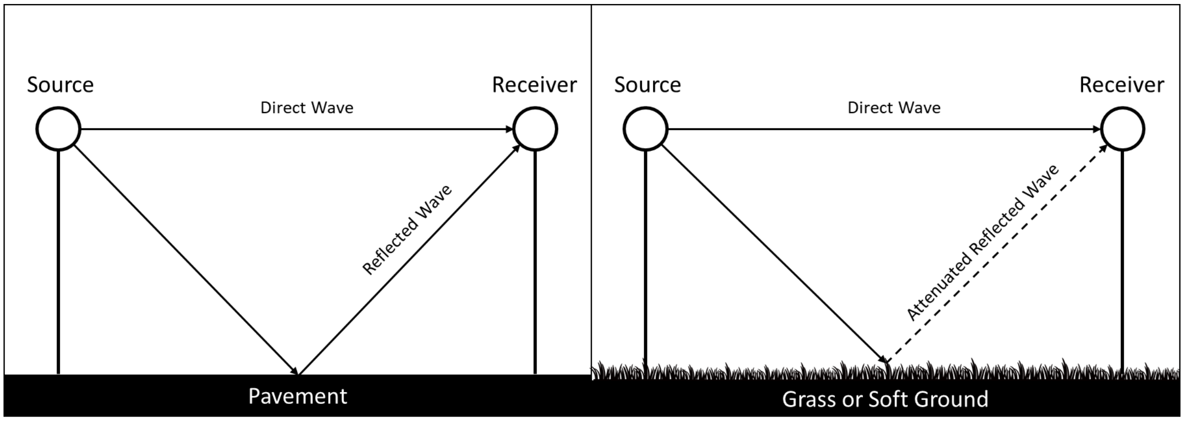

Figure 3. Reflected waves and ground absorption over hard and soft ground surfaces

1.2.3 Effects of Sound on Humans

Humans are sensitive to all the physical qualities of sound discussed previously. As discussed, the higher the amplitude of a sound, the louder and easier it will be to hear by humans. Humans are also more sensitive to components in the frequency range between 1,000 and 5,000 Hertz than outside this range. Therefore, the way a sound is perceived will depend on the level, frequency, duration, and other qualities of the sound. Extremely high amplitudes in the frequency range where humans are sensitive may cause pain or permanent damage to the human hearing system.

Objective metrics have been developed that describe sound relative to how humans experience it. These include frequency-weighting factors to describe how humans experience sounds at different frequencies and includes referencing sounds to a minimum audible threshold rather than using an absolute scale. Noise metrics are reported in decibels, which makes analysis easier within the large range of sound pressures humans can hear. See the glossary for more information about metrics and other subject-specific terms.

The most important metrics used in this report are summarized in Table 2 below. Note that most of these metrics average the sound energy in an environment over a period. The study of environmental noise often seeks to obtain a holistic view of both noise and how it might affect living things in an area. Therefore, averaging metrics are most frequently used.

Table 2. Noise Metrics Used Frequently in this Report

Metric	Description
$L_{Aeq(T)}$	The A-weighted average sound level over the time T. This value is equivalent to the continuous constant sound level that has the same amount of energy as the measured sound over a defined period. Usually, the time T is 1 hour, 8 hours, 16 hours, 24 hours, or another period that is relevant to daily human activities.
L_{dn}	Day-night average sound level (Also shown as DNL). This metric is a 24-hour average of sound levels over the course of the entire day, with a 10 dB weighting added on to sound levels at nighttime hours, usually between 10 pm and 7 am. This is the basic unit of measure for most federal agencies.
L_{day}	The average sound level, with no weighting added, during daytime hours. Usually between 7 am and 10 pm.
L_{night}	The average sound level, with no weighting added, during nighttime hours. Usually between 10 pm and 7 am.
L_{peak}	The peak sound pressure measured within a specified time interval.
L_{max}	Maximum sound level. The maximum time-weighted sound pressure level within a specified time measured using slow or fast response time.

2 Analysis of Adverse Effects

There is a complex relationship between noise exposure and possible adverse effects. Noise exposure can vary by level, frequency, duration, and other acoustic characteristics. Human response to noise can vary not only due to the noise exposure itself, but also due to cognitive processes. The ultimate impact can present itself in many forms ranging from a feeling of discomfort (affecting many) to disease and death (affecting relatively few), as presented in Figure 4.

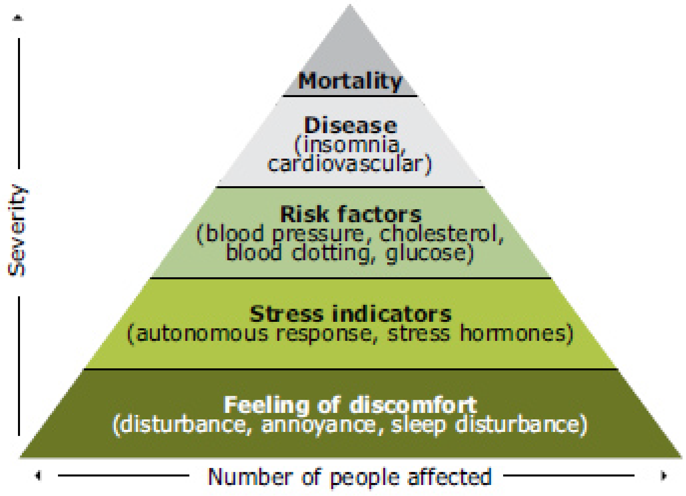

Figure 4 Pyramid of Noise Effects (Source: European Commission, adapted from Babisch 2002, based on WHO, 1972).

Figure 5 depicts the relationship among some adverse effects to noise in terms of direct (physical, or objective noise exposure) and indirect (emotional and cognitive, or subjective perception) pathways (Munzel et al. 2014). The figure demonstrates how noise may contribute to severe impacts through activity interference, annoyance, and sleep disturbance. Chronic exposure to excessive noise and the morbidities it facilitates can be fatal.

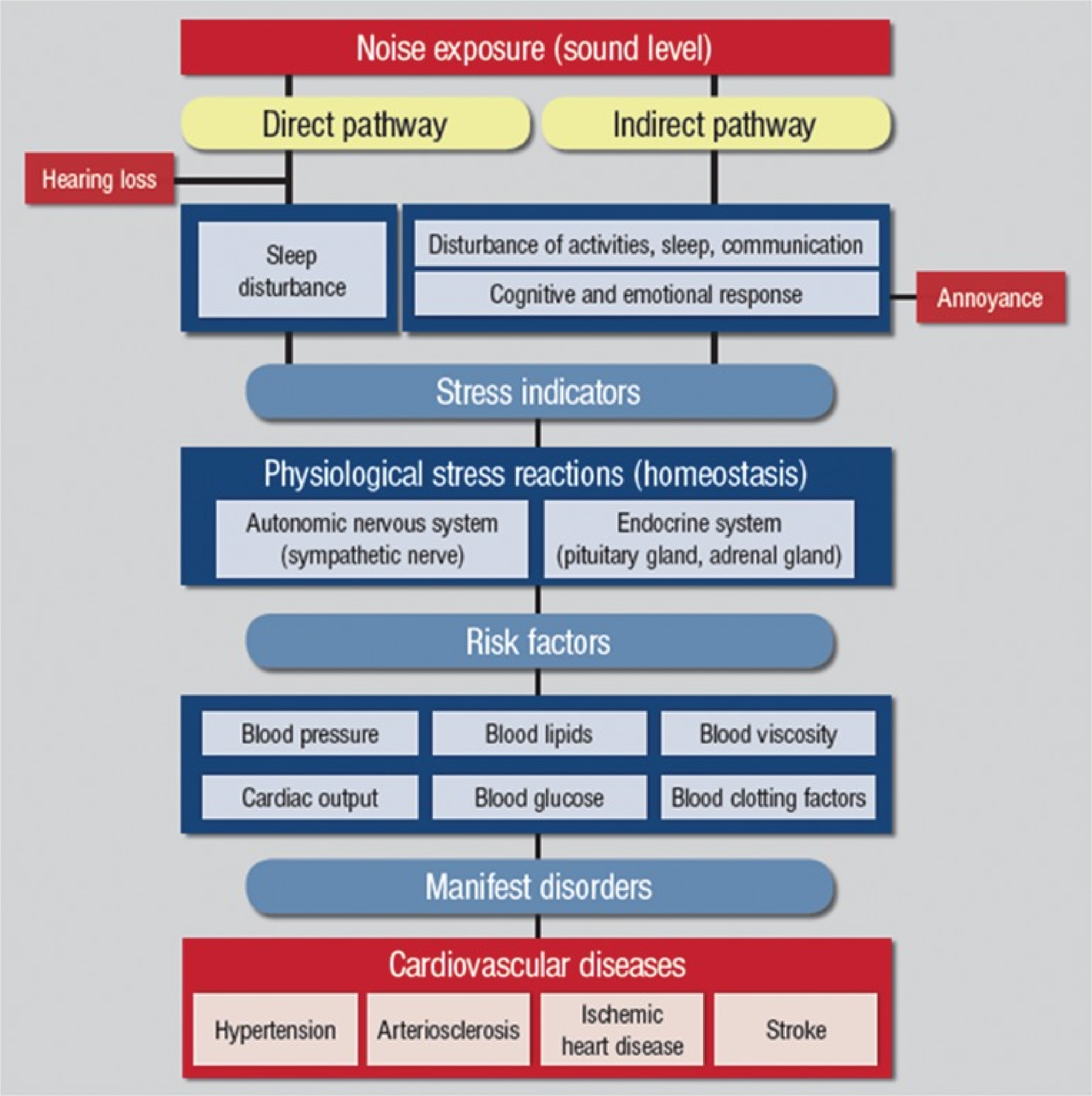

Figure 5 Noise effects reaction scheme (Source Munzel et al. 2014, adapted from Babisch 2002).

This section of the document describes the following adverse effects: hearing loss, activity interference, annoyance, cognitive effects, health and sleep impacts, and financial impacts. Each adverse effect includes subsections that provide:

- A summary on how the Levels Document addressed the topic;
- Findings in research literature that validate or change the information provided in the Levels Document; and
- If applicable, gaps in knowledge on the topic.

2.1 Hearing Loss

Hearing loss due to noise exposure is the shift in noise level threshold at which a person can hear a sound. Exposure to loud continuous, intermittent, and impulsive noises can cause different kinds of hearing loss at different rates. Cross sectional studies as well as medical and biological research from the early 1940s to the present have helped to solidify the understanding of how noise-induced hearing loss (NIHL) occurs, how it can be prevented, and the levels of environmental noise that cause this phenomenon.

2.1.1 How the Levels Document Addressed Hearing Loss

The discussion on hearing loss in the Levels Document began with a list of assumptions and considerations the authors made in order to propose a level of environmental noise to protect against hearing loss. These included:

1) Hearing shifts to non-noise exposed populations are caused by aging and other sources of deterioration rather than noise exposure.
2) Noise levels below hearing threshold levels cannot cause more hearing loss. For example, if a person can only hear sound at or above 70 dB, they will not experience more hearing loss from exposure to levels of noise below 70 dB.

The authors went on to discuss that hearing loss is often experienced first in the range of frequencies surrounding 4 kHz, which is important for speech intelligibility. These factors are used to justify the focus of recommended levels around 4 kHz. The remainder of this discussion refers only to noise at the frequency of 4 kHz on which the Levels Document focused its analysis. Additionally, the Levels Document specified that, while it is desirable to prevent any level of hearing loss from noise exposure, hearing loss is only measurable down to a 5 dB threshold shift, as any shift below this is almost unnoticeable to subjects. Therefore, the recommended environmental noise levels would be aimed at protecting against 5 dB of threshold shift.

The Levels Document used data mainly from two studies in its analysis of hearing loss. One is a public health survey conducted in the early 1960s that reported the hearing threshold levels of adults organized by age range and sex. The other study was an Air Force paper on justifications for noise exposure limitations published in 1973. The study presented summary data of predicted noise-induced permanent threshold shifts (NIPTS) at certain frequency ranges. The predictions were obtained by averaging results from a few different prediction methodologies found in a few important hearing loss studies from the 1960s and 1970s.

While the 1960s public health study provided data based on age and sex, the Levels Document's analysis required comparisons between a non-noise exposed and a noise exposed group of subjects. In order to obtain these subject groups, the authors assumed that differences in hearing threshold levels between men and women in the 55 to 64 year age range are due to differences in noise exposure levels over 40 years. The authors justified this assumption by citing there was minimal evidence of any physiological reasons why hearing levels would be different between men and women in this age range. Thus, the Levels Document uses this group of female subjects as the "non-noise exposed group" and the male subject as the noise exposed group in the remainder of its analysis.

To derive recommendations for noise levels, the Levels Document extrapolated the data from both of the above-mentioned research studies. From the Air Force study, the Levels Document derived a curve that related the 40-year noise exposure levels for 8 hours a day to the percentile of the population that may experience 5 dB of NIPTS. Additionally, the Levels Document derived a curve from data presented in the public health survey that showed the percentage of the population with hearing thresholds above certain noise levels for the apparently non-noise exposed group (55-64 year old women). They termed this curve the "PHS" curve, after the public health survey from which the data were obtained. The combined graph showing these two curves is shown in Figure 6.

To reiterate, curve 1, labeled "5 dB NIPTS AT 4000 Hz" in the figure, gives the 40 year exposure level that is necessary to cause 5 dB NIPTS at a certain percentile of the population. For example, at an exposure of about 75 dB, 20 percent of the population will have at least a 5 dB shift. Reading the rightmost part of the graph, with a 40-year exposure to 67 dB, only 1 percent of the population will have at least a 5 dB shift. Curve 2, labelled "PHS – 4000 Hz" in the figure, gives the hearing threshold levels by percentile, from best hearing to worst hearing, in the apparently non-noise exposed group. For example, 10 percent of "non-noise exposed" group is expected to have hearing threshold levels of at least about 61 dB, while 5 percent of the population is expected to have hearing threshold levels of 71 dB. The horizontal axis represents the percentile of the population distributed by noise induced threshold shift at certain noise levels from smallest shift to largest shift for curve 1, and by hearing threshold level for curve 2.

It is important to recognize that "hearing threshold level" and "noise induced threshold shift" are not necessarily numerically related concepts, even though the two are illustrated on the same graph in the Levels Document. NIPTS is a threshold shift that is caused by noise exposure. Hearing threshold is simply the level a sound must be for a person to hear it. The assumption used in the Levels Document's analysis is that the apparently non-noise exposed group show differences in hearing thresholds due mostly to aging[2], and that any noise induced threshold shift they have experienced is negligible. Therefore, the hearing thresholds of this group represent average amounts of hearing loss experienced by people aged 55 to 64 that would occur without any exposure to excess noise.

The Levels Document explained that, since noise below a person's hearing threshold cannot cause hearing damage according to previously explained assumptions, the 5 dB NIPTS curve could not cross the PHS Curve. In other words, because the apparently non-noise exposed group cannot hear below the levels given by curve 2 in the figure, exposure to noise below those levels cannot cause damage to their hearing. The authors termed the point where these two curves intersect the "critical percentile." The 40-year exposure level at this critical point is about 73 dB. Thus, 40 year exposure levels below 73 dB will not cause any more than 5 dB of threshold shift in the apparently non-noise exposed population. The conclusion was that a reasonable estimate for recommended 40 year, 8 hour workday exposure limits should be 73 dB.

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[2] Hearing loss due to aging is called *Presbycusis.* It is caused by the normal aging process of the auditory system, and is experienced at different rates and at different ages by different people.

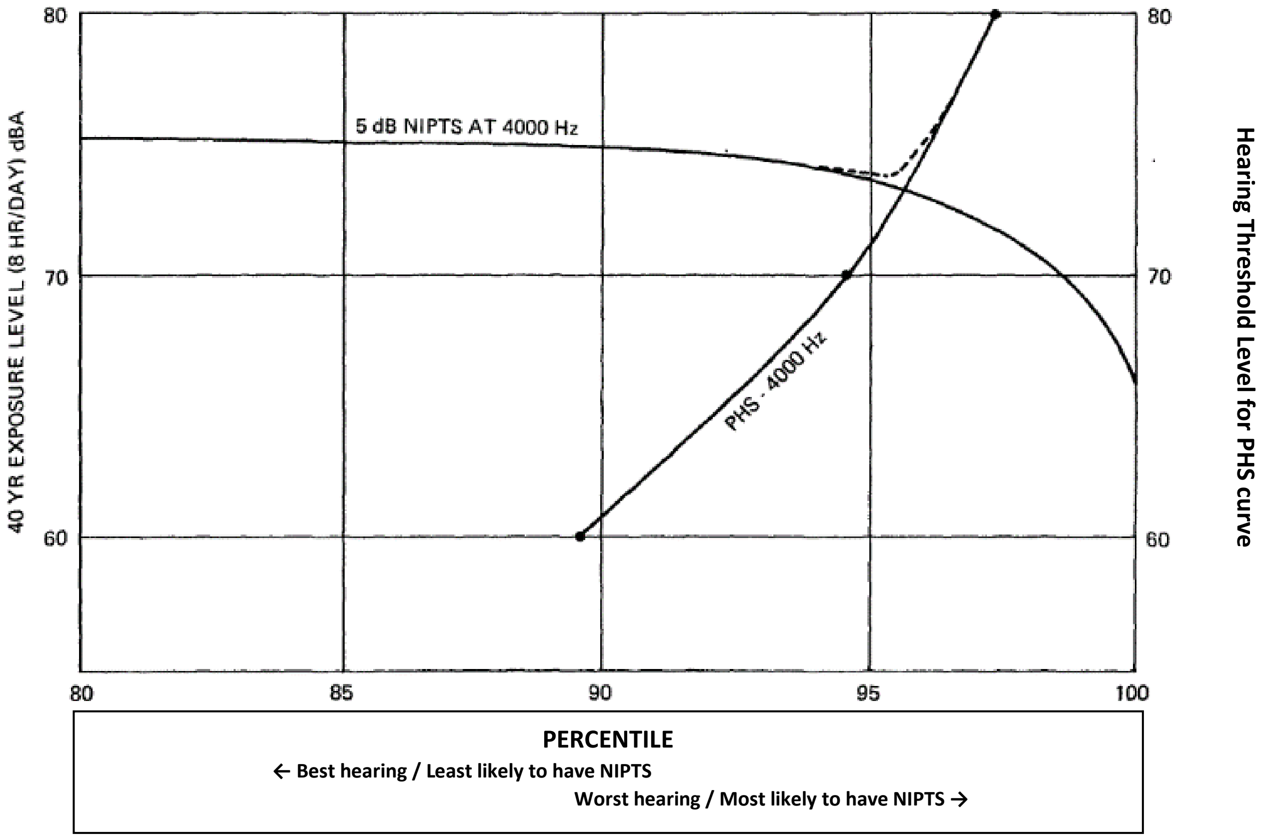

Figure 6 Derived relationships showing 1) percentile of population with 5 dB NIPTS at 4000 Hz with 40-year noise exposure levels and 2) percentile of population with different hearing threshold levels

Additional discussion is provided to account for exposure to intermittent noise and impulsive noise. These analyses mostly involve adjustments using the equal energy principal.[3] An additional hypothesis is used in addition to the equal energy principal, called the temporary threshold shift hypothesis. This states that temporary threshold shifts measured 2 minutes after 8-hour exposure to a certain level of noise is similar to the NIPTS caused after 10 to 20 years of exposure to the same level of noise.

Using the above-mentioned hypotheses, the authors estimated a correction factor of 5 dB for intermittent noise experienced over an 8-hour workday. The Levels Document provided additional correction factors based on the same hypotheses to account for adjustments from a 250-day work year to 365 days of exposure, as well as from an 8-hour workday to a 24-hour day. The adjustments used to obtain the final recommended level are shown in Table 3.

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[3] The equal energy principal states that equal amounts of aggregate sound energy will cause the same amount of measurable damage to the human hearing system, regardless of time duration, intermittency, or other qualities of the sound. That is, if a person is exposed to two different sounds with one being louder but having a shorter duration than the other, but both having the same total sound energy, the two will cause the same damage.

Table 3. Recommended level corrections for intermittency and exposure durations used by the authors of the Levels Document

Noise Level	Correction	Description
73 dB L_{Aeq8hr}	0 dB	Original 8 hour, continuous noise level limit obtained from analysis of data from Public Health Survey and Air Force Report (Critical Percentile analysis)
78 dB L_{Aeq8hr}	+5 dB	Adjustment for intermittency during an 8-hour workday. Obtained by adjusting the equal energy curve to better fit data on temporary threshold shift from intermittent noise level exposure.
76.4 L_{Aeq8hr}	-1.6 dB	Adjustment to account for 365 days of exposure instead of 250 working days per year. Obtained using the equal energy principle.
71.4 $L_{Aeq24hr}$	-5 dB	Reverse adjustment from intermittent noise limit to continuous limit for 24 hours per day, 365 days per year.
70 $L_{Aeq24hr}$	Rounding	Considering assumptions, other sources of uncertainty, and a desire to be conservative, the Levels Document rounded down to 70 dB from 71.4.

The final noise level given by the Levels Document is rounded down to 70 dB for a conservative estimate, considering uncertainties in the original occupational exposure limit analysis and the correction analysis. The uncertainties discussed in the Levels Document include that the various studies used in the analyses do not have comparable study populations, and therefore their results may not be comparable. Additionally, permanent threshold shift may not be noise-induced. There is evidence that other factors may cause threshold shifts; it is difficult to prove that shifts are caused by noise exposure without detailed understanding of a subject's noise exposure history, which is often unavailable or vague. Extrapolations of data were also used extensively in the Levels Document analyses, which introduced inherent inaccuracies and uncertainties in the results.

One noticeable source of uncertainty is the assumption that female study subjects were not exposed to similar noise levels as the male group. Using the data from the female group as a representation of a non-noise exposed population presents some inherent uncertainties. While it might be valid to assume that, in the 1960s when the pertinent studies were performed, women were less likely to be exposed to loud occupational noise than men were, it is difficult to justify the assumption that women were not exposed to noise at all. The authors of the Levels Document did not have access to better data on non-noise exposed populations and therefore used the population assumed to be the least exposed from the sources available. The authors admitted that these assumptions introduced uncertainties and inaccuracies in the resulting analysis. The next section discusses how different analyses of the same studies provided a more nuanced understanding of threshold shifts without including the same assumptions as were included in the Levels Document analysis.

2.1.2 Current Understanding of Noise-Induced Hearing Loss

This section describes 1) data from NIPTS studies used to inform 2) analyses for the Levels Document and International Standards Organization, and 3) resulting predictive levels various agencies recommend or require to protect against noise-induced hearing loss.

2.1.2.1 Data: NIPTS Studies from the 1960s and 1970s

The basic understanding of the noise levels that cause permanent degeneration of hearing ability has not changed substantially since the Levels Document was published. In fact, different regularly updated international standards, recommendations, and regulations on occupational noise continue to utilize the same databases of hearing level data used by the Levels Document. The vast majority of the data used comes from studies performed in the 1960s and 70s (Kowalsksa, Zabarowski, 2017). These databases are summarized in synthesis studies published by three prominent researchers at the time: Passchier-Vermeer in 1968, Robinson in 1968 and Baughn in 1973. The results of these syntheses were summarized and presented in 1973, partially in support of the writing of the Levels Document, by Daniel L. Johnson, a Major in the United States Air Force (Johnson, 1973). In 1977, both Passchier-Vermeer and Robinson published updated syntheses of hearing loss databases with a larger focus on predicting NIPTS from occupational noise exposure. Based on different analysis procedures of similar databases used in the original syntheses, Passchier-Vermeer's and Robinson's second reports were summarized again by Johnson in a 1978 summary in support of the development of international standards on noise induced hearing loss (Johnson, 1978).

The syntheses of hearing loss data by Passchier-Vermeer, Robinson, and Baughn are aggregations of data from cross-sectional studies that reported noise induced threshold shifts in adults and children with estimations of their exposure to certain noise levels over certain periods. Results are usually organized into percentile groups ranging from best hearing to worst hearing from the 1st to the 100th percentile. Similar to most other studies on this subject, the three researchers focused on occupational noise exposure rather than environmental or recreational noise exposure. It is easier to make assumptions about subjects' exposure to occupational noise, as people tend to be exposed to these noises every working day for many years. Since the original studies were performed, there have been very few efforts to update or supplement the original data with either cross-sectional or longitudinal studies on noise-induced hearing loss.

2.1.2.2 Analyses: Comparison of International Standards Organization and Levels Document Analyses

One notable and important standard on which many regulations and recommendations are based was published by the International Standards Organization (ISO). Mentioned previously, the ISO standard 1999:2013 utilized Johnson's later report from 1978, along with a few supplemental research reports, to formulate an algorithm for predicting a person's noise-induced hearing loss resulting from a number of years of exposure over 8 hours per work day. Last updated in 2013, these standards continue to be accepted and used by international organizations to estimate risks of hearing loss both in occupational and non-occupational settings. The equations in the standard take into account aging effects, sex, exposure time, and exposure level to determine hearing loss effects.

There is a clear difference between the results presented in Johnson's 1973 report and his 1978 report. Based on evidence available at the time, both Passchier-Vermeer and Robinson made an important assumption in their second, 1977 syntheses. Below 75 dB L_{eq8hr} noise exposure over 40 years, NIPTS was deemed negligible for all percentiles of the population. This essentially anchors the origin of the resulting curve and lowers NIPTS predicted at higher levels of noise exposure. The results tables in Johnson's second report are skewed by 5 to 8 dB from the values shown in his second report due to this assumption. This difference in results in Johnson's two reports leads to a marked difference between the predicted levels of NIPTS in the Levels Document and the ISO standard. The curves derived by the Levels Document show about 6 dB more threshold shift than those given in the ISO standard at 75 dB L_{eq8hr} of noise exposure.[4]

Figure 7 shows the estimates of permanent threshold shift predicted by the ISO equations at different exposure levels and different exposure timelines. The axes and parameters represented in Figure 7 are comparable to Figure C-2 in the Levels Document. The values shown in the figure are for the 4000 Hz frequency and are based on 40 years of exposure. As previously described, the ISO standard predicts 0 dB NIPTS from 40 years of exposure to 75 dB L_{eq8hr} for all population percentiles. As a comparison, 40 years of exposure to 80 dB L_{eq8hr} of noise is predicted to cause 8.5 dB NIPTS at the 90th percentile by the Levels Document's analysis, while the ISO standard predicts 2.25 dB NIPTS.

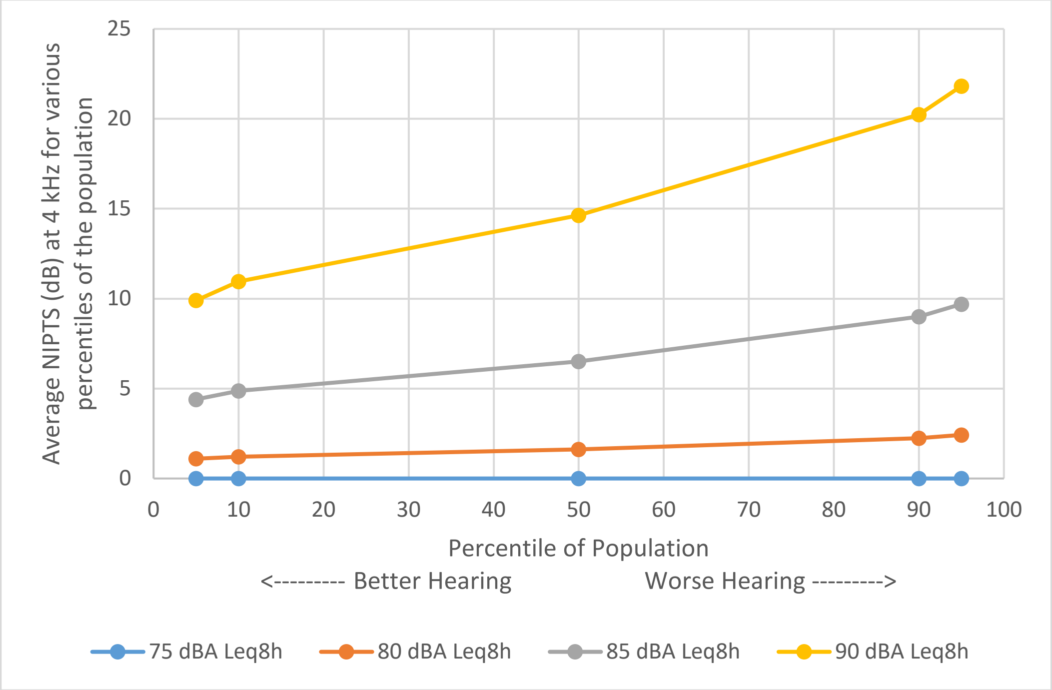

Figure 7. NIPTS Predicted at different 40-year exposure levels and percentiles of the population by the ISO 1999 standard[5]

While the difference between the predicted values of NIPTS in the Levels Document and the ISO standard are primarily due to the differences between results in Johnson's first and second syntheses, there are a few other notable differences between the analyses in the Level's Document and the ISO standard. First, the Levels Document extrapolated data from Johnson's report and the public health

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[4] Johnson does not discuss this difference in his secondary synthesis. In fact, he specifically specifies that Passhier-Vermeer's results in the second analysis for the most part agree to those in the first analysis. This unexpected gap in discussion makes it difficult to fully understand the differences in NIPTS predicted by Levels and ISO.

[5] Obtained using "ISO_1999_2013_Calculations" Matlab functions written by Edward Zechmann and Richard Brown. The functions therein are implementations of the equations and algorithms presented in the ISO 1999:2013 standard.

survey to predict NIPTS for higher percentiles than were presented in an effort to protect a higher percentage of the population. Additionally, the databases used in the ISO algorithms are specific to the 50th percentile, using conversions to account for higher percentiles. NIPTS at the higher percentiles shown in Figure 7 were calculated using these conversions. The uncertainty introduced by using these conversions makes it difficult to compare predicted NIPTS between the ISO standard and the Levels Document analysis. The inclusion of the supplemental studies from the 1970s also shift the predicted NIPTS in the ISO standard to slightly lower values than are shown in the Levels Document. Combined with the differences in the two Johnson reports, these additional differences lead to different predictions between the two analyses.

2.1.2.3 Results: Comparison of Protective Noise Level Recommendations or Requirements

The ISO standard, along with individual analyses of the same databases used by Passhier-Vermeer, Robinson, and Baughn, were used by a number of regulatory bodies to publish environmental and occupational noise exposure limits. Standards that use these sources of data include the U.S. Occupational Safety and Health Administration's (OSHA) occupational noise exposure regulations, the U.K.'s occupational noise control regulations, and the World Health Organization's occupational noise exposure recommendations. As a comparison, some of these regulations and standards are summarized below in Table 4. The exposure limit provided by the Levels Document is also shown for comparison.

Table 4. Comparison of occupational noise level limit for different organizations.

Standard, Recommendation, or Regulation	Noise Level Limit to Protect Hearing Loss (dB)	Protected Percentile	Frequencies defining hearing loss	Exposure Time
U.S. EPA Levels Document	70 dB	100th	4 kHz	24 hours
U.S. OSHA Noise Level Limits	90	25th	2, 3, 4 kHz	8 hours per day limit
U.S. NIOSH[6] Occupational Noise Criteria Recommendations	85	50th	1, 2, 3, 4 kHz	8 hours per day,
U.K. Occupational Noise Regulations	80, 85, 87	50th	1, 2, 3, 4 kHz	8 hour lower, upper, and limit
WHO Occupational Noise Recommendations	85	50th	.5, 1, 2, 4 kHz	8 hours per day,

An important note concerning the data shown above is that choosing a noise level to protect against hearing loss is a decision that must take into account socio-economics of the region, typical environmental noise levels, age distributions of the population, and other factors. Most countries have decided that 5 dB of permanent threshold shift is a reasonable baseline against which to protect, and their noise level limits reflect this decision. Additional differences shown in Table 4 are the different

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[6] National Institute of Occupational Health and Safety, an institute of the Centers for Disease Control

frequencies that regulatory and standards making bodies choose to take into account when making their recommendations. An agency's final regulation or standard level also depends on the specific analysis procedures used, even if the source data and studies are the same.

2.1.2.4 Important Remarks Regarding the Purpose of the Levels Document

While the Levels Document's maximum level to protect against hearing loss seems more stringent than many regulations, it is important to note that this was not a regulatory document, and that the levels therein were meant to be informative and not to be considered standards. Appendix F in the Levels Document discusses how the authors interpreted their own responsibility to provide information on safe levels of noise exposure, and how it differed from the responsibilities of other agencies like that of Occupational Safety and Health. Thus, they based their recommended levels on protecting the entire population at any time of day without considering factors such as socioeconomic costs or current environmental noise levels, while these factors must be considered when establishing regulatory standards. Additionally, the analysis in the Levels Document combined hearing level data with threshold shift data from two different studies. This type of analysis differed from analyses used to set regulatory standards, and resulted in lower recommended levels, as justified in Appendix F of the Levels Document. This difference in analysis procedure explains some of the disparity between the Levels Document's recommendations and other standards and regulations.

2.1.3 Contemporary Research Topics

While understanding of noise-induced permanent threshold shift has not changed significantly since the 1970s, there have been some other areas of research interests in the subject of hearing loss. There is consensus in the scientific community that there are two main causes of acquired hearing loss[7]. The most common cause is aging. Hearing ability naturally deteriorates with age, whether or a not a person is exposed to excessive amounts of noise throughout their lifetime. The second most common cause of permanent hearing loss is excessive noise exposure (Caroll, Eichwald, 2017). These two effects are highly interrelated, and there is a gap in the current understanding of these complex relationships. For example, there is some evidence to suggest that early excessive noise exposure increases the risk of hearing degeneration due to aging even without further exposure to loud noises. In addition to noise and age, other, non-acoustic factors have been shown to affect the ability to hear. For example, hearing loss can be a secondary symptom of other medical conditions, and it has been linked to the use of certain prescription and recreational drugs.

Noise can cause permanent hearing loss by two main mechanisms. Extremely loud, impulsive, short duration sounds can cause ruptures in the eardrum as well as damage to middle ear structures. These types of damage are described further in the impulse noise section of this report. While permanent hearing losses can occur from this type of exposure, most threshold shifts of this kind are only temporary; hearing levels have been shown to return to normal up to a few weeks after the original exposure (Ryan, Kujawa, et al., 2014).

Lower levels of noise can cause hearing loss when exposure is extended to longer periods and repeated over years. This type of damage is associated with degradation of the highly sensitive hair cells in the

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[7] Acquired hearing loss is a hearing threshold shift that a person is not born with.

inner ear that transduce the vibrations in the basilar membrane due to sound signals into electrical signals that are then transmitted by nerves to the brain. These hair cells do not regenerate after being damaged, and thus this degradation is irreversible. Due to resonance frequencies in the outer ear canal, the frequency ranges around 4 kHz are amplified. This is why the 4 kHz frequency range is the first to be affected by permanent threshold shifts (Ryan, Kujawa, et al., 2014). Additional recent research has given insight into the molecular and cellular mechanisms by which hearing loss occur within the inner ear structures, and there has been some early progress in stem cell based therapies and treatments that may recover early damage due to loud noise exposure (Basner, Babisch et al., 2014).

One area where there has been recent research developments is in hearing loss in teens and young adults due to excess noise exposure from portable music listening devices. Noise levels generated by earbuds and headphones can be much higher than would be experienced from environmental noise. Increased use of these personal listening devices in teens and young adults may increase these age groups' risk of hearing loss in the short term as well as later in life. A review by the World Health Organization of five studies on this subject showed that the odds of developing permanent hearing loss for regular personal listening device users might be about four times higher than for non-users. However, there was little evidence in the studies reviewed that would allow a relationship to be developed between the sound levels experienced by the user, and the degree of threshold shift experienced. Additionally, the studies in the review may have biased results, and there was no data linking hearing loss later in a person's life to personal listening device use (Kowalsksa, Zabarowski, 2017).

2.1.4 Summary and Research Gaps

2.1.4.1 Summary of Current State of Research and Understanding

The basic understanding of the noise levels that cause permanent degeneration of hearing ability has not changed substantially since the Levels Document was published.

The Levels Document based its level to protect public health and welfare from hearing loss on three syntheses from the 1960s and 1970s in combination with a separate public health survey reporting basic hearing levels of different population groups. From this "Critical Percentile" analysis, a baseline noise level of 73 dB, that would protect against a maximum of 5 dB noise-induced permanent threshold shift, was derived based on 8 hours of exposure, 5 working days per week, for 40 years. Different levels are given with adjustments for intermittency and 365 days of exposure, 24 hours a day. The final level requisite to protect public health and welfare from hearing loss reported by the Levels Document for 24 hour, continuous environmental noise exposure 365 days a year was 70 dB $L_{Aeq,24hr}$, regardless of the source or type of sound.

Since the original research performed in the 1960s and 1970s, there have been few additional studies published on the effects of continuous occupational noise exposure on hearing levels or hearing loss. The original databases used by different standards making groups have not been updated significantly since these early studies. However, different studies using different analysis procedures and assumptions from the same researchers have led to slightly different results. The later studies, based on the same original databases, were used by the International Standards Organization to derive algorithms to predict NIPTS at different exposure levels and durations. The ISO standard has been generally accepted and used by many regulatory bodies around the world to set standards for workplace and environmental noise exposure. The most recent update of these standards was in 2013, but any updated equations still utilize the original data from the 1960s and 70s. The differences in assumptions used in the Levels Document's analysis and the ISO standard analysis explains most of the differences between NIPTS predicted in these documents.

Also of note is the additional discussion included in the Levels Document concerning the difference between the EPA's responsibility to protect against environmental noise and other agencies' requirements to set occupational health and safety standards. It is expected therefore, that the extrapolations and assumptions used by the Levels Document yielded a lower final recommendation than that presented in other occupational noise standards or literature.

New understanding of the physiological, molecular, and mechanical components of the ear that are affected when exposed to excessive noise may result in new medical treatments that would be able to restore hearing after exposure to loud sounds. Such research is in the early stages of development. Additional recent research has explored the effects of personal listening device use on hearing abilities; however, this research is not yet comprehensive enough to provide decibel level relationships to hearing threshold shifts.

2.1.4.2 Research Gaps

Although there is a generally accepted standard for effects of continuous noise exposure on hearing levels, most of the studies used to develop this standard are cross sectional studies. There are limited data that has directly related subjects' exposure to noise over a timeline of many years to degradation of hearing ability or threshold shifts after certain periods. More longitudinal studies would improve the understanding of how cumulative noise exposure affects human hearing in the short and long term, how the hearing system recovers from temporary threshold shifts, and how excessive exposure contributes to hearing degeneration due to aging.

Additional research may be necessary to determine how medical conditions and use of prescription or other drugs or treatments affect a person's hearing levels directly, or their susceptibility to damage from excessive noise exposure. Because the use of personal listening devices is widespread, more research should also be performed to determine how these devices affect risks of hearing loss in both young adults and older age groups. This requires measurement of noise levels experienced by individuals listening to these devices, as well as longitudinal measurements of effects over longer time spans.

2.2 Activity Interference

2.2.1 How the Levels Document Addressed Activity Interference

The Levels Document proposed noise levels to protect against speech interference in both indoor and outdoor environments. The document stated that indoors, the maximum noise level that will permit relaxed conversation with 100 percent sentence intelligibility is 45 dB $L_{Aeq(24)}$ (assumes a 1.1 meter or greater distance between listener and talker within the same room[8]). The document defined sentence

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[8] Due to the reverberation of sound off walls and other boundaries of the room, at distances of 1.1 meters or greater the level of speech is more or less constant throughout a room.

intelligibility as the percentage of the key words in a group of sentences that are correctly understood by the listener.

The Levels Document assumed a 15 dB reduction in sound level between outdoor and indoor environments (an average reduction assuming partially open windows), so it translated the indoor noise level of 45 dB to an outdoor level of 60 dB $L_{Aeq(24)}$. Outdoors, speech intelligibility decreases with the distance between the listener and talker. At 2 meters between the listener and talker, 60 dB L_{Aeq} will allow for normal conversation with 95 percent sentence intelligibility; speaking in a raised voice will allow for the same sentence intelligibility with noise levels of 66 dB (see Levels table D-1). Sentence intelligibility of 95 percent is considered satisfactory for most situations, because in normal conversation many words can be inferred based on the context (especially if they are familiar words). The Levels Document noted that speech intelligibility is affected by whether the noise and speech frequencies overlap, which makes speech intelligibility more difficult. In addition, as background noise levels increase, participants in a conversation have to either move closer together or raise their voices in order to be understood.

The Levels Document also assumed that annoyance was caused by activity interference, and the levels proposed for protection of the human population against annoyance focused primarily on preventing speech interference. To protect against activity interference and annoyance in residential areas, Levels added a nighttime weighting. The outdoor level was given a 5 dB margin of safety to protect against "non-acoustic" effects that differ between people, locations, and study populations. The document therefore recommended the maximum noise levels to prevent interference of speech and other activities as L_{dn} of 45 dB indoors and 55 dB outdoors for all types of environmental noise in residential areas (see Section 3.3, Annoyance, for more information about noise levels to protect against annoyance).

2.2.2 Current State of Research

2.2.2.1 Speech Interference

Since the Levels Document was published, there has been some additional research on the impact of noise on speech interference. Most of this research addresses a specific aspect of speech interference, and does not explicitly confirm or refute the levels to protect against speech interference that are described in the Levels Document. Given that the acoustics and physical attributes of hearing and speech communication were well understood at the time the Levels Document was published, it is reasonable to conclude that the noise levels to protect against speech interference proposed in that document have not changed.

Several recent studies on speech interference refer to the signal to noise ratio (S/N), or the difference in A-weighted sound pressure level between a person's speech and the background noise source. For example, if a person's speech were the same noise level as traffic noise, the S/N would be 0 dB, while a negative S/N value means that the background noise level is louder than the speech level. Although the Levels Document did not use the S/N measure of speech interference, it did discuss how speech interference is affected by the volume of the speaker's voice with constant background noise, which is essentially a description of the S/N ratio.

The 2000 WHO *Guidelines for Community Noise* (Berglund et al) describes the relationship between speech interference and S/N. The report notes that speech interference is a masking process, whereby interfering noises prevent speech from being understood. As background noise increases, people raise their voices; although this improves speech intelligibility, it does put a strain on both the speaker and listener. Indoors, speech intelligibility also depends on the reverberation characteristics of the room. Very high amounts of reverberation makes intelligibility more difficult, especially when combined with background noise. Based on studies from 1985 and 1990, the report states that for 100 percent sentence intelligibility in listeners with normal hearing, the signal to noise ratio should be at least L_{Aeq} of 15-18 dB. The report notes that this implies that indoors in small rooms, background noise levels above about 35 dB interfere with speech intelligibility at a normal speech volume (speech level of 50 dB). With a raised voice, one can expect 100 percent speech intelligibility up to background noise levels of 55 dB, and with a "straining" vocal effort speech can be intelligible in up to 65 dB of background noise.

Berglund et al noted that this recommended level of 35 dB is lower than the recommended noise levels to protect against speech interference described in the Levels Document, but does not provide an explanation of why this might be the case. One potential reason for the difference is that the two reports used different assumptions about typical/comfortable speech levels, outdoor to indoor noise insulation, and the reverberation characteristics of typical rooms, making comparison difficult. In addition, the 15-18 dB S/N recommended in the WHO report is to allow for 100 percent speech intelligibility. As noted above, 100 percent speech intelligibility is not typically needed for effective communication.

Studies that are more recent have evaluated the impact of noise on speech interference in different outdoor environments. Alvarsson et al (2014) studied the effect of aircraft noise on speech intelligibility in an outdoor living space (in a pergola). Study participants listened to recordings of aircraft noise as well as a list of 50 words. The study found that aircraft noise adversely affected speech intelligibility starting from aircraft noise levels of approximately 55 dB(A) or an S/N(A) of 0 dB. This is similar to the Levels Document, which stated that background noise levels of 60 dB L_{Aeq} outdoors will allow for normal conversation with 95 percent sentence intelligibility. The study also investigated alternate models for measuring speech interference, but found that the simple A-weighted S/N ratio was nearly as good an indicator of speech intelligibility as were two more complex models.

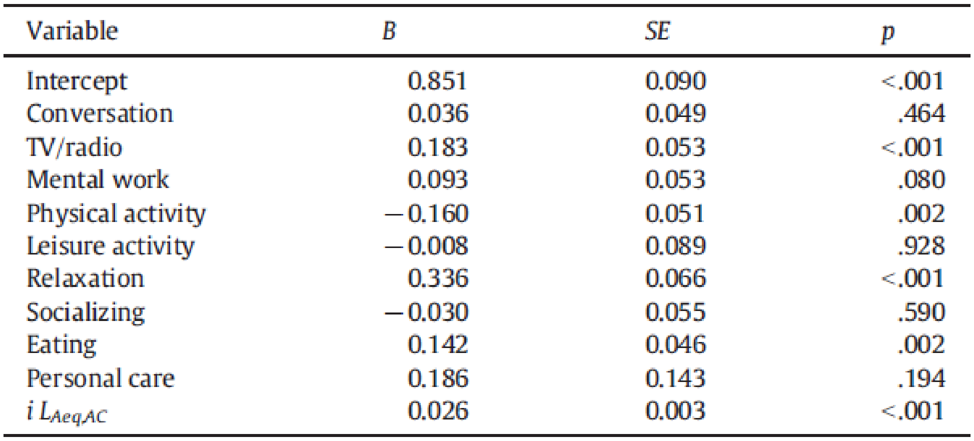
Lee and Jeon (2011) tested the effects of combined noise sources on speech transmission in open public spaces. The test was conducted in a laboratory setting, and the authors used a computer to model the noise of an open public space surrounded by buildings, as well as road traffic noise and stationary and impulsive construction noise. Study participants listened to recordings of words and were asked to rank their "listening difficulty" on a scale of 1 to 4. Participants were also assigned a word intelligibility score based on the percentage of words they understood correctly. The study found that speech intelligibility for combined noise sources in an urban space was most affected by the temporal characteristics of construction noise. Speech transmission performance decreased as construction noise levels increased by 15 dB in sound fields exposed to steady state noise; however, speech transmission performance did not change as much in the situations with impulsive construction noise. The study also found that the subjective measurement of listening difficulty rating had greater variation than the word intelligibility scores, and seemed like an inappropriate measure of speech transmission in noisy urban areas.

Other research has evaluated particular elements of speech interference that are out of the scope of this review. For example, studies have investigated the optimum speech levels for effective communication (Kobayashi and Morimoto, 2007), as well as speech intelligibility in particular settings, such as for passengers on a train (Shimokura and Soeta, 2009; Maffei et al 2012).

2.2.2.2 Other Activity Interference

Studies on other types of activity interference primarily rely on surveys of residents to correlate annoyance or disturbance during particular activities to noise levels. Bartels et al (2015) conducted a study with 55 individuals living near Cologne/Bonn airport in Germany. Study participants were asked to rate their annoyance on an hourly basis, and an individualized L_{Aeq} was calculated for aircraft noise based on information about the participant's whereabouts, the window position, and a potential outdoor to indoor attenuation of the aircraft noise level. The study found that annoyance to aircraft noise was higher while participants were watching TV/listening to radio, relaxing, and eating (see Table 5). Aircraft noise occurring during physical activities was perceived as less annoying. The study found no significant effect of conversation disturbance on annoyance, but the authors noted that this contradicts prior research and the expectation of a causal relationship between speech interference and annoyance. The authors suggest that annoyance may be higher for watching TV/listening to the radio than for speech communication because people in conversation adjust their speech volume to adapt to noise, and someone can ask the person they are speaking with to repeat if they did not hear. However, the frequent and intermittent nature of aircraft noise means that someone would have to adjust the volume on the TV repeatedly in order to hear, which they might find more annoying.

Table 5: Table 3 from Bartels et al 2015 showing the correlation between annoyance to aircraft noise and various activities



Variable	*B*	*SE*	*p*
Intercept	0.851	0.090	<.001
Conversation	0.036	0.049	.464
TV/radio	0.183	0.053	<.001
Mental work	0.093	0.053	.080
Physical activity	−0.160	0.051	.002
Leisure activity	−0.008	0.089	.928
Relaxation	0.336	0.066	<.001
Socializing	−0.030	0.055	.590
Eating	0.142	0.046	.002
Personal care	0.186	0.143	.194
$i\,L_{AeqAC}$	0.026	0.003	<.001

Note: The table shows the results of a generalized estimating equation (GEE) analysis to test the contribution of various activities on aircraft noise annoyance in the previous hour. Annoyance was rated on a scale of 1-5, and aircraft noise was mentioned in the question. A positive regression coefficient (B) means that annoyance was rated higher when this activity was carried out; a negative regression coefficient indicates lower annoyance when this activity was carried out (Bartels et al, 2015).

Hall, Taylor, and Birnie (1985) used surveys to determine the relationship between activity interference and annoyance. The activities included indoor and outdoor speech, getting to sleep, and awakening (see section 3.5, Health and Sleep Impacts, for more information on noise and sleep disturbance). The authors found that all of these activities were predictors of annoyance with a significant effect. For speech interference, there was no significant difference by noise source (air, road, and rail).

2.2.3 Summary and Research Gaps

There have not been substantial changes to the information presented in the Levels Document on speech interference since that document was published. There have been few recent studies on the noise levels at which speech is disrupted, and those few studies do not seem to update the overall finding from the Levels Document that speech is likely to be disturbed at 45 dB L_{dn} indoors and 55 dB L_{dn} outdoors in residential areas. Much of the ongoing research on speech interference focuses on particular aspects of communication, such as how to best measure speech intelligibility, or on particular settings, such as on train cars or urban public spaces. Therefore, we did not identify any major research gaps within the topic of speech interference.

For disruption of other activities, such as watching TV, relaxing, and other recreation, findings are based on asking about activities in surveys of annoyance. For a given noise level, some activities have been found to lead to greater annoyance. These include interference with speech communication, watching TV, relaxing, and eating. Other factors that affect annoyance findings are described in detail in the Annoyance section of this report. Asking about activities during surveys of annoyance to noise may help to clarify the relationship between noise levels, activity interference, and annoyance.

2.3 Annoyance

Annoyance, or a person’s individual adverse reaction (Pederson, 2007), from environmental noise is often described as the main or most important effect of noise by international noise experts (Guski, Schreckenberg, Scheumer, 2017). It is a complicated, difficult to model issue, with research results often differing substantially within and between different studies. Annoyance can be both the cause of and a response to other adverse effects; however, it is important to discuss annoyance as a standalone response to environmental noise exposure.

2.3.1 How the Levels Document Addressed Annoyance

The Levels Document reported that annoyance was caused by activity interference. The noise levels proposed for protection of the human population against annoyance focused on preventing primarily speech interference. By setting a level of acceptability to prevent speech interference, the Levels Document assumed that these levels would prevent widespread reports of annoyance from affected populations as well.

The Levels Document also included discussions of results from a number of annoyance survey studies. Three of these studies were on annoyance to aircraft noise, and one was a study of perceived noisiness of automobile traffic in urban residential areas. Results from the three aircraft annoyance studies were used to justify a prediction of annoyance impacts at the recommended, speech-interference-based noise levels; the Levels Document did not consider the urban noise annoyance data in its impact predictions. The aircraft annoyance studies were performed in the United States and the United Kingdom between 1961 and 1971, and included 9 airports in total. The surveys used yes or no questions about activity interference and annoyance to assess whether a respondent was highly annoyed or not.

The combined results from these surveys are shown in Figure 8. These data points are aggregations of responses at ranges of noise exposure levels across the data sets used in the analysis from which this figure was drawn. It is not specified by the Levels Document or the source how these aggregations were performed.

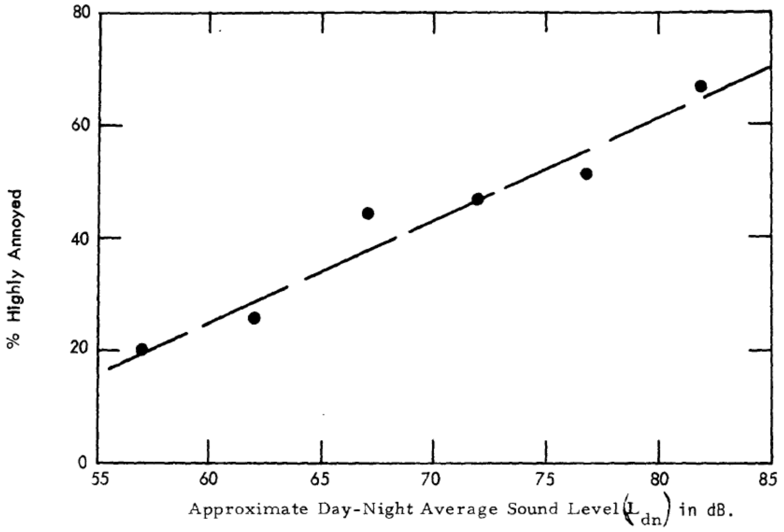


Figure 8. Levels Document combined results from London surveys and US survey: percent highly annoyed relationship to L_{dn}

The results shown in Figure 8 appear to be linear over the exposure range, and the Levels Document notes that this figure makes it seem like the results from the three annoyance surveys are consistent. The U.S. aircraft noise annoyance study also provided a relationship between the percent of the population that issued complaints about aircraft noise ($\sqrt{\%C}$), and the percent of the population that indicated they were highly annoyed (%HA). This relationship is shown in equation 1. The study that proposes this relationship does not provide metrics or measures for how reasonably this curve fits the data presented.

$$\%HA = 12.3\sqrt{\%C} + 4.3 \tag{1}$$

The Levels Document combined the apparently linear results from Figure 8 and the relationship in equation 1 into a single relationship between the environmental noise level and the percent complaints. The resulting relationship is used to derive the prediction that at 55 dB, 1 percent of the population is likely to complain about environmental noise, and 17% of the population may indicate being highly annoyed in an annoyance survey.

The authors of the Levels Document decided these results were not comprehensive enough to base a recommended sound level on them. Specifically, the Levels Document states, “the levels of environmental noise that are associated with annoyance depend upon local conditions and attitudes, they cannot be clearly identified in terms of the national public health and welfare.” The recommended sound level presented is 45 dB L_{dn} indoors and 60 dB L_{dn} outdoors for protection against speech interference. The recommended outdoor level was given a 5 dB factor of safety, making the final recommended level of outdoor environmental noise 55 dB L_{dn}. The 5 dB factor of safety is intended to protect against "non-level related factors" that differ between people, locations, and study populations.

The Levels Document ended the discussion on annoyance with a summary of predicted impacts at the recommended level of 55 dB L_{dn}, repeating the prediction of 17% highly annoyed and specifying that this level is dependent on attitude and other non-acoustical factors. The prediction of 1% of the exposed population complaining is used to justify acceptance of 17% of people being highly annoyed. A number of caveats should be noted concerning the studies used in the Levels Document's analysis of noise annoyance:

1) The three survey studies used activity interference based questions to assess annoyance. Only in the London surveys was one direct annoyance question asked.
2) The three studies all classified a respondent as being highly annoyed if they scored in the upper 50% of the annoyance scale.
3) While the London surveys contained noise exposure data that could be converted to L_{dn}, the U.S. surveys reported noise exposure only in Composite Noise Ratings (CNR). CNR is a weighted metric that is calculated based on the maximum noise level of a single event and the number of events. The Levels Document converts results to L_{dn}. Accurate conversions between CNR and L_{dn} require the number of events and the peak sound levels during those events. However, in the absence of these data, the authors of the Levels Document used approximate conversions. These approximations introduce inaccuracies in the graphs and data presented by the Levels Document, and thus the resulting predictions as well.
4) The data presented in Figure 8 (Figure D-13 in the Levels Document) comes directly from Borsky's analysis of the London and U.S. surveys. It only includes percent highly annoyed from respondents categorized as having moderate fears of the sound source or a moderate belief of misfeasance by the aircraft operators, and ignores responses from high or low fears or feelings of misfeasance. Data from people with moderate feelings about the sound source were said to represent an average of the dataset as a whole. (Borsky, 1973).

The possible sources of uncertainties and inaccuracies due to the caveats laid out above call into question the accuracy of the predicted percent highly annoyed at the recommended levels of environmental noise in the Levels Document. This is in addition to the small number of survey studies, data points, and study populations used in this analysis. While the proposed exposure-response relationship simplifies predictions of adverse effects, the narrow study population and studies included make it impossible to apply this relationship to the nation as a whole. For these reasons, any comparison of these results with other, more recent synthesis studies should be made with caution.

The caveats above indicate that the Levels Document generally did not consider the complex physical, physiological, and psychological process by which a person becomes annoyed to environmental noise. In order to model the exposure-response relationship accurately, a comprehensive understanding of this process is necessary which takes into account the multiple factors that affect a person's attitude toward noise. The following section will discuss these factors in depth as they relate to noise exposure and annoyance.

2.3.2 The Annoyance Exposure-Response Model

In order to better assess the findings of noise annoyance survey research and understand the large variation in results over the last 60 years of research, it is important to recognize the theoretical pathway by which an annoyance response is produced from a noise source. Figure 9 shows an example of such a pathway or model. The remainder of this sub-section describes each element of the model and how it affects the overall exposure-response relationship.

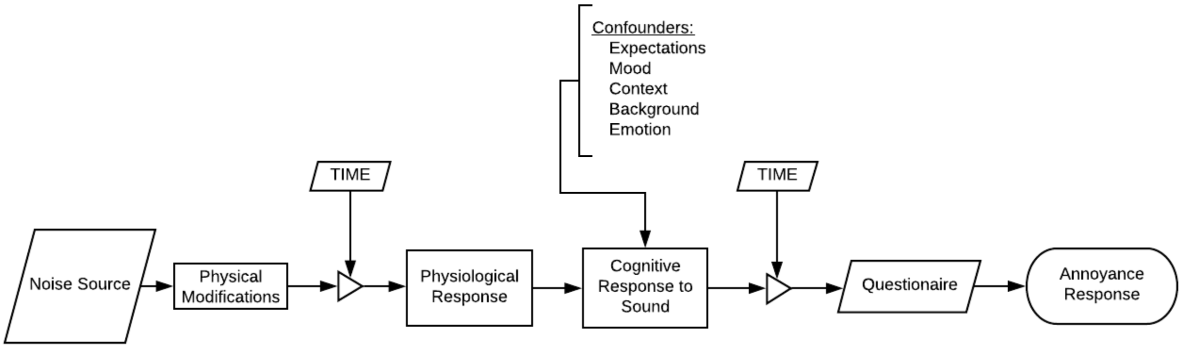


Figure 9. Annoyance exposure-response model.

2.3.2.1 Noise source

The noise source can be a moving source such as a transportation mode (i.e., air, rail, or road), or it can be stationary like a quarry or a wind turbine. The characteristics that differentiate the noise from various sources include the sound level produced, frequency content of the sound, intermittency, and the presence of pure tones. For example, highway noise tends to be a continuous noise source with broad frequency content, whereas aircraft noise consists of individual events that have more noticeable pitch or pure tones due to the operation of turbines or propellers.

The metric by which sound is measured and described can also affect how the annoyance response is quantified. While instantaneous sound levels can be useful for describing short-term, physiological effects of noise and sound, longer term averaging metrics are more apt to describe longer-term impacts of noise exposure like annoyance. While L_{dn} is most often used to relate noise exposure to annoyance survey responses, there are both benefits and drawbacks to its use. L_{dn} accounts for a full day, including nighttime sensitivity, as well as frequencies audible to the human ear. L_{dn} does not account for aspects of sound such as tonal content, impulsiveness, sharpness, and other qualities that have been shown to have a large effect on annoyance, and therefore are rarely included in published exposure response relationships.

2.3.2.2 Physical Modifications

Physical modifications describe how the sound travels from the source to the receiver. The ground over which the sound waves travel, the presence of natural or infrastructure barriers, and the weather can all have an effect on the levels of sound actually experienced by a person. Some of these factors are designed specifically to attenuate the sound levels reaching a receiver, like highway sound barriers or residential buildings with exterior walls designed to absorb sound rather than transmit it.

The most obvious physical modifications are the differences in levels experienced indoors versus outdoors. The Levels Document assumed that outdoor noise levels were about 15 dB higher than indoor levels. The authors came to this assumption based on a 1971 study by the Society of Automotive Engineers on indoor household noise from aircraft. This study reported average indoor noise levels in warm and cold climates around the country. The study reported reduction of decibels between indoor and outdoor noise levels for both a “windows open” and a “windows closed” situation in both region types. The approximate national average difference for the windows open scenario was 15 dB, while for closed windows the approximate difference was 25 dB. The Levels Document chose the more conservative, windows open estimate for their analysis of levels to protect the public health and welfare.

Other research, both in the 1970s and more recent, have found a range of differences between noise measurements indoors versus outdoors. Overall, the open windows condition usually shows a 10-15 dB reduction between outdoor and indoor sound levels, while the windows closed condition shows a 20-30 dB reduction. The difference can change with the frequencies and qualities of the sound striking the building, the geometry of the building, and the materials with which the building is constructed. In addition, most studies do not study the actual sound transmission characteristics of the building walls themselves, only the indoor noise levels in comparison with the outdoor ones. Thus, measurements include indoor noise sources such as noise from appliances or HVAC systems, or noise produced by building occupants (Locher, Piquerez, et al., 2018; Naim, Gulliver, Fecht, Hansell 2017).

2.3.2.3 Physiological Response

The physiological response represents the physical, sensory, and neurological response to noise, such as inner ear mechanisms and how the brain receives and processes acoustic information. It is well understood and can be studied objectively through laboratory studies where test subjects are stimulated by different types of sounds. The way a sound is perceived physiologically is affected by slight differences in people’s hearing ranges, neurological sensitivity to different frequency ranges, and differences in how quickly people adapt to changing sound stimuli. Relationships between physical sounds and how the brain perceives the sound can be measured by asking targeted questions using well-defined descriptive terms for the sounds. Studying how humans perceive changes in sound level, tone, or other aspects is also an effective way of describing these physiological phenomena. (Zwicker, Fastl, 1999)

2.3.2.4 Cognitive Response to Sound

Cognitive response to sound is the most difficult element in the annoyance exposure-response model to study, and is the main reason why the Levels Document did not focus on annoyance for their noise level recommendations. The Levels Document referred to these effects broadly as “attitudinal biases” towards sound that may not have anything to do with the noise itself or even the environment in general.

The confounders shown in Figure 9 list a few examples of attitudinal biases toward sound. Prior experiences with a certain type of noise, expectations about noise, beliefs about whether or not the noise can be abated, beliefs about the necessity of the sound source, or basic changes in emotional state can all have an effect on a subject's annoyance response. Individual noise sensitivity is also recognized as an important factor in how a person responds to environmental noise (Pederson, 2007).

It is difficult to quantify the effect of confounding factors in cognitive response on annoyance results. Measurement of these effects relies on people's answers to survey questions and cannot be objectively measured, so it may be impossible to know if a person's answers to these questions accurately reflect the annoyance response to noise. In addition, it is difficult to target these factors as independent variables in analysis of exposure-response relationships. Researchers who find correlations between noise exposure and annoyance often concede that large variations in data points should be expected due to difficulties measuring cognitive response variables (Miedema, Oudshoorn, 2001). Some of these effects are easier to measure than others. Age, length of time as a resident in the study region, the study region itself, and income brackets can all be measured objectively as part of demographic questions in annoyance surveys. Even so, researchers have found that subjective attitudinal factors, like fear of the sound source or expectations of changes, have a substantially larger effect on annoyance than demographic variables (Schreckenberg, Schuemer, 2010).

Overall, researchers have found that the effects of the confounding "non-acoustic" factors can account for up to 60 percent of the range in annoyance ratings seen in annoyance survey studies (Kroesen, Molin, van Wee, 2008). Other researchers have shown that certain non-acoustical factors, specifically negative expectations concerning the sound source and fear of the sound source, can predict noise annoyance more accurately than the sound exposure level (Schreckenberg, Schuemer, 2010).

2.3.2.5 Survey Questionnaire

The survey design can affect how respondents report annoyance. Survey design may include differences in negative and positive connotations, usage of certain words, and the rating scales used in the surveys. Early surveys from the 1960s and 1970s, varied widely in how they assessed how annoyed a respondent was to noise. Some surveys asked a direct annoyance question, and others determined overall annoyance from a set of activity interference ratings. This variation makes it difficult to compare results from early surveys directly. While performing mathematical conversions is sometimes an option, these are often approximations and thus introduce more uncertainty in results.

The International Commission on Biological Effects of Noise (ICBEN) has published standard survey questions to assess annoyance to environmental noise, with the most recent standard published in 2003. Additionally, the Transportation Research Board has sponsored recent research that led to the development of protocols for conducting large-scale social surveys on aircraft noise annoyance. These new protocols are currently being used by the FAA (Miller, Cantor, et al., 2014). In exposure-response studies, annoyance questions are usually asked on a 5-point verbal, or an 11-point numerical scale. The 5-point verbal scale has 5 options of responses ranging from "not at all annoyed" to "extremely annoyed." The 11-point numerical scale ranges from 0 to 10, with 0 indicating not at all annoyed and 10 indicating extremely annoyed. The responses from these questions are often converted to the "percent highly annoyed" metric. On the 5-point scale, respondents indicating in the top two categories (top 40%) are labeled as highly annoyed. In the 11-point scale, respondents indicating an 8 or higher (top 3 categories or top 27%) is labelled as highly annoyed. While the specific questions asked can have a large effect on annoyance results, the acceptance of these standard procedures has greatly increased the comparability of data across studies.

2.3.2.6 Time

Time affects the annoyance response at two locations in the model in Figure 9. The first time input describes short-term effects at the biological hearing system level, and the second describes longer-term cognitive effects.

Short-Term Biological Effects: The time input between physical modifications and physiological response reflects the human auditory system's ability to adjust its own sensitivity depending on short-term changes in sound exposure. This concept is very similar to how the iris within the human eye opens and closes the pupil depending on the amount of light to which the eye is exposed. By reducing sensitivity to rising amplitudes of sound, the ear can proactively prevent certain amounts of discomfort, even low levels of pain. However, this effect only works to the extent that rates of changes in sound levels are slow enough and the changes are small enough for the ear to compensate. Just as walking from a dark space into bright sunlight can be painful or make a person's eyes water, impulsive noise is often more painful or damaging to the human auditory system because there is not sufficient time for the hearing system to make the necessary adaptations.

Long-Term Cognitive Effects: Several long-term time factors affect a person's annoyance response to noise. To a certain extent, people who are exposed to noise for months or years report less annoyance to these noises because they have been conditioned to, or "gotten used to," these environmental noises. For example, people who have lived in cities for many years often report being less annoyed by roadway traffic noise than those who have moved to the area more recently. However, if noise is seasonal or intermittent, annoyance can actually be higher than for constant noise levels. The time of day, as well as season of the year are also time-related variables that affect the annoyance response after the cognitive response. The time between hearing a noise and responding to survey questions can also affect the resulting annoyance response. Additionally, there is evidence that the actual exposure-response relationship across a population may change slowly over time with changing public attitudes toward environmental noise, the economic vitality of a region, or changes to the noise sources themselves (Guski, Schreckenberg, Schuemer, 2017).

2.3.3 Recent Studies and Syntheses

Since the Levels Document was written, a wealth of annoyance survey data have been published. Earlier studies tend to focus on specific noise sources like aircraft noise or road traffic noise. Prominent researchers have combined the data from many different mode-specific studies into synthesis reports. These studies relate percent highly annoyed and raw annoyance ratings (0 to 100) to the day-night average sound level.

Schultz published one of the first syntheses of social surveys on noise annoyance in 1974. In this highly influential paper, Schultz offered a predicting equation for community reaction to L_{dn} based on 11 social surveys spanning multiple noise sources. Schultz only used survey data with comparable bases for categorizing a respondent as being highly annoyed or not. Survey data that were not based on easily comparable highly annoyed metrics were not included in his regression. While the resulting approximation curve was the best available predictor of community annoyance at the time, these results did not take into account differences in sound sources, non-acoustic factors, and other variables that are now known to have as large or larger effects than noise exposure on annoyance responses (Schultz, 1978).

In 1989, Sanford Fidell published an updated version of the Schultz curve that combined studies performed since Schultz's original paper was published with the data originally analyzed by Schultz. Fourteen newer studies were included in the 1991 report, all published between 1978 and 1985. Similar curve fits were performed in Fidell's paper as were included in the Schultz publication. The results in Fidell's updated analysis do not vary significantly from Schultz's results. The updated fits show marginally higher annoyance predictions at lower sound levels and slightly lower annoyance at higher sound levels using the same quadratic curve fitting method as Schultz (Fidell, Barber, Schultz, 1989).

In 2001, Miedema and Oudshoorn published another important annoyance synthesis. Based on similar survey data as the Fidell study obtained in the 1970s and 1980s, this statistical analysis was one of the first comprehensive studies to offer different exposure-response relationships for different transportation modes in a combined study. Miedema and Oudshoorn included data from Europe and the United States in this synthesis. Unlike Schultz, Miedema and Oudshoorn computed the probability that a person exposed to a certain noise level would respond with a certain annoyance rating on a 0 to 100 point scale. Relationships of percent highly annoyed to L_{dn} were calculated from these probability equations and are included as an alternative result for ease of calculation (Miedema, Oudshoorn, 2001).

The most recent major synthesis of annoyance survey data was published in support of the World Health Organization's (WHO) development of noise level recommendations for the European region, completed in 2018. This synthesis of over 100 studies presents exposure-response relationships by transportation mode. The analysis used data from studies performed since 2000. The combined dataset represents annoyance survey responses from over 60,000 respondents. This synthesis includes a wider breadth of regions, economies, and countries in the regression analysis than many other studies to date.

Figure 10 through Figure 12 show the results of the regression analyses for aircraft, road traffic, and rail noise from the WHO study. WHO displayed the Miedema and Oudshoorn relationships for comparison with the data from studies reviewed by the WHO researchers and on which the WHO regressions are based. The data points used in the WHO regressions were obtained using the regressions in the studies reviewed. The researchers took values of the regression equations at 5-decibel intervals, and then performed an overall regression using the full set of data points from all studies reviewed for each transportation mode. Thus, the equations provided can be thought of as averages of regressions from different studies, not regressions of the actual survey data from the original studies. The full range of study data is thus not shown on the graphs nor is it included in the WHO regressions. Note that the noise levels use the L_{den} metric.

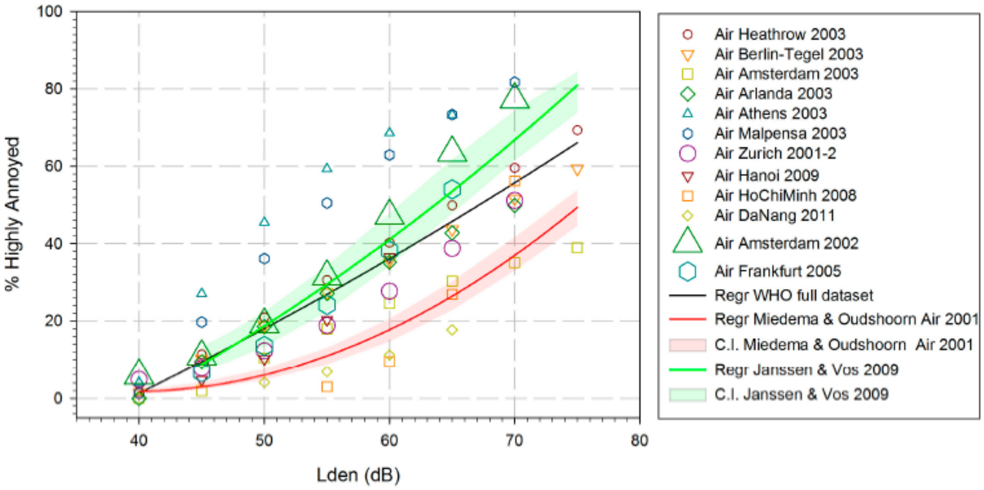


Figure 10. Percent highly annoyed related to aircraft noise levels in different regions. The black line here shows the correlation derived by the WHO researchers. The red line shows Miedema and Oudshoorn's correlation

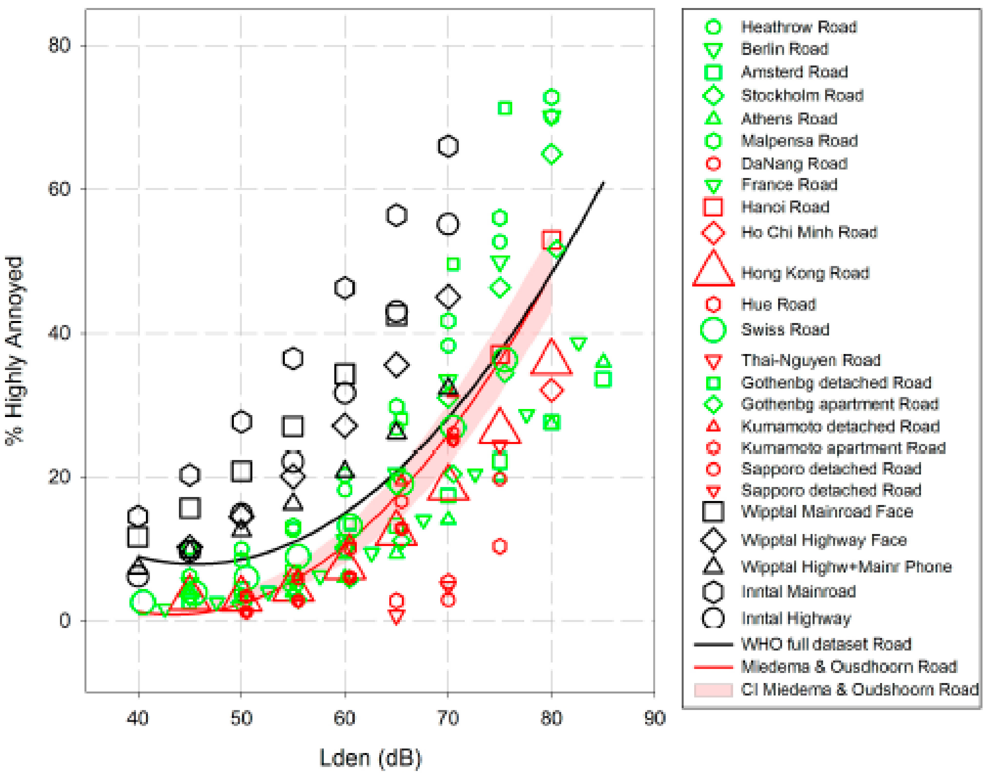


Figure 11. Percent highly annoyed related to roadway noise in different regions. The black line here shows the correlation derived by the WHO researchers. The red line shows Miedema and Oudshoorn's correlation

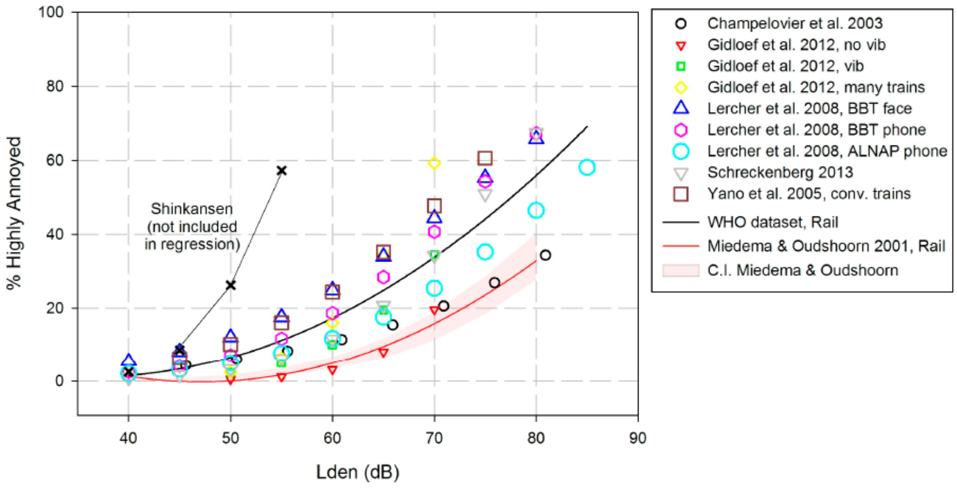


Figure 12. Percent highly annoyed related to railway noise in different regions. The black line here shows the correlation derived by the WHO researchers. The red line shows Miedema and Oudshoorn's correlation

One notable feature of the data depicted in the WHO results is the large range in percent highly annoyed at some sound levels. For example, for aircraft noise, percent highly annoyed ranges from 10% to 70% at 60 dB. For road traffic noise, the range is about 5% to 50% highly annoyed at 60 dB L_{den}. The use of L_{den} in the WHO studies reflects an attempt to account for slightly higher noise sensitivity in early evening hours. The use of this metric may make it more difficult to compare results from this study to other study results. The smallest range is found for railway noise, where the percent highly annoyed ranges from 2% to 25%. The large ranges in percent highly annoyed across many studies suggest that there are more variables that affect a subject's annoyance response to noise than the levels of noise to which that subject is exposed. As discussed in the previous section, the major contributors to these variations could be due to differences in cognitive response to noise between subjects and study populations (Guski, Schreckenberg, Schuemer, 2017).

2.3.3.1 Comparison between Studies

Table 6 shows a comparison of the results given by different studies discussed above. The values of percent highly annoyed are the values given by the regression equations in each study at 55 dB L_{dn}. The results given by the Levels Document are also presented below, but comparison to this highly annoyed statistic should be done with care, as discussed previously.

Table 6. Comparison of results from different annoyance syntheses at 55 dB L_{dn}.

Study	Year	%HA	Notes
WHO Aircraft	2014	26.7	Survey data from Europe and Asia only
WHO Roadway	2014	11.0	
WHO Railway	2014	11.3	
Miedema Aircraft	2001	11.0	Survey data from North America, Europe, and Australia
Miedema Roadway	2001	6.6	
Miedema Railway	2001	2.4	
Fidell	1991	8.2	Combination of air, road, and rail noise
Schultz	1978	3.9	Combination of air, road, and rail noise
Levels Document	1974	17	Only aircraft noise; caveats discussed in Section 3.3.1

From the Miedema and WHO results shown in Table 6, aircraft noise is perceived as more annoying than rail and roadway noise. This is probably due to a few different factors. When noise contains more pure tones, as is the case with aircraft noise, people usually indicate they are more annoyed. The intermittency of aircraft noise might also be more annoying because people cannot habituate to intermittent sounds in the same way as continuous sounds. Feelings about the nearby airport or aircraft in general will also play a role, as these are confounding cognitive factors.

One feature evident in the data presented in Table 6 is the apparent rise over time in percent highly annoyed between 1978 and 2014. This is especially observable in the case of aircraft noise. One possible explanation for this increase is the different regions and countries included in the different studies. The WHO study is the first to include a substantial amount of data from Asian countries. On the other hand, U.S. studies are not included in the WHO report, mainly due to the lack of U.S. annoyance studies performed after the 1980s. Other researchers have noted that reported annoyance to aircraft noise seems to have risen since the studies performed in the 1970s. Different methodologies between old and new studies, increases in how quickly aircraft operations change at many airports, and changing attitudinal factors have all been discussed as possible reasons for this apparent increase. It is difficult to know if there are actual annoyance changes over time due to the lack of longitudinal studies performed over a period of time in the same region. More consistency in regions and methodology across the body of research will help control for certain confounding variables and thus improve understanding of annoyance to noise (Guski, 2017).

2.3.3.2 Studies on Confounding Factors

A few recent studies have attempted to examine how much activity interference and attitudinal variables affect annoyance responses to noise. Specifically, a study in 2010 and a study in 2015 used statistical techniques to analyze which non-acoustical factors explained the variance seen in the exposure-response relationships like the ones studied by the WHO researchers (Schreckenberg, Schuemer, 2010; Bartels, Marki, Muller, 2015). The 2010 study was able to show through beta coefficient analysis that the most important predictors of long-term annoyance were negative expectations of changes to the sound source, fear of the sound source, and the actual sound exposure level (beta coefficients 0.33, 0.37, and 0.25, respectively). Beta coefficients are results of statistical regression analyses that give an idea of how sensitive annoyance is to changes in the relevant predictor. Higher beta values mean that annoyances changes more with changes in that predictor than with others predictor variables.

The two non-acoustical variable studies also show that interference with relaxation, eating, watching TV, or listening to the radio is more related to annoyance than interference with conversations. The noise level proposed in the Levels Document does not account for the importance of non-auditory activities. Despite this newer understanding, it is hard to assess levels of environmental noise with these factors in mind because there is no easy way to quantify attitudinal differences in a study population, and these factors may change in different study populations and over time (Schreckenberg, Schuemer, 2010; Bartels, Marki, Muller, 2015). However, with more data and surveys that address these complicated variables, a better understanding of their importance to the annoyance response will be obtained.

2.3.4 Summary and Research Gaps

The Levels Document specified that annoyance from environmental noise exposure was mostly caused by activity interference, specifically speech interference. The Levels Document discussed a number of annoyance studies and used results from three studies on aircraft noise annoyance at nine airports to calculate a prediction for the annoyance impact at the proposed level to protect against speech interference. While the studies used in this analysis were influential at the time, there were a number of simplifications and conversions to the data used that make the prediction dubious. Overall, the authors of the Levels Document did not feel there was substantial evidence available to determine a level requisite to protect against annoyance.

As described in the annoyance exposure-response model, some aspects of an annoyance response to noise can be measured and observed objectively and quantitatively, while others are complex social and attitudinal differences between participants and regions that are often subjective and self-reported.

Despite the wealth of annoyance survey data available, there are large discrepancies in correlations derived from different data sets. Percent highly annoyed can range from 10% to 70% in different studies at the same noise exposure level. The large range may be caused by various non-acoustic effects like attitudinal differences or age range of the study population. Some studies have given a better idea of which non-acoustical factors are more important in predicting an annoyance response.

Research gaps include controlling for or quantifying the effect of confounding, non-acoustic variables in annoyance studies. Studying distributions of confounding variables both within study populations and across multiple studies will provide a better understanding of their overall effect. Systematic corrections for non-acoustical factors may also be studied in an attempt to reduce variance in the study data through more focused survey questions or annoyance rating scales. Another way to control for these confounding factors is to perform similar studies in the same region over longer periods. Differences in culture and general environment can be controlled for in this way.

An additional area where more research is needed is in the use of alternate or multiple metrics to describe the source of noise. While L_{dn} is useful for describing long-term annoyance from cumulative noise exposure, it fails to capture qualities of the sound that may play a part in the annoyance exposure-response relationship. Correlations of percent highly annoyed to other metrics may give smaller ranges in percent highly annoyed at certain noise levels and may be more representative of the exposure-response model described previously.

Another major research gap is the lack of U.S. annoyance surveys performed after the 1980s. The most recent published syntheses and research have been done exclusively on foreign study populations, and the results are difficult to extrapolate to the U.S. This gap is currently being addressed by the Federal Aviation Administration in a nationwide mail and telephone survey. While the results of this survey are not yet published, they are expected to update the exposure-response curves informing the FAA's consideration of national policy on aviation noise.

2.4 Health and Sleep Impacts

2.4.1 How the Levels Document Addressed Health and Sleep Impacts

The Levels Document assumed that protection against noise-induced hearing loss is sufficient for protection against other health effects of noise. The document stated, "At this time, there is insufficient scientific evidence that non-auditory diseases are caused by noise levels lower than those that cause noise-induced hearing loss" (p. 22).

The Levels Document identified potential pathways for non-auditory health effects of noise, although it noted that a causal link had not yet been established. It stated, "Noise of lesser amplitude than that traditionally identified for the protection of hearing causes regular and dependable physiological responses in humans. Similar noise-induced physiological changes in sensitive animals regularly leads to the development of stress-related disease. The implications of generalizing from these animal studies to humans is not clear" (Appendix E, p. 210).

The Levels Document mentioned several physiological changes caused by noise, but noted that the link between these effects and long-term health had not been established. These physiological impacts include:

- Pain in the auditory system, change in balance, and startle reflex (caused by intense, very loud noise typically only found in occupational settings);
- Sleep interference;
- Fatigue, irritability, or insomnia;
- Stress; and
- Cardiovascular system impacts (vasoconstriction of the peripheral blood vessels and pupillary dilation)

Regarding sleep specifically, the Levels Document provided a theory that protecting against outdoor speech interference would also protect against sleep interference. It states, "[M]aintenance of this [55 dB L_{dn}] outdoor level will provide an indoor L_{dn} of approximately 40 dB with windows partly open for ventilation. The nighttime portion of this L_{dn} will be approximately 32 dB, which should in most cases, protect against sleep interference" (p. 39).

Since the Levels Document was published, additional research has been conducted to establish the relationship between noise exposure and negative health effects, particularly around sleep disturbance and cardiovascular impacts. This research is summarized below.

2.4.2 Current State of Research

In the last several decades, much research has been done on the effects of noise exposure on sleep disturbance and cardiovascular and metabolic health. Significant advancements in the understanding of the effect of noise on sleep have been made. There is less evidence about the relationship between noise and adverse cardiovascular outcomes, and a great deal of ongoing research in this area.

2.4.2.1 Sleep Impacts

Nighttime noise can disrupt sleep, either by making it difficult to fall asleep or by causing people to wake up during the night. Whether or not an individual's sleep is disrupted depends on individual characteristics such as noise sensitivity or age, noise exposure levels, and situational factors such as sleep stage (see Figure 13). Noise is one of many factors that can disrupt sleep; other factors include health conditions like sleep apnea, or work or family commitments that limit sleep duration.

Sleep is critical to many aspects of human health, including cognitive performance, memory, metabolism, immune and hormone function, and cardiovascular system (Watson et al, 2015). Sleep disturbance or curtailed sleep may lead to short-term effects, such as drowsiness and decreased performance. If chronic sleep disturbance occurs, it can lead to long-term health effects, including negative cardiovascular outcomes (Basner and McGuire, 2018).

The negative health impacts of sleep disruption and curtailment have been well documented in epidemiological studies (for example, see Watson et al, 2015; Somers et al, 2008). Therefore, this literature review focuses on the relationship between noise exposure and sleep disturbance rather than the impacts of sleep disturbance itself.

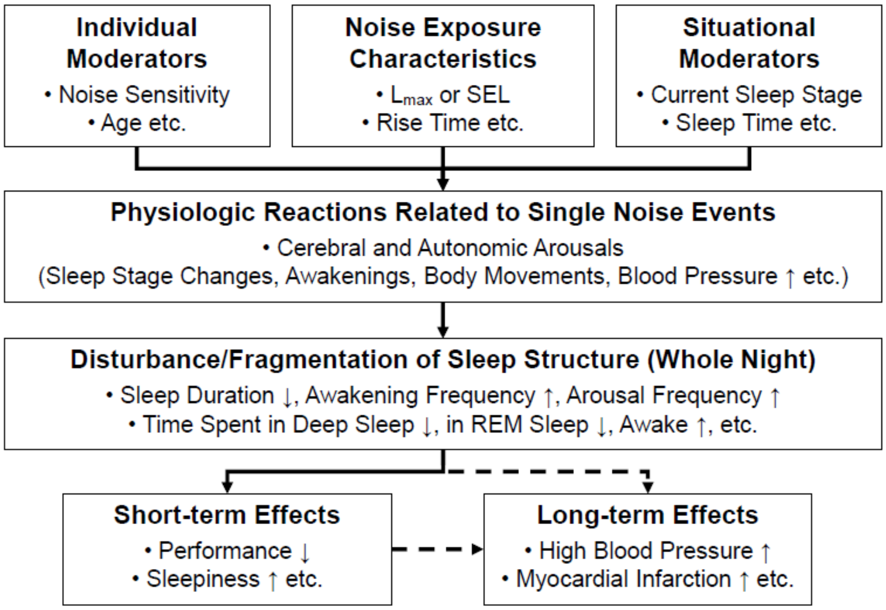


Figure 13: Summary diagram of the effects of noise on sleep. The dashed lines indicate the health consequences that may develop if sleep is disturbed by noise over long periods. (Source: Figure 1 from Basner and McGuire 2018).

Studies that investigate the impact of noise on sleep attempt to isolate the impact of noise by comparing similar populations exposed to different noise levels or by controlling for potentially confounding factors at the individual level. Studies on the effects of noise exposure on sleep typically use one of several methodologies for measuring sleep and sleep disturbance: polysomnography, actigraphy, signaled awakenings, and questionnaires. Basner and McGuire (2018) describe these methods based on relevant literature:

- *Polysomnography* is considered the “gold standard” of sleep measurement. It involves the simultaneous measurement of brain electric potentials, eye movements, and muscle tone in 30-second increments throughout the night. Polysomnography is the only method that allows for the measurement of sleep stages and sleep structure. However, it requires specialized personnel to attach and detach the electrodes and visually score sleep stages. This limits the sample size of studies that use polysomnography.
- *Actigraphy* infers sleep or wake from wrist movements measured with a watch-like device that is typically worn for 24 hours. These devices are now available on the consumer market, but unlike polysomnography do not provide information on sleep stages.
- *Signaled awakenings* involve participants pressing a button when they wake up during the night. A challenge with this approach is that it requires participants to wake up and be motivated to press a button, so may be less accurate than methods that do not rely on people to take an action.
- *Questionnaires* or surveys are used to ask about past awakenings or other aspects of sleep quality, and may refer to one night or longer periods. These subjective assessments of sleep do not always agree with objective measurements. In addition, when a question asks specifically about a noise source it may bias the responses.

The studies on noise exposure and sleep reviewed as part of this literature review were meta-analyses that analyzed two types of studies: those that used polysomnography to estimate the noise level at which someone would be awakened, and those that used surveys on self-reported sleep disturbance.

Measuring Awakenings

One of the most comprehensive recent studies on the connection between noise and sleep was conducted by the World Health Organization in 2018 (Basner and McGuire). The study involved a systematic review of 74 articles published between 2000 and 2015 on the effects of environmental noise exposure on sleep. The study involved a pooled analysis of polysomnographic studies on the acute effects of transportation noise on sleep. In also included a meta-analysis of questionnaires linking road, rail, and aircraft noise exposure to self-reports of sleep disturbance (that portion of the study is described in the Self-Reported Sleep Disturbance section below).

For the pooled analysis, the authors estimated the effect of noise on sleep disturbance by calculating both an unadjusted model and a model that was adjusted for age, gender, weekday, and time from sleep onset. They used the unadjusted model to derive exposure-response relationships between noise levels and the probability of awakening. These exposure-response relationships are shown in Figure 14. The study found that for a noise level of 55 dB ($L_{AS,max}$), the probability of an additional awakening or change to sleep stage 1 (S1) in a 90-second window after the noise event was approximately 5 percent for road, aircraft, and rail noise.

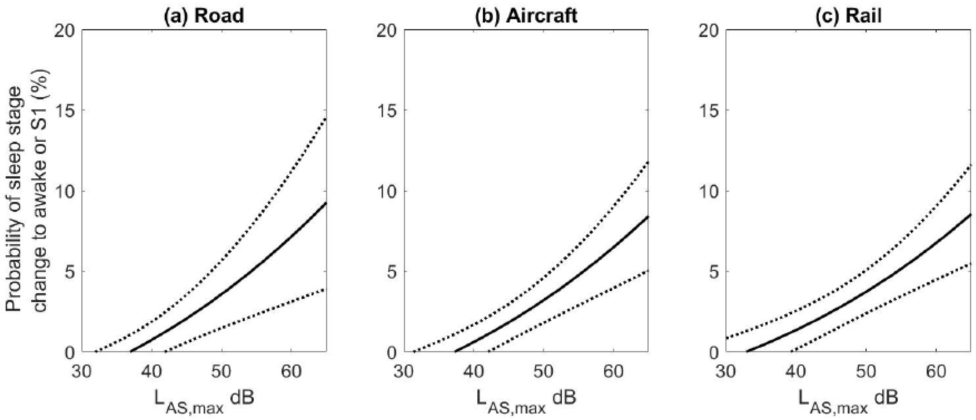


Figure 14: Basner and McGuire functions showing the probability of additional sleep stage changes to awake or S1 in a 90-second time window following a noise event depending on the maximum indoor sound pressure level (L_{ASmax}). Dashed lines indicate 95% confidence intervals. The results shown are for the three unadjusted models based on transportation noise source. Source: Figure 6 from Basner and McGuire 2018.

Self-Reported Sleep Disturbance

The Basner and McGuire study also involved a meta-analysis of surveys that used self-reported sleep outcomes. The authors used data from the studies reviewed to derive exposure-response relationships for the percent highly sleep disturbed for the different sleep outcome measures: awakenings from sleep, difficulty falling asleep, and a combined estimate. Since each of the studies in the meta-analysis asked different questions about sleep disturbance and had different response options, the authors calculated a binary variable for highly sleep disturbed based on the data in the individual studies reviewed. They categorized respondents as highly sleep disturbed if they chose the top two ratings for sleep disturbance on a 5-point scale (top 40%) or the top three ratings on an 11-point scale (top 27%), or if they reported symptoms of sleep disturbance three or more times per week.

For L_{night} between 40 and 65 dB, the meta-analysis found a statistically significant association between noise exposure and sleep disturbance when the noise source was mentioned in the question. These exposure-response relationships are shown in Figure 15. In general, respondents reported higher sleep disturbance (both falling asleep and awakenings) for aircraft noise than for equivalent levels of road and rail noise. When the noise source was not specifically mentioned, for most of the sleep measures and noise sources there was an association between noise and sleep disturbance, but these associations were not statistically significant. The authors note that this indicates that the context or wording of the questions could bias the results. In this case, directing someone’s attention to a noise source may make it more likely that they will say that this noise source disrupts sleep.

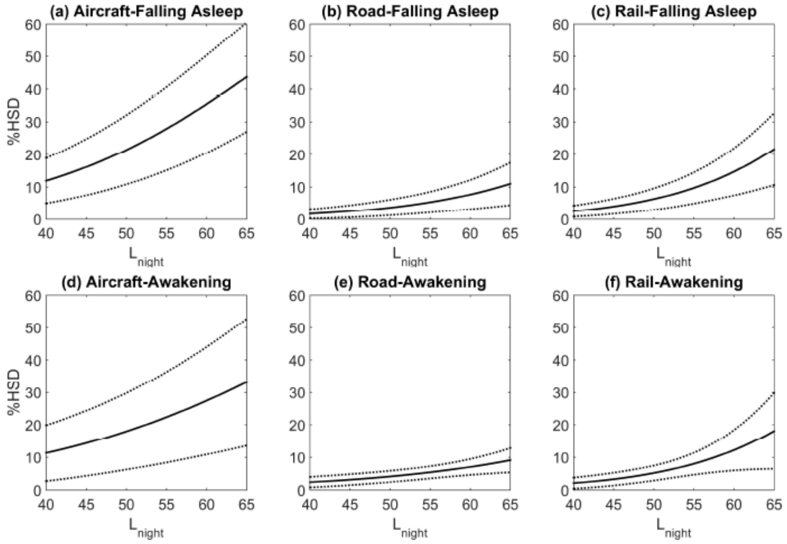


Figure 15: Basner and McGuire functions showing the percent highly sleep disturbed (HSD) based on responses to questions on awakenings or difficulty falling asleep for road, rail, and aircraft noise. The graphs are for studies that asked about how noise affects sleep, and the dashed lines are 95% confidence intervals (Source: Figure 7 from Basner and McGuire 2018).

The exposure-response models in Figure 15 allow for the estimation of the percentage of people who are expected to be highly sleep disturbed at different noise levels. For example, when the noise source was mentioned in the question, the percentage of study participants that were highly sleep disturbed for L_{night} levels of 45 dB of road noise was approximately 3 percent, while for rail noise that figure was 3.3 percent. For aircraft noise, approximately 15 percent of the study population was estimated to be highly sleep disturbed for the same noise level. While the article does not provide an explanation for why the percentage highly sleep disturbed was higher for aircraft than for other noise sources, this may be due to either the characteristics of aircraft noise or to people's reactions to the noise. People perceive intermittent noise like aircraft flyovers differently than constant noise such as road traffic, even though the average noise (L_{night}) may be the same. This intermittent aircraft noise may cause more sleep disturbance, or people may report being more sleep disturbed because they are annoyed by aircraft flyovers (see the Annoyance section 3.3). In addition, aircraft noise has more high frequency tones than other noise sources, and aircraft pass overhead, which could cause people to perceive danger and awaken.

The meta-analysis used by Basner and McGuire was similar in methodology to a previous study conducted by Miedema and Vos (2007). That study involved a re-analysis of pooled data from studies on the association between self-reported sleep disturbance and exposure to nighttime transportation noise. Since the studies reviewed used different scales for sleep disturbance, the authors translated the results into a scale of 0-100, based on the assumption that a set of sleep disturbance categories divides this range into equally spaced intervals. Based on this 100 point scale, Miedema and Vos categorized sleep disturbance as follows:

- 72.01-100: Highly sleep disturbed
- 50.01-72: Sleep disturbed
- 28.01-50: At least a little sleep disturbed

The authors then developed functions for the percentage of people who were highly sleep disturbed for different L_{night} levels between 45 and 65 dB (see Figure 16). These functions show that at the same average nighttime noise-exposure level, aircraft noise is associated with more self-reported sleep disturbance than road traffic, and road traffic noise is associated with more sleep disturbance than railways. For example, at an L_{night} of 45 dB approximately 3.6 percent of the participants reported being highly sleep disturbed from road noise, while 2.3 percent were highly sleep disturbed from rail noise, and 4 percent were highly sleep disturbed from aircraft noise.

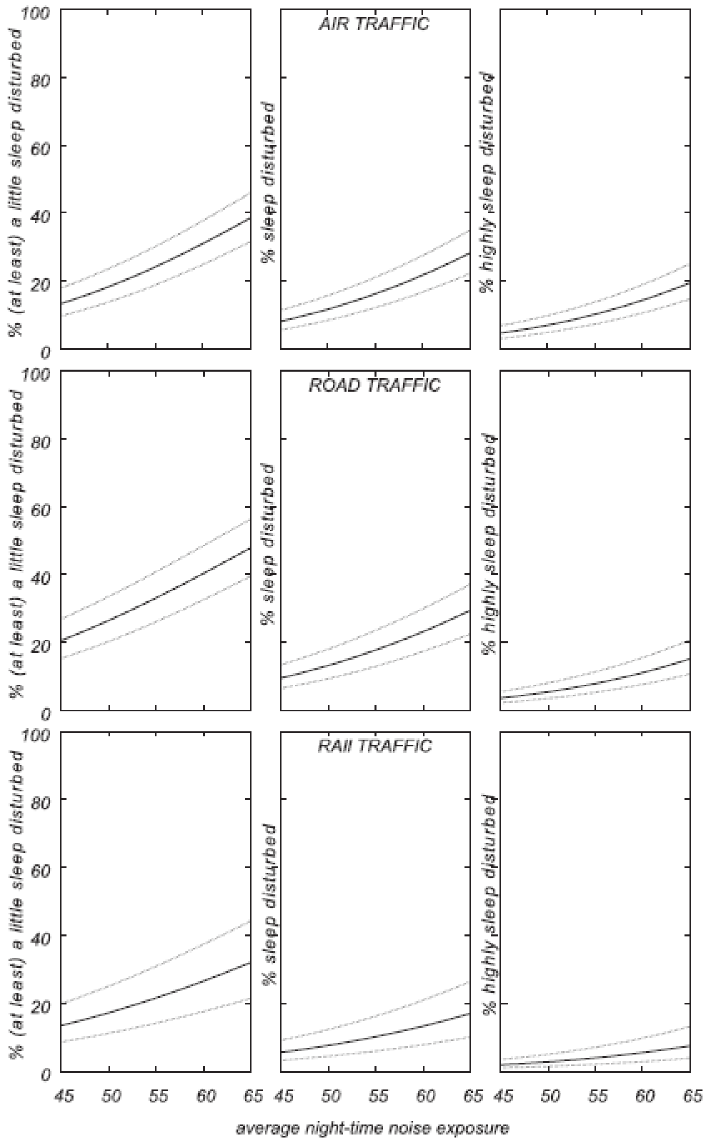


Figure 16: Functions showing sleep disturbance measures in relation to the average nighttime exposure outside at the most exposed façade. The dashed lines show 95% confidence intervals. (Source: Figure 1 from Miedema and Vos 2007).

While the estimates for disturbance from road and rail noise in Miedema and Vos are similar to Basner and McGuire, the percent highly sleep disturbed from aircraft noise was more than 10 percentage points lower at all noise levels studied. Basner and McGuire suggest several potential reasons for these differences. The studies used different methodologies to derive the models and reviewed different studies as part of the meta-analysis. For example, Basner and McGuire included several studies from Japan and South Korea, where attitudes towards noise could be different from Europe. In addition, Miedema and Vos looked at studies conducted between 1971 and 2004, while Basner and McGuire looked at studies from the year 2000 or later. Recent updates to annoyance exposure-response curves have found an increase in annoyance for aircraft noise, but not for other noise sources (see Annoyance section 3.3); this increase in annoyance could also present itself as an increase in self-reported sleep disturbance.

The Miedema and Vos study also looked at the age of respondents and found that the association of noise-induced sleep disturbance with age has an inverse U-shape, with the strongest reaction found between 50 and 56 years of age, and lower effects at both younger and older ages. The authors suggest that the lower effect of noise at higher ages may be because hearing capacity declines with age. However, they note that this does not explain the lower effect of noise at younger ages or the inverted U-shape of the data, and suggest that it may be due to age-related changes to the way the brain processes information.

2.4.2.2 Cardiovascular and Metabolic Impacts

Noise can lead to adverse cardiovascular health outcomes by disrupting sleep and/or causing stress. Studies on the impact of noise on cardiovascular health look at different health outcomes. These include hypertension, ischemic (coronary) heart disease, and stroke. Metabolic outcomes such as diabetes and obesity have also been studied.

Research on the connection between noise exposure and cardiovascular impacts typically involves observational studies that look for associations between the occurrence of disease and the exposure to noise at a population or individual level. Since these observational studies do not include a randomized control group, they aim to demonstrate associations rather than trying to establish causation. These studies may be:

- cross-sectional studies (measures health outcomes in a population at a period in time);
- cohort studies (following a group within a population for a specified period of time); or
- case control studies (retrospective studies that compare cases who have a certain condition with a control group known not to have developed the outcome of interest) (Coggon et al).

Ecological studies, which compare outcomes at the population or community level rather than the individual level, are also used.

Van Kempen et al (2018) conducted a literature review of studies on the association between cardiovascular and metabolic outcomes and noise exposure by evaluating 61 studies across different health outcomes and transportation noise sources. The authors calculated the change in health metric (relative risk, blood pressure change, or change in body mass index or waist circumference) per 10 dB (L_{DEN}) noise level increase for each noise source (air, road, and rail traffic) and health outcome (risk of hypertension, ischemic heart disease, stroke, diabetes, and obesity). It also ranked the quality of the evidence for the association between the noise source and health outcome using a modified version of the GRADE criteria (see Table 7).[9]

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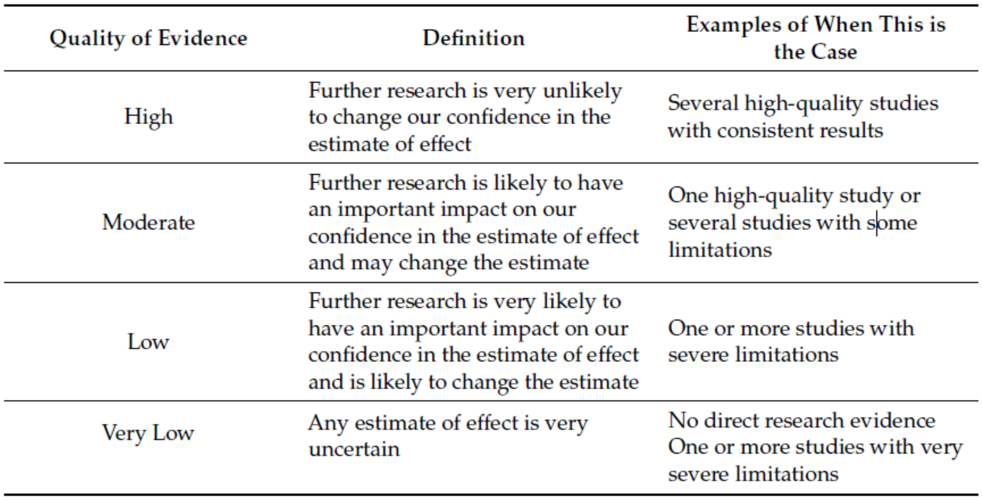
[9] For more information on GRADE to rate quality of evidence and strength of recommendations, see: https://www.bmj.com/content/336/7650/924.

Table 7: The levels of quality of evidence of the GRADE system (Source: Table 1 from Van Kempen et al 2018)



Quality of Evidence	Definition	Examples of When This is the Case
High	Further research is very unlikely to change our confidence in the estimate of effect	Several high-quality studies with consistent results
Moderate	Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate	One high-quality study or several studies with some limitations
Low	Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate	One or more studies with severe limitations
Very Low	Any estimate of effect is very uncertain	No direct research evidence One or more studies with very severe limitations

The authors applied the GRADE criteria to each of the individual articles, as well as to the overall findings for each combination of noise source and health outcome. Although many of the individual studies reviewed found statistically significant associations between noise exposure and cardiovascular outcomes, for most of the summary findings the authors ranked the quality of evidence as low using the GRADE criteria (see Table 8), indicating that future research is likely to change the findings. The authors rated the quality of evidence as low largely due to study designs (e.g., mostly ecological and cross-sectional studies rather than more robust case-control or cohort studies), limited number of studies on the topic, or conflicting results between studies. The strongest evidence was for the association between road traffic and ischemic heart disease (IHD), which the authors rated as moderate. For this association, the studies reviewed indicated that the risk of IHD increases continuously for road traffic noise levels from about 50 dB L_{DEN}. The relative risk of the incidence of IHD per 10 dB L_{DEN} was 1.08 within the range of 40-80dB.[10] Compared with cardiovascular outcomes, Van Kempen et al found fewer studies that looked at the impact of noise on the metabolic system (diabetes and obesity), and the results were not consistent. The authors state that it is too early to draw connections about the impact of noise on the metabolic system.

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[10] The relative risk is the ratio of the probability of an event occurring in an exposed group compared with the probability of it occurring in a non-exposed group.

Table 8: Summary of findings from Van Kempen et al 2018.

Health outcome	Noise source	Number of studies reviewed	Quality of evidence supporting association between noise source and health outcome
Hypertension	Air traffic	10	Very low
	Road traffic	27	Very low
	Rail traffic	6	Very low
Ischemic heart disease (IHD)	Air traffic	7	Low
	Road traffic	19	Moderate
	Rail traffic	4	Very low
Stroke	Air traffic	7	Low
	Road traffic	6	Low
	Rail traffic	1	Low
Diabetes	Air traffic	2	Low
	Road traffic	3	Low
	Rail traffic	2	Low
Obesity	Air traffic	2	Low
	Road traffic	6	Low
	Rail traffic	4	Low

Another recent literature review (Peters et al, 2018) focused on aviation noise and cardiovascular impacts. This study involved a review of 17 studies on aircraft noise and cardiovascular impacts that were published between 2013 and 2017. Sixteen of the studies were based in Europe, and one was based in the U.S. The literature review found that the studies generally report statistically significant associations between aircraft noise and a range of adverse cardiovascular outcomes. In particular, adverse cardiovascular outcomes were found to have statistically significant associations with nighttime aircraft noise exposure. The associations between aircraft noise and cardiovascular outcomes were stronger in subgroups either that were more highly exposed to aircraft noise or that had risk factors for adverse cardiovascular outcomes. The article also suggests areas for further research, which are described in the Research Gaps section below.

In the U.S., the largest recent study on the impact of transportation noise on cardiovascular outcomes involved a study of aviation noise across 89 airports (Correia et al, 2013). The study used a dataset of Medicare billing claims information of 6 million adults over age 65 living near airports, and noise contours of outdoor L_{dn} provided by the FAA (starting at 45dB).[11] The health outcomes studied were hospital admissions for cardiovascular disease, including heart failure, heart rhythm disturbances, cerebrovascular events, ischemic heart disease, and peripheral vascular disease. The study used two types of statistical analysis to determine the effect of noise on cardiovascular outcomes. First, the authors used a hierarchical Poisson regression model to calculate the percentage increase in the zip code level hospital admission rate associated with a 10 dB increase in the zip code level aircraft noise (within the 45 dB contour and higher). They also adjusted for potential confounding variables, including

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[11] The noise contours were based on results modeled in FAA's Integrated Noise Model version 7.0a (2007).

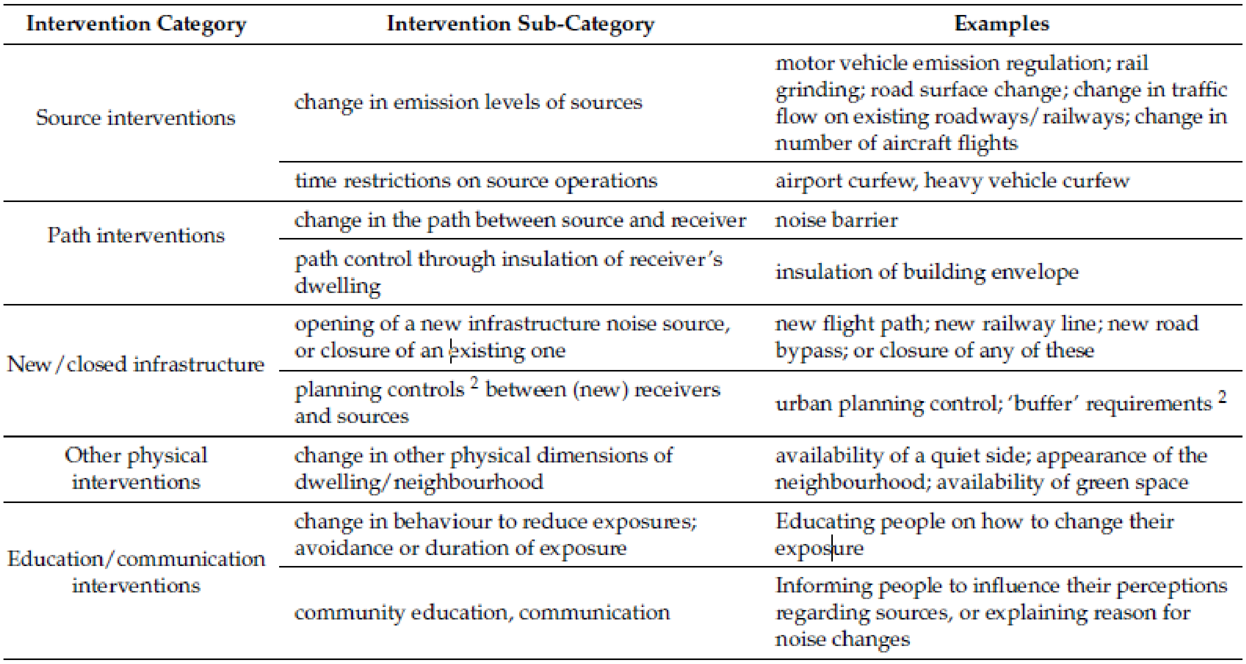
socioeconomic status (specifically percentage Hispanic and median household income) and air pollution (zip code level fine particulate matter [$PM_{2.5}$], ozone concentrations, and road density). Based on this analysis, the study found that across all of the airports in the study, a zip code with a 10 dB L_{dn} higher noise exposure had a 3.5% higher cardiovascular hospital admission rate.

This study also investigated the evidence of a potential non-linear association between exposure to aircraft noise and hospital admission. The authors studied this by replacing the aircraft noise exposure variable (originally defined as a continuous variable) with a categorical variable indicating low, medium, or high exposure to aircraft noise (50 dB or less, 50-55 dB, and higher than 55 dB). Based on this analysis, the study found evidence of a threshold for the effect of noise on cardiovascular hospital admissions. It found consistent statistically significant associations in only the highest exposure group (>55 dB).

2.4.2.3 Intervention Studies

Another category of studies on the relationship between noise and health looks at how health outcomes compare before and after an intervention to reduce noise. Brown and Van Camp (2017) conducted a literature review of studies from 1980 to 2014 on evidence of the effects of transportation noise interventions (for aircraft, road, and railroad noise) on human health. They categorized the interventions as shown in Table 9 below.

Table 9 Noise Interventions (Source: Brown and Van Camp 2017 Table 1)



Intervention Category	Intervention Sub-Category	Examples
Source interventions	change in emission levels of sources	motor vehicle emission regulation; rail grinding; road surface change; change in traffic flow on existing roadways/ railways; change in number of aircraft flights
	time restrictions on source operations	airport curfew, heavy vehicle curfew
Path interventions	change in the path between source and receiver	noise barrier
	path control through insulation of receiver's dwelling	insulation of building envelope
New/closed infrastructure	opening of a new infrastructure noise source, or closure of an existing one	new flight path; new railway line; new road bypass; or closure of any of these
	planning controls [2] between (new) receivers and sources	urban planning control; 'buffer' requirements [2]
Other physical interventions	change in other physical dimensions of dwelling/ neighbourhood	availability of a quiet side; appearance of the neighbourhood; availability of green space
Education/communication interventions	change in behaviour to reduce exposures; avoidance or duration of exposure	Educating people on how to change their exposure
	community education, communication	Informing people to influence their perceptions regarding sources, or explaining reason for noise changes

The analysis of studies in the literature review showed that many of the interventions were associated with improvements in health outcomes irrespective of the source type, intervention type, or outcome measured. For road noise, the authors found evidence in the studies reviewed of a statistically significant association between three types of interventions (path, new/closed infrastructure interventions, and other physical) and reduced sleep disturbance. One of the studies reviewed evaluated a source intervention on sleep disturbance from road traffic noise, but it did not find a statistically significant effect. The study also found evidence of an association between other physical interventions and cardiovascular effects. For aircraft noise, they found evidence of an association between new/closed infrastructure and reduced sleep disturbance. None of the studies reviewed looked at other types of interventions and sleep disturbance for aircraft noise. Similarly, none of the studies reviewed looked at the sleep disturbance or cardiovascular effects of rail noise.

Despite numerous studies finding associations between different noise interventions and health outcomes, the authors found that there was not enough evidence to compare health outcomes across interventions to determine which interventions are most effective. This was because there were many possible combinations of noise source, health outcome, and intervention type, and most of the combinations did not have more than several studies. There was also no clear evidence about the threshold of noise exposure change needed to result in a change in health outcome.

2.4.3 Summary and Research Gaps

The Levels Document assumed that protection against noise-induced hearing loss is sufficient for protection against other health effects of noise. Since the Levels Document was published, there has been substantial research on the connections between noise and sleep and noise and cardiovascular outcomes. It is now well understood that noise levels lower than those necessary to cause hearing loss (i.e., 70 dB $L_{Aeq(24)}$ per the Levels Document) can lead to other negative health outcomes including disrupted sleep and adverse cardiovascular outcomes.

Numerous studies have found a statistically significant association between noise exposure and sleep disturbance or curtailment, across all transportation noise sources. Sleep disruption can lead to both short and long term physiological impacts. Studies have used polysomnography to determine the noise level that is likely to awaken someone. A recent pooled analysis by Basner and McGuire (2018) indicates that at a noise level of $L_{AS,max}$ 55 dB, the probability of an additional awakening or change to sleep stage 1 (S1) in a 90-second window after a noise event is approximately 5 percent for road, aircraft, and rail noise. However, waking up once due to noise does not necessarily mean that an individual will feel disturbed by the noise or experience negative physiological effects.

Many studies have used questionnaires to establish exposure-response relationships between noise exposure and self-reported sleep disturbance. Meta-analyses of these studies (Basner and McGuire 2018; Miedema and Vos 2007) indicate that for a given noise level, self-reported sleep disturbance is higher for aircraft noise than for road or rail noise. For a nighttime noise exposure (L_{night}) of 45 dB, approximately 2-4 percent of respondents report being highly sleep disturbed from road or rail noise. These studies differed on the percentage of people highly sleep disturbed from aircraft noise, with a range of 4-15 percent at 45 dB. While most research studies of sleep disturbance or nighttime noise use cumulative metrics such as L_{dn} or L_{night}, further research is needed to determine whether the cumulative impact of noise or the effects of single noise events predominate in characterizing sleep disturbance.

As devices that use actigraphy to measure sleep based on wrist movements are becoming more widely available on the consumer market, there is an opportunity to use the data generated by these devices to further study the connections between sleep and noise and to complement other methodologies such as polysomnography and questionnaires. An advantage of actigraphy is that it allows for data collection from larger numbers of people than polysomnography. Future work will be needed to manage and analyze this crowd-sourced data and to determine if the relationships between noise and sleep derived from actigraphy are similar to those from other forms of sleep measurement.

The evidence for the relationship between noise exposure and adverse cardiovascular and metabolic outcomes is more limited. Although individual studies have shown a statistically significant association between noise exposure and adverse cardiovascular outcomes, there is not consistent evidence across studies for all noise sources and cardiovascular outcomes. The most consistent findings are for the association between ischemic heart disease and road traffic noise, where a recent meta-analysis found that the risk of IHD increases continuously for road traffic noise levels from about 50 dB (L_{DEN}) (Van Kempen et al, 2018).The evidence for the effect of noise on metabolic outcomes is even more limited.

Many of the studies on noise and cardiovascular and metabolic outcomes use cross-sectional or ecological study designs rather than the more robust methods of cohort studies and case control studies. There have also been a limited number of these studies conducted in the U.S., particularly on a large scale. Further research is needed to more definitively establish the relationship between noise exposure and cardiovascular and metabolic outcomes, and the noise levels at which these outcomes are experienced.

Another area for further research includes determining the noise metrics that are most predictive of cardiovascular outcomes (Peters et al, 2018). Similar to sleep disturbance, most studies of cardiovascular use L_{dn}, L_{Aeq}, or similar metrics that average noise across the day and/or night. However, further research is needed to determine whether these metrics or metrics that focus on the effects of intermittent noise sources should be used.

In addition, the effects of noise on health may not be evenly distributed across a population. Age, other health conditions, or socioeconomic status may all affect how an individual reacts to a given noise exposure. Further research is needed to determine how the association between noise exposure and health changes across different subgroups (Peters et al, 2018).

On the topic of interventions to reduce noise, further research is needed to determine the relative impacts of different interventions on sleep disturbance and health outcomes, across all noise sources. If this research concludes that certain interventions have a greater health benefit for the same amount of noise reduction, these interventions could be encouraged.

2.5 Cognitive Effects

This section describes research on the effects of noise on children’s learning, cognitive development, and cognitive performance. Research on this topic has examined a variety of cognitive outcomes, including reading comprehension, long and short-term memory, and standardized test scores. This section discusses the effects of environmental noise on cognition in children of varying ages, although most of the studies focus on elementary school-aged children.

2.5.1 How the Levels Document Addressed Cognition

The Levels Document discussed recommended noise levels to protect public health and welfare in different settings, including educational settings (classrooms, school buildings, and school grounds not used for athletics). The primary consideration for determining these levels is the prevention against activity interference, and in particular speech interference.

The Levels Document recommended the following levels for educational facilities:

- To prevent against activity interference: $L_{eq(24)}$ of 45 dB indoors, and $L_{eq(24)}$ of 55 dB outdoors (the document states that it provides the outdoor levels because teaching will sometimes occur outside the school building).
- To prevent against hearing loss: $L_{eq(24)}$ of 70 dB for both indoors and outdoors. The document notes that an $L_{eq(8)}$ of 75 dB may be acceptable as long as the exposure over the remaining 16 hours per day is low enough to result in a negligible contribution to the 24-hour average, i.e., no greater than an L_{eq} of 60 dB.

The Levels Document did not discuss the possibility that noise could affect children in schools in ways other than activity interference or hearing loss (e.g., through distraction or other cognitive impacts).

2.5.2 Other Guidelines for Noise Levels at Schools

The 1999 *WHO Guidelines for Community Noise* set recommendations for children's environmental noise exposure in school playgrounds and classrooms that differ slightly from the Levels Document in purpose and levels. The Guidelines stated:

- School playgrounds should not exceed 55 dB L_{Aeq} during play to protect against annoyance.
- School classrooms should not exceed 35 dB L_{Aeq} during class to protect against speech intelligibility and disturbance of information extraction.

Recent analyses (Clark and Paunovic, 2018) have noted that 35 dB L_{Aeq} is a very low level of noise exposure and considered unachievable by some. The WHO *Environmental Noise Guidelines for the European Region* were updated in 2018, but do not provide specific recommendations for school environments.

2.5.3 Current State of Research

Since the Levels Document was published, additional research has been conducted on the impact of noise on cognition. The sections below describe theories on the pathways through which noise affects cognition, research on noise at school and cognition, and research on noise at home and cognition. Overall, there is evidence that aircraft noise exposure negatively affects children's learning, but there is limited information available for other noise sources.

2.5.3.1 How Noise Affects Cognition

Noise can affect children's learning in several ways. First, noise can impair speech communication and listening comprehension (Clark and Paunovic, 2018; Klatte et al 2013). Speech interference is of particular concern for school environments because if children cannot hear fully in school it is more difficult for them to learn. In addition, children have more difficulty understanding speech in noisy conditions than adults do. One explanation for this is that children have less developed vocabularies, so they do not have the same ability as adults to use stored phonological knowledge or context clues to reconstruct words that are masked by noise (Klatte et al. 2013). Children also have less developed attention skills, which makes it harder for them to focus on speech if background noise is present (Klatte et al. 2013). For a more detailed discussion of the noise levels to protect against speech interference, see Section 2.2, Activity Interference.

Beyond speech interference, noise can affect children's learning and cognition by affecting memory, attention, and stress. Memory may be affected because irrelevant sounds are directly incorporated into working memory, interfering with relevant information (Klatte et al, 2013). Noise can also capture a child's attention, which may keep them from remembering important information (Klatte et al, 2013). In loud environments students may also "tune out" noise, a strategy that they may over-generalize by tuning out information important to learning as well (Clark and Paunovic, 2018). Additionally, noise exposure can lead to annoyance, which can cause physiological and psychological stress responses, affecting a child's ability to concentrate and learn effectively, as well as their mood (Clark and Paunovic, 2018). Finally, many students who go to school in loud areas are also affected by noise at home, which can disrupt their sleep (Clark and Paunovic, 2018). As described in the Health and Sleep Impacts section, sleep disturbance can hinder memory, performance, and other factors that could affect learning.

2.5.3.2 Noise and Cognition in School Environments

A recent meta-analysis of studies on the relationship between noise and cognition (Clark and Paunovic, 2018) was conducted in support of the new WHO *Environmental Noise Guidelines for the European Region*. The authors reviewed 34 papers on noise and children's cognition, and evaluated the strength of the evidence using the GRADE methodology (see the Health and Sleep Impacts section for a description of the GRADE methodology). The majority (74%) of the studies evaluated aircraft noise, while 32% looked at road noise. Only 9% of the studies evaluated rail noise, and 9% evaluated combined noise sources.[12] The majority of the studies used a cross-sectional design, while fewer used more robust study designs such as longitudinal studies (looking at the same population over time) or intervention studies (measuring cognition before and after a change in noise levels). The studies looked at various outcomes of cognition and learning, including reading and oral comprehension, memory, attention, impairments assessed through standardized assessments such as the SAT, and executive function deficit.

Table 10 summarizes key findings from Clark and Paunovic on the effects of environmental noise on cognition across different noise sources and cognition outcomes, as well as their assessment of the quality of evidence. The authors found that there was moderate quality evidence for a harmful effect of aircraft noise on reading and oral comprehension, standardized assessment tests, and long- and short-term memory. There was also moderate quality evidence for a harmful effect of railway noise on standardized assessment tests. The authors rated all other combinations of noise sources and cognition outcomes as having low or very low quality evidence. They note that this does not mean that the individual studies themselves were of low quality, but rather the overall evidence across the studies was of low quality. Many of the individual studies showed significant effects, but the overall evidence was

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[12] Since some of the studies considered multiple noise sources, the percentages add up to over 100%.

rated low because of a limited number of studies, conflicting findings across studies, or the methodology of particular studies (e.g., cross-sectional design rather than methods that are more robust).

Table 10: Summary of quality of the evidence and assessment of effect for environmental noise effects on cognition (Table 2 from Clark and Paunovic 2018).

	Environmental Noise Exposure		
Cognitive Domain	Aircraft Noise: Quality of Evidence & Assessment of Effect	Road Traffic Noise: Quality of Evidence & Assessment of Effect	Railway Noise: Quality of Evidence & Assessment of Effect
Reading and oral comprehension	Moderate quality—harmful effect	Very low quality—no effect	n.a.
Standardized assessment tests	Moderate quality—harmful effect	Very low quality—harmful effect	Moderate quality—harmful effect
Long-term and short-term memory	Moderate quality—harmful effect	Very low quality—harmful effect	Very low quality—harmful effect
Attention	Low quality—no effect	Very low quality—no effect	Very low quality—no effect
Executive function	Very low quality—no effect	Low quality—no effect	n.a.

n.a. no studies available to evaluate.

Several large-scale studies of the impact of noise on cognition in children have been conducted in recent years. Although many of these were included in the Clark and Paunovic review, the information in the individual studies provides additional details on the relationships between noise and cognition, and as such are described in more detail here. The RANCH study was a cross-national, cross-sectional study of nearly 3,000 children aged 9-10 attending 89 schools near airports in the Netherlands, Spain, and the United Kingdom (Stansfeld et al., 2005). The study found statistically significant associations between exposure to chronic aircraft noise and impairment of reading comprehension and recognition memory. In particular, a 5 dB difference in aircraft noise was associated with a 2-month reading delay in the UK and a 1-month reading delay in the Netherlands (national data on reading delay was not available for Spain). In the Netherlands and Spain, a 20 dB increase in aircraft noise was associated with a decrease of one-eighth of a standard deviation on a reading test; in the UK, the decrease was one-fifth of a standard deviation (see Figure 17).

The RANCH study also found that exposure to road traffic noise was linearly associated with improvements in episodic memory, which the authors noted, was not the expected outcome and required further study. The study did not find statistically significant effects for the association between aircraft noise and impairment in working memory, prospective memory, or sustained attention, or for the association between road traffic noise and reading comprehension, recognition, working memory, prospective memory, or sustained attention.

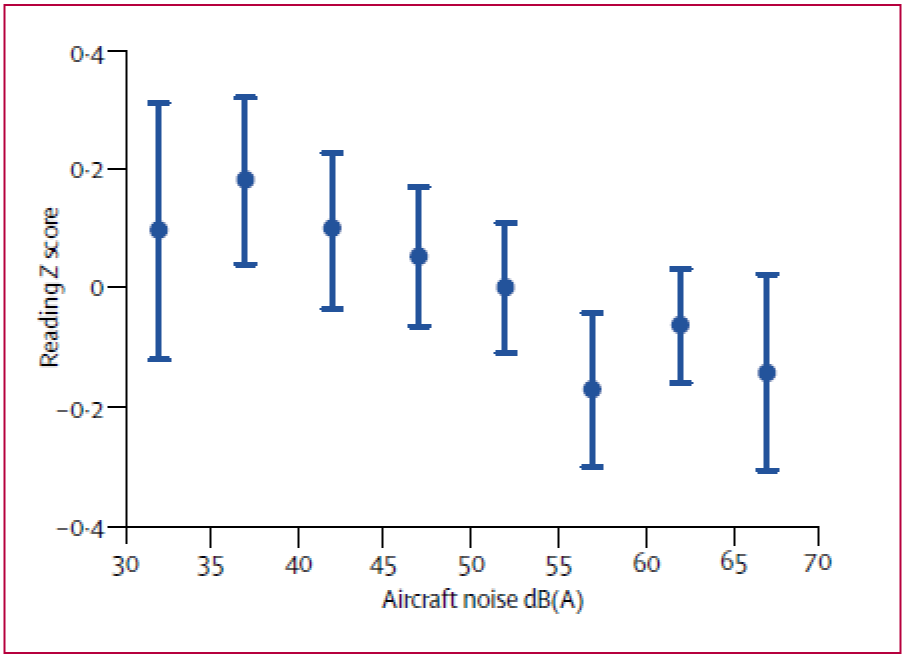

Figure 17: Adjusted mean reading Z score (with 95% confidence interval) for 5 dB bands of aircraft noise, adjusted for age, sex, and country. Figure 1 from Stansfeld et al, 2005.

In 2013, a follow-up to the RANCH study was conducted in the UK to assess the longitudinal effects of aircraft noise on children's cognition (Clark et al, 2013). The study involved 461 children in London aged 15-16 years who had also participated in the original RANCH study. The study found that aircraft noise exposure at both primary and secondary schools was associated with poorer reading comprehension at age 15-16, but this finding was not statistically significant. The authors noted that the study's small sample size might explain the lack of statistical significance for this finding.

Hygge et al. (2002) also evaluated the effects of aircraft noise on learning over time. The authors used the opening of a new airport in Munich, Germany and associated changes in flight patterns to conduct a before/after study of the effects of noise on cognition. 326 children (average age 10.4 years) took part in the study, and the authors measured cognitive outcomes once before the switch and twice afterwards (up to two years following the switch). The authors found that after the switch, long-term memory and reading decreased for the group newly exposed to noise near the new airport, and improved for the group formerly exposed to noise near the old airport. Short-term memory also improved for the formerly exposed group.

The NORAH study evaluated the effects of chronic exposure to aircraft noise on the cognitive performance and quality of life of schoolchildren near Frankfurt Airport in Germany (Guski et al., 2016). The study involved 1,242 children who were 8 years old from 29 schools near the airport. Cognition outcomes were studied through performance tests, in particular reading tests, and through surveys with children, parents, and teachers. The study found a significant linear association between aircraft noise levels at school and decreasing reading performance in second graders. In particular, a one month delay in reading was observed for an increase in noise levels by 10 dB (L_{Aeq} 8:00am-2:00pm).

In the United States, the Airport Cooperative Research Program sponsored a study on the effects of aircraft noise on student performance near 46 airports (National Academies, 2014). The study found statistically significant associations between airport noise (measured as exposure to DNL of 55 dB or higher) and student mathematics and reading test scores, after controlling for demographic and school factors (such as the presence of sound insulation). The study also found that for a sample of 119 schools, the effects of aircraft noise on children's learning were no longer statistically significant once the school installed sound insulation.

2.5.3.3 Noise at Home and Cognition

While cognition is primarily studied in school environments, several studies have evaluated the impact of noise at home on children's cognition. One challenge with this approach is that because a child's school is typically near their home, children who go to schools in noisy areas tend to live in noisy areas as well; therefore, it is difficult to disentangle the effects of noise at home and at school. Clark et al. (2006) analyzed RANCH study data along with data on aircraft noise exposure at home. The authors found that increasing aircraft noise exposure at home was statistically significant and linearly related to poorer reading comprehension. However, there was no additional effect of aircraft noise exposure at home after adjustment for aircraft noise exposure at school. In other words, aircraft noise exposure at home was highly correlated with aircraft noise exposure at school (see Figure 18).

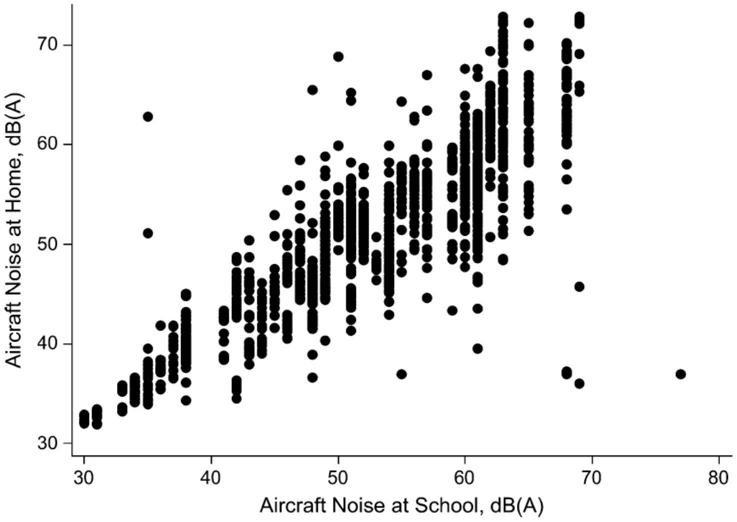

Figure 18: Association between aircraft noise exposure at home and at school, based on data from the RANCH project collection from 2001-2003 (Figure 2 from Clark et al. 2006)

Matsui et al. (2004) attempted to study the effect of noise exposure at home by finding situations where there was variation between noise at home and noise at school. The authors looked at cognition outcomes for fourth graders at 10 schools with high aircraft noise levels (16-hr outdoor L_{Aeq} >63dB) near Heathrow airport in London. Data on aircraft noise exposure levels at the children's homes was also collected, and ranged from under 57dB to over 66dB. The study found an association between aircraft noise exposure level at home and impairment of immediate and delayed recall of memory. This association remained even after adjusting for the noise exposure level at school. The study did not find an association between noise levels at home and reading comprehension or sustained attention.

2.5.4 Summary and Research Gaps

Since the Levels Document was published, research has established that noise disrupts children's learning not only by interfering with speech, but also by affecting memory and attention. Studies have found that there is an association between exposure to aircraft noise and impaired cognition in children, particularly around the outcomes of reading comprehension, memory, and standardized test scores (Clark and Paunovic, 2018; Stansfeld et al., 2005; Guski et al., 2016; National Academies, 2014). Studies indicate that when there is an increase in aircraft noise exposure, cognition outcomes are likely to degrade (and conversely when there is a reduction in aircraft noise exposure cognition outcomes are likely to improve) (Hygge et al., 2002; National Academies, 2014).

There have been few studies on the impacts of other noise sources (such as road, rail, and stationary noise) on cognition, and there is not enough information to establish a clear association (Clark and Paunovic, 2018). Similarly, due to the correlation between noise exposure at home and at school, it is difficult to establish the effect that noise at home has on cognition. At least one study has found an association between aircraft noise exposure levels at home and memory (Matsui et al., 2004).

Additional research is needed to further understand the connections between noise and children's learning. Longitudinal and follow-up studies of the impact of noise exposure and learning over time (similar to Clark et al., 2013) could help establish the long-term effects of noise on learning. More studies are also needed to confirm whether the associations between aircraft noise and cognition are also present for other noise sources, such as road traffic, rail, and stationary noise. In addition, the majority of studies on noise and cognition have evaluated elementary school-aged children. Additional studies with both younger children and teenagers could help broaden our understanding of the impacts of noise on learning. Finally, situations where noise levels at school and at home differ should be studied to better understand the association between noise and cognition in residential settings. If there is a significant association between noise at home and cognitive outcomes, it may be partially driven by sleep disturbance, as well speech interference or distraction.

2.6 Financial Impacts

The Levels Document did not consider financial impacts of noise. The HUD noise regulation states "environmental noise is a marketability factor which [sic] HUD will consider in determining the amount of insurance or other assistance that may be given."[13] Monetizing the effects of noise may inform decisionmaking for developers and regulators.

2.6.1 Current State of Research and Science

Volpe selected six studies that considered the financial impacts of noise exposure. Impacts were in terms of effects of noise from various sources on apartment rents or property values.

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[13] 24 CFR §51.101 (a)(4)

Studies of the financial impacts of noise typically use a hedonic regression methodology, which estimates correlations by evaluating actual market data as a function of property characteristics and environmental factors. This methodology is considered more accurate than contingent valuation, which uses surveys to ask people their willingness to pay for different elements (Theebe 2004). However, estimates derived from hedonic regression models are highly dependent on which variables are selected and controlled for, as well as decisions made by the researcher about the form of the regression equation (Theebe 2004). Five of the six studies reviewed used the hedonic regression methodology.

Another method for studying this topic uses a natural experiment to observe changes in property values after a change in noise exposure (Almer, Boes, and Nüesch 2017). However, it is difficult to find such situations in the real world, so there are a limited number of natural experiments on this topic. One of the studies reviewed used a natural experiment.

Studies on the impact of noise on housing values typically measure the change in property values per dB increase in noise (several studies refer to this measure as noise depreciation sensitivity index, or NDSI), or they look at housing prices inside and outside of a noise contour (e.g., 65 dB).

The studies reviewed covered different transportation noise sources (aviation, roadway, and rail) and evaluated the impact of noise on apartment rents or property values. Studies were conducted over different times, but in aggregate covered data collected between 1997 and 2012. Three studies were domestic and three were from Europe. All studies found a decrease in housing prices associated with noise exposure; however, the magnitude of this discount varies. The results of these studies are summarized in Table 11 below and in the annotated bibliography.

Table 11 Impacts of Noise on Housing Values Summary of Findings

Method used	**Author and date**	**Region studied**	**Transportation mode**	**Housing type**	**Noise Metric**	**Noise discount**
Natural experiment (before and after changes in flight patterns)	Almer, Boes, and Nüesch (2017)	Zurich, Switzerland	Aviation	Apartment rents	L_{Aeq}	1.7% per dB
Hedonic regression	Theebe (2004)	Amsterdam, Netherlands	Mixed traffic noise (road, rail, aviation)	Residential property values	L_{Aeq}	0.3-0.5% per dB (over 65dB)
	Brandt and Maennig (2011)	Hamburg, Germany	Mixed traffic noise (road, rail, aviation)	Condominium listing prices	L_{den}	0.23% per dB
Hedonic regression with noise contours	McMillen (2004)	Chicago, IL	Aviation	Residential property values	L_{dn}	Over 65 dB: 9.2%
	Ozdenerol, Huang, Javadnejad, and Antipova (2015)	Memphis, TN	Road traffic	Residential property values	L_{dn}	45-50 dB: 1.6% 50-55 dB: 3.7% 55 and above: 4.3%
	Walker (2016)	Memphis, TN	Rail	Residential and commercial property values	L_{dn}	Over 65dB: 14-18%
Literature review of hedonic regression studies	Nelson (1980)	Multiple locations (literature review)	Aviation	Residential property values	Varied (literature review)	0.4 to 1.1% per dB
	Nelson (1982)	Multiple locations (literature review)	Road traffic	Residential property values	Varied (literature review)	0.4 +/- 0.23% per dB

For the two studies that used hedonic regression to measure the impact on housing prices per dB decrease in noise (i.e. used the NDSI metric), a 1dB increase in noise was associated with between 0.23 percent and 0.5 percent decrease in property values (Brandt and Maennig 2011; and Theebe 2004). This is in line with a literature review from the 1980s that found an NDSI ranging from 0.4 to 1.1 percent for aviation noise and of 0.4 +/-0.23% for road traffic noise (Nelson 1980 and 1982). A natural experiment studying rents before and after changes in flight patterns found a 1.7 percent decrease in rents associated with a 1 dB increase in noise (Almer, Boes and Nüesch 2017).

Theebe (2004) notes that there may not be a linear relationship between noise impacts and property values, since noise is measured on a logarithmic scale. This study evaluated the NDSI for 5dB ranges rather than assuming a linear relationship. Brandt and Maennig (2011) also found that price discounts depend on the noise level, and that they are substantially lower for low levels of road noise as well as substantially higher for high noise levels than the price discounts estimated based on a linear trend.

Two of the studies that used contours to measure the impact of noise on housing prices used a 65 dB contour. The houses inside the contour had a 9.2 to 18 percent lower value compared to those outside the contour (Walker 2016; and McMillen 2004). One study looked at 45-50 dB, 50-55 dB, and over 55 dB, and found a 1.6, 3.7, and 4.3 decrease in property values, respectively (Ozdenerol et al 2015).

2.6.1 Summary and Research Gaps

While there is agreement in the research reviewed that an increase in noise is associated with a decrease in property values, there is not conclusive information about the magnitude of this effect. Even when studies use similar methodologies (e.g., hedonic regression), they study different geographic areas, housing types, and noise sources and control for different factors in the regression equation. This makes comparison between studies difficult. A detailed analysis that accounts for differences in these factors, or conducting repeatable studies with consistent study parameters could help to determine the magnitude to which noise affects housing prices.

The natural experiment methodology offers a promising approach for understanding the financial impacts of noise. However, it is challenging to find situations where it is possible to compare the same houses before and after a change in noise. Potential sources of data are environmental assessments or environmental impact statements for projects that are expected to change noise levels in a community. As researchers find opportunities to study financial impacts of noise before and after a change in noise exposure (e.g., a change in flight patterns or the installation of a noise wall), they should compare the results to results from a hedonic regression methodology to see if they are similar. This type of comparison may help to advance the state of knowledge about the most appropriate methodology for studying the financial impacts of noise.

3 Analysis of Special Noise Sources

3.1 Impulse Noise

3.1.1 Levels Document and Interim HUD Standard

The Levels Document provided a detailed overview of the characteristics of impulsive noise sources that distinguish it from continuous noise sources. Important attributes associated with impulse noise include high peak sound pressure level relative to average over the event, short duration, fast rise time, daily or other cumulative exposure to repeated impulses, individual susceptibility to inner ear damage, and the wide frequency content due to the short durations of the sound. The Levels Document provided examples of impulse noise events and their noise levels, presented in Table 12.

Table 12 Some typical values of peak SPL for impulse noise (in dB re 0.00002 N/m2) Source: Levels Document Table G-1

SPL	Example
190+	Within blast zone of exploding bomb
160-180	Within crew area of heavy artillery piece or naval gun when shooting
140-170	At shooter’s ear when firing hand gun
125-160	At child’s ear when detonating toy cap or firecracker
120-140	Metal to metal impacts in many industrial processes (e.g., drop-forging; metal-beating)
110-130	On construction site during pile-driving

Assessment of acceptable levels of impulse noise is based on hearing loss alone. Based on the data discussed in the Hearing Loss section, the Levels Document proposed an overall limit on impulse noise peak sound pressure level of 145 dB. This limit was identified based on temporary threshold shift data from exposure to short durations of sound (see section 2.1 on Hearing Loss for more information on temporary threshold shift). The Levels Document specified that this level applies to “isolated [impulse] events, irrespective of type, duration, or incidence at the ear.” In addition, the Levels Document recommended assessing impacts from impulse noise separately from continuous noise, despite recommendations found in international standards at the time.

For more specific limits, the Levels Document used an adjustment of a hearing loss curve published by the Armed Forces-National Research Council Committee on Hearing and Bio-Acoustics (CHABA) working group in 1968. The curve is a function of impulse duration based on a nominal exposure of 100 impulses per day. The CHABA limits were meant to protect 95% of the population from a maximum of 20 dB of NIPTS after 20 years of exposure. The authors of the Levels Document adjusted this curve to protect 90% of the population from 5 dB NIPTS. This adjustment translates to a 12 dB shift down of the CHABA curve. The CHABA differentiated its proposed limits based on the decay rate of the impulse energy. Impulses that oscillate after the initial impulse have more energy, and thus can cause more damage, so CHABA proposed slightly lower limits for these types of impulses. The Levels Document used this slightly more conservative estimate for the limits it proposed for impulse noise.

The Levels Document also discussed how the number of impulses experienced per day affects hearing loss from impulse noise. This discussion briefly summarized a number of studies that proposed different curves for adjusting the allowable peak pressure in an impulse based on the number of impulses per day. The Levels Document stated that an equal energy curve centered on 100 impulses per day approximately fit the data presented in these studies. Using the equal energy curve, the Levels Document suggested an adjustment of the limit given by the dashed curve in Figure 19 by -10 dB for every 10-fold increase in the number of impulses per day above 100. For example, a 1 ms impulse gives a nominal limit of about 140 dB for 100 impulses per day. For 1000 impulses per day, the acceptable level is 130 dB. For 10 impulses per day, the acceptable level is 150 dB.

The Levels Document provided other adjustments for factors like the rate of repetition of the impulses and an adjustment for the angle of incidence on human ears. Overall, the authors provided an absolute limit of 167 dB peak SPL for impulses having durations less than 25 microseconds, regardless of the number of impulses per day. The plot in Figure 19 summarizes the limits proposed by the Levels Document for different durations and frequencies of impulses.

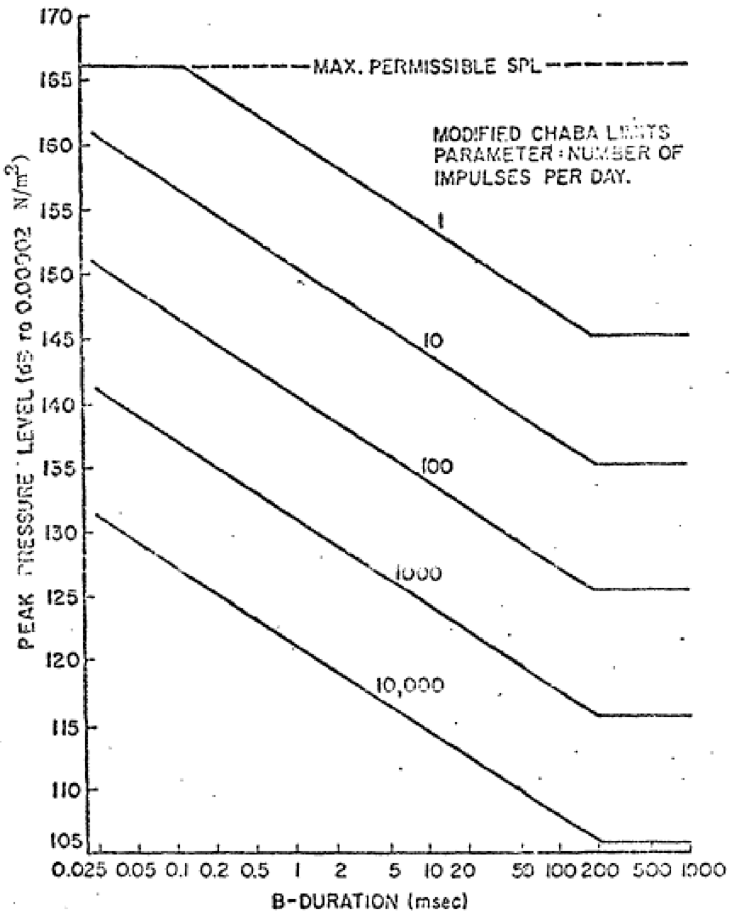

Figure 19. Impulse noise limits to protect against hearing loss as a function of duration of the impulse, based on the CHABA 1968 limit curves. The different lines represent limits for different numbers of impulses experienced per day. The actual limit is a function of the duration of the impulse. The longer the impulse, the more energy the impulse contains, and thus the noise level limit must be lower to prevent the same amount of damage to the ear.

The Levels Document specified that there was limited information to inform the choice of a level requisite to protect against annoyance or sleep disturbance from impulse noise, and that there was no clear evidence of permanent effect on public health and welfare at the time of study.

This section of the Levels Document also discussed sonic boom noise and the available information at the time of writing. The discussion was mostly based on data collected from an Oklahoma City study of 1964 where residents were regularly exposed to sonic booms for six months. The study used annoyance and interference surveys to assess the relationship between peak overpressure of the boom and these effects. The resulting recommendations were to limit peak overpressure based on the number of booms per day.

HUD's noise regulation 24 CFR §51.103(b) defines an interim standard when loud impulsive sounds are experienced at a site. The "day-night average sound level produced by the loud impulsive sounds alone shall have 8 decibels added to it in assessing the acceptability of the site... Alternatively, the C-weighted day-night average sound level (L_{Cdn}) may be used without the 8 decibel addition, as indicated in §51.106(a)(3)." Appendix I to Subpart B to Part 51 defines a loud impulsive sound as one for which:

> "i. The sound is definable as a discrete event wherein the sound level increases to a maximum and then decreases in a total time interval of approximately one second or less to the ambient background level that exists without the sound; and
> ii. The maximum sound level (obtained with slow averaging time and A-weighting of a Type 1 sound level meter whose characteristics comply with ANSI S1.4-1971) exceeds the sound level prior to the onset of the event by at least 6 decibels; and
> iii. The maximum sound level obtained with fast averaging time of a sound level meter exceeds the maximum value obtained with slow averaging time by at least 4 decibels."

3.1.2 Current State of Research on Impulse Noise

3.1.2.1 Hearing Loss from Individual and Repeated Exposure to Impulse Noise

The CHABA report referenced in the Levels Document continues to be one of the better measures of damage risk from impulse noise exposure available today. This report is still referenced today in many studies and standards. To protect 95% of the population from 20 dB NIPTS, CHABA proposed the curves shown in Figure 20. The A-duration curve limits impulses with rapid, non-oscillatory decay rates. The B-duration curve limits impulses with oscillatory decay patterns.

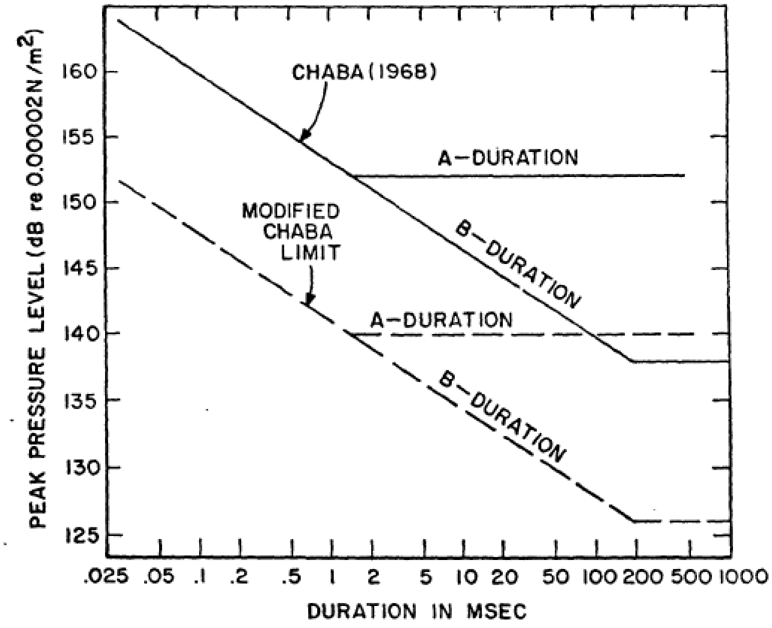

Figure 20. CHABA Impulse Noise Limit Curve, with the Levels Document Adjustment to protect 90% of the population from 5 dB NIPTS.

While the CHABA report is still applicable, the U.S. Army Research Laboratory has sponsored the development and validation of a model that uses fundamental concepts of physics and biology to analyze the human hearing system. The Auditory Hazard Assessment Algorithm for Humans (AHAAH) was developed in the 1980s and continues to be validated by peer reviewers and researchers. The U.S. Army uses the model to predict hearing loss from gunshots, and the American National Standards Institute has shown interest in creating a standard for this model (Price 2010).

Other than the development of AHAAH, there have been a number of studies on occupational noise exposure and hearing loss, many of which note that the study subjects were exposed to some type or level of impulse noise in these occupational settings. Because these are cross-sectional studies on very specific populations, the noise exposure situations are often unique and there is little consensus in the levels of impulse noise exposure required to produce specific levels of hearing loss. Many studies note the presence of impulse noise in the noise environment under examination, but do not measure the duration, number experienced per day, repetition rate, or even the peak sound pressure level of the impulses. These studies focus on the overall noise exposure, often over the course of an 8-hour workday. Therefore, these more recent studies do not offer a greater understanding of hearing loss effect of impulse noise than the CHABA report from the 1960s (Lie, Skogstad, et al., 2015).

Despite the variability and lack of specificity of data on the effect of impulse noise, researchers generally agree that impulse noise can be more damaging to the human hearing system than the amount of sound energy in an impulse would predict using a model of hearing loss based on continuous noise. Because of this, many standards and regulations recommend a 5 to 10 dB reduction in the applicable continuous noise limit if impulse noise is present in the noise environment (Lie, Skogstad, et al., 2015; Starck, Toppila, Pyyko, 2008).

HUD's regulation and interim standard for impulse noise aligns with the 5 to 10 dB range in noise level penalty recommended by some standards and regulations. This interim standard approximates the increased risk of physiological damage of impulse noise by raising the post-development ambient noise level by 8 dB. As a programmatic response, it is simple, easily communicated, and effectively reduces the assessment burden on grantees while protecting public health and investment. However, this adjustment is in contrast to the Level's document recommendation to assess continuous noise and impulse noise separately. Additionally, substantial research has not yet been performed that allows for the assessment of the individual hearing loss effects of impulse noise separate from continuous noise. Therefore, the validity of a penalty on ambient noise levels or a reduction in applicable noise level limits cannot be verified until more specific and focused data are available which updates the information and relationships in the original CHABA report.

3.1.2.2 Annoyance to Non-Aircraft Impulse Noise

Although the levels of impulse noise that cause hearing loss are well understood, the effects of such as annoyance from longer-term exposure to lower energy impulse noise is not as well understood. There is very little research on environmental impulse noise besides sonic boom impulse noise, making it difficult to perform community annoyance surveys addressing impulse noise (Fidell and Pearsons 1994). The few survey-based studies on annoyance from environmental impulse noise were mostly carried out in Europe as early as the 1970s, with the most recent studies being carried out in the early 2000s. While some of these studies recommend the use of certain metrics in exposure-response correlations for impulse noise, they often specify many caveats and admit that the data differ significantly from other studies (Rylander and Lundquist 1996; and Brink and Wunderli, 2010).

Across most discussions and research papers reviewed, it is generally agreed that annoyance from impulse noise is greater than continuous noise. One researcher suggested that annoyance from impulse noise grows at twice the rate as annoyance from non-impulse noise events of numerically equivalent A-weighted SEL (Fidell, Pearsons, Feb. 1994). Some studies show that C-weighted metrics correlate better with annoyance from impulse noise than typical A-weighted metrics. C-weighting better accounts for lower frequency noise present in impulse noise. (Page, 2014; Maglieri, 2014; and Fidell and Pearsons, Feb. 1994).

Studies sometimes report annoyance to impulse noise in relation to the level of continuous noise that causes the same amount of annoyance in the study population. In these cases, the difference between the cumulative impulse noise level and continuous noise level to cause the same amount of annoyance ranges from 5 to 12 dB across studies. The range in the differences reported indicates more standardized study tactics need to be employed to obtain a more focused difference in sound level. Additionally, while these reported metrics might capture a study population's reaction to cumulative impulse noise exposure, they do not take into account other aspects of impulse noise that might cause annoyance. These other aspects include distribution of impulse events, rate of repetition, and wide frequency ranges, as discussed in the Levels Document (Fidell and Pearsons, Feb. 1994; Fields, 1997; and Maglieri, 2014).

3.1.2.3 Annoyance from Supersonic Aircraft (Sonic Boom Impulse Noise)

Much of the available research data on impulse noise is focused on sonic boom noise exposure. There is a wealth of published laboratory based simulated sonic boom annoyance data. Laboratory studies can control the shape and amplitude of the sonic boom signature and the measurements of exposure levels have high confidence. Results from these early studies have pinpointed overpressure and rise time as the aspects of sonic booms that are most related to annoyance and perceived loudness (Maglieri, 2014). However, it is not straightforward to determine the relationship between laboratory studies on immediate annoyance from a singular sonic boom and community annoyance. Moreover, some syntheses admit that laboratory studies, while valuable, do not produce the type of data necessary for selection of a final metric and level to assess acceptability of exposure to such environmental noises (Fidell, Pearsons, Oct. 1994).

There have been several large-scale community exposure survey studies on sonic booms over time, mostly from 1965 to 1985.[14] A more recent study was the Waveforms and Sonic Boom Perception and Response (WSPR) study at Edwards Air Force Base in 2011 (Page, 2014). These studies usually attempt to obtain exposure-response relationships by measuring sonic booms in a specific region and then distributing surveys in various forms to the exposed population. Generally, studies find that as the maximum air pressure during the sonic boom rises, so do levels of annoyance and reported complaints. Studies report similar trends for increases in the number of booms experienced per day.

Most published studies of annoyance to sonic booms use military-style aircraft to produce sonic booms. This is because commercial supersonic flight annoyance studies are difficult due to the ban on overland commercial supersonic flight operations. Military-style aircraft performing super-sonic dive maneuvers can simulate fairly well a boom signature that might be produced from a future supersonic commercial aircraft, but these studies can only be performed on localized and select populations (Fidell, Pearsons, Oct. 1994). One recent lengthy and in-depth synthesis report by NASA concluded that “selection of a final metric and level cannot happen until a demonstration vehicle having a low-amplitude shaped signature is flown to assess its community acceptance” (Maglieri, 2014, pp. 366).

Different assumptions and study procedures across the body of research make it difficult to compare the outcomes and establish recommended levels or metrics for annoyance to sonic boom. Annoyance survey design, assumptions about prior exposure to impulse noise, and different exposure timelines all factor into differing study outcomes. Fields specified, “… it is not possible to predict the size of [the difference in reaction between continuous noise exposure and sonic boom exposure]” (Fields, 1997, pp. 65). Page et al. presents a plot comparing WSPR data points with other sonic boom and impulse noise annoyance data. The distribution of these data points does not indicate any immediate trend between sonic boom or other impulse long-term noise exposure and percent of the study population that was highly annoyed (Page, 2014, pp. 158).

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[14] Studies frequently referenced include the 1965 Oklahoma City study mentioned in the Levels Document, a 1962 St. Louis study, a 1970 study by NASA conducted in Chicago, Denver, Atlanta and other cities (Maglieri, 2014), and a 1984 long-term exposure study in Nevada (Fields 1997).

While conclusions about metrics and levels are difficult to reach from currently available research, there has been renewed interest from multiple agencies in the U.S. Government, as well as international entities, to explore the reintroduction of supersonic flight in the commercial aviation market. NASA's "Quiet Super Sonic Flights 2018" project was carried out near Galveston, Texas as a baseline to understand noise levels and community annoyance in preparation for tests with an experimental low-boom supersonic vehicle. The term "sonic thump" is being used to describe these shaped, lower peak overpressure booms. The hope is that with lower, shaped sonic booms, annoyance will decrease in the exposed population.

3.1.3 Summary and Research Gaps

The hearing loss effects of impulse noise were relatively well understood at the time of the writing of the Levels Document. The Levels Document put an absolute limit of 167 dB on impulses below 25 microseconds in duration, with varying lower limits on longer impulses dependent on the number of impulses experienced per day. As an overall limit applying to standalone impulses of any duration, the Levels Document provided a limit of 140 dB.

There has been some development of new models to assess hearing loss, but earlier CHABA research remains relevant and applicable today. Some newer studies attempt to measure permanent hearing loss as a result of exposure to noise environments which include impulse noises, but there is little consensus among the research, and they often do not report specific information about the impulses themselves. One conclusion that research generally has agreed on both at the time of writing the Levels Document and presently is that it is more accurate to assess the hearing loss effects of impulse noise separately from continuous noise. Assessing these effects in studies requires controlling for a large number of variables, including exposure to continuous noise, which can be difficult to do in cross-sectional studies. Currently, there is not sufficient research that accomplishes these types of controls, but longitudinal studies on the individual effect of impulse noise on hearing loss that control for extraneous variables may lead to more consensus in the research community. Additionally, in modern hearing loss studies, noting actual acoustical characteristics of impulses when assessing environmental or occupational noise, rather than only noting the presence of such sounds in the noise environment, will help validate or invalidate the current interim HUD standard.

Specific annoyance studies on non-aircraft impulse noise are limited and usually focus on cumulative noise exposure metrics, as well as peak sound level during the event. To improve the understanding of impulse noise annoyance, future research should consider aspects of impulse noise that might cause annoyance other than cumulative exposure or peak sound level. Future studies should seek to align specific study parameters, procedures, and assumptions for comparison, as these factors can substantially change the outcomes of a study. This alignment may lead to the development of a more widely applicable exposure-response relationship for annoyance to impulsive noise.

There is renewed interest in research on annoyance from sonic booms, exemplified by recent and currently ongoing NASA studies. NASA's "Quiet Super Sonic Flights 2018" and related upcoming research aims to study reactions of non-acclimated residents to shaped, low-amplitude sonic booms from an experimental aircraft. This will directly address the gaps in data on shaped-boom demonstration vehicles reported by Maglieri in 2014. In addition to low amplitude boom research, other gaps include the lack of focused procedures for studying differences in annoyance from single events and cumulative exposure, as well as the number of booms experienced per day (Page, 2014). These procedures will produce data sets that are more comprehensive and in turn more confident correlations and metric recommendations.

3.2 Stationary Noise Sources

While the majority of this report focuses on the adverse effects from transportation noise sources, there are a variety of other, “stationary” sound sources that can cause substantial environmental noise. Stationary sources can elicit similar reports of annoyance, sleep disturbance, and activity interference from residents as do transportation sources. Most transportation noises are intermittent, with individual transportation events occurring at relatively regular intervals. Conversely, stationary noise sources are often continuous during times when the facility is operational. Various individual noise sources and activities, with different noise and operational characteristics, emit different sounds throughout the working period. Because of the differences from transportation noise sources, the sounds from stationary sources must be treated differently in measurement procedures and when considering the relevant adverse effects (Murphy, King, 2014).

This section describes the noise characteristics of quarries, rail yards, industrial sites and temporary construction, wind turbines, and commercial space launch sites.

3.2.1 How the Levels Document Addresses Stationary Noise Sources

The authors of the Levels Document did not address stationary noise sources directly. Certain stationary sources were mentioned throughout the discussion in the appendices, but specifics and in-depth discussion about the noise levels and other information about those sources was not included. One area where stationary sources were mentioned was in the recommended levels of environmental noise given in the final section of the narrative of the document. Noise levels to protect against hearing loss and activity interference were presented for a number of different land use categories. Among these categories was industrial land uses. It was noted that the variety of activities carried out in industrial areas may make it difficult to determine a level to protect against activity interference, so only the level to protect against hearing loss, 70 dB L_{Aeq} for 24 hours of exposure, was provided.

The Levels Document provided some discussion in the appendices that indicated while industrial and construction noises were not widespread relative to other noise sources, when industrial operations were nearby, they generated substantial complaints, and even the threat of legal action. The glossary also mentioned industrial sites in the definition of Impulse Noise, noting that these types of noise may characteristically be associated with explosions, impacts, discharge of firearms, and many industrial processes. Some specific stationary sources were also identified in the Impulse Noise section of this document. For example, metal-to-metal impacts in industrial processes were identified as having a peak noise level of 120-140 dB in close proximity to the sound source.

3.2.2 Discussion of Specific Stationary Sources

The following sections include general discussions of a few notable stationary noise sources. Specific data are provided where available. The qualities of the noise produced in these sources have many similarities between them, including potential for impact noises, pure tone frequencies, and intermittent variable sounds, as well as the variety of locations these sources can exist.

3.2.2.1 Quarries

Quarries are a type of open-pit mine usually used to extract different types of stone from the ground to be used as building materials. Unlike sub-surface mines that consist of tunnels and shafts, quarries are open to the surface of the earth. They are usually an inverted conical pit in the ground, expanding downward and outward as material is either dug or blasted from the sides of the pit. Quarry locations can vary greatly, but active quarries are rarely located in densely populated urban areas. Usually, the closest residences are located several miles away from the actual quarry; however, sometimes homes are much closer and quarry access roads sometimes pass very close to residential properties. Thus, the noise from heavy trucks traveling on these roads must also be accounted for when assessing the environmental noise impacts of the quarry (Thomas, Liu, 2013). These traffic noise sources will not be discussed in depth in this section, as these are not characterized as stationary sources.

Methods of extracting material from the quarry include blasting, drilling, and operating diesel-powered excavation tractors and other equipment. Other noise-making activities at quarries involve jaw crushing of stone material, moving and processing material with conveyer belts or large trucks, loading trucks or rail cars for transportation away from the quarry site, and operation of those vehicles within the site boundaries.

Quarry noise sources can have different qualities and produce different noise levels for different amounts of time. Explosions from blasting produce impulse noises that might be up to 120 dB for durations under 1 second. More sustained noise is generated from operation of vehicles or equipment with internal combustion engines or from on-site processing of the extracted material. Motorized machines can range from excavating equipment to dump trucks, all of which are used in different areas of the mine and thus can result in different noise levels at receiver locations. Most equipment used in quarries ranges between 80 and 100 dBA L_{max} when measured from 50 feet away. When the distance to receivers, shielding, and ground and air absorption are taken into account, models usually show that noise from quarry operations ranges from 35 to 53 dB L_{den}, with receivers ranging from 2,000 ft. to around 6 miles away from the noise sources within the quarry property (Benchmark Resources, 2011; Bansah, 2015; Thomas, Liu, 2013)

One interesting aspect of quarries is that, as excavation activities dig deeper into the earth and the mine reaches greater depths, there is more shielding from residential receiving locations. Thus, many studies and models report that the noise level will decrease over an extended period as the quarry is dug deeper. While this shielding may result in some attenuation, additional reflections of sound waves from the sides of the quarry would reduce the amount of attenuation actually experienced at receiver locations. Sophisticated computer modeling may be necessary to accurately predict future noise at mid- to end-state quarry development. HUD's regulation requires noise projections 10 years from project occupancy (24 CFR 51.106(e)).

The qualities of the sounds produced from quarries and experienced at residential receiver locations vary in frequency content, duration, and overall contribution to an average daily noise level. As noted previously, blasting operations may produce very loud, very brief sounds. While the durations of blasting noises are short, depending on how often and the time of day at which they occur, they can elicit annoyance responses anytime and sleep disturbance if they happen early in the morning. Steady state sounds produced by heavy machinery engines and material processing produce lower levels of noise overall but the sustained nature of these sounds increases the effect they have on humans listening to the sound. Pure tone content in these sounds might also increase the annoyance effects these sounds might cause.

Regulations usually applicable to quarry noise is specific to the state or region in which the quarry is located. Some regions include noise limit standards in zoning regulations. Mendocino County in California, for example, provides limits specifically related to surface mining depending on the length of time the sound occurs. The maximum sound allowable is 85 dB in any moment (i.e., L_{max}) and down to 65 dB for 30 minutes (i.e., L_{Aeq}). Other regions utilize general standards for findings of significant impact based on increases to ambient noise levels from other sources caused by the project, in this case development or expansion of a quarry. In these cases, if the project is predicted to increase the ambient noise levels in the area by a certain amount, certain abatement measures are required (Benchmark Resources, 2011; Mendocino County, 2017).

3.2.2.2 Rail Yards

Rail yards are large properties containing many parallel sections of rail that are used to organize and build trains from individual rail cars. Rail is an efficient way to move freight over long distances, so rail yards are usually the interface between freight trucks and freight rail. While some rail yards can be located in rural areas and far from receivers, they are often located in densely populated urban areas with many residential receptors in close proximity. Due to the size of these facilities, many residences can border a single rail yard, and the noise can be hard to mitigate with barriers. A common aspect of rail yards is the long hours of operation. The 24-hour nature of the freight rail industry necessitates operation throughout the day and night, which increases the risk of sleep disturbance for residents surrounding these sites.

The range of noise levels experienced by residential noise receptors around a rail yard varies with the size of the yard, the types of rail industry the yard serves, the design of the yard, and the frequency and duration of activities occurring in those areas. The FTA Transit Noise Vibration and Impact Assessment Manual includes a reference level of 118 dBA Maximum SEL as the typical maximum sound level experienced 50 feet from the center of a rail yard. Individual noises emanating from the rail yard may vary significantly from this reference level. The FRA sponsored a measurement campaign in the 1980s with the goal of assessing occupational noise sources on rail yards. This research report gives a good idea of ranges of noise levels produced by specific activities on a rail yard. Table 13 shows some values for noise levels reported in the FRA study from different rail yard activities. An approximation of the sound level at 50 feet away is also shown in parentheses. For the most part, the maximum values shown here are in good agreement with the maximum SEL given in the impact assessment manual.

Table 13. Selected noise levels and qualities of noise producing activities in rail yards measured 100 ft. away from noise source. Values in parentheses indicate an approximate sound level adjusted to 50 ft. from the sound source (Urman, 1987).

Noise Source	Noise Level (L_{Aeq} for duration of activity)	Qualities
Moving Locomotive	76-80 (82-86) dB	Steady state, broadband noise with elevated low frequency content.
Idling Locomotive	65-71 (71-77) dB	Steady state, broadband noise with elevated low frequency content.
Car Coupling Impacts	91 (97) dB	Short duration impact noises, sometimes with pure tone content.
Car Retarders	110 (116) dB	Very high-pitched squeal, with pure tone content ranging from 2 to 4 kHz.

One major concern many residents voice is the noise from rail yard retarders. These retarders are essentially brakes attached to short sections of track that slow the movement of free rolling freight cars as they move from one end of the rail yard to another. Retarders work by clamping down on the rolling wheels of a car as it moves through the section equipped with a retarder. The friction between the retarder and the moving wheel causes the wheel to vibrate and emit a high-pitched, sustained noise that can reach the levels shown in the table above. These noises are intermittent but can occur at frequent and varying intervals depending on the switching activities in the yard. As retarders are located in many places throughout a railyard, including near the property boundary, it is easy for residential receivers to be located quite close to these sound sources. Retarder noise can cause activity interference, annoyance, and possibly cardiovascular effects due to the high pitched, pure tone frequencies that are included. One notable example from Bellevue, Ohio had residents surrounding a rail yard issue a lawsuit against the freight company that owned the yard regarding the retarder noise. Residences reported that the sustained noises resulted in speech interference, other activity interference, sleep interference, and decreases in property value (Ouriel, 2017).

Federal regulations[15] enforced by FRA limit the sound from all rail sources including rail yards. In addition, NEPA guidance[16] requires analysis of predicted impacts for proposed projects and consideration of abatement measures. Impacts are separated into no impact, moderate impact, and severe impact categories depending on the predicted noise level as a result of a project's implementation, and the existing noise level in that area. Federal requirements to limit noise at rail yards are summarized in Table 14. State or public policies that relate to general environmental noise levels may also apply depending on the location of the rail yard.

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[15] 40 CFR Part 201 (EPA) and 49 CFR Part 210 (FRA)

[16] FTA Transit Noise Vibration and Impact Assessment Manual, which also applies to FRA projects

Table 14. FTA and FRA noise standards for rail yards

Stationary Rail Noise Source	Noise Standard at the Receiving Property	Reference
Retarders	83 Ladjavemax(fast)	40 CFR Part 201.14
Car-Coupling Operations	92 Ladjavemax(fast)	40 CFR Part 201.15
Locomotive Load Cell Test Stands	65 dBA $L_{90(fast)}$	40 CFR Part 201.16
All rail sources, new projects	L_{dn} at residential land uses. Level depends on existing and project noise exposure	FTA Transit Noise Vibration and Impact Assessment Manual

$L_{adjavemax}$ = Adjusted average maximum sound level

L_{90} must be validated by determining that L_{10}-L_{99} is less than or equal to 4dB (A)

3.2.2.3 Industrial Sites and Temporary Construction Sites

3.2.2.3.1 Industrial Sites

Similar to rail yards, industrial sites can be located anywhere ranging from sparsely to densely populated areas. Factories, freight distribution centers, ports, workshops, refrigeration plants, and power generation plants are all basic examples of industrial sites that can produce substantial amounts of noise. When these sites are located in urban areas, the number of residents that may live near them can be substantial. The noise from these sources can affect residential areas in different ways and at different levels.

It is difficult to characterize noise from industrial activities because there are many different pieces of machinery or activities that make noise. The combined effects from individual sources are often difficult to model due to varying noise characteristics, types of sites, and surrounding areas. However, the European Commission Working Group Assessment of Exposure to Noise developed some basic default values for different types of industrial areas. These levels are given in terms of sound power in dB per meter squared (L_{WA}/m^2). The levels have been converted here for ease of comparison to sound pressure level at 100 ft. from the sound source. Table 15 shows these sound levels. The exact definitions of these land use types is not specified. The source database for the levels in the table gives other defaults for specific industrial use types. A selection of these are also included in the table (European Commission WG-AEN, 2007; van den Berg, 1999).

Table 15. Sound Pressure Levels from Industrial Land Uses from the European Commission Working Group

Type of Industrial Use	Sound Pressure Level at 100 ft. (30 m) (dB L_{Aeq})
Heavy Industries	57
Light industries	52
Commercial Uses	52
Ports	57
Refineries	62
Gravel/Ore/Coal Transfer Stations	57
Warehousing Facilities	47
Outdoor Shipyard	62

While the values listed above are time-based average sound levels, the noise emanating from an industrial area can vary significantly throughout the day, the week, or even seasonally. Manufacturing processes can produce impact or impulse noises, pure tone frequencies in high and low frequency ranges, and intermittent noises at varying frequencies depending on the activity. Developers often must model sound from each of these activities to produce an overall estimate of the community noise that will be produced from the project (Murphy, King, 2014).

A number of actions can be taken by industrial site managers or owners to reduce the noise created by their site. Noise attenuating exterior walls can be used to reduce the amount of noise that exits the facility. For reasonably small outdoor industrial sites like logging mills, noise barriers between residential land and the facility can be a feasible method of reducing the amount of noise that reaches the receiver. Industrial equipment often comes with noise ratings that specify the sound power produced when in operation. Purchasing equipment that has a lower noise emission rating can help reduce the overall noise levels produced while the facility is operational (Murphy, King, 2014).

There are few regulations that directly limit the noise produced by industrial sites. In the U.S., new industrial projects often must go through an environmental impact analysis process. Increases in ambient environmental noise in surrounding areas due to the project are categorized and project sponsors commit to different abatement actions based on the degree to which noise levels will be increased. These analyses require noise modeling procedures and measurements of existing ambient noise levels to determine the overall effect that changes to existing site or a new industrial site will cause.

3.2.2.3.2 Construction Noise

Temporary construction sites can often be located in very close proximity to residential areas, especially in cities where infrastructure projects constantly necessitate the use of loud machinery and activities close to apartment buildings or row houses. Demolition, diesel engine sounds, cutting building materials, and air or water pumps are all examples of high noise producing activities that might be found in a temporary construction site. In addition, the need for construction projects to adhere to timely schedules often requires long working days that begin early in the morning such as at 7 am.

British Standards have provided a database of standard noise levels produced by some construction activities. These standards are used for noise and vibration control on construction sites. Some examples of levels produced by certain activities is shown in Table 16. These levels are sustained L_{Aeq} values measured 30 feet (10 m) from the noise making activity.

Table 16. Noise levels from individual pieces of construction equipment used in British construction noise standards

Equipment/Activity	L_{Aeq} (dB(A))
Bulldozer Clearing Site	75
Water Pump	65
Hydraulic Hammer	89
Gas Powered Circular Saw	91
Angle Grinder	80

As with industrial noise sources, the continuous noise values shown above do not necessarily capture any tonal qualities or intermittency that might occur as construction work is carried out. Therefore, the overall L_{Aeq} or L_{dn} metrics may not be sufficient to characterize the noise effects that construction has on the surrounding area.

Similar to industrial noise sources, a number of precautions or actions can be taken to reduce noise from construction sites. Noise attenuating fencing around construction sites has been shown to have an effect on the noise levels emanating from a site. Particularly noisy activities can be scheduled during less noise sensitive times of the day, often when people are at work. As with industrial equipment, construction equipment is often rated for the noise it produces. Purchasing quieter equipment can reduce the overall noise level produced at a construction site.

Regulations that limit construction noise are usually most concerned with the time of day at which construction sites may operate. Usually, sites are only allowed to operate between 7 am and 7 pm, times that are focused on reducing sleep disturbance. These allowable times may vary from one regulatory region to another. Some regions have specific noise level restrictions depending on the activities being carried out and the time of day they are occurring (Berkeley, CA Construction Noise Standards; Murphy, King, 2014).

3.2.2.3.3 Adverse Impacts of Noise from Industrial and Temporary Construction Sites

Because of the variety of types of sounds produced from industrial sites and construction sites, a value of L_{dn} describing noise from an overall industrial source might not capture the specific types of sound that might be produced. Impact noises in factories, continuous whirring from refrigeration plants, and intermittent operation of bulldozers and tractors can all have different adverse effects on communities and residents in affected areas. Combinations of these types of sounds can result in simultaneous occurrences of adverse effects, which is describe in detail in the adverse effects section of this report.

Some studies have shown that residents in surrounding areas are less annoyed or bothered by noise from industrial and construction noises when they feel the site owner or operator has proven to be a “good neighbor.” In other words, they communicate well about the noise produced in their site, express mutual concern when neighbors object to activities being carried out, and show that actions are being taken to reduce the impact the site has on surrounding areas. A very rough estimate has shown that the level of communication can have a +5 dB allowance or a -5 dB penalty depending on the level of communication with surrounding residents (Murphy, King, 2014).

Despite the options of noise mitigation techniques available to industrial site operators, the most effective method of reducing industrial noise impacts on residents is to limit the number of residents that can live in the immediate vicinity of an industrial area. Land use planning around industrial land uses is an important part of mitigating effects of noise on humans, and preventing residential development near these sites should be a priority for operators and local governments.

3.2.2.4 Wind Turbines

Wind turbines are not often located in highly populated areas. While there has been an increase in the number of large wind farms installed in the U.S. and internationally, most are either in rural or forested areas relatively far away from highly populated regions. It is difficult to install a large wind farm facility in a densely populated area due to the large amount of property needed. There are, however, examples of individual wind turbines located in urban areas that may be more of a concern for surrounding residents. Several states in the U.S. have published recommendations or statutes regarding minimum distances of wind turbines or wind farms to residential areas. Distances defined by the statutes usually depend on the power output and maximum blade height of the turbine. A few notable examples are shown in Table 17 (Heibel, Durkay, 2016).

Table 17. Selected state standard or statute regarding distance of wind turbines to residential locations.

State	Standard or Statute Setback Distances
Connecticut	Distance to any property lines: - Greater than 65 megawatts: Distance ≥ 2.5 times height of turbine - Less than 65 megawatts: Distance ≥ 1.5 times height of turbine
Kentucky	1,000 Feet from property boundary of residential land owner, and 2,000 feet from residential neighborhood, school, hospital or nursing home facility
Ohio	Between 5 and 50 megawatts: Distance ≥ 1.1 times height of turbine, and 1,125 feet from property line
Wisconsin	Distance to residences: - Residences on property not hosting turbines: Distance ≥ 3.5 times height of turbine - Residences on property hosting turbines: Distance ≥ 1.1 times height of turbine

Wind turbines and wind farms usually produce a combination of aerodynamic and mechanical noises. The main source of aerodynamic noise from wind turbines is from vibration of turbine blades as they rotate. The force of the wind on the moving blades causes vibrations at low but possibly audible frequencies. Because of the circular movement of the blades, the sound level caused by these vibrations might rise and fall in a regular pattern, a concept called amplitude modulation. There is some evidence that amplitude modulated noise can be more annoying than other patterns of noise, but the perception of amplitude modulated noise is a complicated issue and more research is needed. Mechanical noises produced from wind farms include the movements of the generators, but the raised height of the generators means there is often significant attenuation of noise between the source and the receiver. Occasionally, maintenance equipment on the ground may produce noise at these sites, but noises from trucks driving and construction activities will be extremely brief and temporary (Murphy, King, 2014).

Another concern surrounding the noise produced by wind turbines is the possibility of emitting infrasound. The limitations of human hearing significantly reduce the perception of sound below 20 Hz. Even at very high sound pressure levels, infrasound is not likely to be audible. The implication is that annoyance and hearing loss are not usually considered as possible direct effects of exposure to environmental infrasound. However, concerns about neurological, cardiovascular, and genetic abnormalities due to infrasound exposure have been considered. These health effects have been summarized colloquially as “wind turbine syndrome,” as residents attribute those symptoms to this phenomenon.

Scientific studies have generally been unable to provide conclusive evidence showing whether the noise from wind turbines can have negative health effects on surrounding residents. A few scientific studies have indicated that some specific health effects may be associated with infrasound at extremely high sound energy levels. Despite this possibility, several Australian studies have shown that natural sources of infrasound and low frequency audible sounds are similar to those produced by wind turbines and in wind farms (Murphy, King, 2014).

The Basner and McGuire study discussed in the sleep disturbance section included a review of studies on wind turbine noise and sleep outcomes. Out of six studies reviewed, four of them found an association between wind turbine noise levels and increased sleep disturbance. These studies found that sleep disturbance due to wind turbine noise may occur when noise levels are above 40 or 45 dBA.[17] However, for two of the studies less than 10 percent of study participants were exposed to these levels, making it difficult to draw conclusions to the broader population. The possible effects of infrasound at different levels should be researched further in order to build robust understanding.

The noise produced by wind turbines changes significantly with the speed of the wind. Higher wind speeds usually generate higher background noise levels, making it challenging to distinguish the effect of wind turbines on environmental noise. Therefore, analysis is usually performed on the wind turbine noise and the background noise levels at a variety of different wind speeds. As an example, a typical 3MW turbine produces overall sound power levels between 100 and 107 dBA at wind speeds ranging from about 10 to 20 mph. This translates to a range of between 42 and 49 dBA at a distance of 1,000 ft. Evidence suggests that, as wind speeds reach some critical value, the sound levels reach an asymptote and do not increase further. Other studies have calculated sustained sound levels of up to 44 dBA at high wind speeds (Murphy, King, 2014; ESS Group, INC, 2010)

Noise limits for wind turbines have been recommended by European working groups, and noise from new wind turbine projects are often regulated by existing local environmental standards that limit how much implementation of the project can increase the existing noise levels in the area. Often a limit of up to 5 dB above existing noise levels is recommended. Some regions allow 10 dB above ambient levels due to the project. This allows noise limits to increase slightly as both background noise and wind turbine noise increase with wind speed. Regulations usually require modeling of predicted effects on environmental noise in the surrounding areas before a project can be approved for development.

3.2.2.5 Commercial Space Launch Sites

Commercial space launches are becoming more frequent. Private companies are offering continuously cheaper options to send heavier payloads into orbit around Earth, supporting communications companies, scientific endeavors, and global navigation systems. Multiple companies are developing new rocket models for use in human space flight missions and missions with heavier payloads. Space launch sites are usually not located extremely close to any populated area, but because of the noise levels and frequencies associated with space launches, noise levels can be significant in areas miles away from the immediate launch site (Page et al, 2018).

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[17] The studies included in this review used different noise metrics; four used A-weighted sound pressure level (SPL), one used L_{den}, and one used L_{night}.

There are two important unique concerns for the noise produced by space launches. First, rocket engines produce very loud, very low frequency noise that can travel much further than sound waves at higher frequencies produced by other transportation sources. Lower frequency noise does not experience as much attenuation in the air as higher frequencies. This means that residents may hear rocket launches from miles away. Second, rockets usually reach supersonic speeds early on in their flight paths, so they produce a sonic boom in the areas over which they travel at these speeds. While many flight trajectories of space launches are above large bodies of water when the vehicles reach supersonic speeds, sonic boom impulses can travel far enough in air unimpeded such that they can reach residential areas on land. The development of reusable booster rockets should also be considered. These engines reenter the atmosphere at supersonic speeds and land at similar sites to where they took off. In these cases, multiple sonic booms are produced over the course of a rocket launch (Page et al, 2018).

To date, no measurement standards have been created or are widely followed to assess a space launch agency's impact on the surrounding noise environment. Because of the relatively recent acceleration in development and public attention on space flight operations, there are ongoing efforts to develop these standards. Some space launch companies have developed models predicting noise levels and sonic boom overpressures in areas surrounding the launch site. SpaceX, for example, predicted maximum noise levels of 100 dB $L_{A,max}$ at a distance 6 miles away from the launch site in Brownsville, Texas. A large section of the town of Port Isabel, including many residential areas, is included in this range. SpaceX also modeled noise from the landing procedures of its reusable rockets for a launch at Cape Vandenberg Air Force Base. Again, areas about 5 miles away from the launch point experienced noise levels up to 100 dB $L_{A,max}$ (Page et al, 2018).

Similar modeling exercises have been performed for the sonic boom overpressures experienced in areas surrounding launch sites. An important aspect of the sonic booms from rocket launches is that they are not heard near the actual launch point. Because rockets cover a substantial distance before reaching supersonic speeds, the sonic booms footprints are produced miles away from the launch site. For the same launch in Texas, SpaceX predicted the largest overpressures of 3 psf to occur 45 miles away from the launch site. In most cases, these footprints are distributed over the surface of the ocean; however if launches are ever performed over land, sonic booms would be a significant concern for residents in areas far away from the actual space launch site (Page et al, 2018).

Recently, the National Academies of Sciences, Engineering, and Medicine sponsored development of modeling methods for rocket noise and sonic booms during space launches in an effort to develop industry standards for these operations. This methodology includes in depth procedures to calculate environmental noise and sonic boom footprints during different stages of rocket flight. In addition, this project included development of a few modeling software systems that integrate the methods developed for ease of use and expedited modeling and analysis. In addition to modeling techniques, noise measurement procedures for different types of rocket launches are detailed. These include configuration of microphone arrays for overall noise level measurement as well as sonic boom measurements. Future work detailed in the report includes noise measurements of launch events, validations of the various models produced as part of this effort, and expansion of the spaceport, spacecraft, and flight trajectory profiles to enhance the variety of scenarios that can be studied using the modeling software (Bradley, et al., 2018).

3.2.3 Summary and Research Gaps

Stationary sources of environmental noise vary significantly in size, sound quality, noise levels, locations, and in applicable standards and regulations. While developers are usually most concerned with transportation noise sources, stationary sources like industrial areas, quarries, and rail yards can all significantly contribute to noise levels in surrounding communities. Overall noise from stationary sources is usually a combination of noise from individual sources that can have varying noise levels during different times of the day and in different areas within the site. Fully understanding the effects of noise usually requires a comprehensive analysis of noise from that specific site. Overall, the most effective method for reducing impacts of noise in communities surrounding stationary noise sources is effective land use planning, including prevention of residential developments around these noise-producing sites.

There are some specific areas where more research would improve understanding of the adverse effects of these specific noise sources. Focused studies on the health effects of wind turbines should be performed to improve the general understanding of the impacts of environmental infrasound. Additionally, the perception of and possible annoyance from amplitude modulated noise from wind turbines should be studied. Noise from commercial space launches should be measured to assess community impacts, and methodologies to measure and model these launches should be further refined. New technology developments in both of these industries will warrant continued investigations of the related environmental noise impacts.

4 Gap Analysis and Recommendations

This section summarizes gaps and recommendations identified in earlier sections of this report.

Hearing Loss Research Gaps

The basic understanding of the noise levels that cause permanent degeneration of hearing ability has not changed substantially since the Levels Document was published.

Conduct longitudinal studies to improve understanding of the effects of cumulative noise exposure on human hearing. Although there are generally accepted standards for effects of continuous noise exposure on hearing levels, most of the studies used to develop these standards are cross sectional studies. Few sources of data have directly related noise exposure over time to hearing loss or threshold shifts. More longitudinal studies would improve the understanding of how cumulative noise exposure affects human hearing in the short and long term, how the hearing system recovers from temporary threshold shifts, and how excessive exposure contributes to hearing degeneration due to aging. Recent research on the biological processes (physiological, molecular, and mechanical components of the ear) that are affected by excessive noise may also contribute to understanding on the noise levels that affect hearing.

Activity Interference Research Gaps

For speech interference, there have not been substantial changes to the information presented in the Levels Document since it was published; therefore, no major research gaps were identified. For other activities (e.g., watching TV, relaxing, and other recreation), findings are based on asking about activities in surveys of annoyance, and one gap was identified.

Improve understanding of the relationship between activity interference and annoyance. It would be helpful to define the relationship between activity interference and annoyance, as interference with certain activities may cause more annoyance than other activities. A recommendation to build this understanding is to include questions in annoyance surveys about disruption of specific activities.

Annoyance Research Gaps

Overall, the authors of the Levels Document did not feel there was substantial evidence available to determine a level requisite to protect against annoyance beyond that associated with speech interference. Some aspects of an annoyance response to noise can be measured and observed objectively and quantitatively, while others are complex social and attitudinal differences between participants and regions that are often subjective and self-reported. While there has been substantial research on annoyance internationally, gaps in research on annoyance to noise are described below.

Account for confounding factors in quantifying percent highly annoyed. Despite the wealth of annoyance survey data available, there are large discrepancies in correlations derived from different data sets. Percent highly annoyed can range from 10% to 70% in different studies at the same noise exposure level. Research gaps to control for or quantify the effect of confounding, non-acoustic factors in annoyance studies include:

- Studying distributions of confounding variables both within study populations and across multiple studies to provide a better understanding of their overall effect.
- Developing systematic corrections for non-acoustical factors in order to reduce variance in the study data. This may include more focused survey questions or annoyance rating scales.
- Performing similar studies in the same region over longer periods. Differences in culture and general environment can be controlled for in this way.

Assess metrics used to describe annoyance. While L_{dn} is useful for describing long-term annoyance from cumulative noise exposure, it fails to capture qualities of the sound that may play a significant part in the annoyance exposure-response relationship. Alternate or supplemental metrics may be considered to describe the noise source in a way that captures these qualities. Models relating percent highly annoyed to other metrics may produce better correlations or have less unexplained variance and may be more representative of the exposure-response model described in this report.

Conduct noise annoyance studies in the U.S. Few annoyance surveys have been performed in the U.S. since the 1980s. The most recent published syntheses and research have been done exclusively on foreign study populations, and the results are difficult to extrapolate to the U.S. This gap is currently being addressed by the Federal Aviation Administration in a nationwide mail and telephone survey.

While the results of this survey are not yet published, the results are expected to update the exposure-response curves informing the FAA's consideration of national policy on aviation noise.

Health and Sleep Impacts Research Gaps

The Levels Document assumed that protection against noise-induced hearing loss is sufficient for protection against other health effects of noise. It is now well understood that noise levels lower than those necessary to cause hearing loss can lead to other negative health outcomes including disrupted sleep and adverse cardiovascular outcomes.

Understand and use new types of large-scale data collection to assess sleep impacts. As devices that use actigraphy to measure sleep based on wrist movements are becoming more widely available on the consumer market, there is an opportunity to use the data generated by these devices to study the connections between sleep and noise and to complement other methodologies such as polysomnography and questionnaires. An advantage of actigraphy is that it allows for data collection from larger numbers of people than polysomnography. Future work will be needed to manage and analyze this crowd-sourced data and to determine if the relationships between noise and sleep derived from actigraphy are similar to those from other forms of sleep measurement.

Assess metrics used to describe sleep disturbance. While most research studies of sleep disturbance or nighttime noise use cumulative metrics such L_{dn} or L_{night}, further research is needed to determine whether the cumulative impact of noise or the effects of single noise events predominate in characterizing sleep disturbance.

Assess metrics used to describe cardiovascular impacts. Most studies of cardiovascular outcomes use L_{dn}, L_{Aeq}, or similar metrics that average noise across the day and/or night. However, further research is needed to determine whether these metrics, or metrics that focus on the effects of intermittent noise sources, should be used to predict cardiovascular outcomes.

Substantiate the relationship between noise exposure and cardiovascular and metabolic health outcomes. Although individual studies have shown a statistically significant association between noise exposure and adverse cardiovascular outcomes, there is not consistent evidence across studies for all noise sources and cardiovascular outcomes. The evidence for the effect of noise on metabolic outcomes is even more limited. Further research is needed to more definitively establish the relationship between noise exposure and cardiovascular and metabolic outcomes, and the noise levels at which these outcomes are experienced.

Assess demographics in the association between noise and health. The effects of noise on health may not be evenly distributed across a population. Age, other health conditions, or socioeconomic status may all affect how an individual responds to a given noise exposure. Further research is needed to determine how the association between noise exposure and health changes across different subgroups.

Determine the relative impacts of different interventions. Further research is needed to determine the relative impacts of different interventions on sleep disturbance and health outcomes, across all noise sources. If this research concludes that certain interventions have a greater health benefit for the same amount of noise reduction, these interventions should be encouraged.

Cognitive Effects Research Gaps

Noise disrupts children's learning not only by interfering with speech, but also by affecting memory and attention.

Consider studying how road, rail, and other noise sources affect cognition in home and school environments. Most studies consider the effects of aircraft noise, with few studies based on other noise sources. There is an association between exposure to aircraft noise and impaired cognition in children. Due to similarities in noise exposure between home and school environments, it is difficult to understand the underlying causes of the association between noise and cognition, such as sleep disturbance, speech interference, or distraction. Studying a variety of noise sources (i.e., aviation, road, rail, and stationary) and receptors (i.e. school and home) will improve understanding of the effect of noise on cognition.

Financial Impacts Research Gaps

While there is agreement in the research reviewed that an increase in noise is associated with a decrease in property values, there is not conclusive information about the magnitude of this effect.

Account for differences in study factors to understand how much noise affects property values. Even when studies use similar methodologies (e.g., hedonic regression), they study different geographic areas, housing types, and noise sources and control for different factors in the regression equation. A detailed analysis that accounts for differences in these factors, or conducting repeatable studies with consistent study parameters could help to determine the magnitude to which noise affects housing prices.

Consider applying the natural experiment methodology to validate hedonic regression. As researchers find opportunities to study financial impacts of noise before and after a change in noise exposure (e.g., conducting a natural experiment by evaluating a change in noise following a change in flight patterns or the installation of a noise wall). Potential sources of data are environmental assessments or environmental impact statements for projects that are expected to change noise levels in a community. Compare the results to results from a hedonic regression methodology to see if they are similar. This type of comparison may help to advance the state of knowledge about the most appropriate methodology for studying the financial impacts of noise.

Impulse Noise Research Gaps

The hearing loss effects of impulse noise were well understood when the Levels Document was published. The lack of modern research on the hearing loss effects of impulse noise separate from continuous noise is a gap to being able to validate standards that combine impulse and continuous noise. Specific studies on annoyance to non-aircraft impulse noise are limited. There is renewed interest in research on aircraft annoyance from sonic booms.

Measure acoustical characteristics of impulse noises when present in noise environments during hearing loss studies. Many studies on occupational or environmental noise exposure and the relationship with permanent hearing loss, only note the presence of impulse noise in the environment. These often do not measure the specific acoustic characteristics of the impulses, and focus only on continuously measured noise levels. Measuring acoustic characteristics of impulses during these studies will provide more data from which to assess the individual effect of impulse noise on hearing loss.

Conduct more repeatable studies on annoyance to non-aircraft impulse noise in order to understand the exposure-response relationship. Available studies are limited, and the study design (parameters, procedures, and assumptions) differ too much for comparison across studies. Comparable results across more studies may lead to the development of a more widely applicable exposure-response relationship for annoyance to impulsive noise. One approach would be to create federal noise research guidelines that recommend funded researchers to include design elements, procedures, or questions that ensure comparability.

Continue to build knowledge on supersonic aircraft noise. Ongoing, long-term research includes developing experimental aircraft that create low-amplitude sonic booms and evaluating responses from populations who are not acclimated to sonic booms. Additional research gaps include developing standard procedures for studying differences in annoyance from single events, the number of events in a day, and cumulative exposure. These procedures will produce data sets that are more comprehensive, which will help in the selection of the best metrics to obtain the highest correlations.

Stationary Noise Sources Research Gaps

Stationary sources of environmental noise vary in size, sound quality, noise levels, locations, and in applicable standards and regulations.

Support effective land use planning techniques. Overall noise from stationary sources such as industrial areas, quarries, and rail yards is usually a combination of noise from individual sources that can have varying noise levels during different times of the day and in different areas within the site. Land use planning is the most effective method to reduce noise impacts on residents.

Build understanding on the possible effects of noise from wind turbines on humans. Possible effects may include health effects due to infrasound, perception and possible annoyance from amplitude-modulated noise, and sleep effects for residences in close proximity to wind turbines.

Continue to study and refine models and methods to assess noise and community impacts from commercial space launches. Development in technologies related to commercial space transport have garnered interest by industry. Launch sites with frequent use could produce concern by communities, and further investigation is warranted.

Annotated Bibliography

General

The following studies were cited in introductory sections of this report:

U.S. Environmental Protection Agency. 1974. *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety*. 550/9- 74-004. https://nepis.epa.gov/Exe/ZyPDF.cgi/2000L3LN.PDF?Dockey=2000L3LN.PDF

> *Baseline for this research report. Developed in response to a requirement in the Noise Control of 1972.*

U.S. Environmental Protection Agency. 1978. *Protective Noise Levels: Condensed Version of EPA Levels Document.* 550/9-79-100. https://nepis.epa.gov/Exe/ZyPDF.cgi/20012HG5.PDF?Dockey=20012HG5.PDF

> *This publication was intended to complement the Levels Document. It interpreted the contents of the Levels Document in less technical terms*.

Federal Transit Administration. 2018. Transit Noise and Vibration Impact Assessment Manual. FTA Report No. 123. https://www.transit.dot.gov/research-innovation/transit-noise-and-vibration-impact-assessment-manual-report-0123

> *FTA guidance manual for noise and vibration. Includes: overview of noise; procedures for predicting and assessing noise and vibration impacts of proposed transit projects; descriptions of noise and vibration mitigation measures; construction noise and vibration; and how to present these analyses in FTA environmental documents.*

Munzel, Thomas & Gori, Tommaso & Babisch, Wolfgang & Basner, Mathias. (2014). Cardiovascular Effects of Environmental Noise Exposure. European heart journal. 35. 10.1093/eurheartj/ehu030. https://www.researchgate.net/publication/260684620_Cardiovascular_Effects_of_Environmental_Noise_Exposure

Review by subject matter experts based on current literature on the mechanisms and impact of noise on the cardiovascular system. Describes the relationship among effects of noise on the auditory system, sleep disturbance, impairment of cognitive performance, stress, and health issues.

Hearing Loss

Sliwinska-Kowalska, M., Zabarowski, K. (2017). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Permanent Hearing Loss and Tinnitus. *International Journal of Environmental Research and Public Health*, 14(10), 1139. https://doi.org/10.3390/ijerph14101139.

Systematic review of the possibility of contracting permanent hearing loss from extensive use of personal listening devices (headphones or earbuds) at loud volumes. The introductory section speaks briefly about hearing loss effects of environmental noise, but recognizes that no method of assessing the risks of hearing loss from environmental noise have yet been developed, and so the international occupational noise standard is used. The rest of the study focuses on hearing loss from PLDs. The study concludes that while there may be a higher risk of hearing loss in regular PLD users, better, more controlled studies would build understanding of the risk.

Johnson, D. L. (1973). Prediction of NIPTS Due to Continuous Noise Exposure. *Joint EPA/USAF Study, Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio.* Report Number AMRL-TR-73-91/EPA-550/9-73-001-B.

Comparison of the relationship of noise exposure to noise induced permanent threshold shift as predicted by currently available works of Passchier-Vermeer, Robinson, and Baughn. The data from the three reports are presented in multiple tables, sometimes interpolated and sometimes extrapolated. A relationship between the degree of hearing loss and the amount of continuous noise exposure is derived from these data.

Johnson, D. L. (1978). Derivation of Presbycusis and Noise Induced Permanent Threshold Shift (NIPTS) to be used for the Basis of a Standard on the Effects of Noise on Hearing. *Technical Report, Aerospace Medical Research Laboratory, Wright Patterson Air Force Base, Ohio*. Report Number AMRL-TR-78-128.

Provides various sets of tables that attempt to summarize much of the existing knowledge of the expected effects of noise on the hearing threshold levels of a population. Relationships between noise exposure and NIPTS are derived for different frequencies and lengths of exposure.

International Standards Organization. (2013) ISO 1999:2013 (2013) Acoustics — Estimation of noise-induced hearing loss. https://www.iso.org/obp/ui/#iso:std:iso:1999:ed-3:v1:en

Internationally accepted and updated standard for estimating hearing loss due to occupational noise exposure. Can also be used to estimate hearing loss from environmental noise exposure. Presents procedures in statistical percentiles and at different exposure frequencies and levels.

Zechmann, E., Brown, R. (2015). ISO 1999:2013 User Written Matlab Package. *Package of Matlab functions, Matlab File Exchange.* https://www.mathworks.com/matlabcentral/fileexchange/53565-iso-1999-2013

> *Matlab functions written by Edward Zechmann and Richard Brown. The functions therein are implementations of the equations and algorithms presented in the ISO 1999:2013 standard.*

Carroll, Y., Eichwald, J., Scinicariello, F., Hoffman, H., Deitchman, S., Radke, M., Themann, C., Breysse, P. (2017). Vital Signs: Noise-Induced Hearing Loss Among Adults – United States 2011-2012. *Centers for Disease Control and Prevention: Morbidity and Mortality Weekly Report.* 66(5) 139. http://dx.doi.org/10.15585/mmwr.mm6605e3

> *Hearing loss data from the 2011-2012 national health and nutrition examination survey is studied. The presence of audiometric notches was evaluated in adults aged 20-69 years. Results indicated that 24% of the adults studied had audiometric notches. One third of people who reported being exposed to loud noise at work had notches.*

Ryan, A. F., Kujawa, S. G., Hammill, T., Le Prell, C., & Kil, J. (2014). Temporary and Permanent Noise-induced Threshold Shifts: A Review of Basic and Clinical Observations. *Otology & neurotology: official publication of the American Otological Society, American Neurotology Society [and] European Academy of Otology and Neurotology*, 37(8), e271–e275. https://dx.doi.org/10.1097%2FMAO.0000000000001071

> *Review of basic and clinical findings relevant to defining temporary threshold shifts and permanent threshold shifts. Broad review of scientific literature resulted in conclusions that verified the idea that humans are more sensitive to noise between 4 and 6 kHz frequencies. Biological aspects of damage to hearing system were reviewed and explained, including damage to cochlea hair cells and auditory neurons.*

Basner, M., Babisch, W., Davis, A., Brink, M., Clark, C., Janssen, S., & Stansfeld, S. (2013). Auditory and non-auditory effects of noise on health. *Lancet (London, England)*, 383(9925), 1325–1332. https://dx.doi.org/10.1016%2FS0140-6736(13)61613-X

> *Review of effects of noise. Topics discussed include occupational noise induced hearing loss, diagnosis of noise induced hearing loss, annoyance to noise, sleep disturbance, cognitive performance and others. Each section broadly summarizes the effect of noise, including general levels associated with the effect and the level of maturity of the scientific evidence for the effect.*

Activity Interference

The following studies were reviewed for the Activity Interference topic:

Alvarsson, J. J., Nordström, H., Lundén, P., & Nilsson, M. E. (2014). Aircraft noise and speech intelligibility in an outdoor living space. *The Journal of the Acoustical Society of America*, 135(6), 3455–3462. https://doi.org/10.1121/1.4874625

> *This study evaluated the effect of aircraft noise on speech intelligibility in an outdoor living environment. Participants listened to recordings of aircraft noise and phonetically balanced*

words in this outdoor setting, and the authors measured speech intelligibility at different background noise levels.

Bartels, S., Márki, F., & Müller, U. (2015). The influence of acoustical and non-acoustical factors on short-term annoyance due to aircraft noise in the field — The COSMA study. *Science of the Total Environment*, 538, 834–843. https://doi.org/10.1016/j.scitotenv.2015.08.064

Used hourly surveys of residents near a busy airport to analyze the relationship between noise level, activity disrupted, and annoyance to aircraft noise. Activities studied included speech communication, watching TV/listening to radio, relaxing, eating, and physical activity.

Berglund, B., Lindvall, T., & Schwela, D. H. (1999). *WHO Guidelines for Community Noise*. https://apps.who.int/iris/handle/10665/66217

Summarized existing research about a variety of noise topics, including speech interference. Intended to serve as a resource to local, regional, and national decision-makers on noise policy.

Hall, F. L., Taylor, S. M., & Birnie, S. E. (1985). Activity interference and noise annoyance. *Journal of Sound and Vibration*, 103(2), 237–252. https://doi.org/10.1016/0022-460X(85)90236-6

Developed an event-based model that expressed the probability of activity interference or annoyance occurring at any given noise level and tested the model with data from sites in Ontario exposed to aircraft, road traffic, or train noise. Activity interference findings were based on surveys of residents. The study found that speech communication and sleep are activities that are correlated with annoyance to noise.

Kobayashi, M., Morimoto, M., Sato, H., & Sato, H. (2007). Optimum speech level to minimize listening difficulty in public spaces. *The Journal of the Acoustical Society of America*, 121(1), 251–256. https://doi.org/10.1121/1.2382499

Evaluated the optimum speech levels for speech communication in public spaces by using measures of listening difficulty as rated by study participants.

Lee, P. J., & Jeon, J. Y. (2011). Evaluation of speech transmission in open public spaces affected by combined noises. *The Journal of the Acoustical Society of America*, 130(1), 219–227. https://doi.org/10.1121/1.3598455

Tested the effect of combined noise sources on speech transmission. Participants were given listening tests with different combinations of background noise from a typical urban square, road traffic noise, and stationary and impulsive construction noise, and speech intelligibility was measured.

Maffei, L., Masullo, M., Alexeeva, N., Palmieri, U., & Senese, V. P. (2012). The Speech Intelligibility Aboard Metros in Different Running Conditions. *Acta Acustica United with Acustica*, 98(4), 577–587. https://doi.org/10.3813/AAA.918539

Investigated the influence of noise on speech intelligibility inside metro trains under two different driving conditions (tunnel straight route and tunnel curve).

Shimokura, R., & Soeta, Y. (2009). Evaluation of speech intelligibility of sound fields in passenger train compartments. *Acoustical Science and Technology*, 30(5), 379–382. https://doi.org/10.1250/ast.30.379

Evaluated the speech intelligibility of announcements from PA systems on a passenger train.

Annoyance

The following studies were reviewed for the Annoyance topic:

Bartels, S., Marki, F., Muller, U. (2015). The Influence of Acoustical and Non-Acoustical Factors on Short-Term Annoyance Due to Aircraft Noise in the Field — the COSMA Study. *Science of the Total Environment*, 538, 834. http://dx.doi.org/10.1016/j.scitotenv.2015.08.064

Field study investigated aircraft noise-induced short-term (i.e., within hourly intervals) annoyance in local residents near a busy airport. Study aimed at examining the contribution of acoustical and non-acoustical factors contributing to noise annoyance ratings. Results include explained variance metrics for different factors including acoustical factors, operations statistics, and personal situational factors.

Borsky, P. (1973). A New Field-Laboratory Methodology for Assessing Human Response to Noise. *NASA Contractor Report,* NASA CR-2221. Columbia University. Langley Research Center. https://ntrs.nasa.gov/search.jsp?R=19730009397

Review of effects of noise on humans, and proposal of new methodology for assessing human response to noise pollution. This paper includes a comparison of data from British and American aircraft noise annoyance surveys. Average percent highly annoyed response rates are presented for different ratings of fear or feelings of misfeasance for the aircraft operators or airports.

Fastl, H., Zwicker, E. (1999). Psycho-Acoustics: Facts and Models, Second Edition. *Springer*.

Comprehensive textbook representing collection of data describing the processing of sound by the human hearing system. This book includes quantitative relations between sound stimuli and auditory perception. Contains solutions of practical benefit for engineers and applications in research fields. One of the leading textbooks on the subject of psychoacoustics.

Fidell, S., Barber, D., Schultz, T. (1991). Updating a dosage–effect relationship for the prevalence of annoyance due to general transportation noise. *Journal of the Acoustical Society of America*, 89(1), 221. https://doi.org/10.1121/1.400504

Update of Schultz's 1978 analysis with new data from surveys and studies performed in the 1970s and 1980s. Similar results to Schultz's work are presented, including an average dose-response curve for noise and percent highly annoyed. It is noted that the 1978 relationship still provides a reasonable fit to the data despite the vast amount of new data included in this study.

Guski, R. (2017). The Increase of Aircraft Noise Annoyance in Communities: Causes and Consequences. *Proceedings of the 12th International Commission on Biological Effects of Noise (ICBEN) Congress on Noise as a Public Health Problem.* http://www.icben.org/2017/ICBEN%202017%20Papers/Keynote04_Guski_4164.pdf

> *Keynote conference presentation on data indicating a rise in aircraft noise annoyance in communities at given L_{Aeq} values. The paper discusses several potential causes of this process including changing study methodologies, contextual changes, increases in number of aircraft movements, changes in fleet composition, and attitudinal changes.*

Guski, R., Schreckenberg, D., Schuemer, R. (2017). Guidelines for the European Region: A Systematic Review on Environmental Noise and Annoyance. *International Journal of Environmental Research and Public Health*, 14(12), 1539. https://doi.org/10.3390/ijerph14121539

> *Systematic review of the dose response relationship between noise and annoyance. Quantitative meta-analysis was performed on 57 studies along with other data received from study authors. Studies included in the analysis were acoustical and social survey studies linking noise exposure to standard annoyance responses. Results were tentative dose response relationships combining the data obtained from the literature review for air, rail, and road transportation.*

Miedema, H., Oudshoorn, C. (2001). Annoyance from Transportation Noise: Relationships with Exposure Metrics DNL and DENL and Their Confidence Intervals. *Environmental Health Perspectives*, 109(4), 409. https://doi.org/10.1289/ehp.01109409

> *Presentation of model of the distribution of noise annoyance with the mean varying as a function of the noise exposure. Model is fitted to data from noise annoyance studies for aircraft, road traffic, and railways separately. Confidence intervals are provided for the resulting analysis. Noise metrics used for the curve fitting are DNL and DENL. Polynomial approximations of relationships implied by these models are presented as well.*

Miller, M., Cantor, D., Lohr S., Jodts, E., Williams, D., et al. (2014). Research Methods for Understanding Aircraft Noise Annoyances and Sleep Disturbance. *The National Academies of Sciences Engineering and Medicine.* Transportation Research Board. https://doi.org/10.17226/22352

> *Research procedures for studying annoyance and sleep disturbance from aircraft noise. This includes surveys and survey procedures, as well as summaries of results from previous surveys. Metrics reported include response rates to different kinds of surveys, biases for different survey types and question types, and budgeting analyses for different survey types.*

Pederson, T. H. (2007). The "Glenlyd" Noise Annoyance Model: Dose Response Relationships Modelled by Logistic Functions. *Summary Report for the Danish Ministry of Science, Technology, and Innovation.* https://assets.madebydelta.com/assets/docs/share/Akustik/The_Genlyd_Noise_Annoyance_Model.pdf

> *Summary of the dose-response model conceived by Danish research group for acoustics and electronics. This report includes a description of a nuanced functional model of annoyance that allows easier analysis of dose models. Also presented is a synthesis of dose response data and*

curves from aircraft noise, roadway noise, railway noise, and wind turbine noise. Also discussed are non-acoustic factors that affect annoyance to noise, along with modifiers to model equations for these factors.

Schreckenberg, D., Schuemer, R. (2010). The Impact of Acoustical, Operational and Non-Auditory Factors on Short-Term Annoyance due to Aircraft Noise. *39th International Congress on Noise Control Engineering, June 2010.* Lisbon, Portugal.

Re-analysis of data of the Frankfurt Noise Annoyance Study 2005 to identify acoustical, operational and non-acoustical factors contributing to the explanation of short-term annoyance (hourly annoyance). Statistical analysis results are indicated in terms of correlation factors, beta coefficients, and other metrics to determine which factors have higher relations to various annoyance ratings. Both attitudinal factors and activity interference are included as factors that affect short and long-term annoyance to aircraft noise.

Schultz, T. (1978). Synthesis of Social Surveys on Noise Annoyance. *Journal of the Acoustical Society of America*, 64(2), 377. https://doi.org/10.1121/1.382013

Review and synthesis of data from several social surveys on noise annoyance from different noise sources. Analysis results include an average curve derived from the annoyance data from 11 of the surveys reviewed. It is reported that it was the best currently available relationship for predicating community annoyance due to transportation noise at the time of writing.

Naim, F., Gulliver, J., Fecht, D., Hansell, A. (2017) Assessing the Relationship of Indoor and Outdoor Noise at Residential Dwellings in London. *12th International Commission on the Biological Effects of Noise Congress on Noise as a Public Health Problem, June 2017*. Zurich, Switzerland.

Exploration of indoor and outdoor noise levels to understand the relationship between the two. The study aims to assess how well outdoor noise levels predict indoor noise levels, as many epidemiological studies use outdoor noise levels to assess health impacts of noise. Continuous noise measurements were made inside and outside each measured residence for three consecutive days. Locations are grouped by primary noise sources, included aircraft, highways, railroads, etc.

Locher, B., Piquerez, A., Habermacher, M., Ragettli, M., Röösli, M., Brink, M., … Wunderli, J. M. (2018). Differences between Outdoor and Indoor Sound Levels for Open, Tilted, and Closed Windows. *International journal of environmental research and public health*, 15(1), 149. https://dx.doi.org/10.3390%2Fijerph15010149

Study aimed at determining sound level differences between indoors and outdoors for different window positions, building locations, and building characteristics including age, construction material, etc. Linear regression models were developed relating the indoor L_{Aeq} *and the outdoor* L_{Aeq}

Health and Sleep Impacts

The following studies were reviewed for the Health and Sleep Impacts topic:

Basner, M., & McGuire, S. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Effects on Sleep. *International Journal of Environmental Research and Public Health*, 15(3), 519. https://doi.org/10.3390/ijerph15030519

> *Systematic review of the effects of environmental noise exposure on sleep based on 74 studies conducted between 2000 and 2015. The study involved a meta-analysis of surveys linking road, rail, and aircraft noise exposure to self-reports of sleep disturbance. The study also involved a pooled analysis of polysomnographic studies on the acute effects of transportation noise on sleep.*

Brown, A., & van Kamp, I. (2017). WHO Environmental Noise Guidelines for the European Region: A Systematic Review of Transport Noise Interventions and Their Impacts on Health. *International Journal of Environmental Research and Public Health*, 14(8), 873. https://doi.org/10.3390/ijerph14080873

> *Literature review of studies from 1980 to 2014 on evidence of the effects of transport noise interventions on human health. Transportation sources included road traffic, railways, and air traffic, and health outcomes included disturbance, annoyance, cognitive impairment of children, and cardiovascular diseases. Interventions included actions to change the noise exposure as measured at the external façade of the residence, and actions such as communication or education aimed at changing health outcomes but not people's exposure to noise. The analysis showed that many of the interventions were associated with changes in health outcomes irrespective of the source type, intervention type, or outcome measured.*

Coggon, D., Rose, G., & Barker, D. (n.d.). *Epidemiology for the uninitiated* (4th Edition). Retrieved from https://www.bmj.com/about-bmj/resources-readers/publications/epidemiology-uninitiated/8-case-control-and-cross-sectional

> *Background resource on types of epidemiological studies, including case-control, cross sectional, and ecological studies.*

Consensus Conference Panel, Watson, N. F., Badr, M. S., Belenky, G., Bliwise, D. L., Buxton, O. M., … Heald, J. L. (2015). Joint Consensus Statement of the American Academy of Sleep Medicine and Sleep Research Society on the Recommended Amount of Sleep for a Healthy Adult: Methodology and Discussion. *Sleep, 38(8)*, 1161–1183. https://doi.org/10.5665/sleep.4886

> *Summary of the findings and methodology for an American Academy of Sleep Medicine and Sleep Research Society Consensus Statement regarding the recommended amount of sleep to promote optimal health in adults.*

Correia, A. W., Peters, J. L., Levy, J. I., Melly, S., & Dominici, F. (2013). Residential exposure to aircraft noise and hospital admissions for cardiovascular diseases: multi-airport retrospective study. *BMJ*, 347(oct08 3), f5561–f5561. https://doi.org/10.1136/bmj.f5561

Study investigates whether exposure to aircraft noise increases the risk of hospitalization for cardiovascular diseases in older people residing near airports. The study uses a dataset of approximately 6 million older people residing near 89 airports in the U.S., and noise contours provided by the FAA. Finds a statistically significant association between exposure to aircraft noise and risk of hospitalization for cardiovascular diseases among older people living near airports.

Miedema, H. M. E., & Vos, H. (2007). Associations Between Self-Reported Sleep Disturbance and Environmental Noise Based on Reanalyses of Pooled Data From 24 Studies. *Behavioral Sleep Medicine*, 5(1), 1–20. https://doi.org/10.1207/s15402010bsm0501_1

Study involves a re-analysis of pooled data from studies on the association between self-reported sleep disturbance and exposure to nighttime transportation noise. Develops functions that give the percentage highly sleep disturbed, sleep disturbed, and (at least) a little sleep disturbed people due to aircraft, road traffic, and railway noise in relation to the average nighttime outdoor exposure level at the facade most exposed to the source concerned.

Peters, J. L., Zevitas, C. D., Redline, S., Hastings, A., Sizov, N., Hart, J. E., … Wellenius, G. A. (2018). Aviation Noise and Cardiovascular Health in the United States: a Review of the Evidence and Recommendations for Research Direction. *Current Epidemiology Reports*, 5(2), 140–152. https://doi.org/10.1007/s40471-018-0151-2

Review focuses on recent findings on the relationship between aircraft noise and cardiovascular outcomes (over the last five years) and directions for future research. Epidemiological studies generally report statistically significant associations between aircraft noise and adverse cardiovascular outcomes, although with limited evidence within the USA. Sleep disturbance, associated with nighttime noise, has been shown to be a risk factor for cardiovascular disease given associations with inflammatory markers and metabolic changes.

Somers, V. K., White, D. P., Amin, R., Abraham, W. T., Costa, F., Culebras, A., … Young, T. (2008). Sleep Apnea and Cardiovascular Disease. *Journal of the American College of Cardiology, 52(8)*, 686–717. https://doi.org/10.1016/j.jacc.2008.05.002

Describes the types and prevalence of sleep apnea and its relevance to individuals who either are at risk for or already have established cardiovascular disease.

Van Kempen, E., Casas, M., Pershagen, G., & Foraster, M. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cardiovascular and Metabolic Effects: A Summary. *International Journal of Environmental Research and Public Health*, 15(2), 379. https://doi.org/10.3390/ijerph15020379

Systematic review of the literature dealing with observational studies on the association between environmental noise exposure and the cardiovascular and metabolic systems. The article aims to update some of the existing exposure-response relationships, and to evaluate the overall quality of the evidence.

Cognitive Effects

The following studies were reviewed for the Cognitive Effects topic:

Clark, C., Head, J., & Stansfeld, S. A. (2013). Longitudinal effects of aircraft noise exposure on children's health and cognition: A six-year follow-up of the UK RANCH cohort. *Journal of Environmental Psychology*, 35, 1–9. https://doi.org/10.1016/j.jenvp.2013.03.002

> *Follow-up study to the RANCH study on noise exposure and cognition six years after the original data collection. The purpose of the study was to evaluate the long-term effects of aircraft noise exposure on children's learning and health.*

Clark, C., Martin, R., Van Kempen, E., Alfred, T., Head, J., Davies, H. W., … Stansfeld, S. A. (2006). Exposure-Effect Relations between Aircraft and Road Traffic Noise Exposure at School and Reading Comprehension*. American Journal of Epidemiology*, 163(1), 27–37. https://doi.org/10.1093/aje/kwj001

> *This study involved the evaluation of RANCH study data on noise exposure at school and cognition outcomes, combined with information on aircraft noise exposure at home. The study found no additional effect of aircraft noise exposure at home after adjustment for aircraft noise exposure at school.*

Clark, C., & Paunovic, K. (2018). WHO Environmental Noise Guidelines for the European Region: A Systematic Review on Environmental Noise and Cognition. *International Journal of Environmental Research and Public Health*, 15(2), 285. https://doi.org/10.3390/ijerph15020285

> *Review to assess the quality of evidence for the association between environmental noise exposure and cognition. Based on 34 studies, the review describes the effects of environmental noise on cognition across different noise sources and cognition outcomes, and assesses the quality of evidence for each combination of noise source and cognition outcome.*

Guski, R., Klatte, M., Moehler, U., Müller, U., Nieden, A. zur, & Schreckenberg, D. (2016). *NORAH (Noise Related Annoyance, Cognition, and Health): Questions, designs, and main results*.

> *Study on the effects of chronic exposure to aircraft noise on the cognitive performance and quality of life of schoolchildren near Frankfurt Airport.*

Hygge, S., Evans, G. W., & Bullinger, M. (2002). A Prospective Study of Some Effects of Aircraft Noise on Cognitive Performance in Schoolchildren. *Psychological Science*, 13(5), 469–474. https://doi.org/10.1111/1467-9280.00483

> *Before/after study on the association between noise and cognition when a new airport opened in Munich and led to changes in noise exposure at schools near the new and old airports.*

Klatte, M., Bergström, K., & Lachmann, T. (2013). Does noise affect learning? A short review on noise effects on cognitive performance in children. *Frontiers in Psychology*, 4. https://doi.org/10.3389/fpsyg.2013.00578

Literature review on the pathways through which noise affects children's learning. Includes information on the effects of noise on speech interference, non-auditory tasks, and cognitive development.

Matsui, T., Stansfeld, S., Haines, M., & Head, J. (2004). Children's cognition and aircraft noise exposure at home--the West London Schools Study. *Noise & Health*, 7(25), 49–58.

This study examined the effects of noise exposure at home on children's cognitive performance. The study involved students attending schools near London's Heathrow Airport where noise exposure at school and at home differed.

National Academies of Sciences, Engineering, and Medicine 2014. *Assessing Aircraft Noise Conditions Affecting Student Learning, Volume 1: Final Report*. Washington, DC: The National Academies Press. https://doi.org/10.17226/22433.

Nationwide study at schools near 46 airports in the U.S. The purpose of the study was to identify the relationship between aircraft noise exposure and student performance, taking into account the effect of school sound insulation and other confounding factors.

Stansfeld, S. A., Berglund, B., Clark, C., Lopez-Barrio, I., Fischer, P., Öhrström, E., … Berry, B. F. (2005). Aircraft and road traffic noise and children's cognition. *The Lancet*, *366*(9487), 715–716. https://doi.org/10.1016/S0140-6736(05)67174-7

Describes the methodology and results of the RANCH study, a cross-national, cross-sectional study of the effects of aircraft and road traffic noise on children's learning in the Netherlands, Spain and the United Kingdom.

Financial Impacts

The following studies were reviewed for the Financial Impacts topic:

Almer, C., Boes, S., and Nüesch, S. (2017). Adjustments in the housing market after an environmental shock: evidence from a large-scale change in aircraft noise exposure. *Oxford Economic Papers*. https://doi.org/10.1093/oep/gpw071

Evaluated apartment rents around Zurich airport before and after a change in aircraft noise due to changing flight patterns. Found that apartment rents in areas exposed to more aircraft noise decreased for two years, then stabilized at a lower equilibrium.

Brandt, S., & Maennig, W. (2011). Road noise exposure and residential property prices: Evidence from Hamburg. Transportation Research Part D: Transport and Environment, 16(1), 23–30. https://doi.org/10.1016/j.trd.2010.07.008

Used hedonic regression models to examine the effects of road noise on condominium prices in city of Hamburg, Germany. Found price discounts of 0.23% following a 1 dB(A) increase in road noise, and that price discounts depend on the noise level (higher for higher noise levels).

McMillen, D. P. (2004). Airport expansions and property values: the case of Chicago O'Hare Airport. *Journal of Urban Economics*, 55(3), 627–640. https://doi.org/10.1016/j.jue.2004.01.001

> *Used transaction data to estimate the effect of airport noise on property values around Chicago O'Hare airport. The results indicated that home values were about 9% lower within a 65 dB noise contour band of O'Hare in 1997.*

Nelson, J. P. (1980). Airports and Property Values: A Survey of Recent Evidence. *Journal of Transport Economics and Policy*, 14(1), 37–52.

> *Literature review of hedonic regression studies on the impact of aviation noise on residential property values. Found that aviation noise has a negative impact on property values, ranging from 0.4 to 1.1% per dB of noise increase.*

Nelson, J. P. (1982). Highway Noise and Property Values: A Survey of Recent Evidence. *Journal of Transport Economics and Policy*, 16(2), 117–138.

> *Literature review of hedonic regression studies on the impact of highway noise on residential property values. Found that highway noise has a negative impact on property values, of approximately 0.4% per dB of noise increase.*

Ozdenerol, E., Huang, Y., Javadnejad, F., & Antipova, A. (2015). The Impact of Traffic Noise on Housing Values. *Journal of Real Estate Practice and Education*, 18(1), 35–54.

> *Evaluated the impact of traffic noise on property prices in Shelby County, TN using a hedonic regression model. Found that traffic noise, in general, has a significantly negative impact on housing values, and that the discount on housing values increases as the noise nuisance levels increase.*

Theebe, M. (2004). Planes, Trains, and Automobiles: The Impact of Traffic Noise on House Prices. *Journal of Real Estate Finance and Economics*, 28(2/3), 209–234.

> *Estimated the impact of mixed traffic noise on property prices near Schiphol airport in Amsterdam using sales transactions and noise data for 100m by 100m areas. Found a non-linear relationship between traffic noise and housing prices, with an average of about a 5 percent discount.*

Walker, J. K. (2016). Silence is Golden: Railroad Noise Pollution and Property Values. *The Review of Regional Studies*, 45, 75–89.

> *Used a dataset containing property values and manually collected noise measurements in Memphis, Tennessee to estimate the impact of train noise pollution on commercial and residential property values. Results showed that locations within the 65 dB contour resulted in a 14 to 18 percent decrease in residential property value.*

Impulse Noise

The following studies were reviewed for the Impulse Noise topic:

Brink, M. & Wunderli, J.-M. (2010). A field study of the exposure-annoyance relationship of military shooting noise, *Journal of the Acoustical Society of America,* 127, 2301, https://doi.org/10.1121/1.3337234

> *This article reported a field study on noise annoyance from military shooting with small, midsize, and heavy weapons that was carried out among residents living near eight different training grounds of the Swiss army. Results are varied, with a 5-point annoyance scale more closely relating to noise exposure and sound exposure level relating most to variations in annoyance.*

Fidell, S., Pearsons, K. (Feb. 1994). Comparison of Methods of Predicting Community Response to Impulsive and Nonimpulsive Noise. *NASA Ames Research Center, High-Speed Research: Sonic Boom,* Volume 1, 177-189

> *Examination and review of methods of predicting community response to both impulse and non-impulse noise. This includes derivation of dosage-response relationships from a few different data sources including Schultz in the 1970s and CHABA data sources. Conclusions specify that impulsive noise is more complex and that fewer data exists than for general transportation noise*

Fidell, S., Pearsons, K. (Oct. 1994). Deriving a dosage-response relationship for community response to high-energy impulsive noise. *1994 NASA Sonic Boom Workshop: Atmospheric Propagation and Acceptability Studies*, 185-192

> *Mathematical exercise utilizing existing data sets and a curve fitting method to derive dosage response relationship for high-energy impulse noise to community annoyance. Conclusions indicate that CDNL with a response bias correction factor produces a better fitting curve than previously obtained.*

Fields, J.M. (1997). Reactions of Residents to Long-Term Sonic Boom Noise Environments. *NASA Final Contractor Report,* https://ntrs.nasa.gov/search.jsp?R=19970023685

> *Report of a combined social survey and noise measurement program for 14 communities in the western U.S. (Nevada). The 6 month study is one of the main sonic boom research programs referenced today is part of the overall data set in this subject.*

Maglieri, D., Bobbit, P., Plotkin, K., Shepherd, K., Coen, P., Richwine, D., (2014). Sonic Boom: Six Decades of Research. *NASA Langley Research Center*, https://ntrs.nasa.gov/search.jsp?R=20150006843

> *Large-scale synthesis on all subjects surrounding sonic booms. Section on response to sonic boom was reviewed in depth. Generally, the data varies enough that conclusions are difficult to make. However, it is clear from the research that shaped sonic booms can have a large impact on community response to sonic boom exposure.*

Page, J., Hodgdon, K., Krecker, P., Cowart, R., Hobbs, C., Wilmer, C., Koening, C., Holmes, T., Gaugler, T., Shumway, D. (2014). Waveforms and Sonic Boom Perception and Response (WSPR): Low-Boom Community Response Program Pilot Test Design, Execution, and Analysis. *NASA Technical Report, Langley Research Center,* https://ntrs.nasa.gov/search.jsp?R=20140002785

> *Large-scale study using Edwards AFB and surrounding communities on response to sonic boom exposure. Correlations and dose response relationships are studied for different assessment metrics.*

Price, G.R., (2010). Auditory Hazard Assessment Algorithm for Humans (AHAAH). *U.S. Army Research Laboratory, Model Website*, https://www.arl.army.mil/www/default.cfm?page=343

> *Website on U.S. Army Research Laboratory site with a few articles detailing the development and verification process for the AHAAH model. Articles reviewed include the executive summary, cat exposure studies, and functional descriptions of the model.*

Ryalander, R., Lundquist, B. (1996). Annoyance Caused by Noise from Heavy Weapon Shooting Ranges. *Journal of Sound and Vibration,* 192, 1, 199-206, https://doi.org/10.1006/jsvi.1996.0183

> *Survey based study in Switzerland studying annoyance to heavy weapon shooting ranges. Results are compared to earlier similar studies and exposure-response is related to the number of noise events exceeding 90 dB* L_{cx} *(C-weighted sound pressure level averaged over 1 second).*

Starck, J., Toppila E., Pyykko, I. (2003). Impulse noise and risk criteria. *Noise and Health Journal*. 5:63-73. http://www.noiseandhealth.org/text.asp?2003/5/20/63/31687

> *Review of national risk criteria and available standards, studies, and data on the risk of damage from impulse noise. Discusses industrial impulse noise as well as shooting noise as a risk of hearing impairment. Specifies that international risk assessment methodologies need to be developed.*

Lie, A., Skogstad, M., Johannessen, H. A., Tynes, T., Mehlum, I. S., Nordby, K. C., … Tambs, K. (2016). Occupational noise exposure and hearing: a systematic review. *International archives of occupational and environmental health*, 89(3), 351–372. https://dx.doi.org/10.1007%2Fs00420-015-1083-5

> *Systematic literature review of occupational noise studies, specifically focusing on the effect of noise exposure on hearing. Gives quantitative results for overall occupational noise exposure. For impulse noise, concludes that effects seem to be more deleterious than for continuous noise.*

Stationary Sources

Murphy, E., King, E. (2014). Environmental Noise Pollution: Noise Mapping, Public Health, and Policy. *Elsevier Inc.* Chapter 6, Industrial and Construction Type Noise, 173. https://doi.org/10.1016/C2012-0-13587-0

> *Textbook on addressing the key debates surrounding environmental noise pollution with focus on the European Union. The authors used their considerable research experience in this field in this benchmark reference across disciplinary, policy, and national boundaries. Chapter 6 includes*

discussions of multiple non-transportation noise sources including windmills, industrial sites, construction sites, and quarries.

Thomas, G., Liu, Y. (2013). Cowal Gold Mine Extension Modification Noise and Blasting Impact Assessment. *SLR Consulting Australia Ltd.* Report number 610.10052-R1.

Noise impact assessment relating to proposed modifications to an existing gold mine in New South Wales. The assessment included measurements of existing ambient noise levels, and modeling of resulting noise levels from specific mining activities. Modeled noise level increases in residential areas surrounding the mine are given, including those from blasting operations. Noise levels resulting from changes to road traffic volumes were also modeled.

Benchmark Resources. (2011). Moody Flats Quarry Project Environmental Impact Report: Noise Impact Analysis. *Benchmark Resource with Shasta County Department of Resource Management, 19005 Placer Street, Suite 103, Redding, CA, 96001*

Noise impact assessment for installation of a quarry in Shasta County, California. The assessment was performed to model the project's impact on environmental noise levels on surrounding areas. Compliance with county standards was examined as well. The analysis included measurement of ambient noise levels in the area as well as modelled sound levels resulting from project implementation.

Bansah, K. J., Bosompem, A. (2015). Predicting the Levels of Noise from Quarry Operations. *24th International Mining Congress and Exhibition of Turkey, April 14-17, 2015.* Antalya, Turkey. https://doi.org/10.13140/rg.2.1.4122.5201

Study on the impacts of mining activities on the sounding noise environment for a quarry in Ghana. Notable among these impacts is noise emission from sources such as machinery, drilling, blasting, dumping and crushing. 25 days of monitoring was conducted for 24 hours each day. The noise from different activities was modelled at different receiver locations. Some recommendations are given to reduce the levels of noise generated at the quarry.

Mendocino County, CA, Code of Ordinances. Ch. 22.16 – Surface Mining and Reclamation, Section 070: Permit Operational Standards. (2017). https://www.conservation.ca.gov/smgb/reports/Documents/Ordinances-County/Mendocino.pdf

Standards for operating surface mines. Stipulates noise standards at the receiver for surface mining operations. Overall, this policy provides regulations for all surface mining operations in Mendocino County, CA.

Urman, S. (1987). A Survey of Railroad Occupational Noise Sources. *Transportation Research Board. Transportation Research Record 1143. National Research Council, Washington, D.C.*

Measured noise levels are presented for various railroad industry noise sources, including railroad classification yards, locomotives, and cabooses. Alternative control methods for sound reduction are outlined.

Oriel, A. (2017). Lawsuit Rails against train yard's deafening noise levels. Sandusky Register. Retrieved from http://www.sanduskyregister.com/story/201703170035

> *Article detailing a lawsuit filed by residents living nearby a railyard in Bellevue, Ohio. Residents complained of high noise levels, squeals from retarders, and a lack of regard on the part of the operator for the effect the yard had on surroundings.*

European Commission Working Group on Assessment of Exposure to Noise (WG-AEN). (2007). Good Practice Guide for Strategic Noise Mapping and the Production of Associated Data on Noise Exposure, Version 2.

> *Position paper aimed at helping member states of the EU undertake noise mapping and produce the associated data as required by Directive 2002/49/EC of the European Parliament. Contains discussions and recommendations for noise source, propagation and receiver related issues. Also provides discussion on modeling toolkits and the accuracy thereof. Provides default values of sound power levels for industrial sites.*

van den Berg, M. Van den Burg, M. (1999). Industry Data. Retrieved from https://rigolett.home.xs4all.nl/GV/kenind.htm and translated using google translate.

> *Database of default values of noise produced by different types of industrial areas. Averages are given in sound power decibels per meter squared and can be adjusted based on the lot size of the industrial site.*

Berkeley California Community Noise Standards. (2009). Berkeley, CA, USA. *City Clerk, Title 13 Chapter 13.40.* https://www.codepublishing.com/CA/Berkeley/html/pdfs/Berkeley13.pdf

> *Standards and regulations defining community noise limits, times of day when noise-generating activities are acceptable, and abatement criteria. The goals of the regulation are to limit the number of intrusive, offensive, and excessive noises that occur in the city of Berkeley, CA.*

Heibel, J., Durkay, J. (2016). State Legislative Approaches to Wind Energy Facility Siting. Retrieved from http://www.ncsl.org/research/energy/state-wind-energy-siting.aspx *National Conference of State Legislatures.*

> *Discussion and list of legislative approaches to wind energy facility siting regulations in different states. Currently available regulations, standards, or recommendations are tabulated and compared.*

ESS Group, Inc. (2010). Sound Survey and Analysis Report: Proposed Wind Energy Facility in the Town of Brewster Massachusetts. *Cape and Vineyard Electric Cooperative, Inc*. https://www.rd.usda.gov/files/UWP_MA01-CVEC_Brewster_EA-App4.pdf

> *Predicted noise levels from full operation of the proposed wind energy facility were evaluated with respect to applicable state and local noise regulations for both high wind speed conditions and low wind speed conditions. Operational noise is assessed at the property line of the proposed facility and at the closest noise-sensitive land use in the surrounding community.*

Page, J., Solman, G., Stahl, L. (2018). Commercial Space Launch Noise and Sonic Boom Research Roadmap. *Volpe National Transportation Systems Center, for the Federal Aviation Administration.* Internal report not published.

> *Overview of the burgeoning area of space development, including the commercial business landscape and the state of the art of space vehicles from a community noise perspective. Examines models relevant to space launch noise, and gives some modeled noise results in appendices for specific space launch situations.*

Bradley, K. A., James, M. M., Salton A. R., Boeker, E. R. (2018). Commercial Space Operations Noise and Sonic Boom Modeling and Analysis. *National Academies of Sciences, Engineering, and Medicine. The National Academies Press*. https://doi.org/10.17226/25100.

> *Report detailing the development of a rocket noise and sonic boom model for commercial space operations that can be integrated with FAA's Aviation Environmental Design Tool. A database was developed of existing vehicle/engine data to be used for modeling purposes. The resulting models are based on the rocket noise model "RUMBLE" and the sonic boom model "PCBoom."*