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11 Human Response to Aircraft Noise

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Introduction

If noise is defined as sound that produces adverse effects, then aircraft are a major source of noise affecting, at least to some extent, the work and leisure activities of a large proportion of people in nearly all developed countries. Although only a small percentage of the propulsion energy of an aircraft is converted into sound, that percentage represents a large power source. The sources of aircraft noise most responsible for community and ground crew effects are the high-velocity jet exhausts, fans, internal turbomachinery, propellers, rotors, internal combustion engine exhausts, and, for supersonic aircraft, sonic booms. Those sources most responsible for passenger or flight crew effects are turbulent boundary layers, propellers, helicopter gear boxes, jet exhausts, internal combustion engine exhausts, and structureborne vibration from unbalanced rotational forces. However, there is not a one-to-one relationship between sound energy and any given noise effect. To effectively control the noise, that is, reduce those components that are most responsible for adverse human effects, it is necessary to thoroughly understand the physical characteristics of the sound and how each of those characteristics can affect human response.

Adverse effects of aircraft noise include hearing loss, task performance degradation, speech intelligibility reduction, sleep interruption, and general feelings of annoyance. A number of nonauditory physiological effects that may adversely affect health are claimed to result from noise exposure. It is not possible in the limited space of this chapter to examine all the potential effects of aircraft noise in great detail. Since nearly all effects of noise on humans rely on the perception of sound by the hearing mechanism, the human auditory system and the general perception of sound are discussed. However, the major concentration of this chapter is on annoyance response and methods for relating physical characteristics of sound to those psychosociological attributes associated with human response. Results selected from the extensive laboratory and field research conducted on human response to aircraft noise over the past several decades are presented along with discussions of the methodology commonly used in conducting that research. Finally, some of the more common criteria, regulations, and recommended practices for the control or limitation of aircraft noise are examined in light of the research findings on human response.

Those readers with particular interest in the effects of noise on task performance, sleep interruption, health, or other nonauditory physiological functions are referred to the general reference texts of references 1 to 3.

Perception of Sound

The human auditory system is capable of sensing, analyzing, or interpreting fluctuations in air pressure over an extremely wide range. The interested reader can find more details of this fascinating sensory system in many modern textbooks such as reference 4. The following sections, however, provide a brief overview of hearing anatomy and theory and those attributes which are considered most critical to human response to aeroacoustic noise sources.

Anatomy of the Ear and Hearing Theory

The auditory system consists of the outer (pinna and ear canal, or external meatus), middle (ossicular chain), and inner (cochlea) ears and the associated pathways to the brain. A diagram of the internal hearing organs is shown in figure 1. Air pressure fluctuations in the external meatus vibrate the tympanic membrane, or eardrum, which is coupled mechanically to the fluid-filled inner ear through the bones (malleus, incus, and stapes), tendons, ligaments, and muscles which make up the ossicular chain located in the middle ear. The mechanical linkage forms the impedance-matching interface between air and the fluid-filled cochlea.

The tensor tympani and stapedius muscles in the middle ear are capable of impeding the motion of the ossicular chain and are responsible for the acoustic, or aural, reflex. This reflex, which is involuntary in most people, attenuates intense sounds and thereby offers some protection to the sensory organs in the inner ear.

The vibratory motion of the stapes is coupled to the fluid-filled cavity of the cochlea through the oval window. Pressure fluctuations cause a traveling wave to pass along the cochlear partition, or basilar membrane, with the ultimate excitation of the hair cells situated on the basilar membrane within the organ of Corti. The mechanisms of nerve cell excitation and transmittal of neural signals to the brain are beyond the scope of this review but can be found in most texts on hearing such as reference 4.

Since the cochlear partition decreases in stiffness from the stapes, it acts as a low-pass filter, with the result that the end further from the stapes is more responsive

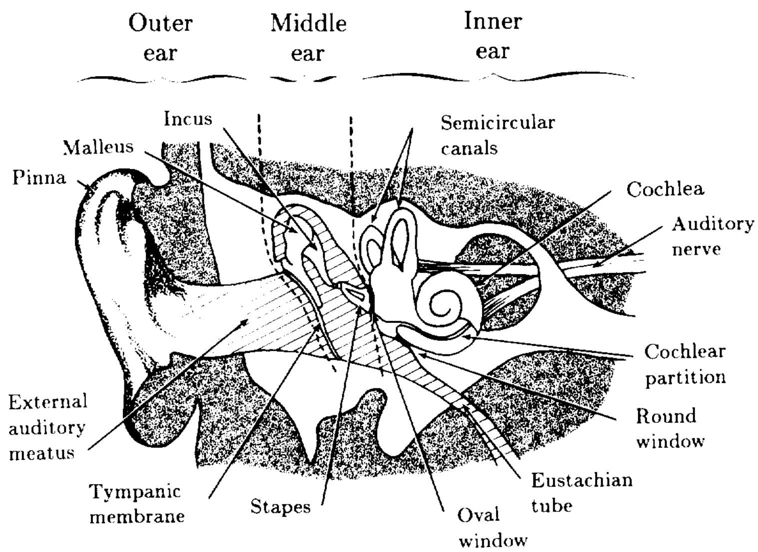


Figure 1. Cross section of the human ear.

to low frequencies. This mechanism facilitates the frequency analysis capabilities of the auditory system, particularly at higher frequencies, and forms the basis of the "place" theory of hearing. In addition, the "volley" theory proposes that analysis is performed by the central auditory nervous system, particularly at low frequencies, and that frequency information is transmitted in volleys of neural discharges which are phase locked to the pressure fluctuations. It is now generally accepted that neither theory can fully explain the sensitivity and selectivity of the auditory system over the total frequency range and that a better explanation is found in an interaction of both mechanisms.

Because of the complexity of the auditory system and the interfaces between the acoustical, mechanical, and neurological systems, it is not surprising that the response of the auditory system to sounds with differing spectral and temporal characteristics is not easy to predict or measure. However, several generalities can be stated:

1. The human auditory system is sensitive to a very wide range of air pressure fluctuation. The pressure ratio of the threshold of pain to the threshold of audibility is approximately 1 million.

2. The audible frequency range of hearing is normally considered to be 20 Hz to 20 kHz. However, the sensitivity is not uniform across the frequency range; lower sensitivity occurs at both the high- and the low-frequency end of the range.

3. One sound can mask the perception of another sound of lower intensity. In general, although the masking is most efficient if the frequency contents of the two sounds are similar, a sound with lower frequency content than a given sound is more efficient at masking the given sound than is a sound with higher frequency content.

4. Sound at high sound pressure levels can cause both temporary and permanent threshold shifts in hearing ability. Levels greater than about 180 dB can rupture the tympanic membrane, and levels greater than about 85 dB can cause significant temporary or permanent loss of hearing acuity depending on the duration of the noise exposure.

Auditory Phenomena Affecting Perception of Sound

The following sections consider those auditory phenomena that have been found to be important in predicting how people perceive and respond to a given sound in a given situation. The scope of this discussion does not allow a complete treatment of any of these important topics. The reader can find more information in a number of general references including references 2 and 4.

Loudness

Loudness is traditionally defined as the perceived intensity of a sound. Considerable research has been conducted over the last 75 years to investigate how the human auditory system integrates the temporal and spectral information contained in sound waves arriving at the ear so that it may be quantified subjectively in terms of a single overall intensity measure. The basic mechanisms and important parameters have been known and studied for many years (ref. 5); however, the advent of modern electronic and audio systems has resulted in improvements in and refinements to loudness prediction models.

The curves of figure 2 represent the sound pressure levels of octave bands of noise which produce the sensation of equal loudness (ref. 6). As can be seen, the auditory system is neither uniform across frequency nor completely linear with amplitude. Similar equal-loudness curves have been defined for sounds consisting of pure tones. The basic shapes of the equal-loudness curves are similar, with the region of greatest sensitivity occurring at about 3 kHz.

The question of how the auditory system sums the loudness of sounds comprised of more than a single component has also been the subject of much research. The model of loudness summation in reference 7 considers not only the loudness of the individual components but also the concepts of critical bandwidths and mutual masking, or inhibition, between the various sound components. Again the more interested reader is referred to a more complete text (refs. 2–4).

The loudness of a sound has also been found to depend on its duration. The loudness of a constant-amplitude tone increases with increasing duration up to a duration of approximately 200 msec. This duration is commonly referred to as the "integration time of the ear." This temporal summation is believed to take place in the central nervous system rather than in the ear itself (ref. 8). Most research in this area indicates that the loudness increases about 10 dB for a factor-of-10 increase in duration up to the integration time. This type of loudness increase is very important for sounds of short duration such as impulses and is discussed at more length in subsequent sections. There have also been studies that indicate a type of loudness adaptation, or decrease in loudness, with increasing durations beyond the integration time; however, the study of reference 9 suggests that the previously measured adaptation may be an artifact of the test methods used.

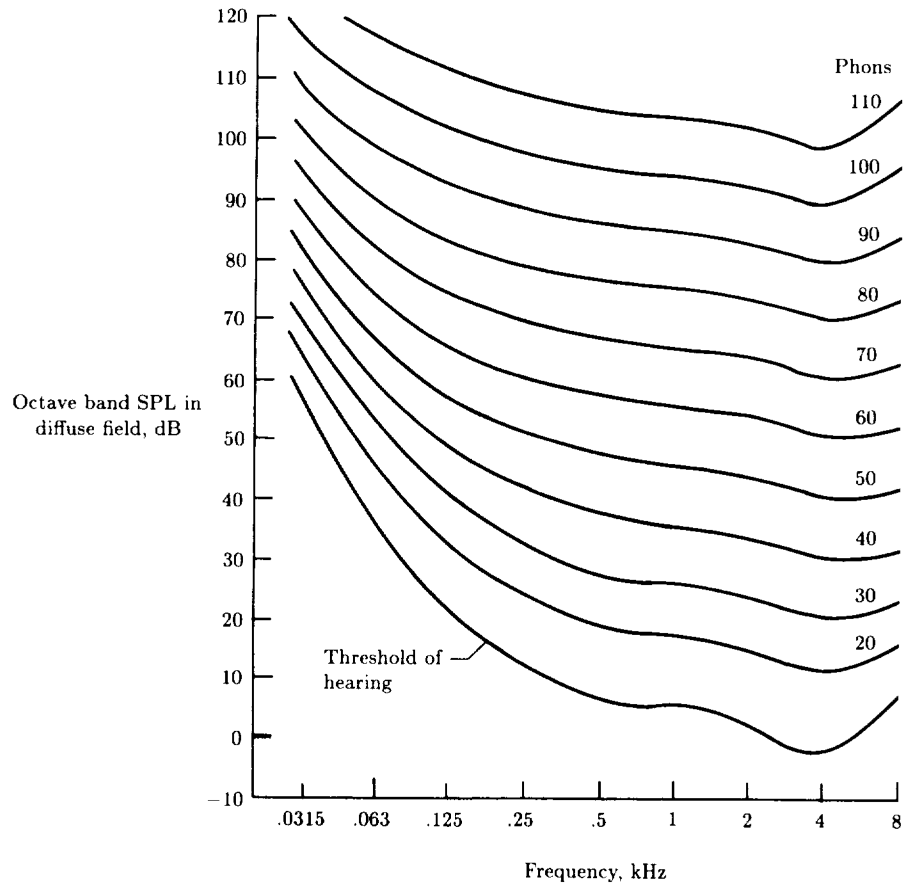


Figure 2. Equal-loudness contours. (From ref. 6.)

Pitch

Pitch can be defined as the perceived frequency of sound. High-frequency tones or narrow bands of noise are heard as being "high" in pitch, and low-frequency tones or narrow bands as being "low" in pitch. Although there has been much research into the perception of pitch, there has been very little consideration of pitch and some related phenomena, other than simple frequency content, in explaining reaction of people to the noise of aircraft or other aeroacoustic noise sources. The potential relevance of these phenomena may be of increasing importance for some configurations of advanced turboprop aircraft which may have counterrotating propellers with unequal numbers of blades.

The relationship of pitch and consonance or dissonance of multiple tones is described in the model of reference 10. A concept of virtual pitch is described which accounts for many psychoacoustic and musical phenomena related to combination and residue tones. A historical review and the determination of the detectability of combination tones which result when two (or more) tones at different frequencies, f_1 and f_2, are heard simultaneously are presented in reference 11. These combination

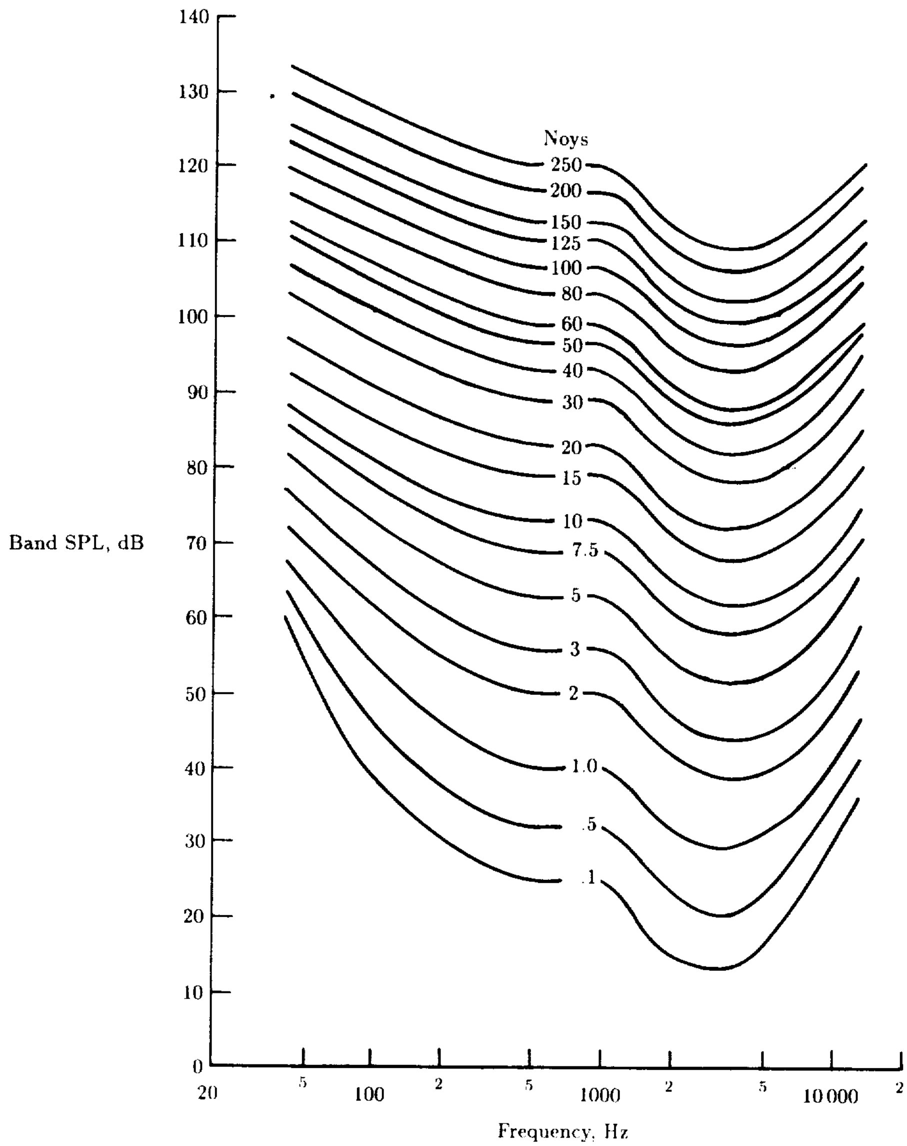


Figure 3. Equal-noisiness contours. (From ref. 14.)

tones include not only the summation ($f_1 + f_2$) and difference ($f_2 - f_1$) tones but also the cubic difference ($2f_1 - f_2$) tone and higher order tones. The "residue" is the pitch produced by a set of frequency components rather than by any of the single components (ref. 12). The low pitch tone associated with large high-bypass-ratio turbofan aircraft engines, commonly called "buzz saw," is one such example. This pitch results from the difference in frequency of the many harmonically related components of the fan shaft frequency rather than from the fundamental itself.

Noisiness

Noisiness was suggested in reference 13 to refer to the characteristic or attribute of a sound which makes it unwanted, unacceptable, disturbing, objectionable, or annoying and which may be distinguishable from loudness. Through extensive laboratory tests a set of equal-noisiness contours were determined (ref. 14). As indicated in figure 3, these curves have the same general shape as the equal-loudness contours of figure 2 although there are some differences particularly at high frequencies.

The temporal summation of noisiness has been shown to be very similar to that of loudness for durations less than the integration time of the ear. However, the summation for noisiness continues for durations considerably in excess of that time. Based on analysis of data from many studies, 3 dB per doubling of duration, or 10 dB for a factor-of-10 change in duration, seems appropriate as a temporal summation factor for noisiness.

Localization and Precedence

The ability to determine the location of sound sources is one of the major benefits of having a binaural hearing system. Localization has been studied nearly as long as has loudness. It is generally recognized that the human auditory system uses both interaural intensity and interaural temporal differences between the ears as cues which are processed in the central auditory nervous system. At low frequencies, temporal or phase differences at the ears are thought to provide the dominant cues, whereas at higher frequencies, intensity differences are thought to provide more useful information. Typical examples from the work of reference 15 on the error in ability to locate a sound source are shown in figure 4. As indicated, the error is greatest in the frequency region about 3 kHz where the localization cues are more ambiguous. The localization errors are minimal directly in front of the head, and with head movement most people can locate the origin of a sound within 1° or 2°.

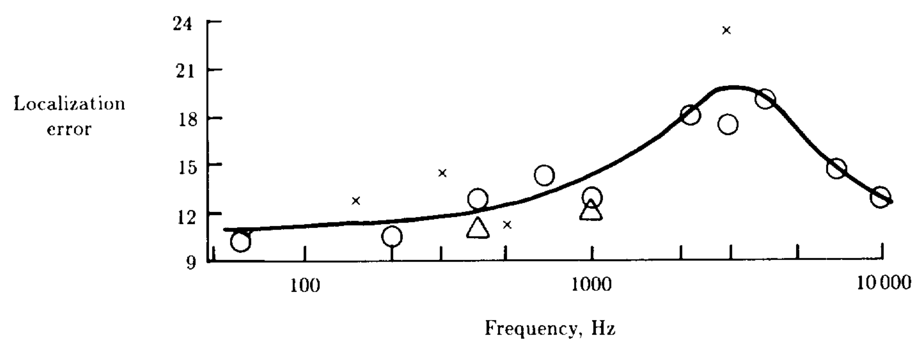


Figure 4. Error in localization as a function of frequency. (From ref. 15.)

Another phenomenon related to binaural hearing is commonly called the Haas, or precedence, effect (ref. 16). This refers to the ability to hear as a single acoustic event the sound from two or more sources radiating nearly identical acoustic signals provided that the signals arrive at the listener's ears with a delay not exceeding

50 msec. In addition the sound appears to originate at the nearer source or that source from which the first signal arrives. Although neither localization nor the precedence effect is as significant in determining human response to aeroacoustic sources as is loudness or noisiness, they may be significant modifiers to that response if the sound is perceived to be too close or in some location where safety is compromised.

Noise Metrics for Predicting Human Response

Considerable research has gone into developing methods to predict the loudness, noisiness, and annoyance of sounds on the basis of measurable physical characteristics of the sounds. In the following sections some of the procedures developed to predict human response to noise from aeroacoustic sources are discussed. Complete details of the calculation procedures can be found in a number of references (e.g., refs. 17 and 18).

Single Events

Loudness Level

Metrics developed to predict loudness have, in general, incorporated various means to account for the human sensitivity to frequency and sound level and the summation of the different frequency components of sound. The most commonly used metric is based on a simple frequency filter (defined as the A-weighting filter) for weighting the spectral content of a possibly complex sound. Although originally intended to approximate the loudness level of sounds with sound pressure level (SPL) between 24 and 55 dB, the A-weighted sound level (SLA) has been found to correlate very well with noisiness and loudness of many sounds with broadband spectra regardless of level. The relative response of the A-weighting filter is indicated in figure 5. The summation of different frequency components is a simple energy

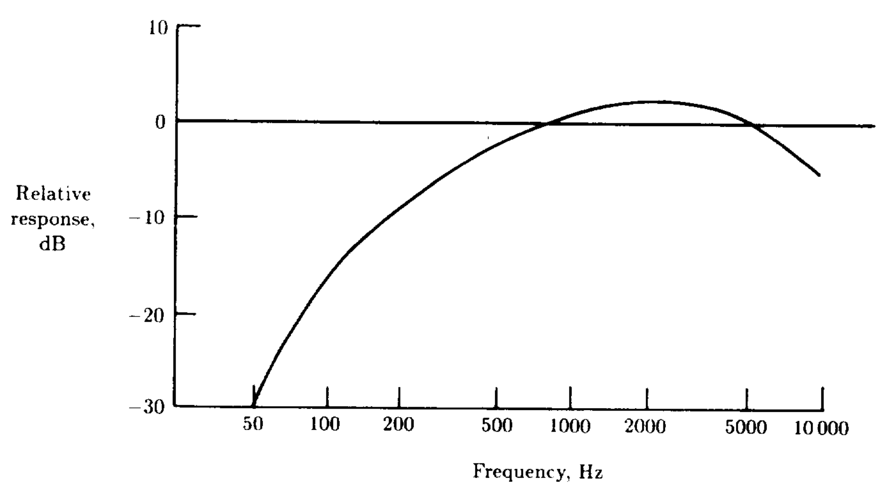


Figure 5. Relative response of the A-weighting filter.

summation after frequency weighting. If the weighting is incorporated in a sound level meter, the root-mean-square (rms) circuitry in the meter performs the necessary summation. If the A-weighting is applied to octave or 1/3-octave band SPL's, the resulting weighted SPL's are summed on an energy basis:

$$L_A = 10 \log_{10} \left[\sum_{i=1}^{n} 10^{L_A(i)/10} \right] \tag{1}$$

where $L_A(i)$ are the weighted SPL's of the frequency bands.

A somewhat more complicated procedure for predicting loudness level (LL_S) was developed by Stevens (ref. 19) and called Mark VI. It accounts for frequency characteristics including nonlinear level effects and in a simplified way for masking and inhibition between frequency components. The unit of loudness, sone, is defined as the loudness of a 1-kHz pure tone with a sound pressure level of 40 dB. The loudness in sones thereby represents a ratio scale with the property that twice as many sones indicate twice the loudness.

The frequency and level characteristics of the Mark VI loudness procedure are shown in figure 6. The loudness in sones $S(i)$ of each octave or 1/3-octave band is determined from the figure or a calculation algorithm. The total loudness is then found from the summation

$$S_t = S_m + F \left[\sum_{i=1}^{n} S(i) - S_m \right] \tag{2}$$

where S_m is the loudness of the loudest band and F is a masking factor, 0.15 for 1/3-octave band data or 0.30 for octave band data. The loudness level in phons is then calculated by

$$L_L = 40 + 10 \log_2 S_t \tag{3}$$

The phon scale has decibel-like properties and a factor of 10 phons represents an approximate doubling of loudness.

Another prediction scheme for loudness level (LL_Z) has been developed by Zwicker (ref. 20) and accounts for more of the complexities of the human auditory system, such as widening of "critical bandwidth" at low frequencies, "remote masking," and different sensitivities to different types of sound fields. In the original formulation of the method, only loudness of stationary sound fields or of time-varying sound fields at a limited number of instants was easily calculated because the method relied on the plotting of 1/3-octave band sound levels and integration under the curve with a planimeter. The development of relatively inexpensive computer systems, however, allows this method to be easily applied to nonstationary sounds. After calculation of the total loudness of the sound in sones S_t using the graphical or computer method, the loudness level LL_Z, in phons, is calculated using the same type of relationship as equation (3).

Perceived Noisiness

The noise metric which is most commonly used to predict the noisiness level of sounds is the perceived noise level (PNL). This metric, which was developed to predict the reported annoying quality of jet aircraft sounds (ref. 13), is calculated

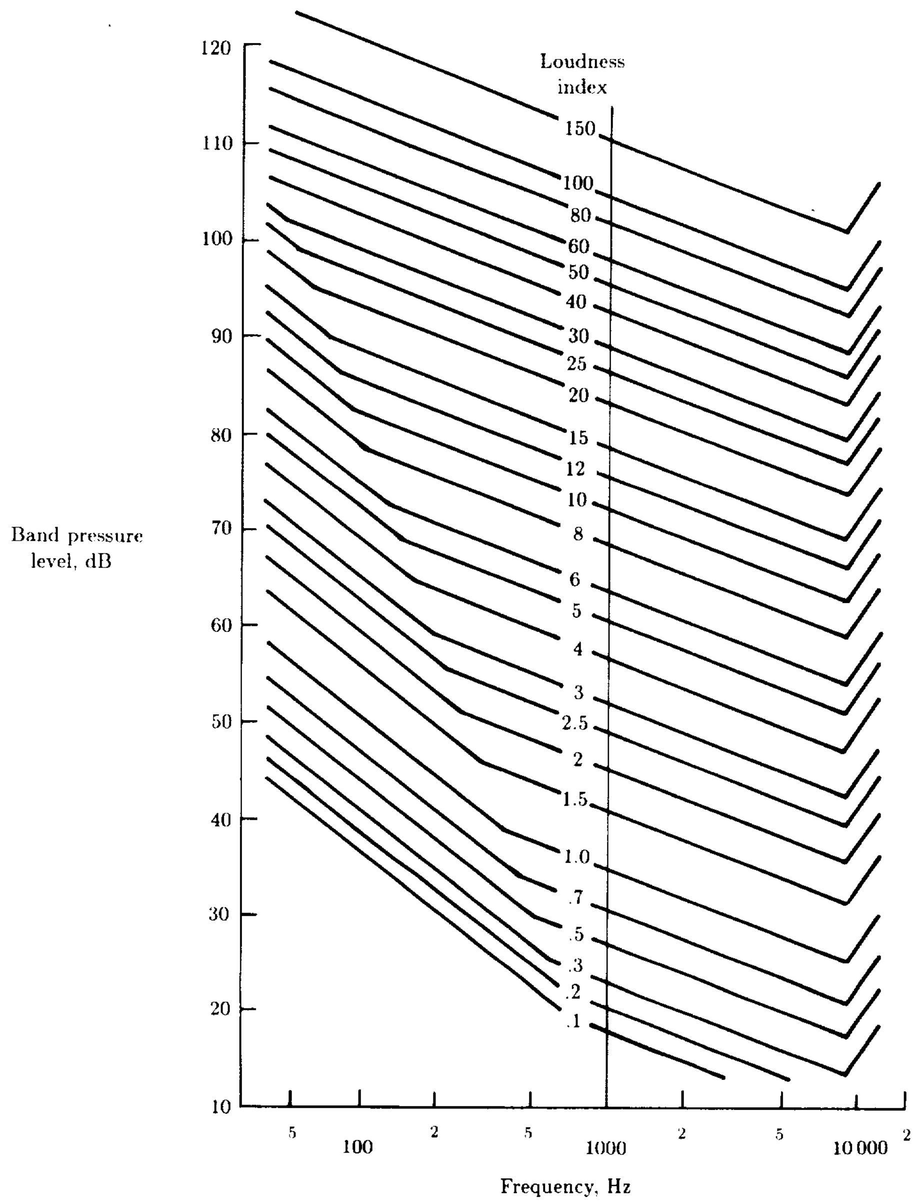


Figure 6. Frequency characteristics for the Mark VI loudness procedure. (From ref. 19.)

very similarly to the loudness level LL_S (ref. 19). The unit of perceived noisiness, noy, is defined as the noisiness of an octave band of noise centered at 1 kHz with a sound pressure level of 40 dB. A sound which is subjectively twice as noisy as the reference sound has therefore a perceived noisiness of 2 noys.

The noisiness of each ⅓-octave band $N(i)$, expressed in noys, is determined by using curves such as those in figure 3, by using a set of tables based on those curves, or by using a computerized algorithm. The noisiness of the total sound at any instant is given by

$$N_t = N_m + F\left[\sum_{i=1}^{n} N(i) - N_m\right] \tag{4}$$

where N_m is the noisiness of the noisiest band and F is the masking factor in equation (2) for the Stevens loudness calculation. The PNL is then given by

$$L_{\mathrm{PN}} = 40 + 10\log_2 N_t \tag{5}$$

The PNL scale is thereby similar to the phon scale for loudness in that it has decibel-like properties, and a factor of 10 in PNL represents an approximate doubling of noisiness.

In much the same way that SLA has been used as a simplified method to approximate the loudness of sounds, another frequency-weighted metric has been used to approximate the noisiness of sounds. The D-weighted sound level (SLD) uses the frequency weighting shown in figure 7, which is comparable to the inverse of the 40-noy contour of equal noisiness (fig. 3). The summation of different frequency components is an energy summation after frequency weighting. The D-weighting filter is also incorporated in some sound level meters which provide the necessary rms circuitry for the summation. If the D-weighting is applied to octave or 1/3-octave SPL's, the resulting weighted SPL's $L_D(i)$ are summed on an energy basis:

$$L_D = 10\log_{10}\left[\sum_{i=1}^{n} 10^{L_D(i)/10}\right] \tag{6}$$

The similarity of the equal-noisiness and equal-loudness contours is obvious by comparing figures 2 and 3. Because of the similarity and reanalysis of data of many

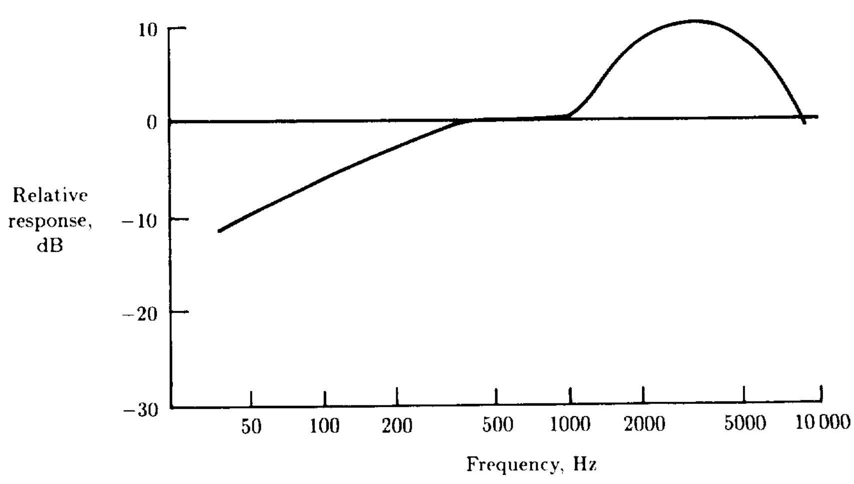


Figure 7. Relative response of the D-weighting filter.

noisiness and loudness experiments, it was proposed in reference 21 that loudness and noisiness were actually manifestations of the same auditory response and could be predicted using a slightly modified set of response curves. This calculation procedure was called Mark VII, perceived level (PL). The unit of perception for PL is based, however, on the perception of a 1/3-octave band of noise centered at 3.15 kHz with a sound pressure level of 32 dB as a reference sound. The frequency weighting for this procedure is given in figure 8. The magnitude of each octave or 1/3-octave band $S(i)$ is determined from the curves in the figure or from a calculation algorithm. The total perceived level of a sound is then calculated using the summation relationship of equation (2). The masking factor F for this newer procedure was proposed to be a function of S_m as indicated in figure 9. The perceived level of the sound is given by the relation

$$L_P = 32 + 9 \log_2 S_t \tag{7}$$

which is based on a doubling of perceived magnitude being equivalent to a 9-dB change in sound level.

A simplified method of approximating the perceived level of a sound was also proposed in reference 21. This metric, analogous to the A-weighted and D-weighted sound levels, is called the E-weighted sound level (SLE) and is computed using the frequency weighting of figure 10.

Tone and Duration Corrections

The advent of fan-jet engines on commercial airplanes was accompanied by a concern of whether the tonal nature of the sound was adequately accounted for by the PNL metric. A number of tone correction procedures were developed and one procedure was incorporated into the noise metric for noise certification of new transport aircraft. It was also proposed that sounds of longer duration were more annoying than those of shorter duration. Therefore a duration correction procedure was also incorporated into the certification noise metric. The certification noise metric developed for large jet airplanes was based on the PNL metric (ref. 13) to account for the basic frequency characteristics and sound pressure levels of the noise which the airplanes made in airport communities. The certification noise metric, effective perceived noise level (EPNL), requires that the PNL be calculated and corrected for significant tones every 0.5 sec and energy summed over the effective duration of the flyover noise (ref. 22). The tone correction procedure consists of identifying tones contained in the spectra, estimating the level differences between the tones and the broadband noise in the 1/3-octave bands containing the tones, determining the value of the tone correction, and adding that value to the PNL to obtain the tone-corrected perceived noise level (TPNL) for each 0.5-sec interval. If the frequency of the tone is less than 500 Hz or greater than 5000 Hz, the correction for that band is one-sixth the level difference (in dB) between the tone and broadband noise; if between 500 Hz and 5000 Hz, the correction is one-third the level difference. The corrections for the bands, however, are limited to 3.3 dB and 6.7 dB, respectively. The overall correction for the time interval is the maximum of the corrections for the individual bands. The EPNL for the flyover is then given by

$$L_{\mathrm{EPN}} = 10 \log_{10} \left[\sum_{i=1}^{n} 10^{L_{\mathrm{TPN}}(i)/10} \right] - 13 \tag{8}$$

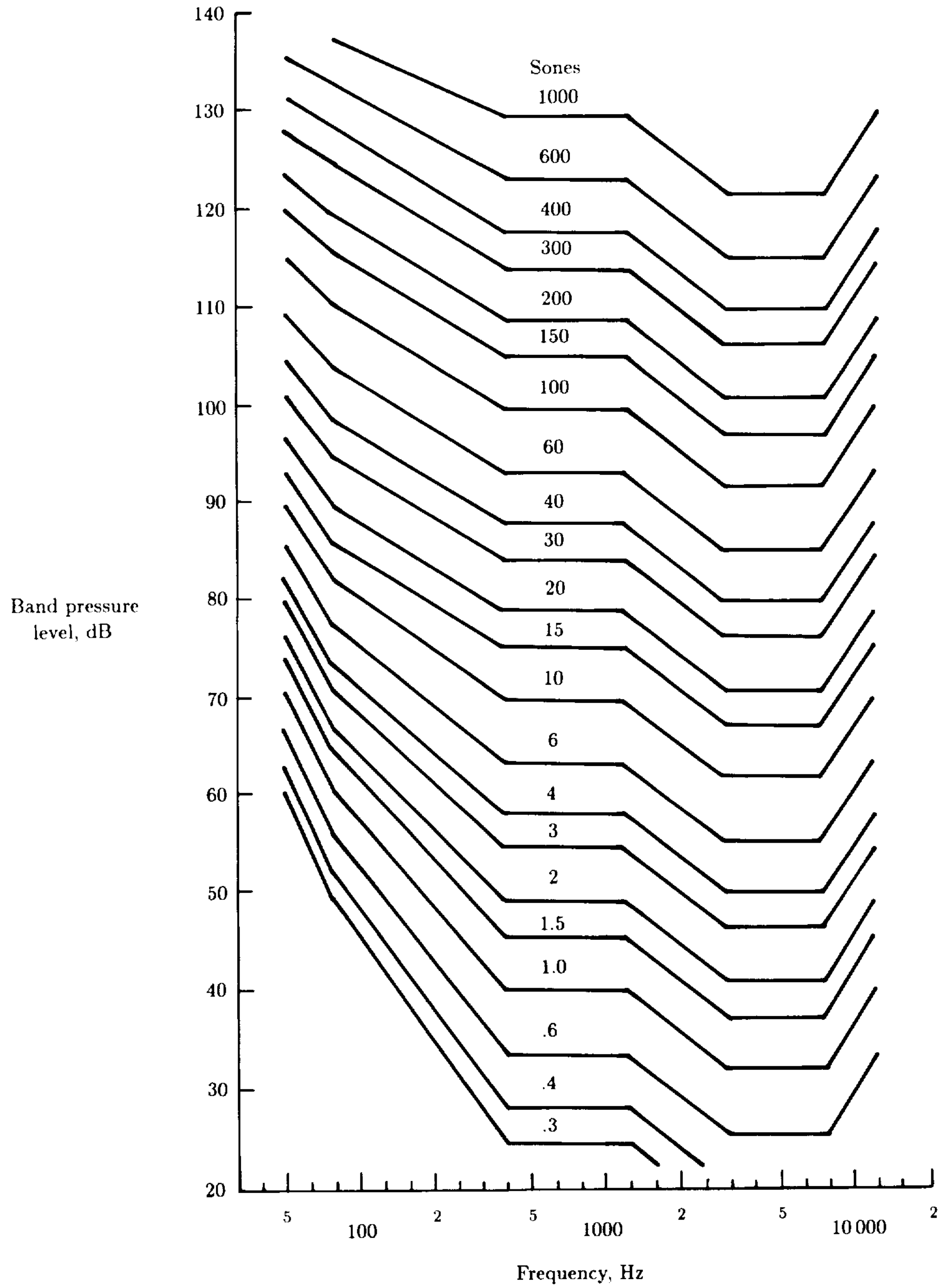


Figure 8. Frequency characteristics for the Mark VII loudness or noisiness procedures. (From ref. 21.)

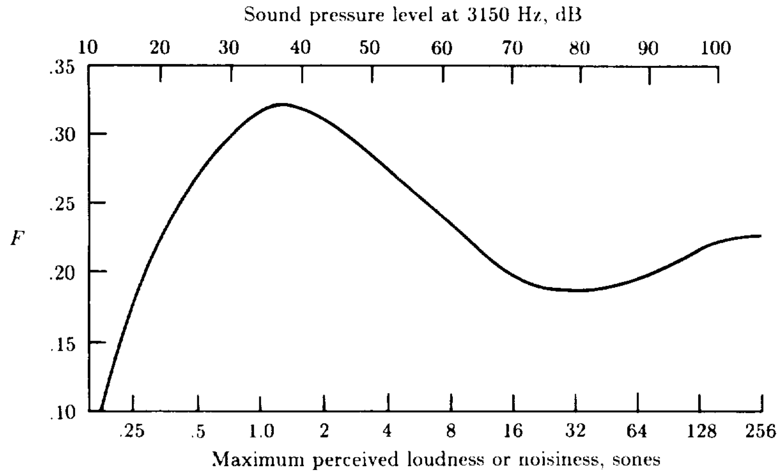


Figure 9. Masking factor F for the Mark VII loudness or noisiness procedure. (From ref. 21.)

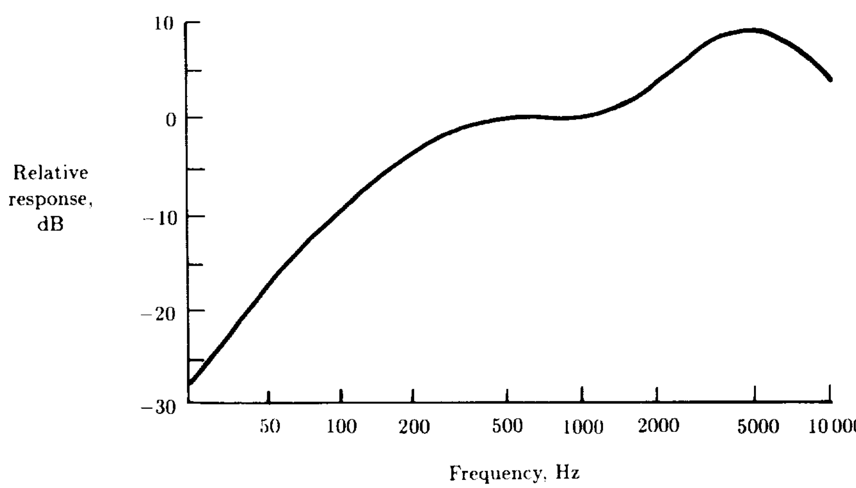


Figure 10. Relative response of the E-weighting filter. (From ref. 21.)

where $L_{\mathrm{TPN}}(i)$ is the value of the TPNL in the ith 0.5-sec interval of the flyover. The summation is over the duration when the $L_{\mathrm{TPN}}(i)$ are within 10 dB of the maximum TPNL of the flyover. The factor of 13 dB is subtracted to account for the difference in the 0.5-sec time increments and a reference duration of 10 sec.

Another duration-corrected noise metric commonly used to predict the annoyance of single aircraft and other noise events is the sound exposure level (SEL). This metric is the energy average over the duration of a noise event referenced to a duration of 1 sec. If the noise level is sampled with period t between samples, the calculation formula is

$$L_{AE} = 10\log_{10}\left[\sum_{i=1}^{n} 10^{L_A(i)/10}t\right] \tag{9}$$

where $L_A(i)$ is the instantaneous A-weighted sound level for the ith sample. For practical purposes the summation is normally limited to the duration for which the instantaneous level exceeds a level 10 dB below the maximum level.

Speech Interference

A number of metrics have been developed to predict the effect that a given noise environment will have on the intelligibility of speech. Several of the methods, including articulation index (AI) and speech transmission index (STI), require more detail to adequately describe the calculation procedures than can be given in this review. The more interested reader is referred to the original work in reference 23 and the suggested modifications in reference 24 for the procedures involved in calculating AI, which predicts how much of the speech spectrum is masked by the noise signal. Because of its wide acceptance and usage, the calculation procedure is covered by ANSI standard S3.5-1969(R1971) (ref. 25). The newer STI method of reference 26 considers the effective signal-to-noise ratio produced by the modulated speech signal and includes the effects of reverberation.

The speech interference level (SIL) is a simpler method for predicting speech interference effects of noise of essentially constant level and is frequently used to quantify aircraft interior noise (ref. 27). The calculation of SIL is the simple numerical average of the unweighted SPL in the four octave bands from 500 Hz to 4000 Hz as defined in ANSI standard S3.14-1977 (ref. 28). Initially the average was defined over the three octave bands which encompassed the frequency range from 600 Hz to 4800 Hz. After the introduction of the "preferred" frequencies for octave bands, the range was modified to include the three newly defined octave bands centered at 500 Hz, 1000 Hz, and 2000 Hz, and the procedure was called preferred speech interference level for a short period. The method has its greatest applicability if the noise is relatively steady, has a smooth spectrum, and is in an environment which is not highly reverberant.

Multiple Events and Total Noise Exposure

Many different noise indices have been suggested to quantify the annoyance potential of time-varying continuous and multiple-discrete-event noises. Those most commonly used for aircraft noise have been based either on the A-weighted level or on the perceived noise level to account for the basic frequency characteristics. The following sections describe several of the more commonly used indices.

A-Weighted Indices

The continuous or multiple-event character of noise is accounted for in the A-weighted indices through energy averaging or summation. The basic index is called the equivalent continuous sound level (LEQ) and is defined as the level of the time-averaged A-weighted sound energy for a specified period of time. The most common periods for averaging are 1 hour, 8 hours, and 24 hours. The LEQ for a given period can be calculated from temporal samples of the A-weighted sound level by

$$L_{\mathrm{eq}} = 10 \log_{10} \frac{1}{n} \left[\sum_{i=1}^{n} 10^{L_A(i)/10} \right] \tag{10}$$

where n is the number of samples and $L_A(i)$ is the level of the ith sample. In addition to its wide use to assess people's reaction to aircraft community noise, LEQ is widely and effectively used to assess reaction to other community noises and to predict hearing loss for long-term noise exposure.

In an effort to account for the possibility that noise occurring when most people are asleep is more annoying than during the day, the U.S. Environmental Protection Agency (EPA) developed noise criteria based on a modified LEQ with a 10-dB penalty for the period between 10:00 p.m. and 7:00 a.m. The index is called the day-night average sound level (DNL) and can be calculated in a number of ways depending on the sound level information available for the day and night periods. If the LEQ is known for both periods, DNL is given by

$$L_{\mathrm{dn}} = 10 \log_{10} \left\{ \frac{1}{24} \left[15(10^{L_{\mathrm{d}}/10}) + 9(10^{L_{\mathrm{n}}/10}) \right] \right\} \tag{11}$$

where L_{d} is the LEQ for the day period (7:00 a.m. to 10:00 p.m.) and L_{n} is the LEQ for the night period (10:00 p.m. to 7:00 a.m.).

Another variant on the equivalent continuous sound level applies not only the 10-dB night penalty but also a 5-dB evening penalty. This index is primarily used in California for airport community noise. The community noise equivalent level (CNEL) is calculated by

$$L_{\mathrm{den}} = 10 \log_{10} \left\{ \frac{1}{24} \left[12(10^{L_{\mathrm{d}}/10}) + 3(10^{L_{\mathrm{e}}/10}) + 9(10^{L_{\mathrm{n}}/10}) \right] \right\} \tag{12}$$

where L_{d} is the LEQ for the day period (7:00 a.m. to 7:00 p.m.), L_{e} is the LEQ for the evening period (7:00 a.m. to 10:00 p.m.), and L_{n} is the LEQ for the night period (10:00 p.m. to 7:00 a.m.).

PNL-Based Indices

Before the EPA adopted DNL for assessment of all community noise, the most widely used index for assessing airport community noise was the noise exposure forecast (NEF). This index was based on EPNL for assessing the impact of each aircraft operation with adjustments for the time and number of occurrences during the 24-hour period. The nighttime adjustment was based on a 10-dB penalty if the average number of aircraft operations per hour during the day and night were the same. If, however, EPNL is known for each event ($L_{\mathrm{EPN}}(i)$) at some location, the NEF is given by

$$L_{\mathrm{NEF}} = 10 \log_{10} \left[\sum_{i=1}^{n} 10^{L_{\mathrm{EPN}}(i)/10} + 16.67 \sum_{i=1}^{m} 10^{L_{\mathrm{EPN}}(i)/10} \right] - 88 \tag{13}$$

where n is the number of events occurring during the day (7:00 a.m. to 10:00 p.m.) and m is the number occurring during the night (10:00 p.m. to 7:00 a.m.). The factor of 16.67 is the night correction factor which applies an effective penalty of 12.2 dB to each event occurring during the night period.

Another PNL-based index is frequently used in the United Kingdom to assess the effects of aircraft noises on communities. The noise and number index (NNI) is based on the average (energy basis) PNL of aircraft noise events "heard" at a location in the community and an adjustment for the number of events occurring during a given period. The calculation formula is

$$L_{\mathrm{NNI}} = \overline{L_{\mathrm{PN,\,peak}}} + 15 \log_{10} N - 80 \tag{14}$$

where $\overline{L_{\mathrm{PN,\,peak}}}$ is the energy average of the peak PNL's of all events which exceed 80 dB during the period, and N is the number of those events. It is interesting to note that the number correction, 15, is greater than a correction based on equivalent energy principles, 10. This results in a correction of 4.5 dB for a doubling or halving of the number of operations rather than the correction of 3 dB for indices such as LEQ or NEF.

Laboratory Assessment of Human Response

Many laboratory experiments have been conducted over the last three decades to determine various aspects of human response to aircraft noise as heard in the airport community and within the aircraft. In most of these experiments, test subjects have judged or rated the annoyance of noise stimuli that the experimenter reproduced in the laboratory. Since the noise stimuli rarely interfere with an activity that the subject prefers or has to do, it is questionable whether true annoyance is involved in the laboratory situation. There has been, however, limited validation of laboratory findings through carefully controlled field studies of response to specific physical characteristics of aircraft noise. Thus it is generally accepted that laboratory testing can play a major role in the assessment of the physical characteristics of noise that can cause true annoyance in real-life situations. The major advantages of laboratory experimentation are the cost savings and experimental control relative to field experimentation. The following sections present some aspects of methodology and findings of laboratory experiments of aircraft community and interior noise which deal with noisiness or the potential for causing annoyance in a real-life situation.

Methodology

Facilities and Stimuli Presentation Systems

The use of modern high-quality headphones to reproduce aircraft or other noises that are used as stimuli in psychophysical tests circumvents several potential problems of facilities and stimuli presentation systems. First, very little consideration need be given to the facility other than providing a measure of creature comfort and a relatively low background noise condition. Normal office or home environments are generally satisfactory. Second, headphones are generally capable of reproducing aircraft-type noises with lower distortion, over a wider frequency range, and at higher intensity levels than are most normal loudspeaker systems. Their major disadvantages are slight discomfort over long periods of time, difficulty of calibration, and variability in stimuli between subjects and tests due to variations in placement on the head. A direct comparison of results of noisiness tests conducted under headphone, anechoic, and semireverberant listening conditions is reported in reference 29. Very little difference in subjective results was found between the three methods.

Although loudspeaker systems suffer from a number of shortcomings, they have been used extensively to reproduce noise stimuli for most subjective tests involving aircraft noise. Loudspeaker systems of all levels of sophistication have been used. Since the efficient response range of a loudspeaker system is related to the physical size of the drivers, most modern systems use multiple drivers of different sizes. As a consequence some reinforcement and cancellation occur at various locations for some frequencies. This can result in less than ideal or flat frequency response in the direct field of even the most expensive and reportedly smooth response systems. Another problem which plagues loudspeaker systems is harmonic distortion at high intensity levels. Loudspeaker systems are, at best, low-efficiency devices; therefore, aircraft noises at realistic outdoor levels are difficult to reproduce, particularly if they contain much low-frequency energy. Loudspeaker systems also have considerable phase distortion. While such distortion is not normally considered important for most broadband noises, it does prevent the realistic reproduction of the time signature of impulsive noises such as blade slap produced by some helicopter operations. It is possible, in some cases, to electronically predistort the phase of different frequency components so that the pressure field at the listener location has the proper phase relationships (ref. 30).

In order to better control loudspeaker-reproduced stimuli and to simulate outdoor listening conditions, many subjective listening tests have been conducted in anechoic chambers. In addition, a limited number of tests have been conducted in progressive wave facilities (ref. 31). These types of facilities have the obvious advantages of reducing the effects of reflected sound and of generally having low background noise levels. However, such facilities have a potential disadvantage of poor visual realism and may cause anxiety in some subjects during tests of long duration.

Many subjective aircraft noise tests have been conducted under semireverberant conditions such as in normal office environments or in special quiet facilities such as audiometric booths. As indicated in reference 29, little difference in results of noisiness tests is anticipated provided that the frequency response characteristics and room acoustics effects on those characteristics are accounted for in the analysis of results or, better yet, by the electronic filtering of the input signals to the sound reproduction system.

A number of special purpose facilities have been built to provide a realistic visual environment in addition to the required acoustic environment (refs. 32–34). The Interior Effects Room located at the NASA Langley Research Center (ref. 35) produced the visual simulation of a living room as well as the acoustic simulation of a typical house structure. Multiple loudspeaker systems were located outside the room structure, and realistic aircraft and other environmental noises were transmitted through the structure. While such attention to detail is most probably unwarranted on purely acoustic grounds, numerous tests were conducted in the facility where both visual and acoustic simulation was required for long-duration, multiple-event, and multiple-noise-source studies. The Passenger Ride Quality Apparatus also located at the NASA Langley Research Center (ref. 36) provided both the visual simulation and the vibration simulation of an aircraft interior as well as acoustic simulation for many passenger annoyance studies.

Psychoacoustic Procedures

The purposes of most laboratory aircraft annoyance studies have been to determine how different physical characteristics of aircraft sounds affect reported annoyance response, how the sounds of different aircraft types will be accepted in communities, or how well different noise metrics predict annoyance or noisiness. Since it is generally recognized that these types of laboratory assessments are not absolute but rather are relative to either the whole set of sounds or to a specific sound used in the tests, comparative types of psychoacoustic test procedures and/or analyses are most often used. Frequently the goal of the tests is to determine noise levels for a set of stimuli which produce equal annoyance or noisiness response. The most commonly used procedures are described in the following paragraphs. Additional information on the various psychometric methods and analysis of data obtained can be found in references 37 and 38. In reference 39 the different procedures for determining human response to aircraft noise were evaluated using a standardized set of test conditions and noise stimuli.

In the method of adjustment (MOA), or method of average error as it is sometimes called, the task of the test subjects is to adjust the intensity of one of a pair of sound stimuli so that each has equal noisiness or some other attribute. Subjects are typically instructed (ref. 14)

> Your job is to listen to the standard noise ... then ... the comparison noise ... and adjust the intensity of the comparison noise until it sounds as acceptable to you as the standard.

Subjects can usually make the adjustment and comparison as many times as necessary for convergence. The experimenter then records the sound level of the variable stimulus for comparison with the level of the fixed stimulus. Both orders of presentation of the fixed and variable stimuli are usually given in the tests to prevent an order bias. By averaging over the reported points of equality for all test subjects or repeated trials for single subjects, the experimenter obtains a statistical estimate of sound levels which produce responses of equal noisiness (or some other attribute) for the two stimuli. These noise levels will be referred to as "levels of subjective equality" (LSE) in subsequent discussions. The exact application of this methodology has been varied between different laboratories and experimenters. In some cases the level of the standard sound is varied and in others the level of the comparison sound is varied. While intuitively MOA has many virtues, it is perhaps the most time-consuming and difficult test procedure for the subject and is therefore rarely used for tests involving many stimuli.

Another frequently used psychometric test method is also based on direct comparisons of pairs of sounds. This method has been called paired comparisons by some experimenters but is more properly called the method of constant stimulus differences (CSD). In this procedure many pairs of noise stimuli, comprised of a standard and a comparison stimulus, are presented to the test subjects who judge which member of each pair is more annoying or noisy. The subjects are typically instructed (ref. 14)

> You are to judge which of the sounds you think would be more disturbing to you if heard regularly ... 20 to 30 times per day in your home.

Each comparison stimulus is presented at a number of levels greater than and less than the standard stimulus. In the course of a test the order of presentation of the standard and comparison stimuli is varied to prevent order bias, and frequently the overall order of presentation of the pairs is varied between different subject groups to minimize learning or other temporal effects. Psychometric functions of the proportion of responses, versus noise level, for which the comparison stimulus is more annoying than the standard are determined using appropriate statistical methods (refs. 37 and 38). Levels of subjective equality (LSE) for all comparison stimuli are then based on estimates of levels which would produce an equal number of positive and negative responses. The CSD procedure generally requires less time for the test subject than does the MOA procedure since the number of comparisons is fixed. However, a comparison of the two methods (ref. 39) indicates that MOA provides somewhat smaller standard deviations in LSE than does CSD and therefore may have slightly better reliability.

The method of magnitude estimation (ME), or fractionation, has been extensively used in experiments concerned with aircraft flyover and interior noise. The task of the subject is to assign a numerical value to each test stimulus, the magnitude of the value being proportional to the perceived magnitude of the stimulus. A reference or standard stimulus is presented and is assigned a convenient numerical value, such as 10, and the subject assigns to a test stimulus a value twice as great (i.e., 20) if it is twice as noisy or annoying, etc. Since the relationship between the magnitude of many types of sensations and a physical measure of their intensity is generally found to be a power function, a plot of the logarithm of the subjective magnitude as a function of the level of a sound is usually found to be linear. The ME procedure thus provides much more information than does the MOA or CSD procedures about response to the noise stimuli. The LSE for each test stimulus can be found by graphical interpolation or regression analysis to estimate the level which produces the same noisiness or annoyance response as the standard. The functional relationship of response to noise level provides estimates of the growth of noisiness with level and convenient comparisons between test stimuli. The subjective responses can be converted into numerical values having properties like decibels from prediction equations based on regressions of noise level on subjective responses for a standard or reference sound presented over a range of sound levels. The total amount of time required by each test subject is approximately one-half that required for a CSD test with the same number of test stimuli. Based on comparisons of results of ME with those of MOA and CSD (refs. 29 and 39), ME provides reliability at least as good as, if not better than, the other comparative procedures.

Another test procedure, numerical category scaling (NCS), has also been used in many aircraft flyover and interior noise subjective studies. This procedure more closely parallels the procedure used in many community noise surveys and has been almost exclusively used in laboratory studies concerned with multiple noise events or multiple noise sources. The task of the subject is to assign a numerical value or a category to each test stimulus which is related to the subject's assessment of annoyance or other attribute of the stimulus. There has perhaps been more variability in the specific application of this procedure than in the other procedures. Different experimenters have used different numbers of categories (4 to 11 is typical), different labeling of categories, and in some cases only labeling of the end points of the scale. Typical analyses and comparisons of the noisiness of the different stimuli are based on linear regression of the subjective responses on measured or computed noise levels or are based on analysis of variance of the responses. Like the responses from the ME procedure, the NCS responses can be converted to a scale having decibel-like properties. Based on the evaluations of reference 39, the reliability of NCS is comparable to that of CSD but not quite as good as that of ME or MOA for determining levels of subjective equality. For comparison of different noise stimuli using the decibel-like computed scale values, the NCS procedure provides reliability very comparable to the ME procedure.

Findings Related to Aircraft Noise Annoyance in the Community

Most laboratory studies of aircraft noise have concentrated on various physical characteristics of the sounds which can affect the noisiness or annoyance of the sounds as heard in the community. Although laboratory settings have also been used to study other effects such as sleep interference, there is considerable concern whether results are directly applicable to the normal environment (ref. 3). In addition it is very difficult to obtain enough data for statistically meaningful interpretation of those results. The reader particularly interested in effects of aircraft noise on sleep is referred to the review in reference 40. The following sections therefore consider only annoyance studies (and some appropriate loudness research) related to those physical characteristics which are considered most influential in determining human response. Additional information on studies of human response to aircraft noise prior to about 1975 can be found in reference 41.

Spectral Content

Very few studies using real aircraft noise have been specifically designed to study the most appropriate frequency weighting and component summation for predicting human annoyance response. Fundamental studies that led to the development of the PNL metric for aircraft noise assessment were conducted using filtered bands of noise of various bandwidths. The problem with using actual aircraft sounds is that most of the other variables, such as duration, tonal content, and Doppler shift, are highly correlated with frequency content through their individual dependencies on distance. Many studies using real or recorded aircraft sounds, however, have examined the subjective results for clues as to which metric or frequency weighting procedure is most highly correlated with reported annoyance. A series of MOA and CSD studies using eight jet and propeller aircraft recordings (ref. 13) indicated that an early version of PNL was less variable in predicting the judged noisiness of the flyover noises than were various loudness measures or simple frequency weighting schemes. In a later field test, using real aircraft overflight noises in outdoor and indoor settings, PNL and LL_S were found superior to SLA and SLD (ref. 42).

An extensive set of CSD tests were conducted (ref. 31) under closely controlled acoustical conditions in a traveling wave facility. Subjects compared a reference octave band of noise centered at 1000 Hz with the noisiness of 120 recorded jet airplane, propeller airplane, and helicopter flyover sounds. Because of the great number of different sounds, the intercorrelation between the various acoustic variables such as duration, Doppler shift, and frequency content was reduced. Some data from this study are plotted in figure 11. The standard deviation of the prediction error, the difference between the judged (or subjective) level and measured noise level for the different metrics, is plotted for all aircraft—jets, turboprops, piston-engine propeller aircraft, and helicopters. In general, LL_Z followed by LL_S and PNL produced less error than SLD and SLA. The noisiness of jet and piston-engine aircraft was predicted better by all metrics than was the noisiness of turboprops and helicopters. It was postulated that the combination of high-frequency (compressor) and low-frequency (propeller) tones of the turboprops and the low-frequency pulsatile nature of the helicopters may have been responsible for the poor performance of the metrics. A subsequent propeller and jet aircraft annoyance study (ref. 43) using NCS methodology reported similar findings that the band summation metrics PNL, PL, and LL_S were somewhat superior to the weighted metrics SLD and SLA. A reanalysis (ref. 44) of data from 23 studies of environmental noises indicated that the more complicated summation metrics LL_S, PL, PNL, and LL_Z in general better predicted loudness and acceptability than the weighted metrics SLA, SLD, and SLE. In addition the weighted metrics SLE and SLD were slightly, but significantly, better predictors than SLA.

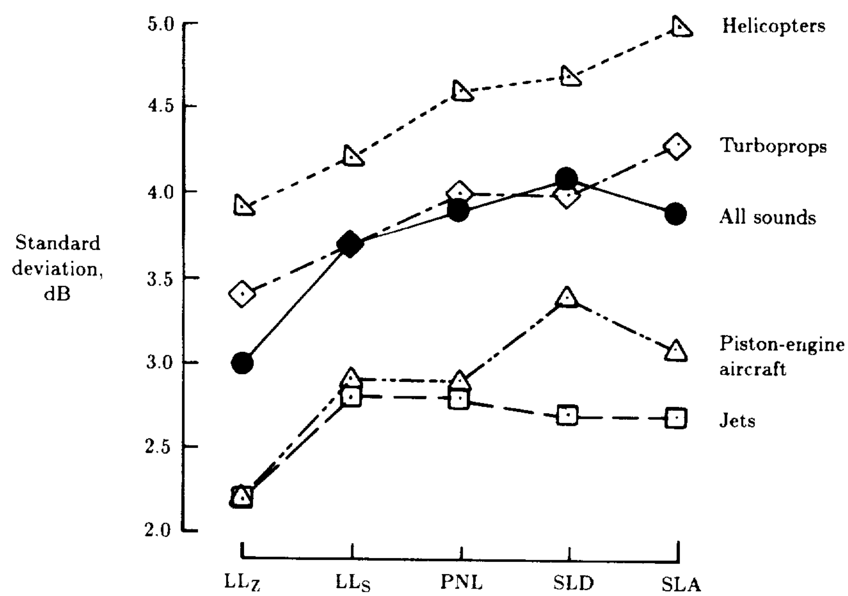


Figure 11. Prediction error for different noise metrics. (Based on ref. 31.)

It is perhaps not surprising that the majority of laboratory noise annoyance studies indicate that the more complicated computed or band summation metrics perform better at their intended tasks than the more simple frequency-weighted metrics. Their summation procedures are empirically based on response to complex sounds. Another finding from most studies, based solely on the spectra of aircraft sounds (i.e., keeping duration constant or the same), is that there seems to be very little difference between annoyance and loudness. The loudness-derived metrics LL_S and LL_Z predict noisiness as well as does PNL, the noisiness-derived metric.

Duration

It is logical to assume that the longer an intense sound is present in the environment, the more annoyance it can cause. The question then arises, how much more annoying? Loudness has been shown not to increase with duration after a few tenths of a second, the integration time of the human hearing system. Thus the effect of duration is potentially different for annoyance and loudness and has been studied extensively for aircraft noise assessment purposes.

In a series of CSD tests (ref. 14) using shaped time histories of recorded helicopter and simulated jet and propeller noise with 1.5- to 12-sec duration, it was found that the judged annoyance of the sounds increased about 4.5 dB for a doubling of duration. An extension of these tests to longer durations (ref. 45) indicated that the duration effect decreased with longer durations. Figure 12 presents the results of both these studies. Based on these results and other laboratory confirmations, a penalty of 3 dB per doubling of duration was incorporated in the noise metric used by the Federal Aviation Administration (FAA) for noise certification of new jet aircraft. This penalty was tested in a laboratory-type field study (ref. 42) and in the extensive laboratory tests (ref. 31) with the general conclusion that the 3 dB per doubling penalty did reduce the scatter and improve the correlation between subjective response and various noise metrics. The necessity of a duration correction was refuted in reference 46 based on results of laboratory tests and examination of previous work. Reference 46 suggested that all studies that showed a significant and large effect of duration used strong duration cues in the instructions to the test subjects and that the subjects actually used a form of cross-modality judgment in which they rated intensity in terms of duration. The lack of an apparent duration effect in some studies was suggested in reference 47 to be the result of cues within the aircraft sounds. Cues, such as Doppler shift, could provide distance and speed information which would result in the listener rating a sound by what he expects to hear rather than by what he actually hears.

A number of the postulates were investigated in the study of reference 48 using computer synthesized flyovers in which spectra, flyover velocity, and altitude could be independently controlled. Thus duration, spectra, and Doppler shift could be uncoupled in the experimental design. The instruction to the test subjects used no duration cue, but rather the subjects were simply instructed to make their NCS judgments when they heard a beep, which occurred at the end of each flyover. Results from the study indicated that the duration correction of 3 dB per doubling was very nearly optimum and that Doppler shift was not significantly correlated with the annoyance judgments. These findings were further substantiated in the study of reference 49, in which recorded aircraft flyovers were modified by playback at higher or lower speeds to change the apparent Doppler shift, by spectral filtering to correct for spectral changes resulting from the playback speed changes, and by shaping the flyover time histories to produce changes in the duration of the flyovers.

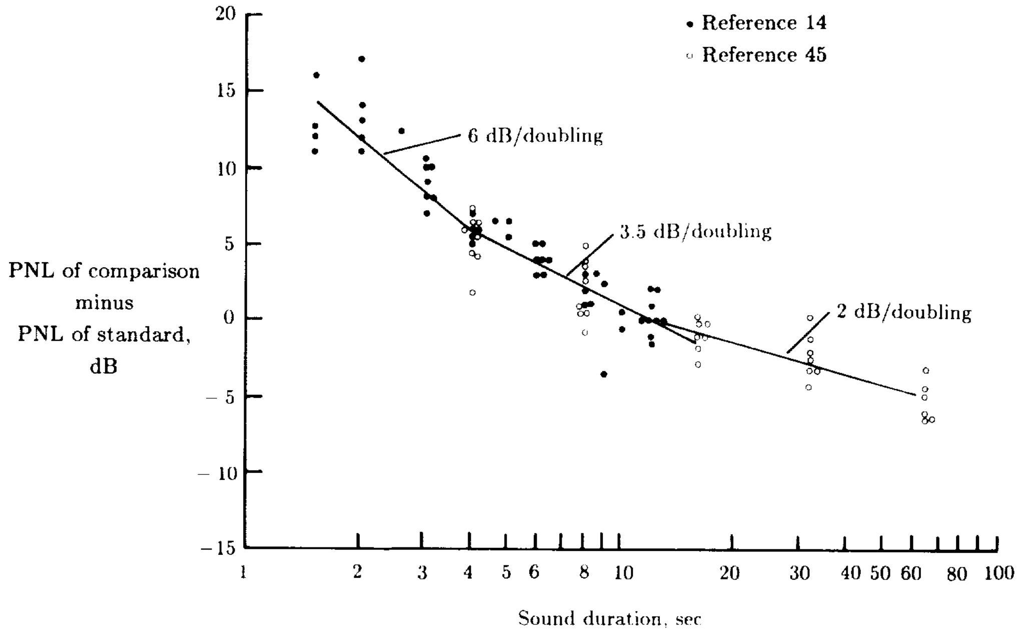


Figure 12. Effect of duration on annoyance. (From ref. 45.)

Tones

The question of whether or not a tone correction or penalty is needed to assess the human response to aircraft noise has been hotly debated since the advent of turbofan jet engines in the early 1960's. As pointed out in a review of research results (ref. 50), most studies that indicated the need for tone corrections used artificial sounds, such as pure tones in shaped bands of random noise, whereas studies that indicated no need for corrections most often used actual aircraft overflights or recorded aircraft sounds.

A typical example of results indicating the need for a tone penalty is shown in figure 13. These summary results, from references 51 and 52, indicate that in order to produce equal noisiness, the sound pressure level of a tone in an octave band of noise must be reduced by as much as 15 dB relative to the same octave band of noise without the tone component. The tone effect increases with tone-to-noise ratio up to 30 dB and increases with frequency up to 4000 Hz. Later results (ref. 53) indicated that modulation of the tones had little effect on judged noisiness of the tone-in-noise complexes, that multiple tones within the noise bands increased the effect by up to 5 dB, but that it made very little difference whether the multiple tones were harmonically related or not. Primarily because of this type of data, the Federal Aviation Administration included a tone correction in the noise certification metric for jet aircraft.

In field and laboratory studies using actual or recorded aircraft sounds, the results have not indicated so conclusively that a tone correction is necessary to assess aircraft noise impact. In a controlled flyover field study (ref. 42), both the FAA and another tone correction procedure gave inconsistent results and offered no significant

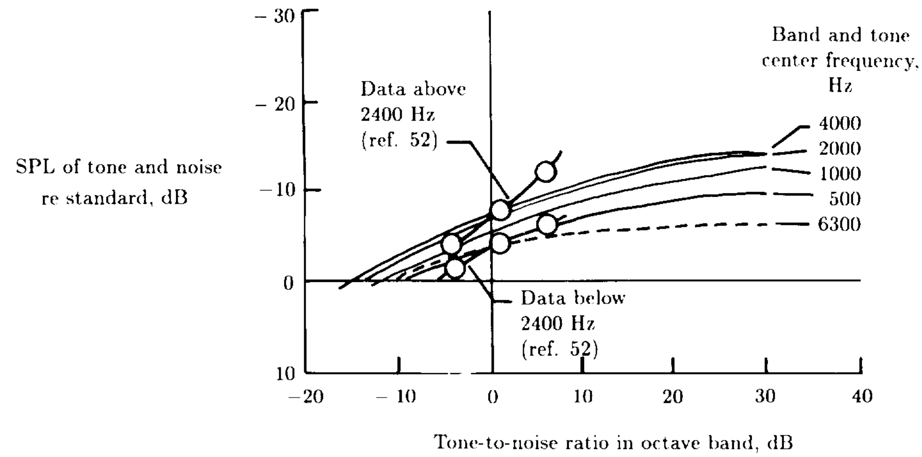


Figure 13. Effect of tone-to-noise ratio on noisiness. (From ref. 51.)

improvement over the non-tone-corrected metrics. Similar results were found in the large-scale laboratory study of reference 31. As indicated by the summary of these results in figure 14, the standard deviation in annoyance prediction error was reduced by the addition of a tone correction only for EPNL for jet aircraft. In all other cases the addition of tone corrections increased or did not change the standard deviation. In a reanalysis (ref. 54) of over 500 aircraft and other spectra with and without tonal components and responses to those spectra, very little evidence could be found to support either the FAA or several other tone corrections.

Repeated Impulses

A characteristic of some helicopter noise which has been reported to cause increased annoyance without an equivalent increase in level, as measured by most of the common noise metrics, is the repetitious impulses called blade slap. Although blade slap can be attributed to several mechanisms, it is generally characterized by a popping or banging sound with a repetition frequency equal to the main-rotor blade passage frequency. In terms of human response and the need to apply a correction to the common aircraft noise metrics to account for increased adverse responses, research studies have been about as inconclusive as they have been for tone corrections. In a review of 34 psychoacoustic studies (ref. 55), the conclusion was reached that helicopter noise should be measured in the same way as other aircraft noise and that no impulse correction was necessary to account for blade slap. Although many studies indicated the need for an impulse correction, nearly all utilized electronically synthesized or modified examples of helicopter noise. Conversely, most of those that indicated no need for corrections used natural live or tape-recorded helicopter sounds. A typical example of the type of mixed results is illustrated in figure 15, which is based on data from a CSD method study of reference 56. In the tests the subjects compared the annoyance of sounds with and without repetitive impulses. For stationary sounds with various levels of added impulses, there was a rather strong trend for increased annoyance without a corresponding increase in PNL as the level of the impulses was increased. For

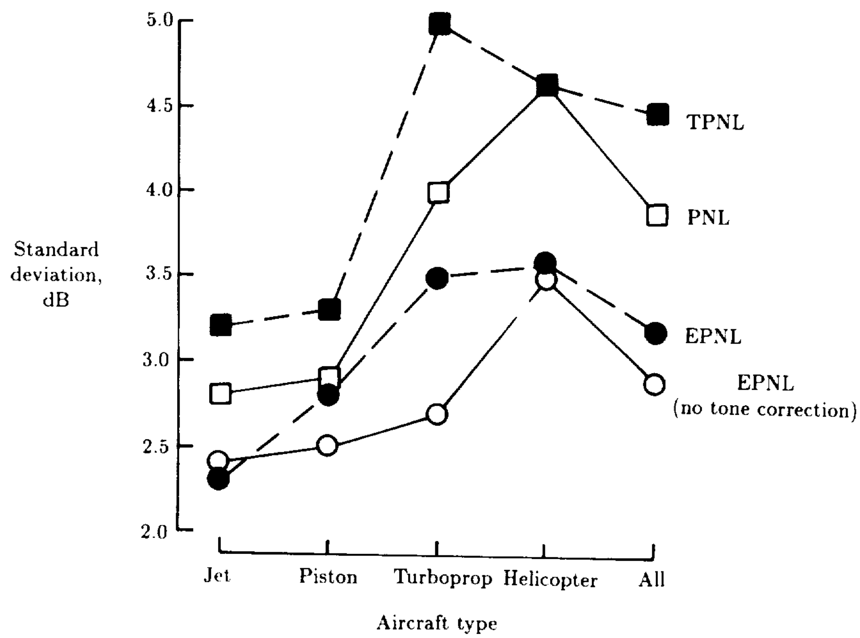


Figure 14. Effect of a tone correction on annoyance prediction error for different aircraft types. (Based on ref. 31.)

transient noises that were recordings of helicopter flyovers, no such clear trend was indicated. Similar results were reported in reference 57. In these tests no significant effects of impulsiveness were found for a limited number of recorded helicopter flyovers, but a significant effect was found for fabricated noises with added pulses.

In a study (ref. 58) in which subjects located indoors and outdoors judged the annoyance of actual helicopter operations using the NCS method, EPNL without any impulse correction was most highly correlated with the reported annoyance. The biggest drawback to this study was that only two helicopter types were used, although one type was flown in such a manner that various levels of impulsiveness were generated for different flyovers. In order to overcome this drawback, an extensive set of tests were conducted (ref. 59) using recordings of 89 different helicopter flights (22 different types) and 30 conventional aircraft flights. These tests utilized both headphone and loudspeaker presentations and compared the NCS and MOA techniques. Results of these tests also indicated no significant need for an impulse correction and in fact indicated that the helicopter sounds were no more annoying than conventional aircraft sounds for the same EPNL.

Sonic Boom

The concern about adverse effects of sonic boom has resulted in the prohibition of commercial supersonic flight over land within the United States. A recent bibliography (ref. 60) includes a very extensive listing of physical and psychological studies of sonic boom. In addition to annoyance due to the actual noise levels produced by a sonic boom, there is perhaps a more important startle reaction due to

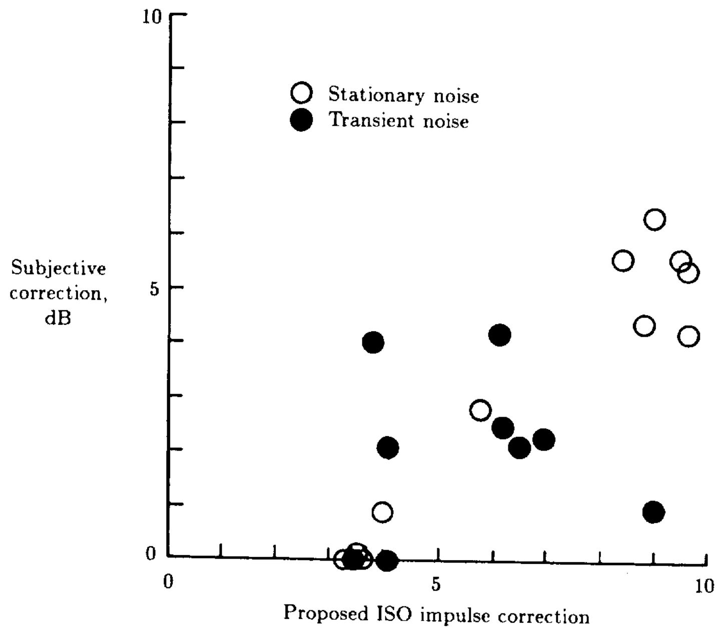


Figure 15. Effect of impulsiveness on subjective response to helicopter-type sounds. (Based on ref. 56.)

the suddenness of the sonic boom sound. The sonic boom noise characteristics result from the N-shaped pressure pulse caused by the compression and rarefaction of air as an aircraft flies at a speed greater than the speed of sound. A Fourier transform of the pressure time history into the frequency domain indicates that the acoustic energy covers a wide frequency range and that the low-frequency cutoff is determined by the duration between the positive and negative pressure peaks. The amount of high-frequency acoustic energy is inversely related to the rise time of the pulse. A series of CSD tests (ref. 61) on simulated and idealized sonic-boom-type N-waves and sawtooth pressure pulses indicated that the duration between the positive and negative pulses was not a major factor of loudness, that loudness increased with a decrease in rise time, and that loudness and annoyance were not very different for sonic-boom-type noises.

Fourier transformation of the pressure time history into the frequency domain serves as the basis of several loudness and annoyance prediction procedures. The method described in reference 62 basically converts the spectral information into 1/3-octave band pressures, corrects for the integration time of the ear, corrects for the large amount of energy at very low frequencies, and then uses the Stevens loudness calculation procedure to predict a composite loudness level. A simplified method of loudness prediction for sonic booms has been suggested in reference 63. Based on analysis of subjective data from outdoor judgments of sonic booms from a test conducted in Meppen, W. Germany, an empirical relationship for determining the loudness of the booms was developed. The loudness in terms of phons is approximated by

$$L = 20\log_{10}(p/p_o) - t - 12 \tag{15}$$

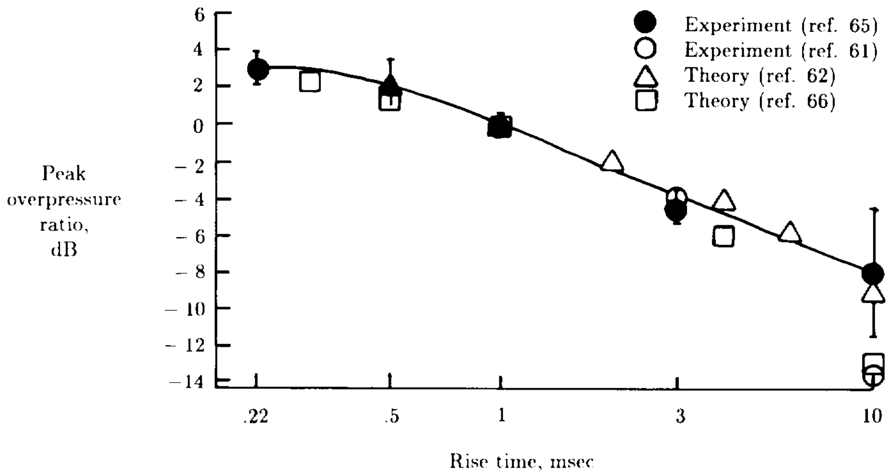
where p is the peak overpressure of the boom, p_o is the reference acoustic pressure, 2×10^{-5} Pa, and t is the rise time in msec. In a later report (ref. 64), also based on results of the Meppen tests, startle reactions were investigated and could be related to a similar function of p and t.

An investigation of sonic boom reaction is presented in reference 65. Some results of these CSD tests are shown in figure 16. The boom signatures were produced using computer-generated electrical signals and special filtering. Effects of rise time and peak overpressure agreed well with previous studies (refs. 61, 62, and 66). Although little effect of duration was found for short durations, a significant increase in loudness was found for durations exceeding 200 msec. Since this duration exceeds the integration time of the ear, it is suspected that the subjects were reacting to both the positive and the negative portions of the simulated N-waves.

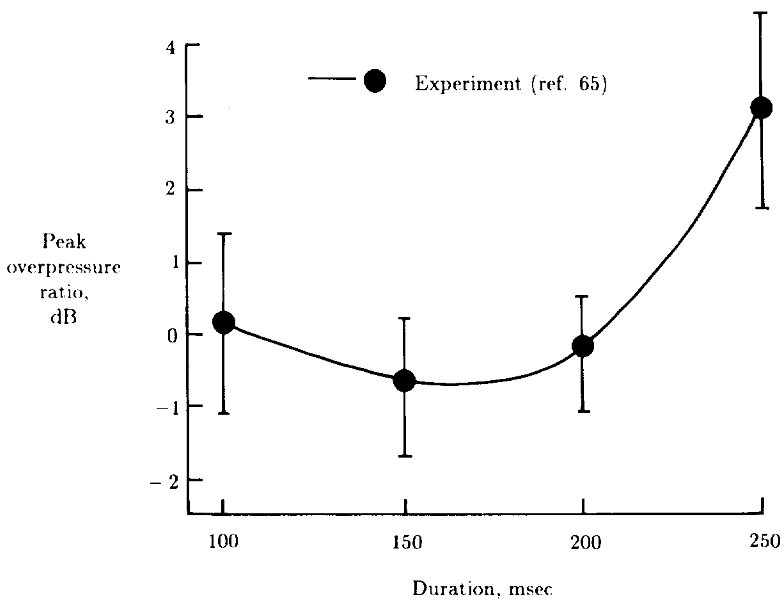
Multiple Noise Exposures and Other Effects

Community annoyance due to aircraft noise exposure is generally considered to depend on the number of flight operations in the community as well as the noise levels of the operations. Although numerous social survey studies have been conducted to determine the relationship of annoyance to noise exposure, the relationship of annoyance to the number of events has remained relatively unresolved. The first major laboratory study to investigate the effects of the number of aircraft events on annoyance was reported in reference 34. In the study, subjects in a living-room-type environment who were engaged in quiet activities, such as reading, made NCS-type judgments on 1-hour-long sessions of aircraft noise exposure. The sessions contained from 4 to 64 aircraft flyover noises of various types. Based on results of the study, the best fit for number of events was about $7 \log_{10} N$ or $N/6$, where N was the number of flyover events per hour. A series of similar tests (refs. 67 and 68) indicated a somewhat larger number effect, $15 \log_{10} N$. However, this effect did not significantly differ from the number effect, $10 \log_{10} N$, implied in the energy-averaging-type metrics, such as LEQ or DNL. Some other findings of the study of reference 68 were as follows. The time of occurrence of the flyovers in the session was not a significant factor; thus annoyance does not decrease significantly after exposure at least for relatively short periods of time (minutes and hours). In addition annoyance decreased with increases in session duration for a fixed number of flyovers in the session; thus the subjects make an averaging-type judgment over time rather than a simple summation. Thus an energy-averaging noise exposure metric may be very appropriate for assessing total community noise exposure.

Another factor that has been considered to affect human response to aircraft noise is the level of the ambient or background noise in which the aircraft noise is heard. Most studies that investigated background noise effects have used NCS procedures in which aircraft noises with different noise levels were heard in a session with a constant background noise. The background noise effects were determined by having the subjects judge the same aircraft flyovers in a number of sessions with different background noise levels. A summary of three different studies (refs. 69–71) is shown in figure 17. A significant reduction in subjective noise level for increasing background noise level was found in each study, and the magnitudes of the effects were very similar as indicated by the high correlation of the pooled data. Although these effects are consistent and significant, the effect is rather small at typical



(a) Equal loudness as a function of rise time.



(b) Equal loudness as a function of duration.

Figure 16. Effect of rise time and duration on response to simulated sonic booms. (From ref. 65.)

aircraft-to-background noise ratios (>20 dB); therefore it is not expected that background noise is a major factor in determining community annoyance to aircraft noise.

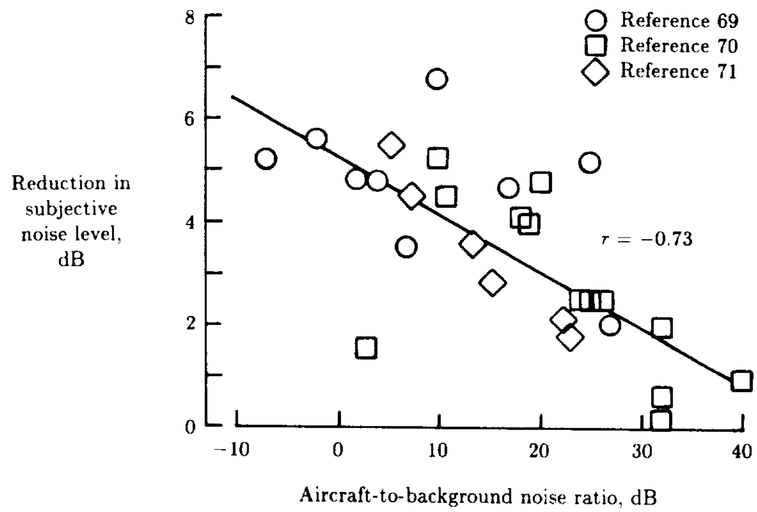


Figure 17. Effect of background noise on aircraft noise annoyance judgments.

Findings Related to Aircraft Interior Noise

The effects of aircraft interior noise on people have received much less specific attention as a research topic than has aircraft community noise. Many reasons may contribute to the apparent lack of interest in aircraft interior noise as a research topic. First, the people exposed to aircraft interior noise normally are willing participants and benefit directly from flying. They have some control over their overall exposure and level of annoyance by simply not flying or by flying in aircraft that provide an acceptable interior noise environment. Second, the airlines tend toward buying aircraft with acceptable interior noise levels as much as economically possible so that the passengers will continue to fly with their airline. Third, the aircraft industry takes whatever noise control measures are necessary and economically feasible to maximize passenger acceptance and sales to the airlines or private operators. And finally, the nature of the noise itself allows application of findings from basic or generic research on human response to noise to guide noise control methods.

Aircraft interior noise environments vary significantly with the type of aircraft and operation. For most flights, however, the cruise phase lasts much longer than takeoff or landing phases or other phases with significant maneuvers which cause variations in noise level or spectrum. Typical cruise noise levels for the interiors of a number of different classes of aircraft are indicated in figure 18 and are compared with the noise levels typically measured in ground transportation systems (ref. 72). Typical interior noise levels in commercial jet aircraft range from 80 dB to 85 dB (A-weighted). Typical general aviation airplanes and helicopters have significantly higher interior noise levels and can create the possibility of hearing damage with long and unprotected exposures. Private business jets are frequently quieter than commercial jets so that better verbal communication is possible between the passengers. The noise levels for large commercial jets are actually optimized so that communication is possible between adjacent seats but a measure of privacy is provided from other passengers.

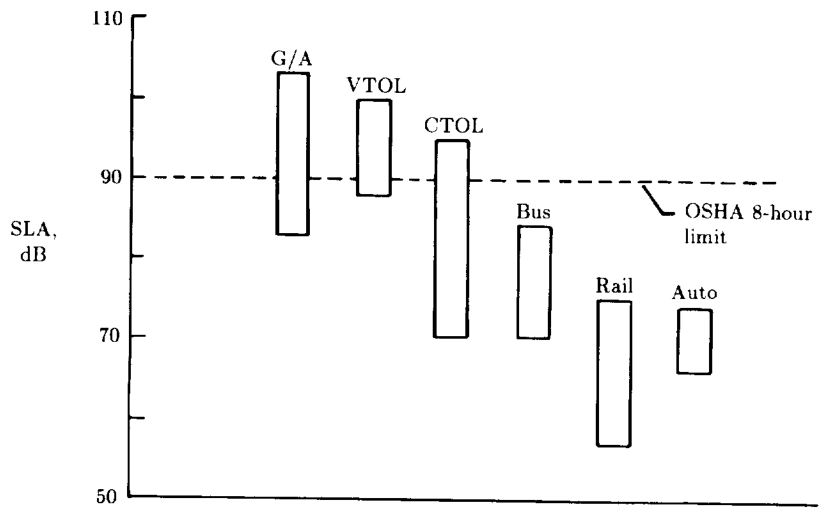


Figure 18. Comparative interior noise levels for different aircraft and ground transportation systems. (From ref. 72.)

The three most important effects of aircraft interior noise on passengers and crew are the potential for permanent hearing loss, speech interference, and general annoyance. Since for the most part aircraft interior noise has constant level and spectrum, generic hearing damage and speech intelligibility research is directly applicable for predicting those effects of the aircraft interior noise environment. A possible exception would be for speech intelligibility in some helicopters where the noise environment is dominated by high-frequency tones. In reference 73 it was found that the commonly used articulation index procedure tended to underestimate the intelligibility scores (percent correct) for a helicopter interior noise environment with very strong pure tone components. The following sections therefore present some research results of factors related specifically to aircraft interior noise annoyance.

Interaction of Speech Interference and Annoyance

Aircraft crew and passengers can suffer from fatigue as the result of the increased vocal effort required to communicate effectively inside aircraft with high noise levels. Thus in addition to the direct effects on general annoyance and speech intelligibility, aircraft interior noise can be the source of increased annoyance which results from the increase in fatigue level.

In reference 74, subjects were asked to rate recorded aircraft interior noises for general annoyance and "communication annoyance," assuming they would want to be able to converse in the noise. Recorded speech noises were presented simultaneously with the aircraft interior noise, and speech intelligibility tests were administered during part of the study. Results of the study are presented in figure 19. The percentage of the subjects who reported that they were highly annoyed by aircraft interior noises was in general greater when the subjects considered verbal communication, particularly in the middle range of the noise levels presented. The communication noise ratings were also found to be significantly correlated with speech intelligibility. Figure 20 presents the communication annoyance ratings grouped according to speech intelligibility and related to noise level. An interaction of noise level and speech intelligibility is clearly indicated. Since speech communication is a common and important activity in aircraft, it must be concluded that speech intelligibility as well as noise level should be considered in determining appropriate noise environments inside aircraft.

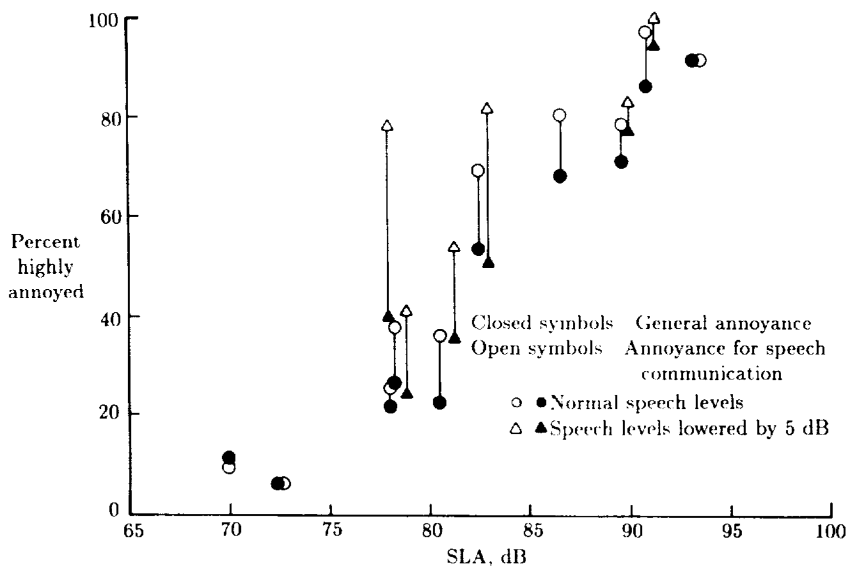


Figure 19. Effects of aircraft interior noise levels on general annoyance and communication annoyance. (From ref. 74.)

Interaction of Noise and Vibration

Aircraft interior noise is usually accompanied by vibration over a wide frequency range. Depending on the level and frequency, the vibration may be sensed through whole-body motion or tactile sensation through the hands or feet or other body members. In 1975 a research program was instituted at the NASA Langley Research Center to develop a ride quality model that would be applicable for predicting human response to the wide range of vibration inputs possible from all types of aircraft. During the research for development of the model, it was found that the effects

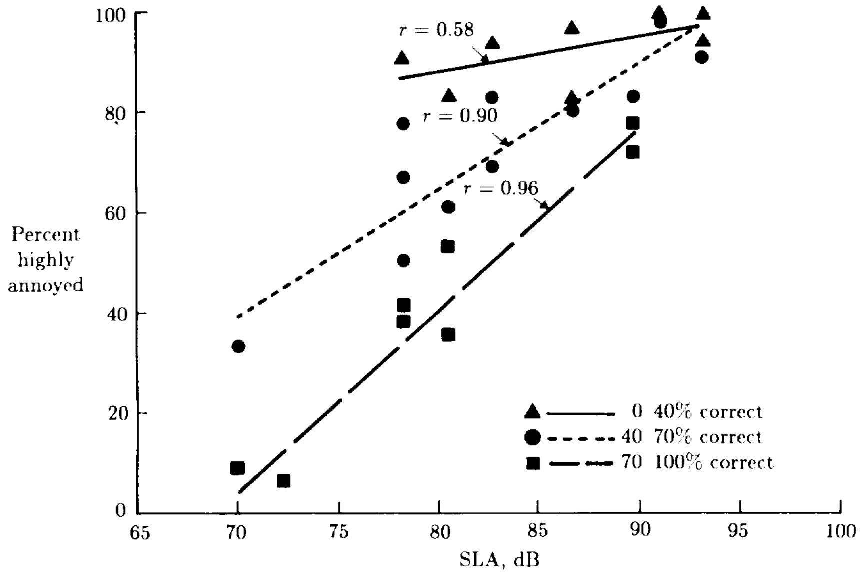


Figure 20. Effects of noise level and speech intelligibility on communication annoyance. r is the product moment correlation coefficient. (From ref. 74.)

of noise and vibration were interactive in determining the acceptability of a given aircraft interior environment.

The ride quality model involves transforming the physical noise and vibration characteristics into subjective discomfort units of noise and vibration using a common scale which can be combined into a single discomfort index (ref. 75). The model was validated in a simulator study using the Passenger Ride Quality Apparatus mentioned previously with recorded helicopter interior noise and vibration (ref. 76). Experienced military helicopter pilots served as test subjects. Typical results from the study are shown in figure 21. The open symbols represent the mean discomfort ratings given by the pilots; the closed symbols are the predicted discomfort ratings from the model. The agreement is good over the range of conditions, and the data illustrate the interaction between noise and vibration in determining total discomfort.

Field Assessment of Human Response[1]

Community noise annoyance surveys are the major source of information about the effects of noise on people in the community. Over 200 social surveys of community response to noise have been performed and over 90 of those surveys have specifically addressed aircraft noise (ref. 77). The reader interested in a more detailed discussion of the findings from field studies of aircraft and other types of transportation noise sources is referred to reference 78. Such studies consist of two main parts: a social survey in which residents in the studied community answer questions about their reactions to aircraft noise and/or other community environmental factors and a noise

[1] Section authored by James M. Fields.

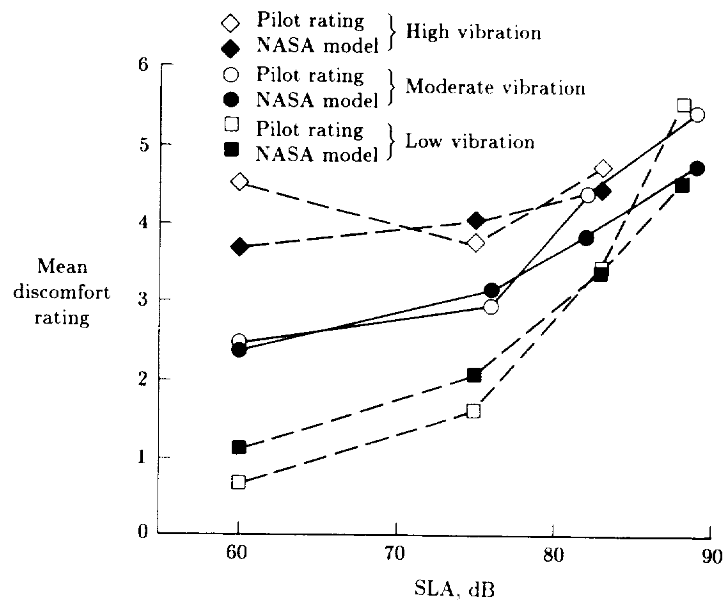


Figure 21. Comparison of pilot discomfort judgments with predictions of the NASA Ride Quality Model showing the interaction of noise and vibration. (From ref. 76.)

measurement survey which provides estimates of the residents' noise exposures. The major advantages of field assessment of the effects of noise are that community residents are exposed to the actual noise environment which can interact with other environmental factors and their personal living conditions to produce feelings of annoyance or dissatisfaction with the environment. The major disadvantages are that a carefully conducted social and physical survey of aircraft noise is expensive and time-consuming but still may not provide the necessary statistical accuracy to test hypotheses of the effects of some acoustical variables. The following sections present some of the methodological considerations and findings of aircraft noise surveys which relate to both individual noise annoyance and community complaint activity.

Methodology

Activity Disturbance and Annoyance Scaling

Activity disturbances are normally studied in a natural community setting by asking retrospective questions in surveys rather than by directly observing specific instances of activity interference as is done in the laboratory. Respondents are asked a series of questions such as the following from the 1967 Heathrow aircraft noise survey (ref. 79):

Do aircraft ever . . .

i. Startle you?

ii. Wake you up?

iii. Interfere with listening to radio or TV?

iv. Make the TV picture flicker?

v. Make the house vibrate or shake?

vi. Interfere with conversation?

vii. Interfere with or disturb any other activity?

Respondents are also frequently asked how annoying they find the disturbance (e.g., "very, moderately, a little") or how often they are disturbed (e.g., "very often, fairly often, occasionally"). In spite of the diverse exposure conditions and the use of self-reports rather than laboratory observations, the surveys consistently show that activity interference consistently increases with increasing noise exposure. A typical example is shown in figure 22, which is from data collected in a survey around the Geneva, Switzerland, airport (ref. 80). These results indicate that communication interference (conversation, radio, TV) is the most frequently mentioned type of activity interference.

Although there is consistency in the qualitative results of activity interference across different surveys, the level of reported activity interference varies widely between surveys (ref. 81). The exact wording of the questions has been found to result in large differences in reported disturbance even within the same survey. Therefore attempts to summarize interference results across studies or to compare results from different studies need to take into account the specific questions asked in the surveys.

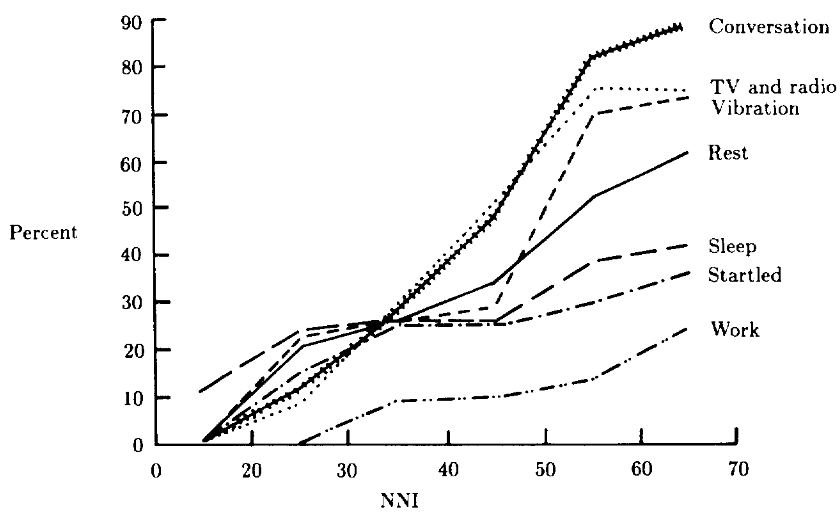


Figure 22. Reported activity interference (percent) as related to aircraft noise exposure around Geneva airport. (From ref. 80.)

Social surveys typically measure annoyance by asking whether specific noises "annoy" or "bother." Since the respondents hear only these questions rather than a philosophical treatise on the "true meaning of annoyance," the annoyance which is measured is nothing more than whatever dimensions are tapped by the particular wording of the survey questions. Questions which are typically used are as follows:

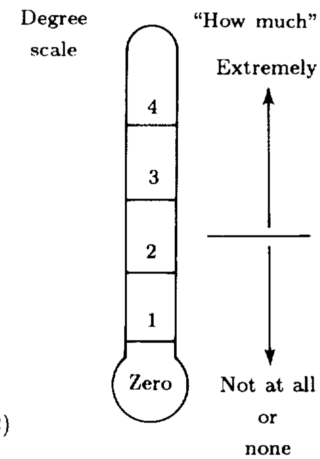
Please look at this scale and tell me how much the noise of the aircraft bothers or annoys you.

Very much
Moderately
A little
Not at all (From the 1967 Heathrow survey, ref. 79)

I will now read a number of noises heard in different neighborhoods.

Which ones do you hear in this neighborhood?

Of those that you hear, how much are you bothered or annoyed? Use the Opinion Thermometer. (From a U.S. survey, ref. 82)



Individual responses to these types of questions can be scored numerically and used to obtain group averages as a function of noise exposure, or they can be scored categorically and used to determine percentages of the population in each category as a function of noise exposure. In an effort to compare results across a large number of surveys for a number of noise sources, the upper 27 to 29 percent of any annoyance scale was used in reference 81 to represent "high" annoyance. Therefore most subsequent studies of community noise annoyance have presented results in terms of the "highly annoyed" dichotomy. There is, however, no scientific reason for choosing a particular dichotomization of the annoyance scale. It may be argued that a "high" annoyance point should be less influenced by personal characteristics and more related to noise level. The only empirical data that compare different annoyance cutting points show that the high annoyance dichotomization is no more closely related to noise level than less severe dichotomizations (ref. 83).

Validity and Reliability

In order to correctly interpret the meaning of annoyance measurements from social surveys, it is important to consider both the validity and the reliability of the annoyance measurements. Validity is defined as the extent to which a question actually measures some "true" underlying annoyance. Reliability is the extent to which repeated measures of some individuals' annoyance are consistent.

The subjective nature of the response of the residents and the possibility that the responses might be biased by the interview procedure have led to carefully designed and tested social survey research procedures for community noise studies. General guidelines for the design and conduct of social surveys can be found in specialized texts (ref. 84). The following practices reduce or eliminate some of the potential biases. Survey questionnaires conceal the focus on noise as long as possible by being presented as studies of general environmental problems. The primary noise annoyance question is presented early in the questionnaire in the context of a list of environmental disturbances. Interviewers are trained to ask all questions exactly as printed so that they do not bias the respondents' answers. Questions are stated in a simple, unbiased manner. And finally, the selection of respondents is based on sampling techniques which ensure that the sampled respondents represent the community as a whole.

Methodological studies of the annoyance measures have given further confidence that other characteristics of the surveys do not bias the results if the guidelines are followed (ref. 78). In general it has been found that answers are not affected by variations in the order of questions or the order in which the alternatives are presented. Studies have found that responses are not distorted by the length of the questionnaire or deliberate falsification on the part of the respondents. Other support for the validity of the annoyance measures comes from the fact that annoyance responses correlate with other variables in a meaningful manner (ref. 85) and are highly correlated with one another as well as with more objective measures such as activity interference, private behavior, and public complaint reports. Annoyance responses also correlate with noise exposures.

Whereas the available research indicates that annoyance responses obtained in surveys are valid, unbiased measures of annoyance, the responses to any single noise environment are highly variable and affected by the exact wording of questions. The reliability of annoyance indices consisting of several questionnaire items has generally met the standard, accepted social science reliability criterion (in terms of product moment correlation), $r \geq 0.80$, although there is still a great deal of variability. When the same individuals were asked about their unchanged noise environments at an interval of about 1 year (ref. 86) only about 35 percent of the variance in response ratings could be explained by their answer on the previous questionnaire. Since respondents in surveys in general must consolidate all their experiences and feelings about noise into a single response and must make a somewhat arbitrary choice between the words or numbers that the interviewer offers, the low level of reliability is not surprising.

Findings Related to Aircraft Noise Annoyance in the Community

Community aircraft noise annoyance is related to noise exposure and other environmental factors as well as to attitudes and other personal factors. The next sections examine results of selected aircraft noise surveys for information related to those factors that can affect community response.

Extent of Aircraft Noise Annoyance

Large numbers of people in nationally representative surveys have reported that they are annoyed by aircraft noise. In the United States an annual national housing survey found that about 8 percent of the population is bothered by aircraft noise in contrast to about 18 percent bothered by road traffic noise (ref. 87). Although aircraft noise was found to be the second most widely heard noise source in England (road traffic noise was the most widely heard source), it was rated as annoying less often than were the noises from children and animals (ref. 88).

It has been generally found in airport community surveys that individual annoyance and the percentage of people highly annoyed increase with increasing aircraft noise exposure. Figure 23 presents the percentage of people highly annoyed (dichotomized according to the top 27 to 29 percent of an annoyance scale after ref. 81) in five European and one U.S. survey as related to their noise exposure in L_{dn} (ref. 3). Using these data and estimates made in 1974 (ref. 89) of the numbers of people living in urban areas of the United States exposed to various levels of aircraft noise, it can be estimated that between 3 million and 5 million people are highly annoyed by aircraft noise in urban areas of the United States alone.

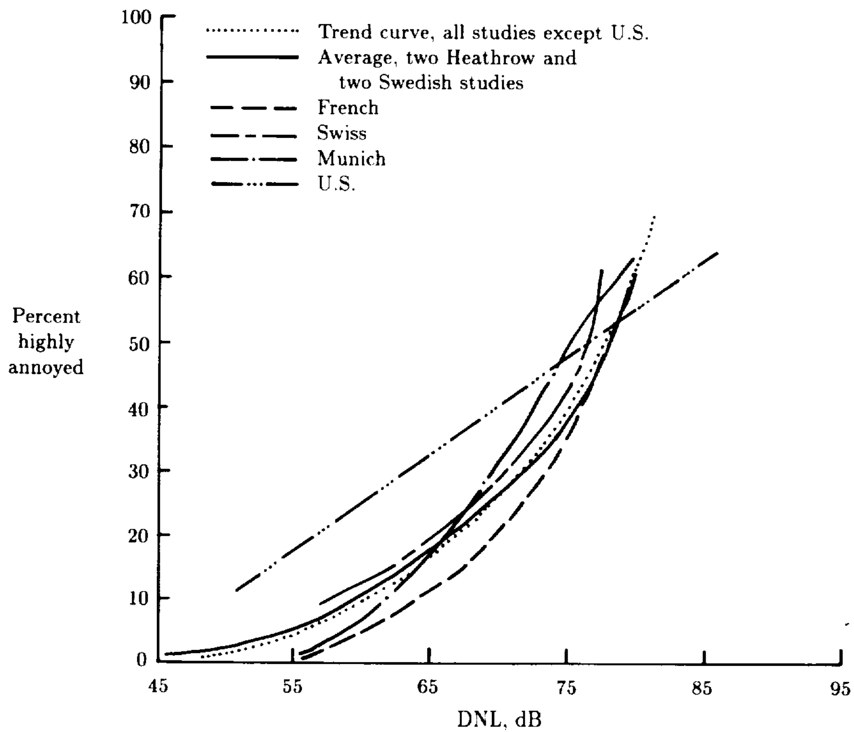


Figure 23. Percentage of respondents highly annoyed in several surveys. (From ref. 3.)

Acoustical and Situational Factors

Community aircraft noise annoyance has been found to be systematically related to noise exposure. The total noise exposure is made up of many single events which result from different aircraft types, occur at different times of day or night in combination with other noises, and vary in noise level, spectral content, and duration. Most information on spectral, duration, and aircraft-type effects has come from laboratory studies. The general findings are that duration affects annoyance and that an energy summation procedure such as used in EPNL or SEL is appropriate. The commonly used A-weighted scale appears to be as useful as the more complex metrics for rating aircraft noise in most environments.

The importance of the number of noise events relative to the noise level of the events has been a major issue in aircraft noise evaluation. The most common method of describing the number effect is the "decibel equivalent" of a tenfold increase in the number of events (ref. 79). The 1961 Heathrow study (refs. 90 and 91) estimated the decibel equivalent to be either 24 $\log_{10} N$ or 15 $\log_{10} N$ depending on the type of analysis used. The 1967 Heathrow study (ref. 79) was specifically designed to estimate the number weighting and reported a value of 4. In a review and analysis of available survey data (ref. 92), it was concluded that the balance of evidence suggests that the number weighting is no more than, and is perhaps somewhat less than, the weighting of 10 $\log_{10} N$ which is implicit in equivalent energy indices such as LEQ.

It is generally assumed that the same noise levels cause more annoyance in residential areas if they occur during the evening or night than if they occur during the day, because more residents are at home and are engaged in more noise sensitive activities (TV viewing, conversation, etc.) and because the noise may be more intrusive given the lowered nighttime ambient noise level. It has been found that after adjusting for the difference in noise levels, people rate their nighttime and evening environments as more annoying than their daytime environments (ref. 93). On the other hand, the study of reference 94 found that people were not sensitive to a change in late-night noise exposure. In this study, conducted around the Los Angeles International Airport, people did not report a reduction in nighttime annoyance after an almost total elimination of nighttime (11:00 p.m. to 6:00 a.m.) flights over the study area. A review of surveys providing information on time-of-day effects (ref. 93) found that good numerical estimates of the relative importance of daytime, nighttime, or evening noises are not available and the results are highly variable. Some studies have reported that the nighttime weighted indices, such as DNL, are more closely related to annoyance than simple unweighted 24-hour indices, such as LEQ; other studies have reported the opposite. The lack of consistency of the survey results may be due in part to high correlation between the daytime and nighttime noise levels at individual airports. As a consequence, it may not be possible to adequately determine the most appropriate time-of-day weightings from conventional surveys.

The reactions of people to aircraft noise in the presence of ambient noise have been addressed with two alternative hypotheses. It is frequently hypothesized that annoyance to a specific noise would be greater when experienced along with a low ambient noise than when experienced along with a high ambient noise. It has also been hypothesized (ref. 95) that an intrusive sound may be more annoying in a high ambient noise because people can become sensitized in general to noise. Early attempts to investigate ambient noise effects in surveys were hampered by inadequate ambient noise level data (ref. 79) or unacceptably small numbers of study sites for each ambient noise category (ref. 96). Results were inconsistent for the magnitude or direction of an ambient noise effect. A large-scale survey (ref. 97) that was specifically designed to study ambient noise effects found that aircraft noise annoyance was not affected by the level of road traffic ambient noise. These findings along with the small ambient noise effects found in laboratory studies suggest that most normally occurring ranges of ambient noise do not strongly affect, if at all, community annoyance to aircraft noise.

Another issue concerning multiple noise sources that has been investigated using data from community noise surveys is the relationship between total noise annoyance and the levels of the individual noise sources. The analyses of reference 98, which examined five alternative models for evaluating annoyance reactions in mixed noise environments, indicated that annoyance reactions were more accurately predicted by any of the more complex models than by the simple measurement of the LEQ of the total environment. Although it was not possible to identify the correct model with the analyses, the findings do suggest that it may ultimately be possible to identify a model for general community noise annoyance that is better than the equivalent energy models LEQ or DNL.

Findings on differences in annoyance between different classes of aircraft have often been contradictory. A study in Australia (ref. 99) found that annoyance around a military airfield was similar or less than that around civilian airports, whereas a study in the Netherlands (ref. 100) concluded that noise annoyance around military airfields was probably greater than around civilian airports at the same noise level. A West German survey (ref. 101) found general aviation noise to be more annoying than commercial aviation noise, but a Canadian survey (ref. 102) found that annoyance differentials varied between questions in ways that were related to differences between the acoustical environments at the general aviation and commercial airports.

Most aircraft noise surveys have been conducted in areas where the noise environments have been largely unchanged for several years. When a noise environment changes significantly over a short time span, however, reactions to the change might differ from the reactions predicted from the relationship between noise exposure and response obtained from the static data. One such example was the lack of change in general and sleep activity annoyance when nighttime operations were severely cutback over certain areas near Los Angeles International Airport (ref. 94). Although there was only a small change in total noise exposure as measured with the DNL index, thus explaining the lack of effect on general aircraft noise annoyance, the lack of effect on sleep-related annoyance is not easily explained. A study of reactions to temporary changes in noise levels around an airport in Burbank, California (ref. 103), found that reactions followed the changes in noise levels; 2 months after the change, reactions were similar to those predicted from the originally collected static data. Studies conducted 1 and 4 years after the opening of Charles de Gaulle Airport near Paris (ref. 104) were consistent with each other and with relationships observed earlier in a static noise situation around the Orly Airport also near Paris. These latter studies suggest that changes in noise exposure do lead to changes in annoyance which, at least after a period of time, would be predicted from static data.

A number of other environmental and situational factors have been hypothesized to affect airport community annoyance. Based on data from a number of surveys, it has been found that double glazing, locations of bedrooms, and other factors related to individualized noise exposure affect annoyance (ref. 78). However, good estimates are not available on the relative effect of a decibel of localized reduction (at the receiver) as opposed to the same reduction at the source. Many studies have found that there are unexplained differences between the reactions found in different study areas (ref. 105). These are sometimes assumed to be due to differences between reactions of people in different countries or different cities. The explanation of such differences is not known, and the possibility clearly exists that there are other important acoustical or situational factors which have not yet been investigated. Given the presence of correlated neighborhood characteristics, knowledge about the effects of these variables is not likely to be obtained except through large-scale, carefully designed surveys that include large numbers of fully described study areas.

Attitudinal and Personal Factors

The large variance in annoyance found in surveys which is not associated with noise exposure factors has led to a number of hypotheses about attitudinal and personal factors that may be associated with annoyance. References 82, 90, and 106 in particular discuss a wide range of variables and their effects on reported aircraft annoyance. The six most consistently reported attitudes that have been hypothesized to affect aircraft noise annoyance, when the actual noise exposure has been held constant or otherwise accounted for, are fearfulness, preventability, noise sensitivity, perceived neighborhood quality, health effects, and non-noise impact of the source.

Respondents who express fear that aircraft may crash in the neighborhood are generally more annoyed than those who express little or no fear of crashes (ref. 79). Similarly, respondents who believe that authorities could do something to reduce the aircraft noise exposure are also generally more annoyed than those who believe that authorities do all that is possible (ref. 107). Those respondents who report that they are sensitive to other noises or to noise in general have also been found to be more annoyed with aircraft noise (ref. 90). The level of sensitivity, however, has never been found to be related to their actual environmental noise level. Increased aircraft noise annoyance has also been found to be related to general negative evaluations of other neighborhood characteristics (ref. 108). The few people who believe that their health is affected by aircraft noise are also likely to be more annoyed by a given noise environment (ref. 90). Finally, people who are annoyed by other intrusive aspects of aircraft, such as lights and odors, are also generally more annoyed by the noise of aircraft (ref. 92).

It is sometimes argued that the above findings indicate that annoyance is caused by these attitudes (refs. 107 and 109). However, the difficulties in providing firm evidence for the nature of the causal relationships have led other investigators to state that although the variables are interrelated, conclusions cannot be drawn about the direction of causation (ref. 110).

Many studies have examined the standard demographic variables of age, sex, marital status, size of household, education level, social status, income, length of residence, type of dwelling, and type of tenure (own or rent). None of the variables, however, have consistently been found to be related to aircraft annoyance response.

Complaint Activity

Individual and group complaint activities, in the absence of social surveys, are indicators of noise impact which are likely to be used by public authorities. Whether or not such actions are good indicators of aircraft noise impact is open to discussion and is examined in the following sections.

Conditions That Affect Public Action

The first condition that affects the amount of public action is that there is a basic underlying dissatisfaction with the existing aircraft noise situation. The consistent relationship between aircraft annoyance and noise level means that there is dissatisfaction in virtually all high aircraft noise areas. The second condition is that there is an identifiable object or authority responsible for the control of noise. The existence of a highly visible and centralized airport authority could help explain why airport noise has been the focus of more public attention relative to the total number of people impacted than has road traffic noise. The third condition is that the group or individual believes that action can lead to a change in the noise situation. Thus beliefs about preventability of aircraft noise could have even more impact on complaints than on annoyance (ref. 90). The fourth condition is that people must be aware of a means of contacting the appropriate authority; when the availability of a telephone complaint service is publicized, the number of complaints rises (ref. 111). The fifth condition required, for group action in particular, is that the social structure of the area and society as a whole facilitate public action. It is obvious that complaints and group actions are much more likely to occur in a democratic society than in a totalitarian society. A sixth condition that can increase the amount of action is a new focal point. The introduction of the Concorde supersonic transport into service at New York and Washington, D.C., in the mid-1970's is an example of a relatively small change in noise exposure causing a major public action.

Complaints as Noise Effect Indicators

Superficially, centrally collected reports of complaint activity have attractive characteristics for monitoring responses to aircraft noise. They are relatively economical to obtain and seem to indicate an important type of disturbance since the complainant must usually go to some trouble to make the complaint. No evidence was found in a survey around Heathrow that complainants have unusual psychological traits such as neuroticism (ref. 90). Although complainants were more annoyed than the average resident around Heathrow, there was no indication that they were a tiny hypersensitive minority; many more equally annoyed residents did not complain. In the Heathrow survey and in the major survey around U.S. airports (ref. 107), complainants were no more likely than the remainder of the population to be sensitive to other noise sources. In the U.S. airport survey, complaint activity was found to be related to the noise exposure but not as strongly as annoyance.

In spite of the fact that complaints seem to be genuine expressions of annoyance, the conclusion has been reached by many researchers (e.g., refs. 112 and 113) that complaint records are misleading indicators of the extent or causes of noise effects in populations. Complaint records seriously underestimate the extent of aircraft noise effects. In a survey around Heathrow, 62 percent of the population were annoyed by aircraft noise, 15 percent were very annoyed, but only 1 percent reported making a complaint (ref. 90).

Complainants differ from the rest of the impacted population in several respects. They are typically articulate and have greater confidence that they can deal with authorities. Consequently, unlike annoyance response, complaint action is affected by social class indicators such as occupation, education, income, and property value (refs. 90 and 107). Complaint activity, unlike annoyance, has also been found to be affected by the individual's attitude toward the noise source (ref. 107). It has also been frequently observed that more affluent neighborhoods complain more about aircraft noise.

Most complaint data are collected by various authorities for nonresearch purposes. The incidence of recorded complaints and how they are categorized, tabulated, and reported could depend heavily on the agency recording the data. It has also been frequently noted that only a few individuals may be the source of a substantial proportion of the complaints. Thus, one might erroneously conclude that aircraft noise bothers only a few well-to-do people who are hostile toward aircraft and that noise impact varies widely in ways which are only loosely related to the aircraft noise exposure.

Noise Regulations, Criteria, and Recommended Practices

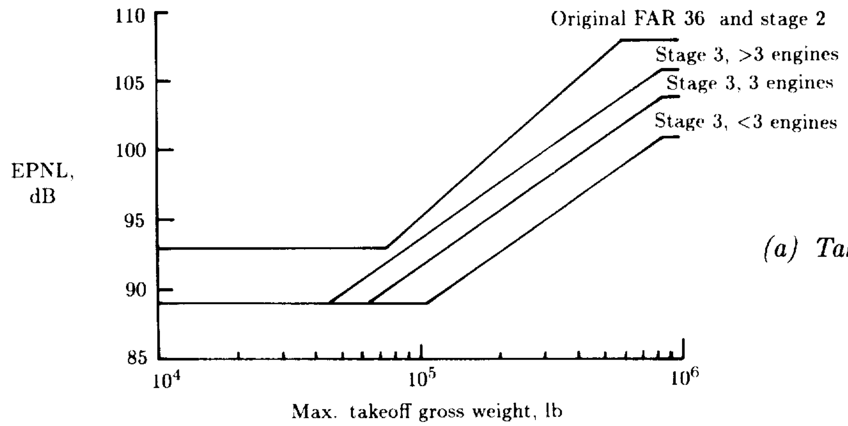
With the increasing awareness of the need to protect the overall environment in the late 1960's and early 1970's, there was increased concern with the community noise environment. The increasing popularity of commercial air transportation and the increasing numbers of large jet transports with high noise levels created adverse environmental conditions affecting an ever-increasing number of residents near commercial airports. As a result of the pressure exerted on the U.S. Congress and the governments of other countries, a number of legislative actions and resulting noise regulations were enacted to reduce or at least limit the growth of the community noise problem. A few of the major actions in the United States affecting aircraft noise in particular are discussed in the final sections of this chapter.

Aircraft Noise Certification

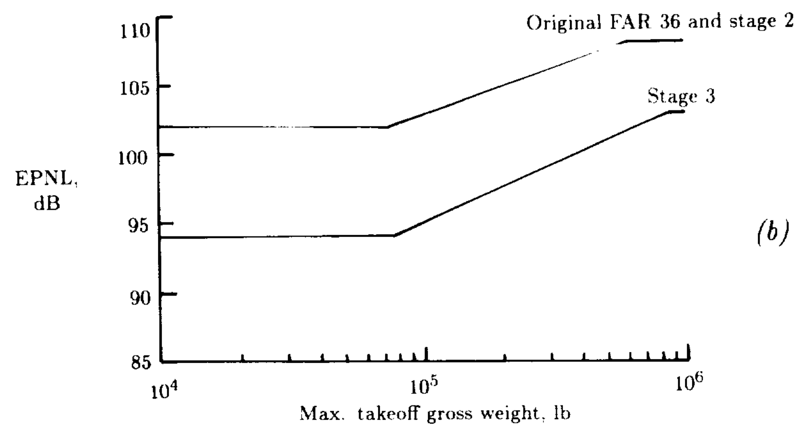
In 1969 the U.S. Federal Aviation Administration issued a noise certification regulation, Federal Air Regulation, Part 36 (ref. 22). This regulation, which is commonly referred to as "FAR 36," was issued with the objective of preventing the escalation of noise levels of civil turbojet and transport categories of aircraft. In order to be given a type certification for operation within the United States, new aircraft were required to be significantly quieter than the turbojet aircraft developed in the late 1950's and early 1960's.

In order to best reflect the annoyance response of people to aircraft noise, the metric selected for use in the noise certification procedure was the effective perceived noise level (EPNL), which considers frequency content, duration, and tone content in addition to overall sound pressure level. The tone corrections were considered particularly important to account for the strong tonal components of the new generation of turbofan engines. The new aircraft were required not to exceed prescribed noise levels at three locations: (1) 3.5 n.mi. (6500 m) from brake release on the runway centerline during takeoff, (2) 0.25 n.mi. (450 m) to the side of the runway centerline at the point of maximum noise level after lift-off during takeoff (later modified to 650 m if more than three engines), and (3) 1.0 n.mi. (2000 m) from touchdown during landing. The noise level limits varied as a function of gross weight of the aircraft as shown by the upper lines in figure 24. For both takeoff and landing, closely prescribed operational procedures had to be followed.

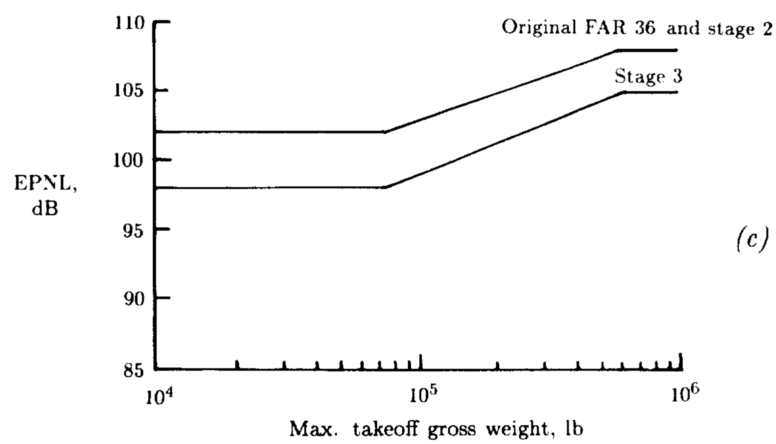
The basic FAR 36 standards have been modified over the years to account for improved technology and reduced noise levels for new generation aircraft (ref. 114). The additional lines in figure 24 represent the current noise limits for newly certified aircraft. The noise limit for a particular transport aircraft, turbojet or propeller; depends not only on the weight of the aircraft but also on the date of application for



(a) Takeoff limits.



(b) Sideline limits.



(c) Approach limits.

Figure 24. FAR 36 noise limits for transport aircraft.

type certification. If application was made prior to January 1, 1967 (stage 1), the aircraft must meet the stage 2 limits in figure 24 or be granted special exception. If application was made after January 1, 1967, but before November 5, 1975 (stage 2), the aircraft must meet the stage 2 limits without exception. If application is made on or after November 5, 1975 (stage 3), the aircraft must meet the stage 3 limits. Through the application of the stage 1 and stage 2 requirements, a number of older and noisier aircraft were forced out of service or had to be upgraded to meet the more stringent rules.

The FAR 36 regulation also covers propeller-driven small airplanes. For this type of aircraft a different noise metric, different operational procedures, and different noise limits are prescribed. These differences were prescribed to reduce the cost of certification for the smaller manufacturer and to reduce the noise for one of the most common and frequently annoying flight operations for small propeller airplanes, low-altitude flights around or near small airports with frequent touch-and-go landings. The metric prescribed for this type of airplane is the simple A-weighted sound level (SLA). The prescribed flight procedure is a constant-altitude flyover at 1000 ft (305 m) at highest normal operating power. The noise limits depend on the weight of the airplane as indicated in figure 25. If certification was applied for after January 1, 1975, the slightly lower maximum limit applies.

The International Civil Aviation Organization, to which most developed nations belong, also issues noise regulations, commonly called Annex 16 (ref. 115), which cover the aircraft categories covered by the FAR 36 and in addition, helicopters. The procedures and noise limits, with only minor exception, are the same as those in FAR 36. Thus, aircraft manufactured in and meeting certification requirements in any member nation can be operated in all member nations.

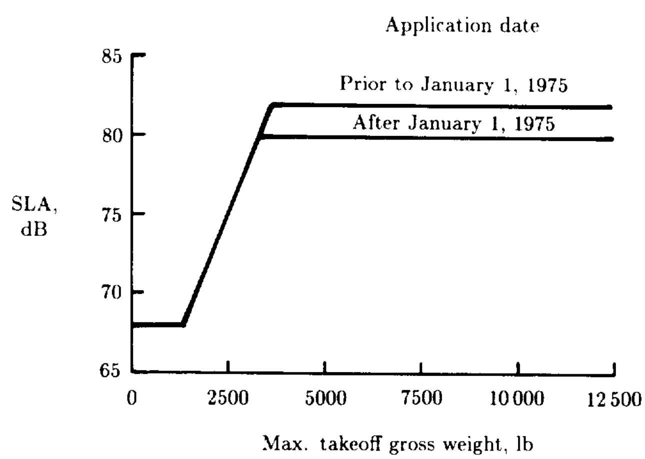


Figure 25. FAR 36 noise limits for small propeller-driven aircraft.

Community Noise Criteria

In the Noise Control Act of 1972 the U.S. Congress directed the Environmental Protection Agency (EPA) to "develop and publish criteria with respect to noise" and "publish information on the levels of environmental noise the attainment and maintenance of which in defined areas under various conditions are requisite to protect the public health and welfare with an adequate margin of safety." To accomplish this goal, the EPA established an august working group of experts in all aspects of human response to noise, including noise-induced hearing loss, other health effects, and activity interference. As a result of this committee's actions and several review meetings, the EPA published what has come to be known as the "Levels Document" (ref. 116). In the document the A-weighted sound level SLA and the day-night average sound level DNL were recommended as a "simple, uniform and appropriate way" for describing the effects of environmental noise. The effects, levels, and appropriate areas for application of the criteria are given in table 1.

These levels are not to be construed as levels that should never be exceeded but rather as a total "dose," or exposure, summed over a period of time. In establishing the activity interference and annoyance criteria, a large amount of consideration was given to aircraft community noise. A summary figure of aircraft annoyance survey and community reaction results was presented which provides relationships between percentage of people highly annoyed, percentage of people who could be expected to

Table 1. Summary of Noise Levels Identified as Requisite To Protect Public Health and Welfare With an Adequate Margin of Safety

Effect	Level	Area
Hearing loss	$L_{eq(24)} \leq 70$ 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
	$L_{eq(24)} \leq 55$ 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
	$L_{eq(24)} \leq 45$ dB	Other indoor areas with human activities, such as schools, etc.

complain, the severity of community reaction, and noise level in DNL. This summary is given in figure 26. The recommended outdoor noise level of $L_{dn} \leq 55$ dB would thereby be expected to cause no adverse community reaction, would cause only a few complaints, but would still cause about 20 percent of the exposed population to be highly annoyed. The percentage of people highly annoyed in this figure, however, is

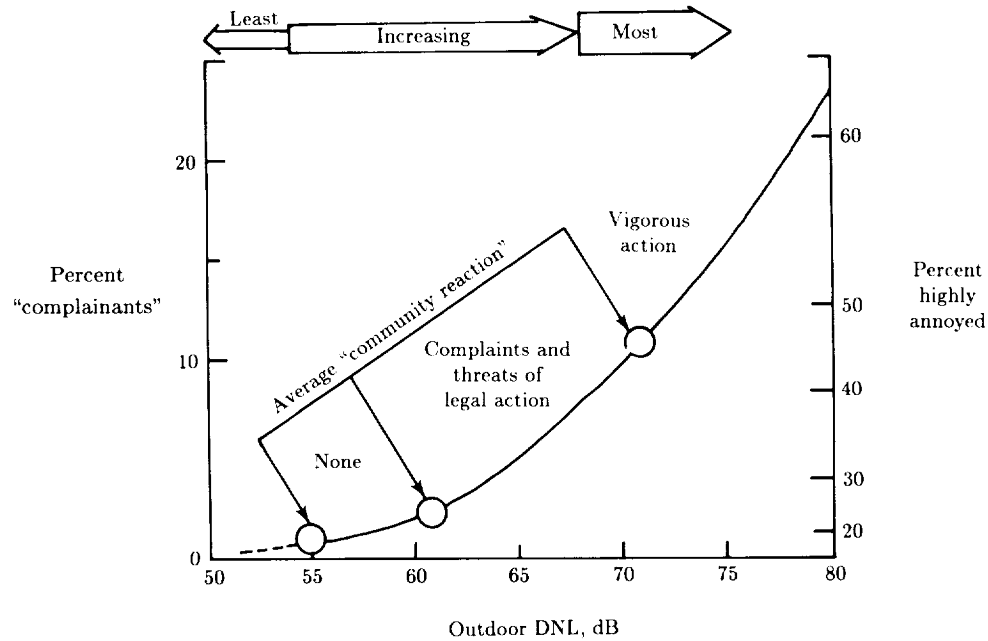


Figure 26. Summary of expected annoyance and community reactions as related to aircraft noise exposure. (From ref. 116.)

greater than the 5 to 10 percent reported in other attempts to summarize community reaction to aircraft noise (refs. 81 and 117).

Land Use Planning

To reduce the adverse impact of aircraft noise on the airport community, it is not always necessary that noise limits be placed on individual aircraft or that operational limits be placed on the air carriers. An equally effective measure is appropriate use of the land around the airport. In 1980 a U.S. Government interagency committee comprised of members from the Environmental Protection Agency, Department of Housing and Urban Development, Department of Defense, Veterans Administration, and Department of Transportation issued noise guidelines for land use planning and control (ref. 118). The stated purpose for land use planning is not to limit development but to encourage noise compatible development, guiding noise sensitive land uses away from the noise, and encouraging nonsensitive land uses where there is noise. The report provides the classification of seven noise zones with a wide range of noise exposure in terms of SLA, DNL, and NEF. Approximately 100 different land uses are then categorized for compatibility with the noise zones.

To obtain Federal financial aid for implementing a noise compatibility program, airports in the United States must comply with the Federal Aviation Regulation, Part 150 (ref. 119). This regulation prescribes the noise metric DNL for measuring the noise and determining the exposure of individuals to noise that results from operations at the airport and the land uses which are normally compatible with the noise exposure. The noise exposure is classified into 6 zones, which are the same as the highest zones of the previously described land use guidelines, and 24 land uses are identified and categorized for compatibility with the exposure zones. The compatibility guidelines are essentially the same as those in the previously described general noise guidelines. The distinction between FAR Part 150 and the previously described general land use guidelines is that an airport must comply with Part 150 in applying for Federal aid for implementing a program which seeks to ensure land compatibility established by the guidelines. Thus, while FAR Part 150 does not directly force land use compatibility, it provides some insurance that airports uniformly assess their problems and that if a noise compatibility program is implemented, it is expected to make a measurable reduction in adverse human response.

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