NEF validation study: (2) review of aircraft noise and its effects

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NEF VALIDATION STUDY:

(2) REVIEW OF AIRCRAFT NOISE AND ITS EFFECTS

The contents of this report are the results of analyses carried out by the Acoustics Laboratory of the Institute for Research in Construction at the National Research Council of Canada. While they are thought to be the best interpretation of the available data, other interpretations are possible, and these results may not reflect the interpretation and policies of Transport Canada.

SUMMARY

This is the second of three reports containing the results of an NEF validation study for Transport Canada. Summaries of the other two reports are included in Appendix 2 of this report.

Airports can be both an asset and a liability to nearby communities. Much of the negative impact of an airport is directly due to aircraft noise. Thus, the trade-offs between the costs and the benefits that an airport provides are very strongly related to the details of exposures to aircraft noise.

This report reviews:

- how people react to aircraft noise,
- how we evaluate aircraft noise exposures,
- various counter measures to reduce aircraft noise problems, and
- limits for acceptable noise levels.

This is the second of two reports intended to provide a comprehensive technical basis for evaluating the use of the NEF measure to quantify aircraft noise in Canada. The first report considered issues related to the calculation of airport noise contours. The two reports will form the technical background for a final report to Transport Canada reviewing all aspects related to the use of the NEF measure.

Some of the major technical findings of this report are as follows:

- The current form of the NEF measure and related accepted noise level limits have evolved based mostly on intuitive arguments from various practical consulting case studies.
- Aircraft noise is very unlikely to lead to permanent noise-induced hearing impairment in populations living near airports.
- There is limited evidence of medical effects related to cardiovascular systems in populations living near a major airport, but this evidence comes from studies by one research team at a single airport.
- When peak outdoor levels exceed 80 dBA, sleep indoors can be disturbed.

- New calculations from the details of aircraft fly-overs more accurately relate outdoor single event levels, SEL, and building facade noise reductions to speech intelligibility. When outdoor aircraft noise SEL exceeds 90 dBA, indoor speech communication can be degraded.
- The Schultz dose-response curve considerably underestimates the percentage of highly annoyed residents near major airports.
- The Perceived Noise Level more accurately reflects human response to noise than the A-weighting, but the difference in prediction accuracy is only 0.5 dB.
- Summing the effect of combinations of levels and numbers of events on an energy basis is as good as any other approach.
- The 12 dB night-time weighting incorporated in the NEF measure is larger than in other aircraft noise measures. There is evidence to suggest that smaller night-time weightings are more correct and that evening weightings are also important.
- There is no evidence that attitudes to aircraft noise change over time independent of noise levels.
- There is little information concerning the negative effects of aircraft noise near smaller airports and the effects of general aviation activities. In previous studies, the effects of airport size and types of aviation activity have usually been confused.
- Reduction of aircraft noise at the source most effectively and universally controls airport noise problems. Although possible reductions over the next few years will be small, it is important to encourage the continuing development of quieter aircraft.
- Various counter measures can be used to provide immediate reductions in noise exposures near airports. Such counter measures must be tailored to the operational and geographical details of each airport.
- Better techniques are needed to provide improved sound insulation of buildings against aircraft noise, and the perceived benefits of such insulation need to be thoroughly evaluated.
- Almost all major developed countries have their own aircraft noise measure, their own set of acceptable noise limits, and their own particular approach to controlling airport noise problems.
- A new set of acceptable aircraft noise level limits have been derived from the best available technical information. These thresholds correspond to: NEF_{CAN} 25 the onset of negative effects, NEF_{CAN} 30 extra sound insulation required, and NEF_{CAN} 35 the maximum acceptable level for constructing new homes. (Where NEF_{CAN} refers to the NEF values calculated by the transport Canada NEF_1.7 program).

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1.0 INTRODUCTION

This is the second major report on a project to evaluate the use of the NEF measure to manage aircraft noise in Canada. The total project involves a complete evaluation of: the basic principles on which the NEF concept is based, the effects of aircraft noise and acceptable noise level limits, as well as the problems of calculating noise level contours.

The first technical report [1] reviewed issues related to the calculation of airport noise contours. These calculated contours are routinely used to determine the use of land worth millions of dollars near airports across Canada. The NEF contours calculated by the NEF_1.7 program were compared with those from other programs. The effects of particular sources of error such as the complexity of the flight path description and excess ground attenuation algorithms were investigated in detail. Schemes for approximate conversions among various aircraft noise measures were devised and are used in a number of the analyses of the present report.

This second report reviews current knowledge concerning the effects of noise on people and whether the NEF measure correctly models negative response to aircraft noise. It is intended that the comprehensive review of existing knowledge included in these two reports will be used as the technical basis for the final project report that will respond more directly to the specific goals of this NEF review project.

Following this introduction, this report includes six chapters of technical material followed by a chapter of conclusions. Chapter 2 reviews the historical development of the NEF measure and other early aircraft noise measures as well as the origins of currently accepted Canadian land use planning limits for aircraft noise. Chapter 3 is an extensive examination of the effects of aircraft noise on people. Existing studies are reviewed and some new analyses presented. Chapter 4 considers various specific issues that relate to the basic principles of the NEF measure. The various possible counter measures against aircraft noise are discussed in Chapter 5. The approaches to regulating aircraft noise in various other countries are compared in Chapter 6. Chapter 7 brings together the material from the earlier chapters to establish new values for acceptable limits for aircraft noise levels. Finally, Chapter 8 presents conclusions that summarise the findings of each chapter of this report.

An earlier report [1] showed that different airport noise prediction programs produced different predictions of NEF values and that the predictions were probably different than measured values of the same situations. To avoid confusion, NEF values predicted by Transport Canada' NEF_1.7 program are referred to as NEF_{CAN} values in this report.

This becomes particularly important when specific aircraft noise level criteria are discussed.

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2.0 HISTORY OF AIRPORT NOISE MEASURES

The Noise Exposure Forecast, NEF, is a single number rating of overall airport noise. It combines the noise levels of individual aircraft and the numbers of aircraft to give a single number rating of the average negative impact of the aircraft noise. The current NEF metric evolved from the earlier Composite Noise Rating, CNR, which was initially developed for general community noise and later modified to evaluate aircraft noise. While these measures were being developed in the United States, other early airport noise measures were being developed in Europe. In the United Kingdom, the Noise and Number Index, NNI, was introduced in the early 1960's. Shortly after this, the Störindex, Q, was introduced in Germany and the Psophique Index, I_p, in France. The development of these aircraft noise measures in the early 1960's was a direct result of the public reaction to the widespread introduction of jet engine powered civil aircraft.

2.1 History of the CNR and NEF Measures

2.1.1 CNR as a Community Noise Measure

There were five major steps in the development of the NEF measure from the initial versions of the Composite Noise Rating, CNR [1]. The CNR was first proposed by Rosenblith and Stevens in 1952. The initial concept was to rate general community noise. This was modified somewhat by the same team from Bolt Beranek and Newman in 1955. In 1957, a new scheme was proposed for considering aircraft noise in terms of a CNR rating. This aircraft noise CNR method was further modified in the early 1960's so that it was based on the perceived noise levels. The full NEF concept was proposed in 1967.

These early developments were largely proposals that were not systematically tested. They were based on concepts that intuition would suggest to be important from experience with consulting case studies. Responses were described in terms of "community response" that generally included references to complaints and legal actions. Such concepts pre-date scientific annoyance surveys and an understanding that complaint data is not a reliable measure of community response.

The initial version of CNR was proposed by Rosenblith and Stevens in 1952 [2]. It was based on octave band noise measurements that were given an equivalent sound pressure level, SPL, in the 300-600 Hz octave frequency band. (An older system of octave bands that is no longer used.) This equivalent SPL was obtained by plotting the measured octave band levels on a system of level ranking contours that were similar to equal loudness contours. The level rank contours were in 5 dB intervals and hence the resulting CNR values were also in 5 dB intervals. A number of corrections were then made to better approximate the expected negative community response. These related to: the presence or absence of pure tone components, impulsive or non-impulsive sounds, repetition of the sound, background noise levels, time of day, and expected community adaptation to the noise. CNR values were determined from noise levels and associated corrections for the data from 11 case studies of community noise problems. The CNR values were then compared with a six-item scale describing the estimated community response. This scale varied from “no annoyance” to “vigorous legal action”. The scheme was a sensible first attempt, but apparently did not relate well to the 11 case study results [1].

The original community noise CNR scheme was modified by Stevens, Rosenblith, and Bolt in 1955 [3]. Changes to the consideration of the repetition of sounds brought the procedure closer to an equal energy approach, and corrections for seasonal variations were introduced. The descriptive scale of community response was reduced from six to five items, and the labels attached to each step were changed. The new scale referred only to “complaints” and “community reaction”. The revised procedure was said to be successful for predicting changes in community response but less successful on an absolute basis.

2.1.2 CNR as a Measure of Aircraft Noise

In the late 1950’s, the U.S. Air Force began developing procedures for evaluating noise levels and for land use planning around air bases. This led to a new variation of the CNR concept specifically for aircraft noise and that included the prediction of aircraft noise levels. The scheme proposed by Stevens and Pietrasanta in 1957 [4] evaluated aircraft noise in terms of its equivalent level in the 300-600 Hz octave band. It no longer included tone and impulsiveness corrections but corrected for repetitions in a true energy equivalent manner. Seasonal corrections and background noise level corrections were retained. The day/night correction was expanded to be a day/evening/night correction with 5 and 10 dB relative corrections for the evening and night periods, respectively. The scale describing community response was reduced to three steps, with the extremes labeled “no concern” and “unquestionably unacceptable”.

A procedure for predicting aircraft noise levels for aircraft on the ground (ground run-up noise) and aircraft in flight was developed [5]. The procedure used the combination of the maximum pass-by level and the effective duration of the pass-by to estimate the total energy received from a single aircraft pass-by. That is, the contribution of each aircraft was essentially described in terms of a sound exposure level, SEL. The calculations included estimates of the directivity of aircraft as well as profiles of aircraft height versus distance from the start of the take-off. The contributions of multiple aircraft were added on an energy basis. No consideration was given to excess ground attenuation.

The use of the CNR measure to evaluate aircraft noise was further modified in 1962 to include the use of Perceived Noise Levels developed by Kryter [6]. Kryter developed a set of equal noisiness functions for sounds in various frequency bands that was quite similar to the Stevens loudness calculation procedure. From the complete spectrum of a noise, a single value termed the Perceived Noise Level, in PNdB, was intended to rank the noise in terms of how noisy it would be perceived. However, the resulting rankings were quite similar to the earlier level ranking contour scheme.

At about the same time, a new airport noise planning document was produced for the U.S. Air Force [7]. It included aircraft noise contours in terms of PNdB as well as other improvements. Several simplifications were also made. Time-of-day weightings were reduced to a single 10 dB night-time weighting. Corrections for background noise levels and community attitudes were dropped. Again by using data from case studies, the resulting CNR values were related to the previous three-category scale describing expected community response. These three categories were essentially: no complaints, some complaints, and vigorous complaints, and are given in detail in Table 2.1. The separations between the regions were set in terms of the sum of the average maximum perceived noise level, $<PNL_{max}>$, and 10 times the logarithm of the number of aircraft, N, i.e.

$$<PNL_{max}> + 10 \bullet \log(N)$$

Initially, the separation between the lower and middle categories was set for this sum equal to 112 and the division between the middle an upper region at 122. In order to ‘give airports the benefit of the doubt’ [1], this last value was increased to 127. To obtain values that were multiples of 5 (because of the desire for 5 dB steps), these values were normalized to a base case of 10 to 30 operations per day by subtracting 12 dB from each. The resulting CNR values of 100 and 115 divided the three regions of the community response scale, as given in Table 2.1 [1]. A similar table with 20 dB lower CNR values was devised for ground run-up noises.

Composite Noise Rating, CNR	Description of Expected Response
< 100	Essentially no complaints would be expected. The noise occasionally interferes with certain activities of the resident.
100 to 115	Individuals may complain, perhaps vigorously. Concerted group action is possible.
> 115	Individual reactions would likely include repeated vigorous complaints. Concerted group action might be expected.

Table 2.1. Relation of calculated CNR values for take-off and landing noise to expected community response.

2.1.3 The Noise Exposure Forecast, NEF

Reports published in 1967 [8, 9] introduced the Noise Exposure Forecast, NEF, scheme as a development from the earlier CNR scheme for aircraft noise. The new NEF procedure included new developments associated with perceived noise levels, removed the limitation of doing all calculations in 5 dB steps, but included no new information on community response to aircraft noise. At the same time, procedures for calculating expected aircraft noise levels in terms of the new NEF measure were also improved.

The perceived noise level concept had been extended to include corrections for the presence of pure tones and for the influence of the duration of each aircraft pass-by. The combination of these two additional factors resulted in a new measure referred to as the Effective Perceived Noise Level, EPNL. Performing all calculations in 5 dB steps was intended as a simplification to make calculations easier, but led to unnecessary errors. The NEF calculation also included an arbitrary constant so that the resulting NEF values were quite different than the corresponding CNR values. NEF values were related to the three levels of community response in Table 2.1 by assuming an approximate equivalence of NEF 40 to CNR 115 and NEF 30 to CNR 100. These approximations were obtained from comparisons of calculated CNR and NEF values[1] shown in Fig. 2.1.

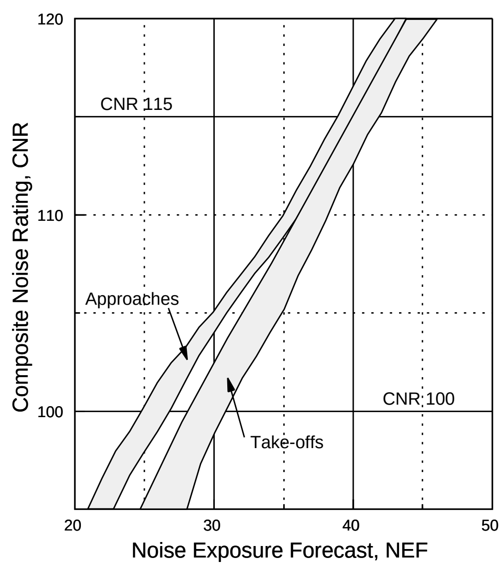

Figure 2.1. Comparison of computed CNR and NEF values from [1].

Thus, these conversions would be influenced by possible errors in these early calculation algorithms.

Bishop and Horonjeff's [8] proposal included a night-time weighting that resulted in night-time operations being counted as 12.2 dB more significant than day-time operations. The weighting was chosen so that with the same number of operations per hour during the night-time hours as during day-time hours, the night-time NEF would be 10 dB greater than the day-time NEF. Because there were nine night-time hours and 15 day-time hours, the number of night-time operations was multiplied by 10(15/9) = 16.67, which is equivalent to 12.2 dB. No evidence was presented to support this particular night-time weighting.

NEF is defined as follows and is summed over all aircraft types and all flight paths:

$$NEF = \langle EPNL \rangle + 10 \bullet \log(N_d + 16.7 \bullet N_n) - 88$$

Thus, by the late 1960's the complete NEF measure had been developed to the form that is used today. At no point was the formulation influenced by any scientific survey of residents' responses to aircraft noise (except, of course, in the development of the EPNL measure that is a part of the NEF measure). The implied principal of energy summation and the night-time weighting were not based on any systematic studies. Expected community response was described in very general terms of complaints. These descriptions were based on consulting experiences from a limited number of specific cases of community noise problems. Although Borsky's [10] early survey results had already indicated that complaint data were not a reliable measure of community response, there was no attempt to develop a noise measure from such systematic surveys of response to aircraft noise.

The NEF measure has been used in Canada, Australia, Yugoslavia, and Hong Kong. However, in Australia the time-of-day weightings were changed as a result of a major subjective survey of residents near Australian airports. The NEF measure was not widely used in the United States where it was developed. In the early 1970's, the political requirement for a single environmental noise measure led to the adoption of the day-night sound level, L_{dn}, in the United States.

2.2 The Development of Other Early Airport Noise Measures

2.2.1 The Noise and Number Index, NNI

The Noise and Number Index, NNI, was derived from the results of the first major survey of residents around London's Heathrow airport. While the CNR and NEF were developed on the basis of a simple energy summation, the NNI introduced the concept of different trade-offs between the noise levels of individual aircraft and the numbers of aircraft. The NNI is defined as follows:

$$NNI = \langle PNL_{max} \rangle + 15 \bullet \log(N) - 80$$

where $\langle PNL_{max} \rangle$ is the mean of the maximum perceived noise levels of the aircraft pass-bys, in PNdB, and N is the total number of aircraft pass-bys.

With this noise measure, doubling the number of operations results in a 4.5 dB increase in NNI values which is greater than the 3 dB increase that would result from a simple energy summation approach. It has been suggested [1] that a simple energy summation measure would have been practically as successful in relating to the response data in the original London survey as was the NNI measure. The controversy concerning the acceptability of the simple energy summation approach will be considered in more detail in Section 5.2.

The German Störindex, Q [11], developed after the NNI, also weighted the influence of the number of operations more than for a simple energy summation. The Q measure was based on a doubling of operations causing a 4 dB increase in the noise measure. Q is defined as follows:

$$Q = 13.3 \bullet \log(\Sigma\, \tau \bullet 10^{(Lmax/13.3)}/T)$$

where τ is the duration of the pass-by, L_{max} is the maximum A-weighted sound level during the pass-by, and T is the time period over which the Q value is calculated. The summation is made over the τ and L_{max} values of all aircraft operations in the time period T. The measure was originally based on maximum PNdB levels.

The French Psophique Index, I_p, was developed in the late 1960's. It is a simple energy summation type measure based on aircraft levels, in PNdB. Although it originally included a complicated two-part night-time correction, it is now a simple 10 dB night-time weighting. It is currently defined as follows:

$$I_p = \langle PNL_{max} \rangle + 10 \bullet \log(N_d + 10 \bullet N_n) - 32$$

where N_d and N_n are the number of operations during the day and night periods, respectively. Values of this measure were initially related to residents' responses from the results of a large survey near four French airports.

2.3 The Introduction of the NEF Measure in Canada

The CNR system was initially used by Transport Canada as a tool for land use planning around airports [12]. Tabular calculations of CNR values were described with a 10 dB night-time weighting. A table of expected community response was also given that was similar to Table 2.1. Thus, initially the American CNR system for aircraft noise was adopted without obvious changes.

The same Transport Canada report [12] also describes the NEF system and compares it with the older CNR method. The critical CNR values of 100 and 115 were converted to NEF values using the results in Fig. 2.1. From these results, CNR 100 was approximated as NEF 30 and CNR 115 was approximated as NEF 40. The table of expected community response from this report [12] is in terms of NEF values and is duplicated here in Table 2.2 below. It is actually very similar to Table 2.1 except that the middle region of Table 2.1 has been expanded into two regions in Table 2.2. and CNR values have been converted to NEF equivalents. Table 2.2 was included in early versions of the CMHC document "New Housing and Aircraft Noise" [13]. This same table is used in more recent CMHC and Transport Canada documents [14,15].

NEF_{CAN} Range	Expected Response
> 40	Repeated and vigorous individual complaints are likely. Concerted group and legal action might be expected
35-40	Individual complaints may be vigorous. Possible group action and appeals to authorities.
30-35	Sporadic and repeated individual complaints. Group action is possible.
<30	Sporadic complaints may occur. Noise may interfere occasionally with certain activities of the resident.

Table 2.2. Relation of expected community response to NEF values from reference [12].

The CMHC documents on airport noise were one result of a three-party collaboration on airport noise problems during the early 1970's in Canada. The National Research Council, Canada Mortgage and Housing, and Transport Canada pooled their efforts to develop a rational approach to airport noise problems. The National Research Council carried out measurements of the sound attenuation of a test house constructed with the support of CMHC. Transport Canada provided the aircraft noise sources. All three parties worked together to produce the above table of acceptable values. The details of this table were a compromise to address several different concerns. There was the desire to ensure that people would be protected from high levels of aircraft noise. There were also concerns about the accuracy of NEF predictions at lower NEF values. Finally, there was also the concern that excessively restrictive limits would eliminate large areas of land from possible residential development with CMHC mortgages.

The currently used descriptions of expected community response are derived from the original CNR descriptions based on general impressions of community response for a small number of specific case studies. These descriptions were not changed to reflect the results of more modern systematic community surveys of residents near airports. They have not been influenced by studies of any Canadian subjects. Thus, there has never been any serious attempt to calibrate values of the NEF measure to the negative effects on residents near Canadian airports.

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3.0 EFFECTS OF NOISE ON PEOPLE

There is a wide range of possible and known effects of noise on people. Some effects are better understood than others. Some suggested effects are based on animal experiments at extremely high noise levels that do not relate to possible noise exposures from aircraft noise. This chapter discusses probable effects of realistic levels of aircraft noise on people.

3.1 Hearing

Studies, mostly of industrial noise situations, have led to a good understanding of the negative effects of noise on our hearing system. Prolonged exposure to sufficiently high levels of noise will permanently damage our hearing system. Of course, there are individual differences, and two people exposed to exactly the same noise will experience slightly different negative effects. Thus, we must consider the problem statistically in terms of the percentage of the population experiencing a specific amount of hearing loss.

Damage to the hearing system is usually described in terms of a shift in our threshold of sensitivity to low level sounds. Such threshold shifts can be either temporary or permanent. The temporary threshold shifts, TTS, that occur after a single exposure to high levels of noise become permanent threshold shifts, PTS, after repeated exposures to high levels of noise.

The expected PTS from prolonged exposure to high levels of noise increases with the level of the noise, with the years of exposure, and varies with frequency. In general, our hearing system is most sensitive at 4 kHz; the largest noise-induced PTS usually occurs at this frequency. Figure 3.1 (from reference [1]) summarizes expected 4 kHz PTS for continuous exposures to noise of 75 to 90 dBA per 8-hour work day. This figure includes maximum 90th percentile, average, and maximum 10th percentile NIPTS values (Noise Induced Permanent Threshold Shifts). The 90th percentile values indicate the expected NIPTS for the most affected 10% of the population. The maximum 10th percentile

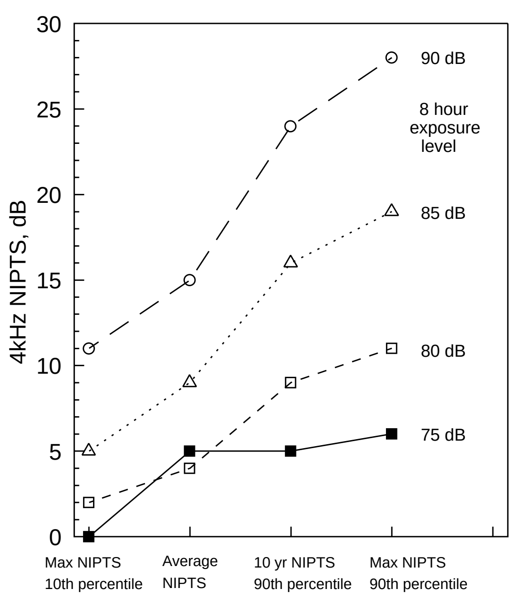

Figure 3.1. NIPTS at 4 kHz by 8 hour per day noise exposure level for various percentiles of the population.

values indicate the maximum hearing loss for the least affected 10% of the population.

From Fig. 3.1, it is seen that at high noise levels (90 dBA per 8-hour day), a significant hearing loss is to be expected in all of the population. For example, at 4 kHz the average NIPTS would be 15 dB, varying from 11 to 28 dB from the least to the most sensitive 10% of the population. However, for exposures of 75 dBA per 8-hour day, the average 4 kHz NIPTS is reduced to 5 dB. From an analysis of data similar to that summarized in Fig. 3.1, the U.S. E.P.A. [1] concluded that below a 24-hour L_{eq} of 70 dBA, no one would be expected to experience permanent hearing loss due to noise exposure.

In addition to noise induced hearing loss, some permanent hearing loss occurs naturally with aging (presbycusis). Kryter [2] has argued that at least some of the hearing loss attributed to presbycusis is actually noise induced hearing loss, and that levels in excess of 55 dBA will lead to some noise induced hearing loss. Others [3] have labeled this suggestion as "simply ridiculous", and there is no real support for the idea that levels lower than 70 dBA (24-hour L_{eq}) contribute to permanent hearing loss.

The level of 70 dBA $L_{eq}24$ is a possible outdoor aircraft noise level in a few areas very close to large airports. (An $L_{eq}24$ of 70 dBA is approximately equivalent to a measured NEF_{CAN} of 41.) Of course, indoor levels would normally be substantially less, and it is unlikely than anyone would be exposed to this level of aircraft noise 24 hours per day.

Results from the U.S. E.P.A. Levels Document[1] were used to estimate the lowest exposure likely to lead to permanent hearing impairment, because they included an “adequate margin of safety”. It seemed preferable to take this more cautious approach to avoid any significant possibility of underestimating the effects of aircraft noise on residents’ hearing. Other references[84] could be used to estimate the likelihood of permanent hearing impairment from residntial exposures to aircraft noise, but they would just show it to be even less likely that residents near airports would develop any permanent hearing impairment due to aircraft noise exposures.

Several studies have considered the possibility of NIPTS in residents near airports. In 1976, Ward [4] reported a study in which subjects were exposed to 6 hours of recordings of landings and take-offs of jet aircraft. The exposures had 8-hour equivalent levels of 95 dBA and peak levels of 111 dBA. Measured TTS values were less than 5 dB at all frequencies, and Ward concluded that the possibility of hearing damage from such exposures was remote.

Parnel et al. [5] measured the hearing levels of residents in two areas. One was a noisy area close to Los Angeles International Airport with peak outdoor aircraft levels of 76 to 101 dBA, and the other was an area of similar demography, but free of significant aircraft noise. There were some high frequency hearing loss differences that indicated a trend for the aircraft noise exposed group to have higher losses. However, overall they concluded that it was not possible to draw firm conclusions concerning the effect of community levels of aircraft noise on hearing.

Andrus et al. [6] measured the hearing of 3,322 students living near Boston's Logan International Airport. The average observed hearing loss was not different in areas exposed to aircraft noise than for a control group in quieter areas. Hearing loss was not related to either the degree or duration of exposure to aircraft noise. A pilot study of a similar experiment was carried out by Fisch in the United Kingdom [7] for students living near London's Heathrow airport. Again, no significant differences between noise-exposed and control groups were found.

The experimental studies near airports or with recorded aircraft noise seem to confirm the expectations from summaries of many industrial noise studies of noise induced hearing loss. Permanent hearing loss is very unlikely at the levels of noise experienced in residential areas near Canadian airports. It is uncommon to find residential areas with aircraft noise levels in excess of NEF 35. The evidence of research suggests that even minor hearing loss is unlikely at levels below a measured NEF of 37 (NEF_{CAN} 41). Even where such very high aircraft noise levels exist, few if any people would be outdoors 24 hours per day and fully exposed.

3.2 Non-Auditory Health Effects

While the effects of noise on hearing are quite well understood, the effects of noise on other aspects of our physical and mental health are much less well understood. This section examines the evidence for various non-auditory effects of noise on health. Health is interpreted quite broadly as defined by the World Health Organization, "a state of complete physical, mental, and social well being and not merely the absence of disease or infirmity".

3.2.1 Psychiatric Effects

The possible threat that noise poses to mental health has been given consideration by several researchers. It has been suggested that annoyance to noise could lead to psychiatric morbidity.

Meecham and Smith [8] conducted a study in areas near Los Angeles Airport to examine the effects of jet aircraft noise on mental hospital admissions. The data, which were collected over a period of 8 months, revealed a higher rate of admissions from the noise exposed area having maximum levels of 90 dBA and higher. Although the authors claimed that the test results were statistically significant at $p \leq 0.1$, this is not usually considered to be an acceptable level for statistical significance. Frerichs et al. [9] pointed out that there were methodological problems with the study. The study made no attempt to control for the possible confounding effects of non-noise variables such as age, race, sex, and family income. Therefore, the conclusions of this study must be questioned.

A more thorough series of studies have been undertaken around London's Heathrow Airport, by examining the correlation between psychiatric hospital admissions and aircraft noise. The first study [10] involved a retrospective survey of psychiatric hospital admissions over a span of two years from two areas with different exposures to aircraft noise. Rates of first and overall admissions were significantly higher in the higher noise area. The authors did not claim that aircraft noise levels were the actual cause of the differences, and they pointed out that other factors may have contributed to patient admission rates.

In a second study, Gattoni and Tarnopolsky [11] attempted to verify these results by analyzing an additional two years of data for the same hospital. Although a trend in agreement with the original findings was found, there were no statistically significant differences in admission rates between noisy and quiet areas.

In an attempt to resolve the question, a more recent study [12] examined psychiatric admissions to three hospitals over a 4-year period in the London Airport area. There was no common pattern of the effect of noise on admissions across all three hospitals. It was concluded that the effects of noise, if any, could only be small, weakly influencing other causal variables, but not overriding them. Kryter [13] re-analyzed this data correcting for the effect of the age and levels of affluence. He claimed to find a more consistent trend of increasing admission rates with aircraft noise level.

Further research into the possible connection between mental illness and aircraft noise was carried out by administering a general health questionnaire to 208 people living in the vicinity of a large airport [14]. The questionnaire was an instrument used to screen for psychiatric disorders. No statistically significant difference in the distribution of psychiatric disorders existed between the high and low noise areas. Symptoms of psychiatric distress were more common among subjects "very annoyed" by noise at any level of exposure. There was evidence of an effect of noise on the incidence of psychiatric disorders among several specific sub-groups that included: females, the young, and subjects with high educational or higher status occupational categories. It was suggested that the relationship between noise and psychiatric morbidity is complex and that factors, such as noise annoyance and sensitivity to noise, should be considered along with social and demographic variables.

The results of community studies of admission rates to mental hospitals are inconclusive, or not statistically significant. In view of the difficulty of controlling for the many demographic variables that could influence such admission rates, it seems unlikely that future studies will be able to demonstrate significant effects of aircraft noise levels on admission rates. As Tarnopolsky et al. [14] have suggested, it does seem possible that future studies will better explain the interaction of annoyance to noise, and noise levels with various forms of psychiatric distress.

3.2.2 Cardiovascular Effects

Noise has a number of transient effects on the functioning of our bodies including on our cardiovascular system. For example, being startled by high level bursts of noise results in vasoconstriction of peripheral blood vessels and a related transient change in blood pressure. Such effects are not necessarily harmful, but are simply how our bodies work in a variety of everyday situations. However, the suggestion has frequently been made that noise could act as a stressor leading to more permanent effects on our cardiovascular system. The search for evidence of such effects has taken several forms and has frequently been associated with people exposed to very high levels of industrial noise. However, a number of studies have focused on subjects exposed to aircraft noise.

It is sometimes hypothesized that frequent temporary elevations in blood pressure caused by noise might lead to a permanent change in blood pressure, and that this may lead to hypertension and a heightened risk of cardiovascular disease. Although some studies did draw correlations between high levels of noise and cardiovascular effects, there are many others that have not found significant relationships.

In an unusual laboratory experiment, Cantrell [15] exposed young men to pulsed tones of 80, 85, and 90 dB SPL continuously for 30 days. For ten days prior to, and ten days following the experiment, physiological, psychological, and hearing measurements were made under quiet conditions. The overall biochemical effect was a rise in plasma cortisol and blood cholesterol levels, beginning at 85 dB SPL. The effect persisted for five days after cessation of the noise.

Jonsson and Hansson [16] reported a significant relationship between noise exposure levels and hypertension in industrial workers. They assumed that workers with greater hearing loss had been exposed to higher levels of noise. Among the workers with greater hearing loss, hypertension was found to be more prevalent. However, in similar studies, Hedstrand et al. [17], Takala et al. [18], and Delin [19] found no significant differences in the prevalence of hypertension between groups with different amounts of hearing loss. Hirai et al. [20] studied labourers in Japan and found significant noise-induced hearing loss but no relationship between noise exposure and increased blood pressure. Hedstrand et al. argued that the amount of hearing loss was not a good indicator of the degree of stress experienced by the workers. Hearing might be more severely impaired because noise was not considered to be so stressful by particular individuals and perhaps they did less to avoid it.

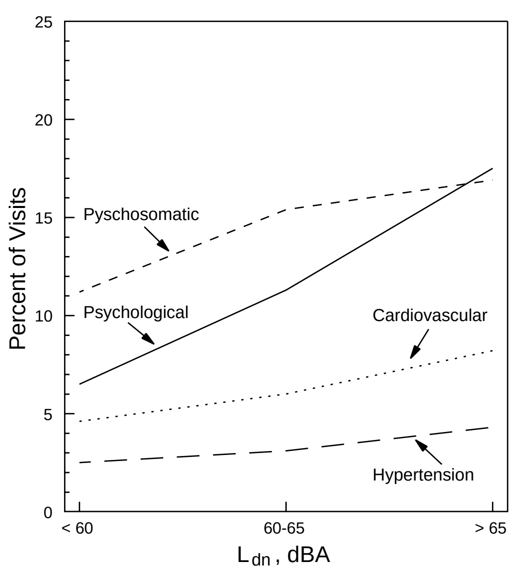

Figure 3.2. Knipschild's general practice survey results showing the effects of noise levels on four types of visits to medical doctors.

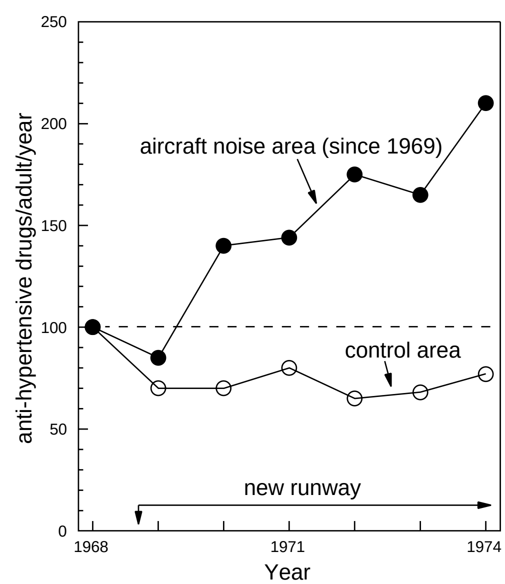

Figure 3.3. Knipschild's comparison of the use of anti-hypertensive drugs in noisy and quiet areas.

Knipschild carried out several studies of residents near Amsterdam's Schipol airport that together are strongly suggestive that aircraft noise is a causal factor in cases of cardiovascular disease. In a general practice survey, the activities of 19 family doctors were monitored [21]. Each patient-visit was classified according to the location of the patients home and the type of medical complaint. After adjustments for the sex and age of the patients, the prevalence of some types of medical problems was significantly related to the aircraft noise level to which the patients home was exposed. Figure 3.2 illustrates some of the principal significant effects from this study. Visits with the family doctor concerning: psychosomatic, psychological, cardiovascular, and hypertension related medical problems all increased significantly with aircraft noise level.

Knipschild and Oodshoorn [22] examined a population near Amsterdam airport before and after an increase in exposure to aircraft noise, and compared it to a nearby non-exposed population. The dependent variable was the purchase of specific prescription drugs, such as tranquilizers, sleeping pills, antacids, and cardiovascular drugs. The investigators found that the use of these drugs in the quieter area was essentially stable, whereas the use of most of these drugs in the noise-impacted area increased steadily over the six year period investigated. This increase was especially noticeable for anti-hypertensive drugs, as illustrated in Fig. 3.3. After the opening of a new runway, there was a systematic increase in the use of anti-hypertensive drugs in the group exposed to the noise associated with this new runway.

Knipschild [23] also reported results of a cardiovascular survey. Table 3.1 illustrates the results from this medical screening program that found higher incidences of several cardiovascular related problems in higher noise areas near Amsterdam's Schipol airport.

Aircraft noise level, L_{dn} in dBA	< 62.5	> 62.5	
Number of participants	3595	2233	significance
Angina pectoris	2.8%	3.0%	n.s.
Medical treatment of heart disease	1.8%	2.4%	$p = 0.04$
Cardiovascular disease	5.6%	7.4%	$p = 0.003$
Pathological E.C.G.	4.5%	5.0%	n.s.
Pathological heart shape	1.6%	2.4%	$p = 0.01$
Hypertension*	10.1%	15.2%	$p < 0.001$

*RR > 175/100 mm Hg and /or use of anti-hypertensive drugs

Table 3.1. Percentages of cases of various cardiovascular problems for high and low noise groups.

Figure 3.4 plots the prevalence of hypertension versus aircraft noise level found in this study. Confounding factors such as: age, sex, relative weight, smoking habits, and degree of urbanization were studied, but could not explain these results.

A questionable study emanates from researchers, Meecham and Shaw [24]. They compared mortality rates for Los Angeles airport area residents exposed to maximum levels of 90 dBA or higher, to those for residents living in a nearby control area with maximum levels of 45 to

50 dBA. The authors noted a 20% higher mortality rate in the noisier area and claimed that this was largely due to increased numbers of deaths caused by stroke and cirrhosis of the liver. Skeptical that jet noise was accountable for the increase in deaths, Frerichs et al. [9] conducted a re-analysis of the data. They could not confirm the original results. They discovered a discrepancy in the number of deaths recorded, and they also found that once confounders, such as age, race, and sex were adjusted for, death rates in both the airport and control areas were nearly identical.

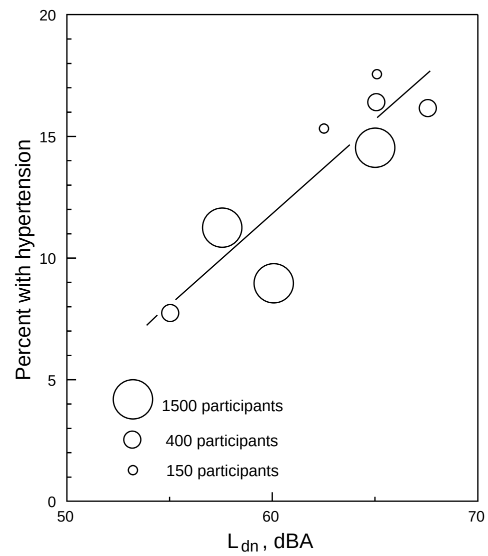

Figure 3.4. Relationship between the prevalence of hypertension and aircraft noise level

However, a very recent paper by Meecham and Shaw [25] reports a statistically significant increase in deaths due to cardiovascular diseases for subjects 75 years and older living in areas of high airport noise. This is again based on data for subjects living in areas of rapidly changing demographic characteristics near Los Angeles International Airport.

Knipschild's quite remarkable studies are strongly suggestive of serious long term effects of aircraft noise on our cardiovascular systems. However, there is very little other reliable research to support his results. A review by Thomson et.al.[85] has criticized some details of the methodology of the Knipschild studies and has suggested that some details of the experimental procedures were not published. Although this leads to some uncertainty as to the complete validity of these results, they cannot be completely rejected. Together they form a disturbing pattern that needs to be further examined in future studies. Further studies are required to attempt to corroborate these results on other groups and at other airports.

3.2.3 <u>Effects on Reproduction and Growth</u>

A number of studies have investigated possible effects of noise on the prenatal and postnatal growth and development of children. A number of these studies have been conducted on populations living near large airports. Of course, many factors other than noise are potential causes of the observed effects. In almost all of these studies, the credibility of the results depends heavily on the care with which the possible effects of the other confounding variables are investigated.

Ando [26] investigated the manner in which infants react to aircraft noise in Itami City, located near the Osaka International Airport. Data for the study were collected through the distribution of voluntary questionnaires. Ando's results suggest that some infant activities such as crying are related to prenatal aircraft noise levels and that longer prenatal exposures led to better adaptation to noise. Only the data from 188 of 307 questionnaires were used, and the reliability of this type of questionnaire data with a quite low response rate is questionable.

A second study [27] repeated the previous work and also claimed a relationship between noise level and birth weight. However, the response rate to the questionnaire in the high noise area was 60%, and only 18-34% in the three lower noise areas. Thus, again response rate problems cast some doubt on the results.

In a third paper, Ando and Hattori [28] examined the association between low Human Placental Lactogen (HPL) levels and noise exposure by conducting a prospective survey. They suggest that on average, HPL levels decrease with noise exposure and imply this constitutes a risk for premature birth. They continue on to state that of 11 mothers who were classified as "at risk"; the average weight of their babies was 2945 g. However, The World Health Organization classifies prematurity as a birth weight of less than 2500 g. Thus, most of the "low" birth weight cases were well above the criterion for premature babies.

Rehm and Jansen [29] conducted a study on births in areas near Düsseldorf airport in Germany. They found no effects that were statistically related to noise levels but did find a tendency for an increased rate of premature births in higher noise levels.

Jones and Tauscher [30] reported higher rates of birth defects in high-noise areas near Los Angeles airport. They analyzed birth certificate data from Los Angeles County for a period of three years for blacks and whites. However, as Bader [31] reveals, birth certificate information in the United States is not recorded in a uniform fashion from hospital to hospital. While one hospital may record the most negligible birth defects, another may omit noting the more serious. There may also be discrepancies in the way that staff record birth defects within the same hospital. A more reliable source of data is needed to verify their findings. In addition, the authors did not adjust for confounding variables, such as differences in the age of mothers, or socioeconomic status.

A more rigorous study, examining the same hypothesis as Jones and Tauscher, was undertaken by Edmonds et al. [32]. They interpreted data that was collected from the Metropolitan Atlanta Congenital Defects

Program. Having compared the rates of 17 categories of birth defects in high and low noise areas, they reported no statistically significant differences between the rates of occurrence in the areas being evaluated. The survey did indicate a higher though still small incidence of spina bifida in the high noise areas, but the results of a subsequent case-control study of spina bifida and noise exposure reported in the same paper did not confirm the results.

A more recent study [33] conducted around Schipol Airport near Amsterdam concluded that there was a higher proportion of incidences of low birth weight in high-noise areas than in low-noise areas. However, confounding variables such as smoking by the mothers and their socioeconomic status were not considered seriously in the analysis of the data. Recent studies have demonstrated that smoking during pregnancy may result in lower birth weight.

Schell [34] found a statistically significant relationship between the length of gestation period and aircraft noise level for subjects near a large U.S. airport. Ando [35] reported that the relative percentages of birth weights under 3,000 g increased with increases in annual aircraft noise levels between 1961 and 1965. Coblentz et al. [36] reported significantly lower birth weights for boys from high noise areas near the two Paris airports. For baby girls, only those from areas near one of the Paris airports had significantly lower birth weights. Schell and Ando [37] examined the growth of children exposed to various levels of aircraft noise. Data was again taken from populations near Osaka airport in Japan. They concluded that the percentage of children of very short stature was related to aircraft noise level.

While some of these relationships might seem alarming, most are not very convincing. There is never a direct relationship between noise level and a specific effect. Subjects are from populations that are on average exposed to higher levels of airport noise. More precise studies are required that would identify the noise exposure of each subject's home. It is also essential to account for all possible confounding variables such as: the health of the mother, the socioeconomic status of the mother, and other health-related aspects of each subject's life style such as smoking habits.

3.3 Sleep

Although there are many publications concerning studies of sleep disturbance due to noise, many of these are reviews of previous studies. The studies that have been carried out are either laboratory or field studies. In laboratory studies, subjects are usually exposed to recorded sounds while they sleep in a laboratory furnished like a bedroom. Such studies usually last only a few nights and hence include effects of incomplete habituation as well as other unnatural ‘lab’ effects. While field studies provide a more realistic setting, it is more difficult to measure and control the noise exposure. Where noise levels are modified as part of a field experiment, incomplete habituation may again affect the results. Some field studies are based on reported sleep disturbance rather than measured disturbance. Such reported disturbance may not relate to actual disturbance.

Sleep is a cyclic phenomenon with various stages of varying sleep depth. When we sleep, we gradually progress from lighter to deeper sleep, usually over an approximately 90 minute cycle. Table 3.2 lists the various sleep stages.

W	wakefulness
M	movement
Stage 1	shallow sleep
Stage 2	light sleep
Stage 3 and 4	deep sleep
REM	rapid eye movement

Table 3.2. Stages of sleep.

People are more easily disturbed in the lighter stages of sleep than during the deeper stages of sleep. Thus, the probability of sleep disturbance will vary considerably according to the sleep stage of the subject during a particular noise exposure.

There are several different levels of sleep disturbance. Sleep stages can be monitored by EEG (electroencephalogram) recordings showing the electrical activity of the brain. The effect of a noise may vary from a small perturbation of the EEG recording to a complete awakening of the subject. It is not clear whether changes to the EEG response such as a change to a lighter sleep stage could have any long-term effects on health. Frequent awakenings can have a measurable effect on performance during the day after the disturbed night.

One of the earlier field studies was a social survey of sleep disturbance to road traffic noise [38]. Significant portions of the subjects reported having difficulty falling asleep and being awakened because of noise. These responses were significantly related to noise levels. However, it is not at all clear whether these responses relate to actual disturbance of sleep or are simply correlates of general annoyance to the traffic noise.

Lukas [39] reported one of the earlier systematic laboratory studies of sleep disturbance to aircraft noise. He found that older subjects were more sensitive to noise and that women were more sensitive to noise during their sleep than were men. The frequency of awakenings was related to the intensity of the noise exposures and there were large individual differences.

Pearsons et al. [40] carried out a field study of six subjects before and after the cessation of night flights over their homes. They found no effect of the cessation of the night flights for indoor noise levels from 60 to 90 dBA. Sleep measurements were repeated: one week before the cessation of flights, immediately after the cessation of flights, and three weeks after the cessation of flights. In view of the large individual variations in response to noise during sleep, it is arguable that a larger sample than the six subjects used in this study is required to accurately reflect disturbance to aircraft noise.

Thiessen et al. [41, 42] carried out several laboratory studies of response to traffic noises. They found strong relationships between sleep disturbance and noise levels in terms of both awakenings and changes in sleep stage. Thiessen's results also clearly demonstrated the effects of habituation. These results are shown here in Fig. 3.5. Each night, subjects were exposed to the noise of seven truck pass-bys having maximum levels of 65 dBA. Over a period of 24 nights in the laboratory, the number of awakenings decreased from four per two nights to approximately one per two nights. Figure 3.5 also shows a trend for a small habituation in the number of sleep shifts per two nights. Since most experiments last much less than 24 nights, their results can be questioned because the subject will

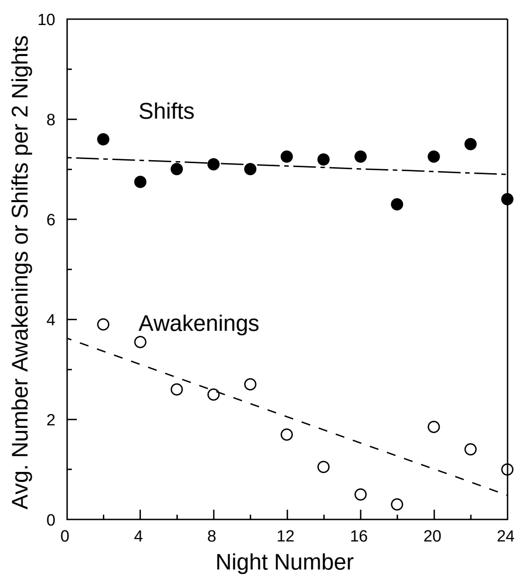

Figure 3.5. Thiessen's results showing the number of shifts in sleep stage and the number of awakenings per two nights of exposure to noise.

not have completely habituated to the new night-time noise levels.

In a review of studies carried out between 1973 and 1980, Griefahn [43] showed results indicating almost complete habituation of awakenings after approximately 10 days of exposure. This is less than indicated by Thiessen's results in Fig. 3.5. However, Griefahn points out that the habituation is not complete and that there is evidence of effects even after several years of exposure. The probability of being awakened increases with both the intensity of each noise event and the frequency of these events. Although the influence of the subjects' sex was not clear, Griefahn reports a systematically increasing sensitivity to be awakened by noise with increasing age of the subjects. In spite of the various observed effects, she concludes that the significance on health of noise-induced sleep disturbance remains unresolved.

Muzet's 1983 review [44] concluded that both laboratory and field studies were necessary. He also pointed out that the number of awakenings is generally not remembered by the subject and hence reported sleep disturbance from social surveys may not be very reliable. Ohrstrom [45] reported that continuous noise had a significantly smaller effect on sleep quality than intermittent noise.

Jurriens [46] analyzed the combined results of several European research teams to study the effects of traffic noise on sleep. Measurements were made in the subjects' homes. Fifty-two of the subjects were normally exposed to traffic noise at home. Another 18 subjects normally slept in quiet environments. The noise levels for the first group were later reduced by either double glazing or by the use of ear plugs. The noise levels for the second group were increased by opening bedroom windows. On average, during noisy nights subjects spent less time in REM sleep. After noisy nights, performance was adversely affected, and reported sleep quality was reduced. Wakefulness increased during the noisy nights, and heart rate increased with increasing sound level. Vallet [47] pointed out that even after five years of exposure to traffic noise, individual noise events increase the heart rate. That is, physiologically we do not get used to noise during sleep.

From an analysis of many sleep studies, Griefahn [48] calculated a threshold for disturbance of sleep by noise, as shown in Fig. 3.6. Her calculations started with determining the levels for which the most sensitive 10% of the population would be disturbed. Then she corrected these levels to represent the most sensitive sleep stage and the most sensitive age group (older subjects). Thus, her threshold contour would actually represent much less than 10% of the population. The upper curve in Fig. 3.6 indicates the threshold below which most (more than

90%) of the population will not be awoken for the given combination of levels and numbers of noise events. The lower curve indicates the noise levels below which there should be no reactions such as shifts in sleep stages. Griefahn suggests that the upper curve must not be exceeded to avoid long-term effects on health and that the lower curve represents a preventative goal. Noise conditions falling below these contours would avoid all but the most minimal effects of noise on sleep.

The Griefahn thresholds shown in Figure 3.6 were discussed in a report for the Health Council of the Netherlands[86]. This report points out that the lower contour in Figure 3.6 indicates that sleep can be disturbed at maximum levels as low as about 50 dBA and that there is no information as to the possible additional effects of larger numbers of noise events that might cause more prolonged disturbance to sleep. They also mention, that as is true for most human response data, there is a degree of statistical uncertainty associated with the contours of Figure 3.6.

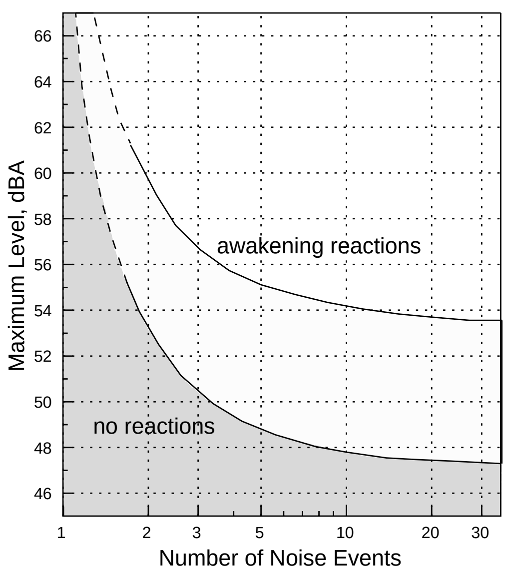

Figure 3.6. Griefahn's summary showing threshold of disturbance by awakening or other lesser reactions to noise during sleep.

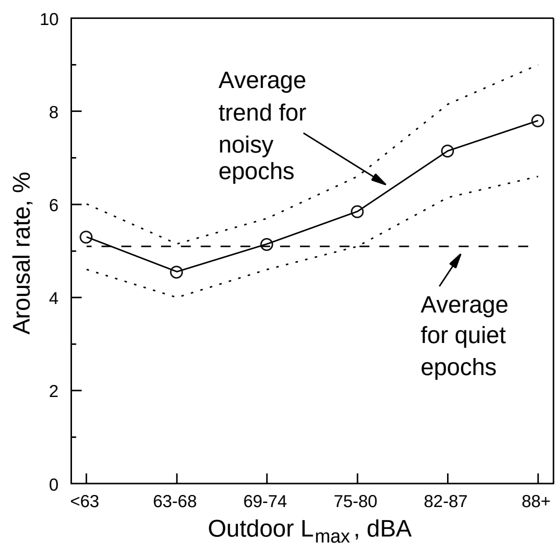

Figure 3.7. Percentage of 30 second sleep 'epochs' during which an arousal probably occurred.

A significant field study has recently been completed in the United Kingdom [49] that claimed very minimal sleep disturbance was caused by aircraft noise. The effect of night-time aircraft noise on residents in their homes near four British airports were compared with outdoor noise levels. Although EEG recordings are the accepted method for assessing effects on sleep, in this study actimeters were used to monitor the activity of the person sleeping. The actimeter output was related to EEG responses for a subset of the subjects. A procedure was found to identify 88% of the awakenings from the actimeter measurements. Each night was divided into 30 second epochs which were classified as noisy or quiet according to whether the maximum outdoor noise level exceeded 60 dBA. Disturbance was determined by the percentage of arousals, indicated by the actimeters, that occurred during the noise exposed 'epochs'.

Figure 3.7 illustrates one of the principal results of the study. It shows the percentage of noise 'epochs' during which actimeter results indicated an arousal. These percentages are shown by noise level groups along with 95% confidence limits. For comparison, the average 5.1% arousal rate for quiet 'epochs' is also shown. From this figure it is seen that arousal rates for noise 'epochs' increase over those for quiet only when the maximum outdoor levels exceed about 75 dBA.

Although the authors claim that their results show that aircraft noise is a relatively minor cause of sleep disturbance, a number of aspects of this study can be questioned. The use of actimeters and the resulting statistics may not be an accurate representation of sleep disturbance. More seriously, it appears that most of the subjects were exposed to relatively low indoor noise levels and that many of the homes had received extra sound insulation.

The use of actimeters is not completely satisfactory; they do not identify all awakenings, and do not provide information on other aspects of sleep such as shifts in sleep stage and the exact onset time of sleep. Expressing the results as the percentage of noise 'epochs' containing an arousal probably underestimates the rate of disturbance. Each aircraft event will tend to be spread over parts of two adjacent 'epochs'. Thus, most aircraft noise events will be counted as two noise 'epochs' without arousal, and the actual rate of disturbance could approach double the reported rates. It would be less confusing to present results in terms of the percentage of aircraft fly-overs that cause arousal.

The British study found a trend for decreasing sleep disturbance with increasing age. This is contrary to other studies, but may be due to the absence of very old subjects (older than 70 years). The predominance of approach noise suggests that the survey sample was not representative of all types of aircraft noise. Subjects' sensitivity to arousal varied with time during a night approximately inversely as the variation in the number of aircraft events. Thus, at the beginning and end of the night-time period, subjects were less sensitive to noise, and the numbers of aircraft operations were greatest. Most laboratory studies have used a more even distribution of noise events which could lead to differences in overall arousal rates.

Of the 385 subjects, only about 85 were exposed to maximum outdoor levels of greater than 80 dBA at least 100 times over the 15 days of the tests (i.e. approximately seven times per night). Thus, most of the subjects (about 78%) were exposed to relatively low levels of aircraft noise. For the 85 subjects exposed to the higher levels of noise, 25% were more aroused during quiet ‘epochs’ than during noisy ‘epochs’. This is partly due to statistical variations of responses, but also suggests that the actual indoor noise levels to which they were exposed were quite low.

Low indoor noise levels would be expected because of the prevalence of double glazing at the subjects homes. Over all sites, 68% of the homes had double or secondary glazing. For the noisiest three sites, at least 90% of the homes had double or secondary glazing. Because of the temperate climate, double glazing is quite rare in the United Kingdom. Clearly, most of these homes acquired double glazing as part of an increased sound insulation package intended to reduce indoor aircraft noise levels. Thus, one can expect that the noise reduction of outdoor noise would be 25 dB or more in most of these homes. One can then calculate that the site-average indoor maximum levels are in the range 50 to 60 dBA. Thus conditions in most of these homes were close to Griefahn's threshold of awakening shown in Fig. 3.6. It is therefore not too surprising that there was a quite low rate of arousals in this British study.

While the British field study is the most extensive to date, it is not the final answer. It is very important that such studies should present results in terms of the numbers of disturbances to specific indoor noise levels. Without this information it is very difficult to compare results with other studies and to evaluate their real meaning. Griefahn’s threshold curves in Fig. 3.6 are the best consolidation of this type of information to date. However, we still cannot be sure of the possible long-term effects on health of noise-induced disturbance of sleep.

3.4 Speech Interference

3.4.1 Factors Influencing Speech Intelligibility

The intelligibility of speech is degraded by interfering noise. When speech levels are well in excess of interfering noise levels, then speech will be completely intelligible. For relatively high noise levels, speech will be masked by the noise and will be completely unintelligible. At an intermediate range of noise levels, speech will be partially intelligible. In rooms, the longer delayed sound reflections or reverberant sound can also reduce speech intelligibility, because the long delayed reflections of one word interfere with or mask following words.

Speech intelligibility can be measured directly using standard lists of speech material. Subjects write down the word or words heard and the percentage correct is the speech intelligibility score. Such speech intelligibility scores are influenced by six factors:

(1) speech source levels,
(2) speech material,
(3) noise levels,
(4) talker to listener distance,
(5) room effects,
(6) individual differences.

Typical speech source levels vary with: the level of vocal effort, the sex of the talker, and between individuals. Thus, when one raises one’s voice to be heard in a large room, the speech is louder than for casual conversation at home. Pearsons et al. [50] have measured a large number of talkers and have produced modern estimates of typical speech levels at a distance of 1 m for both male and female talkers. Figure 3.8 shows their results. The mean speech levels are shown for five levels of vocal effort for both male and female talkers. It is seen that ‘shouted’ voice levels are more than 30 dB greater than 'casual' voice levels. This explains why it is often possible to be heard in noisy situations by raising our voice level.

Speech intelligibility scores are also influenced by the speech material. In normal conversational speech, there are many redundancies and it is not necessary to understand every word to comprehend the meaning of the message. In other situations, there are fewer redundancies and speech intelligibility scores will be lower for the same speech and noise levels. Figure 3.9 (from [51]) illustrates examples of typical speech intelligibility scores as a function of both the speech material and the difference between the speech and noise levels. Of the three examples in this figure, tests using sentences including some redundancies lead to the highest speech intelligibility scores. However, the tests using 1000 single syllable words have the lowest scores because subjects have more difficulty guessing the correct answer under adverse conditions.

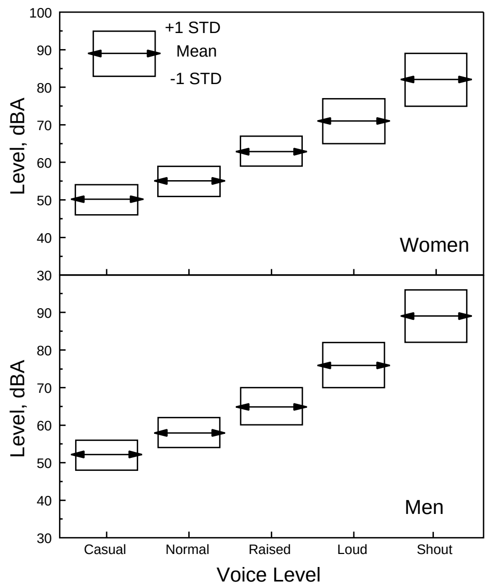

Figure 3.8. Mean speech source levels (±1 standard deviation) at 1 m from the talker for five levels of vocal effort for women (upper) and men (lower).

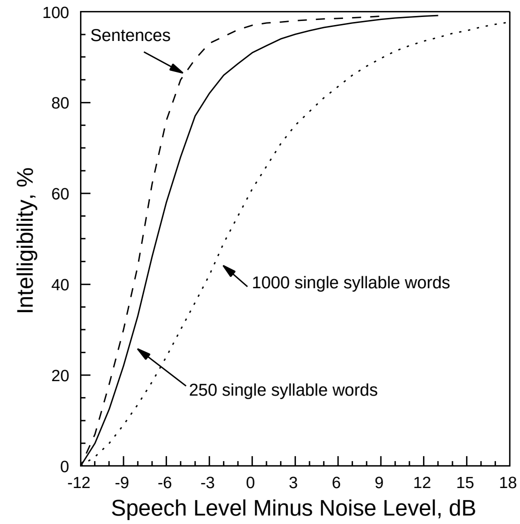

Figure 3.9. Mean speech intelligibility versus speech level minus noise level for three types of speech material.

Figure 3.9 also illustrates that speech intelligibility scores can be related to the signal/noise ratio rather than the separate speech and noise levels. Thus, it is the speech signal/noise ratio, i.e. the difference between the speech and noise levels, that indicates the degree of speech intelligibility to be expected.

Outdoor speech levels would be expected to decrease by up to 6 dB for each doubling of distance from the talker. The speech source levels in Fig. 3.8 are for a distance of 1 m. Thus, at a distance of 2 m speech levels would be expected to be up to 6 dBA lower, and at a distance of 4 m speech levels would be as much as 12 dBA lower than the source levels in Fig. 3.8. If interfering noise levels are more or less constant with distance, then speech signal/noise ratios will decrease rapidly with increasing distance between the talker and the listener for outdoor situations. Accordingly, speech intelligibility would similarly decrease with increasing distance.

Indoor sound levels vary in a more complicated manner with distance from the source. Usually, speech levels in rooms will decrease much less rapidly with distance than they would outdoors. In rooms, speech intelligibility is also reduced by later arriving reflections or reverberant sound that causes the sounds from one word to mask or interfere with subsequent words. This is usually only a significant problem in larger rooms designed specifically for speech communication such as classrooms, lecture theatres, etc.

There are significant individual differences in both speech levels and speech intelligibility scores that influence assessments of conditions for speech. The standard deviations of speech source levels shown in Fig. 3.8 give an indication of the range of speech source levels among individual talkers. This range of speech levels must be considered in determining acceptable conditions for speech. If acceptable conditions are based on mean speech levels, then for half of all talkers conditions would not be acceptable.

There are also significant individual differences in responses to speech intelligibility tests. This is true even when subjects with normal hearing are used. It is also well known that specific groups of people require superior conditions for optimum speech intelligibility. These include younger and older listeners with normal hearing. Thus, optimum conditions for younger adults with normal hearing will not be adequate for some other groups of people.

3.4.2 Conditions for Uncompromised Ideal Speech Intelligibility

From results similar to those illustrated in Fig. 3.9, Houtgast [52] and Bradley [53] both determined that speech would not be significantly affected by noise for signal/noise ratios of 15 dBA or greater. Thus, in simple terms, optimum conditions for speech require a signal/noise ratio of at least 15 dBA. The results of more extensive calculations [54] indicate that indoor background noise levels in excess of 35 dBA will interfere with the intelligibility of speech in smaller rooms.

Some references suggest that background noise levels as high as 45 dBA are acceptable. There is a range of optimum maximum acceptable background noise levels for speech, because many of these optima are based on some form of practical compromise. As Fig. 3.9 illustrates, a small reduction in signal/noise ratio from an optimum of 15 dBA leads to only a small reduction in speech intelligibility. Such small reductions could be compensated for by small increases in vocal effort. There is also a range of minimum levels of speech intelligibility that can be considered to be acceptable. For example, 95% speech intelligibility is a typical minimum acceptable level. Whether or not this would be acceptable would depend on the type of speech material and in particular the amount of redundancy in the speech material. Thus, there is considerable scope for selecting practical compromises for acceptable conditions for speech. Such vagueries can be avoided by determining uncompromised ideal conditions in which speech is not affected at all by interfering noise. Knowing the ideal requirements, one can then contemplate various compromises to meet the needs of various practical situations.

The above requirements of a 15 dBA signal/noise ratio and for a 35 dBA maximum background noise level represent two examples of requirements for ideal conditions for speech. Using the speech source level from Fig. 3.8, one can readily derive ideal conditions for speech in typical domestic rooms. In a typical living room, one would expect that almost all people should be able to communicate with a 'normal' voice level. That is, you should not have to strain to talk to family and friends in your home. To include "almost all" talkers, the 'normal' female voice level less one standard deviation (51 dBA) can be used as a speech source level. (Approximately 85% of talkers would have a 'normal' voice level equal to or greater than this level.) In typical living rooms, talker to listener distances of 2 m or less would be expected. For a typical Canadian living room (volume 50 m^3, 0.4 s reverberation time [55]), speech levels at the listener would be approximately 1 dB less than the speech source level at a 1 m distance. If one subtracts this 1 dBA reduction and the optimum 15 dBA signal/noise ratio from the 51 dBA source level, then an optimum maximum background noise level of 35 dBA is calculated.

For background noise levels of 35 dBA or less, the intelligibility of speech for adult listeners with normal hearing in a typical living room will not be significantly affected by noise for 85% of all talkers. From this ideal condition one could contemplate various compromises such as accepting only a 10 dBA signal/noise ratio. This would lead to a maximum acceptable background noise level of 40 dBA. Similarly, one could require acceptable conditions for 'raised' vocal effort rather than 'normal' vocal effort. This too would increase the maximum acceptable background noise level to 40 dBA. Accepting both compromises would increase the maximum background noise level to 45 dBA. For particular situations, such compromises may lead to reasonably acceptable conditions for speech but not ideal conditions. It is arguable that for residential areas near airports speech communication within homes should be completely unaffected by aircraft noise. Indoor aircraft noise levels in excess of 35 dBA would interfere with speech communication for at least some of the time.

3.4.3 <u>Effects of Time Varying Aircraft Noise Levels</u>

Most studies of the effects of noise on speech have considered relatively constant levels of interfering noise. Aircraft noise is obviously not like these noises in that the level varies considerably with time during an aircraft fly-over. For noisy situations when an aircraft is overhead, intelligibility might be very low. However, when an aircraft is not present, speech intelligibility may be near-perfect. During each aircraft fly-over, intelligibility would vary between the two extremes. Most estimates of the effect of aircraft noise on speech ignore this problem and assume that long term energy average measures of aircraft noise, such as L_{eq}, can be used to calculate the effects on speech. This average level approach does not accurately indicate the effects of aircraft noise on speech communication.

There have been studies of the interference of time varying noise on speech. These have usually only considered noises that vary much more rapidly with time than does aircraft noise. Festen and Plomp [56] found that speech reception thresholds were 4 to 6 dB lower in fluctuating noise than for a steady noise level. However, this improvement for fluctuating noise was not found for subjects with hearing impairment. Arlinger and Gustafsson [57] also found amplitude modulation of masking noise reduced its masking effect on speech. However, the masking noises were amplitude modulated at frequencies of 2 to 20 Hz, representing much more frequent fluctuations than experienced in aircraft noise. Howard-Jones and Rosen [58] also examined the effect of fluctuating noise levels on speech. They too found reduced speech reception thresholds with fluctuations occurring approximately 10 times per second, but did not consider conditions typical of an aircraft fly-over. In an earlier study, Pearsons [59] exposed subjects to tape recorded road traffic noise in a laboratory test. Subjects rated the annoyance of the sounds and also took part in limited speech comprehension tests. Speech intelligibility scores from standard speech intelligibility tests were not obtained, but Pearsons reported a trend for decreased speech interference with fluctuating traffic noise levels.

The expected speech intelligibility during exposure to aircraft noise can be estimated by calculating speech intelligibility on a point by point basis and averaging over a complete aircraft pass-by. Figure 3.10 plots both the indoor sound level and the resulting point-by-point speech intelligibility versus time during an aircraft fly-over.

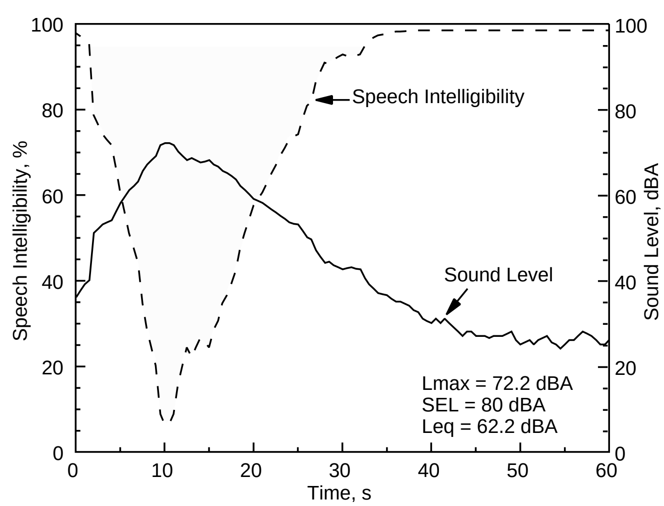

Figure 3.10. Indoor sound level (solid curve and right hand axis) and calculated speech intelligibility score (dashed curve and left hand axis) versus time during an aircraft fly-over.

The solid line represents the indoor sound level during an aircraft fly-over. In this example, the noise level peaks at 72.2 dBA (L_{max}) and the SEL is 80.0 dBA. For the 60 seconds shown on this plot, the L_{eq} would be 62.2 dBA. If the associated speech intelligibility is estimated from the L_{eq} of the aircraft noise, a speech intelligibility score of close to zero would be expected. That is, with a 'normal' female speech voice level of 51 dBA in a typical living room, and an aircraft noise L_{eq} of 62.2 dBA, the signal/noise ratio would be -11.2 dBA. This would suggest that speech communication would not be possible. The L_{eq} measure is an average over a specific time period. Thus, with longer intervals between flights the L_{eq} value would decrease, suggesting that speech intelligibility had improved. Of course, during the actual fly-over, speech intelligibility would not change. An L_{eq} measure is not a suitable measure of the degradation of speech intelligibility by aircraft noise.

On the same figure, estimated speech intelligibility scores have also been plotted. These were calculated at half-second intervals from point-by-point speech signal/noise ratios. Speech intelligibility was related to signal/noise ratio by using the field speech intelligibility test results in Fig. 2 of reference [54]. This relationship is similar to those shown in Fig. 3.9 of this section. The shaded area in Fig. 3.10 indicates where speech intelligibility is unacceptable and is less than 95%. In this one-minute example, speech is significantly degraded for approximately 30 seconds and is easily understood during the other half of the time period. Thus, over this one-minute sample, speech intelligibility is not close to 0% as indicated by the simple analysis of L_{eq} values.

This point-by-point speech intelligibility calculation procedure can be used to more satisfactorily relate speech intelligibility to aircraft noise SEL values. In the remainder of this section, speech intelligibility is first related to varied SEL values for a single pass-by time history. As a second step, it is shown that this same type of relationship is also found when the form of the noise level time history is also varied by varying the distance of the receiver from the flight track.

The calculated speech intelligibility will first depend on the speech source level that is used. While it is desirable to be able to communicate at home with a 'casual' vocal effort, it is probably justifiable to use a speech source level corresponding to a 'normal' vocal effort in these calculations, because this level of effort will only be required for very short time intervals. Aircraft noise is intermittent, and during most of the time speech communication will be either completely unaffected or completely impossible. It is only during the very short intermediate periods when the aircraft is approaching or departing that the level of the voice will have a significant effect. Thus, it is justifiable to use a 'normal' voice level because this level of effort is only required for a very short time during each fly-over.

Speech intelligibility scores were calculated as averages over a one-minute period that included the aircraft fly-over. A one-minute period is a worst case in that it represents a maximum frequency of aircraft noise events. Less frequent flights would give some relief between noise events, but would not modify the effect of each flight on speech communication.

The indoor aircraft noise levels are expressed in terms of an indoor SEL. The indoor SEL is calculated by subtracting the A-weighted noise reduction of the building facade from the outdoor SEL of the aircraft fly-over. Thus, for a given external SEL, one can estimate the effect of a range of building facade noise reductions. The noise reduction of building facades typically varies between 10 and 30 dBA (or more in particular cases). Table 5.1 indicates an average noise reduction of 26 dBA for wood frame homes in cold climates with closed windows. As an example, an indoor SEL of 59 dBA could result from an outdoor SEL of 85 dBA and a facade noise reduction of 26 dBA. (Section 5.3 provides further information on the effects of building insulation.)

Figure 3.11 shows calculated speech intelligibility scores as a function of the indoor SEL for one aircraft fly-over. In these calculations, only the overall SEL values were varied and not the form of the noise level time history. Calculated point-by-point speech intelligibility scores were averaged over a one-minute period, and the calculations were repeated for speech source levels corresponding to 'casual', 'normal', and 'raised' female vocal effort less one standard deviation. Figure 3.11 shows how calculated speech intelligibility scores decrease as indoor SEL values increase from 50 to 75 dBA.

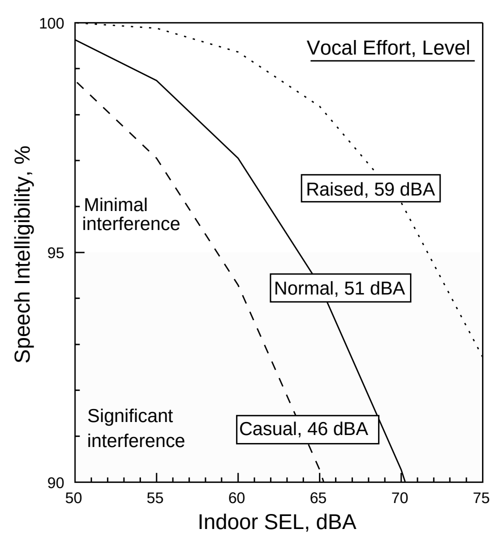

Figure 3.11. Calculated speech intelligibility scores versus indoor aircraft noise SEL for three speech source levels.

The 'normal' vocal effort case in Fig. 3.11 indicates that for acceptable speech communication the indoor aircraft noise SEL must be no greater than 64 dBA. If one assumes the average 26 dBA noise reduction for the closed windows case from Table 5.1, this would correspond to an outdoor SEL of no more than 90 dBA. Thus, when aircraft noise events produce outdoor SEL values of greater than 90 dBA, indoor speech communication will be disturbed even in a well insulated Canadian home with closed windows.

The ‘casual’ and ‘raised’ vocal effort cases in Fig. 3.11 indicate maximum acceptable indoor aircraft noise SEL values of approximately 59 and 72, respectively. By adding an appropriate facade noise reduction to each of these, the corresponding maximum acceptable outdoor aircraft noise SEL can be obtained. The results for these other speech source levels can be used for other more or less critical situations. It is not intended that people in their own homes would have to raise their voices to be understood.

These results have been derived from the time history of a single aircraft fly-by at a 1000 ft distance. Only the SEL values were varied and not the details of the time history of the fly-over. As the measuring point is moved away from the flight track, the pattern of sound level variations with time will change. For an ideal case, maximum levels tend to decrease 6 dB for each doubling of distance from the flight track. However, the integrated SEL values would only decrease by 3 dB per doubling of distance for the same ideal case. At the same time, the effective duration of the pass-by increases approximately proportional to increasing distance from the flight track. The decrease in levels with increasing distance would tend to decrease speech interference, but the increase in effective duration would tend to increase speech interference. It is thus necessary to estimate the combined effect of both variables on the resulting speech interference.

For simplicity, the effect of distance from the flight track on estimated speech intelligibility was examined using simulated aircraft pass-bys. Thus, the sound level time history was calculated point-by-point simply by assuming the aircraft to be a point source traveling at constant velocity along a straight line path. This was repeated for the measuring point at distances of 1000 to 4000 ft (305 to 1220 m) from the flight track. Speech intelligibility scores were again calculated from these sound level time history plots as for the above examples. Figure 3.12 shows the resulting plot of speech intelligibility versus aircraft noise SEL. The data points are a reasonable approximation to a single monotonic relationship, and this curve is quite similar to the ‘normal’ vocal effort case of Fig. 3.11. Thus, one can estimate speech intelligibility scores from only the aircraft noise SEL values without considering the details of the sound level time history or the distance from the flight track.

These results demonstrate that long term average integrated noise measures such as L_{eq} are not satisfactory predictors of speech interference from aircraft noise. The new calculations, from the detailed time history of the aircraft fly-over, show that speech interference is better predicted from aircraft noise SEL values. The new calculations can readily show the influence of: outdoor SEL, facade noise reduction, and speech source levels. Further development is required to optimally include the effects of the frequency of aircraft overflights.

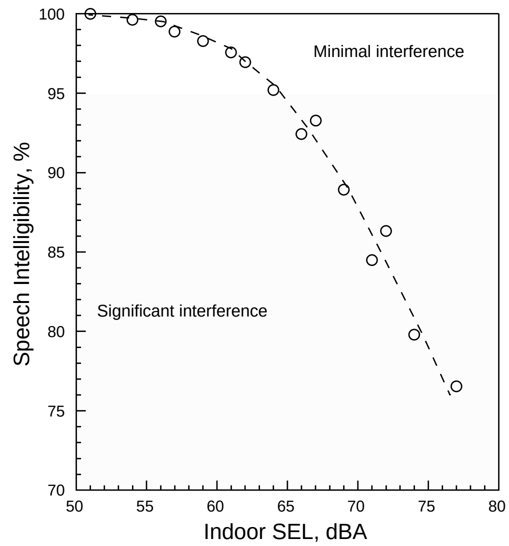

Figure 3.12. Calculated speech intelligibility scores versus indoor aircraft noise SEL for simulated aircraft pass-bys at distances of 1000 to 4000 ft from the flight track.

3.5 Annoyance

3.5.1 <u>General</u>

As discussed in Chapter 2, earlier studies of community response to aircraft noise tended to be based on case studies, anecdotal information, and complaint data. As survey techniques developed, more reliable assessments of community response to aircraft noise were obtained. Such surveys are a considerable improvement because they attempt to correctly sample the entire population exposed to the noise in question and hence provide much more representative results. Various noise surveys have developed a variety of formats for questionnaires and procedures for administering these questionnaires. Similarly, accurate measurements of the noise levels require a good sampling of the noise environment. The quality of noise measurements also varies considerably among surveys, and many aircraft noise surveys have used calculated noise measures obtained from airport noise prediction programs such as the INM model. Borsky's 1978 review [60] discusses many of the problems associated with improved survey procedures.

Better survey techniques led to many improvements, but there has been no standardization of survey procedures. Thus, each new survey produced results that were usually not readily comparable to other survey results. Schultz [61] tried to remedy this problem by compiling a synthesis of a number of surveys. He was able to show that the results of a number of surveys seemed to be quite similar, and he produced his synthesis curve that represented a mean trend of these clustering survey responses.

Although Schultz's work was a major step forward to obtaining some form of consensus, there are many problems that must be resolved concerning the validity of his single dose response curve. Kryter [62] made a number of criticisms of Schultz's original work, but many of these were refuted by Schultz [63]. To make such a synthesis of existing survey results, obtained using a variety of procedures, requires a number of approximations and arbitrary judgments. Having made these approximations and arbitrary judgments, there are many questions as to the validity and meaning of the resulting average dose-response curve.

In forming his synthesis, Schultz expected to get the best agreement by comparing "very or highly annoyed" responses. He tried to standardize by using responses in the top two steps of seven-point response scales (i.e. 2/7 or 28.6% of the scale) or the top three steps of eleven-point response scales (i.e. 3/11 or 27.3% of the scale). Many surveys have used scales with other than seven or eleven categories and with a variety of labels on each scale step. There can be no unique conversion between responses to different questions, with different numbers of response scale steps, and with different labels on the response scale steps. Given similar labels on the response scale steps, one might expect to be able to relate results from the seven- and eleven-point response scales. However, attempts to convert between less similar scales are bound to lead to larger errors.

Some of the problems involved in calculating a consensus dose-response curve can be illustrated by using data from the UWO (University of Western Ontario) road traffic noise survey funded by Transport Canada [64, 65]. This survey included extensive noise and survey data and its design had benefited from the earlier developments in survey techniques. Figure 3.13 illustrates grouped responses to a single item question concerning annoyance to traffic noise. The percentage of subjects responding in the top one, two, or three categories of the seven-point response scale were calculated and linear regression lines calculated. These regression lines are shown on Fig. 3.13 compared with the Schultz curve. In this survey, the top response step was labeled "very annoyed".

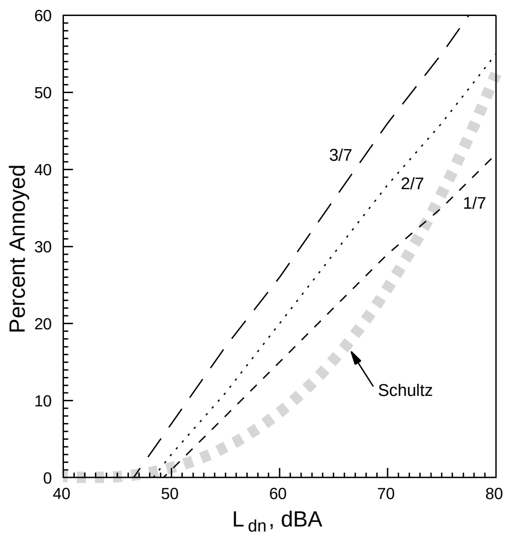

Figure 3.13. Summed percentage annoyed from the top one, two, or three categories of a seven-point response scale compared to the Schultz curve.

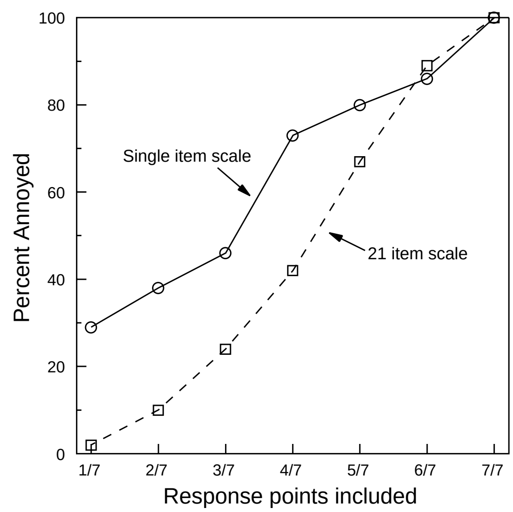

Figure 3.14. Comparison of percentages annoyed from a single item question and from a composite annoyance scale for the summed responses of the top one to seven points of a seven- category response scale.

Using Schultz's procedure of taking responses to the top two categories to be representative of "highly annoyed" produces a regression line well above the Schultz curve. At an L_{dn} of 70 dBA, the regression line indicates an average of about 38% being highly annoyed compared to the approximately 25% according to the Schultz curve. Figure 3.13 illustrates that one could get closer agreement by using the percentage of subjects responding to the top category of the seven-point scale. However, this would not correspond to Schultz's procedure of taking the responses to the top two categories. Alternatively, one could argue that the response scale labels are in some way different than other surveys and hence need to be interpreted differently. Since one knows the desired goal of matching the Schultz curve, the exercise cannot be unbiased and the resulting agreement would certainly be questionable.

Because response scales usually have a small number of steps, choosing between one or another cut-off point results in a large change in the portion of the response scale that is defined as highly annoyed. Figure 3.14 plots the data from Fig. 3.13 as a function of the number of response scale steps that are included in the annoyed group for an L_{dn} of 70 dBA. Including one more or one less step on this seven-point response scale can change the percentage annoyed by approximately 10%. Of course, one cannot move in fractional steps; there is no intermediate information. Matching to scales with fewer response steps is likely to introduce larger errors. For example, from the results of Fig. 3.14 one can estimate that with a five-point scale, deciding between the top category (i.e. 1/5 or 20% of the scale) or the top two categories (i.e. 2/5 or 40% of the scale) would lead to significant differences in the percentage highly annoyed.

It is difficult to determine equivalent meanings of response scale labels for individual questions from different surveys that may even be written in different languages. However, it is probably impossible to compare the meaning of responses to different composite response scales. Composite response scales combine the responses to several individual questions and hence give more reliable results. Figure 3.14 also includes a second curve for such a composite annoyance scale. The composite scale produces a smoother curve, but it generally indicates a much smaller percentage of annoyed subjects. Although it is very desirable to use a composite annoyance scale, getting comparable results between surveys would only be possible if a standard set of questions were to be adopted.

To compare survey results, it is also often necessary to make approximate conversions between various noise measures. Noise measures can be calculated over different time periods, with different frequency, and time of day weightings. In some cases satisfactory conversions are possible, but in others there is not adequate information to make a sufficiently accurate conversion.

3.5.2 <u>Comparisons of Newer Aircraft Noise Surveys with the Schultz Curve</u>

Since Schultz's 1978 publication [61] of his synthesis, several major airport noise surveys have been carried out in various countries. Fidell [66] has up-dated the original Schultz synthesis. By combining results from surveys of various types of noise, the results showed considerable scatter but the mean trend was close to the original Schultz curve. Thus, this up-dating did not lead to significant changes in the original Schultz curve. A number of results suggest that responses vary not only with noise level but also with the type of noise source. In particular, Hall et al. [67] have shown considerable differences in responses to aircraft and road traffic noise. The differences between sources will be discussed in Section 3.5.3 below. However, because of these possible source differences and because the concern of this report is aircraft noise, it seems important to check whether modern aircraft noise surveys agree with the Schultz curve.

Data from six major aircraft noise surveys were examined. These included:

(1) Hall et al.'s Toronto data [67],

(2) a Swiss aircraft noise survey in 1991 [68],

(3) Brooker et al.'s 1985 survey in the United Kingdom [69],

(4) a survey near Oslo's Fornebu airport by Gjestland et al. [70],

(5) the results of two surveys in Osaka [71], and

(6) Bullen and Hede's Australian aircraft noise survey [72,73].

The responses from each of these major aircraft noise surveys were compared to the Schultz curve following Schultz's procedures as closely as possible. The results of this analysis suggest that a number of modern aircraft noise surveys differ from the Schultz synthesis and further demonstrate the problems in making such comparisons.

(a) Hall et al. Toronto aircraft noise survey [67]

Hall and Taylor carried out several careful studies of disturbance due to aircraft noise, and their Toronto survey should be comparable to surveys at other major airports. Their mean percentage highly annoyed with aircraft noise versus L_{dn} curve is compared with the Schultz curve in Fig. 3.15. Schultz did not include this survey in his synthesis and he suggested that it was different because of the use of a bipolar response scale that was not common among other surveys. However, this same bipolar response scale did give good agreement with the Schultz curve for road traffic noise. The difference between the Toronto results and the Schultz curve has not been satisfactorily explained. It could be that subjects near Toronto airport are more sensitive to aircraft noise. It could be that differences in survey procedures (such as the use of a bipolar scale) may be the cause of the differences, or it might be that the Schultz curve is not representative of the disturbance of aircraft noise.

(b) Swiss Survey Aircraft Noise Survey, 1991

A survey of aircraft noise at three Swiss airports, carried out in 1971, was included in Schultz's original synthesis [61]. Schultz found responses from this earlier survey to agree well with results of the other clustering surveys. Results from the new Swiss survey [74] show that there has been no change in the percentage highly annoyed versus noise level between the old and the new surveys. However, the new results do not appear to agree with the Schultz synthesis. This comparison of the two Swiss surveys and the Schultz curve is given in Fig. 3.16.

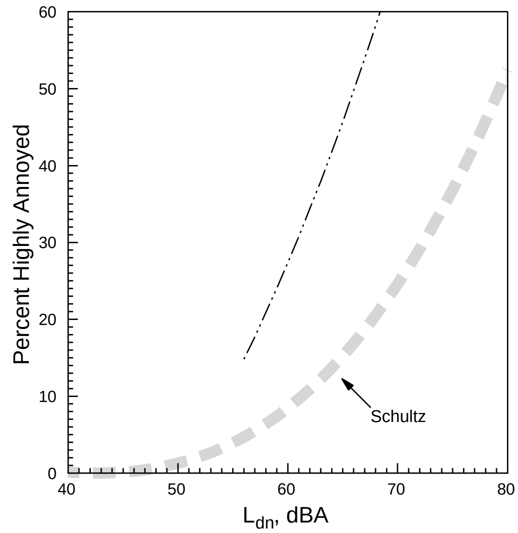

Figure 3.15. Comparison of percentages highly annoyed with aircraft noise versus noise level from Hall et al.'s Toronto survey with the Schultz curve. Regression equation, %HA = 0.0003129•$(L_{dn})^3$ - 40.2.

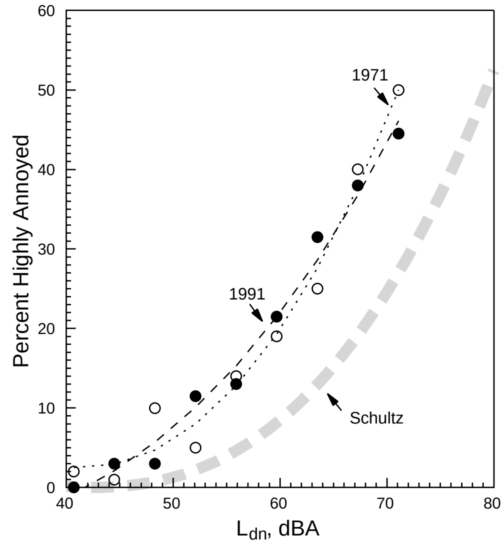

Figure 3.16. Comparison of percentages highly annoyed versus noise level from two Swiss aircraft noise surveys with the Schultz curve. Regression equations,
%HA = -1.768•L_{dn} + 3.474•10^{-4}•$(L_{dn})^3$ + 50.98, (1971)
%HA = -0.2848•L_{dn} + 1.906•10^{-4}•$(L_{dn})^3$ - 1.989, (1991).

The cause of this conflict is due to quite different procedures for converting between the Swiss Noise and Number Index, NNI_S, and L_{dn}. In his synthesis paper, Schultz used the following equation:

$$L_{dn} = 0.833 \bullet NNI_S + 35.3$$

According to Hofmann [66], this is incorrect because it is based on a conversion from L_{eq} values including both aircraft and traffic noise to NNI values based on only aircraft noise. Hofmann suggests a quite different equation,

$$L_{dn} = 0.760 \bullet NNI_S + 31.53, \text{ (for 5\% night operations)}$$

For an L_{dn} of 70, the two equations give NNI_S values that differ by 7 dB. Other conversion equations between these two quantities seem to be in reasonable agreement with the Hofmann equation [69, 75].

The results of the new Swiss aircraft noise survey do not agree well with the Schultz curve and they indicate higher annoyance. The procedure that Schultz used for converting NNI_S values to L_{dn} values is incorrect and therefore the 1971 Swiss survey results do not agree well with the

Schultz curve. The question of conversions from NNI to L_{dn} values needs to be further investigated. In Schultz's original paper, he also described other conversions from NNI to L_{dn} for the second Heathrow survey and for a Swedish aircraft noise survey. It is not clear why these are also quite different from the Hofmann equation above. If Schultz's conversions are found to be inaccurate, then it is quite likely that results from these other surveys would no longer agree closely with the Schultz curve.

(c) Brooker et al.'s 1985 survey in the United Kingdom[69]

A major aircraft noise survey was carried out in the United Kingdom to support the change from Noise and Number Index, NNI_{UK}, to an L_{eq} measure. Data from this survey are shown in Fig. 3.17 along with a curve indicating the mean trend of these results. The 24-hour $L_{eq}24$ values obtained in this survey were converted to L_{dn} values using the following equation,

$$L_{dn} = 1.0439 \bullet L_{eq}24 - 1.2455$$

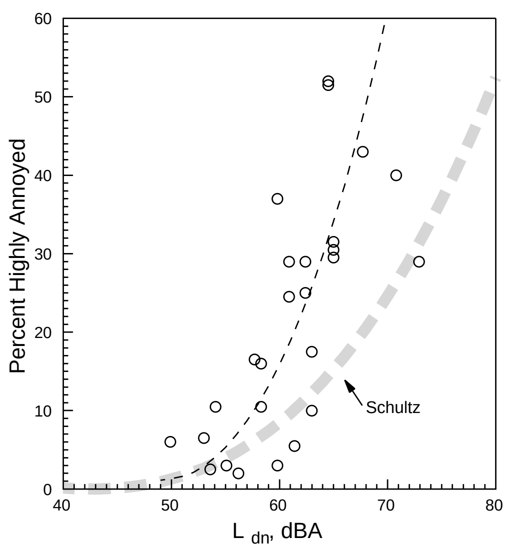

Figure 3.17. Comparison of percentages highly annoyed versus noise level from British Airport Noise Index Study with the Schultz curve. Regression equation,
$\%HA = -0.105 \bullet (L_{dn})^2 + 0.00143 \bullet (L_{dn})^3 + 85.0$.

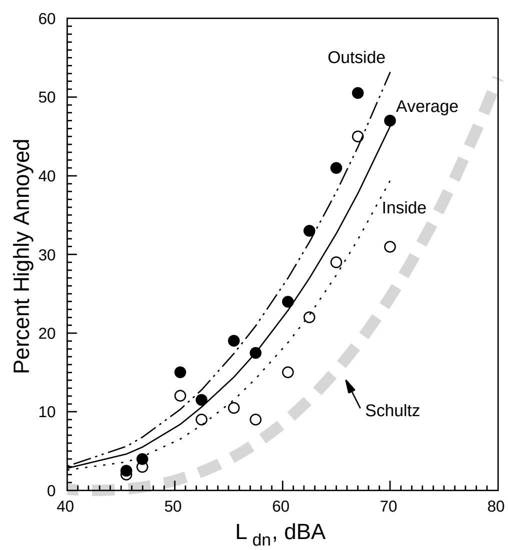

Figure 3.18. Comparison of percentages highly annoyed versus noise level from the Oslo Fornebu airport study with the Schultz curve. Regression equations,
$\%HA = -1.203 \bullet L_{dn} + 3.098 \bullet 10^{-4} \bullet (L_{dn})^3 + 31.16$, (outside)
$\%HA = -1.267 \bullet L_{dn} + 2.689 \bullet 10^{-4} \bullet (L_{dn})^3 + 35.88$, (inside).

The percent highly annoyed scores came from responses to the top step of a single five-point response scale. It is possible that such responses may underestimate disturbance compared to including the top 27-29% of seven- and eleven-point response scales. In spite of this potential for the results to underestimate annoyance, the data again fall significantly to the left of the Schultz curve, indicating greater percentages highly annoyed.

(d) Norwegian Survey by Gjestland et al. [70]

This survey was conducted at homes around Oslo's Fornebu airport. Noise measures were obtained in terms of the Norwegian EFN unit which is on average 1 dB greater than corresponding L_{dn} values. Figure 8 of reference [70] gives the percentage of very annoyed subjects both inside and outside their homes. These appear to be derived from single item questions using four-point response scales. The top step of this scale was considered to be "very annoyed" and hence represents 25% of the response scale. Best fit regression lines were fitted to the Norwegian data and these regression lines and the original data points are compared to the Schultz curve in Fig. 3.18. Both responses indicate greater percentages of highly annoyed residents than suggested by the Schultz curve.

(e) Two Surveys in Osaka [71]

A recent paper by Igarashi [71] gives results for a number of Japanese noise surveys and compares them to the Schultz synthesis curve. He includes the results of two aircraft noise surveys around Osaka airport. Best fit linear regression lines relating the percentage of highly annoyed respondents to L_{dn} values were given for both surveys. These linear regression lines are compared to the Schultz curve in Fig. 3.19. In the more recent second Osaka survey, noise levels were measured in terms of the Japanese WECPNL and Igarashi converted them to L_{dn} values by subtracting 15 dB from the WECPNL values. The percent very annoyed scores were taken from the top step of a five-point response scale. Both surveys seem to have produced similar average results and both

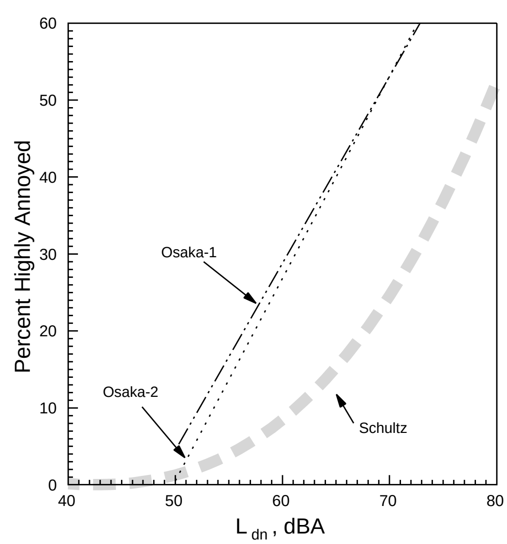

Figure 3.19. Comparison of percentages highly annoyed versus noise level from two surveys at Osaka airport with the Schultz curve. Regression equations, %HA = 2.43•L_{dn} - 117, (Osaka-1)
%HA = 2.63•L_{dn} - 131, (Osaka-2).

indicate greater annoyance than the Schultz curve.

(f) Bullen and Hede's Australian Aircraft Noise Survey [72, 73]

Bullen and Hede carried out a large survey of the impact of airport noise around five Australian airports. It included measurements of noise levels and interviews of 3575 subjects. In Fig. 6 of reference [73], Bullen and Hede included a plot of the percentage highly annoyed versus L_{dn}. These data were obtained using a probit analysis on the responses to the top category of a five-point response scale and is included in Fig. 3.20.

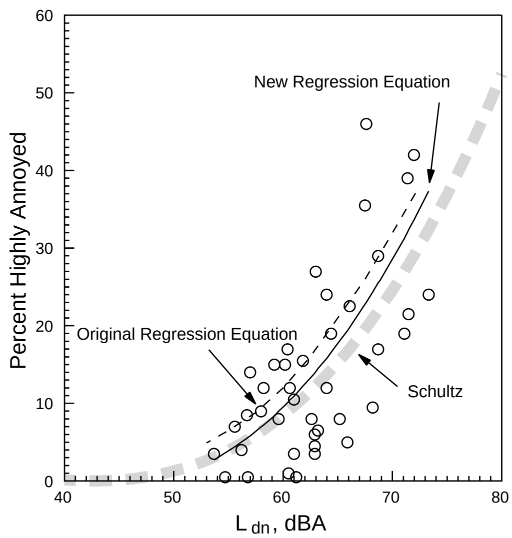

Figure 3.20. Comparison of new regression equation to the percentages highly annoyed (circles) with the original best fit curve and the Schultz curve. New regression equation, $\%HA = -1.594 \bullet L_{dn} + 2.753 \bullet 10^{-4} \bullet (L_{dn})^3 + 45.69$.

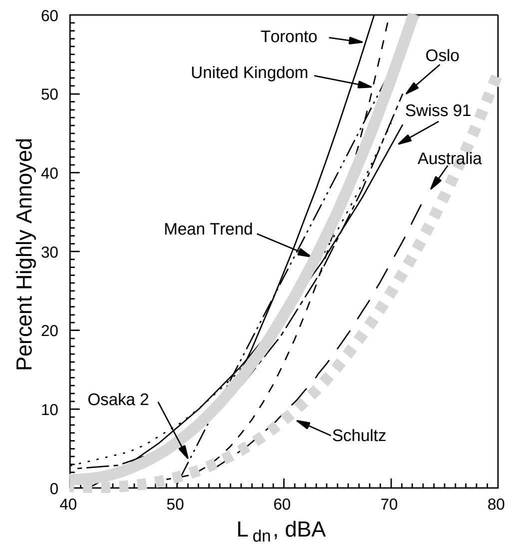

Figure 3.21. Comparison of percentages highly annoyed versus noise level from six modern aircraft noise surveys compared to the Schultz curve. 'Mean Trend' curve shows the mean trend of the five surveys not agreeing with the Schultz curve.

Much of the raw data from this survey is available in Bullen and Hede's original report [72]. To consider the results of this survey in the same manner as the other surveys, a third order polynomial was fitted to the data and a regression line a little different to the published probit analysis result was obtained. The percentage highly annoyed data from this analysis are compared with the Schultz curve in Fig. 3.20. The new best fit third order polynomial is in even better agreement with the Schultz curve.

Thus, the results of this survey differ from the others in that they agree quite closely with the Schultz curve. This survey seems to be a major modern survey that was carefully executed. It is, however, different from the other surveys in that it includes smaller communities and smaller airports. As discussed in Section 4.5, there is reason to believe that this may influence annoyance responses. (Subsequent analyses have shown that the Sydney data agree well with the other large airport studies [83]

The consideration of six newer aircraft noise surveys has indicated that all but one differ significantly from the Schultz curve and that they indicate greater annoyance than the Schultz curve. The mean trends from each of these surveys are compared with the Schultz curve in Fig. 3.21. Five of the six survey results have somewhat similar trends that are about 10 dB to the left of the Schultz curve. A mean trend curve has been drawn through this group of five results, and it indicates considerably greater percentages of highly annoyed people than the Schultz curve.

There is a very strong tendency in the United States to use the Schultz curve as the principal indication of negative impact of all types of transportation noise. The results summarized in Fig. 3.21 very strongly indicate that the Schultz curve should not be considered valid for aircraft noise unless a more extensive re-analysis than the present one can support its validity.

A new examination of the conversions between noise measures such as from NNI values to L_{dn} values is needed and it may lead to a further reduction in the agreement among the original clustering surveys. For example, the 1971 Swiss aircraft noise survey results are closer to the "Mean Trend" curve in Fig. 3.21 than to the Schultz curve.

3.5.3 Comparisons with Other Noise Sources

In making his synthesis of survey results, Schultz [61] assumed that the relationship between annoyance and noise level was independent of the type of noise source. This assumption was essential for him to be able to obtain some consensus among the many different surveys that were in the literature. In the 15 years since Schultz's work was published, there have been many further studies, and it is now more appropriate to ask whether all noise sources produce the same annoyance at equivalent noise levels. Several studies have examined the question of differences between types of noise sources and the effects of combined noise sources. Others have considered the effects of background levels on responses to a specific noise source. Often the background noise has been due to road traffic noise, and studies of the effect of background levels are similar to those of the combined effect of aircraft and road traffic noise.

To examine the effects of source differences, one can compare the results of surveys of different noise sources, but such comparisons are subject to many problems because of the differences in survey methodology. Few surveys have included comprehensive noise measurements and survey questions concerning more than one type of noise source. Hall et al. [67] did carry out such a comparison and compared their results with Schultz's synthesis curve. Sites were chosen near Toronto airport and included a range of both aircraft and road traffic noise levels. Aircraft noise levels were calculated using the Integrated Noise Model computer program. Road traffic noise levels were measured at each site. Figure 3.22 compares the resulting regression lines to the percent highly annoyed responses to both road traffic and aircraft noise with the Schultz curve. This is perhaps the best evidence that responses are source dependent. All data were from the same survey and were obtained using the same procedures. The annoyance to road traffic noise responses agree very closely with the Schultz curve. The percent highly annoyed to aircraft noise regression line tends to be more than 10 dB to the left of the Schultz curve. Hall et al. investigated many possible causes of this source difference but were forced to concluded that equal levels of aircraft and road traffic noise are not equally annoying.

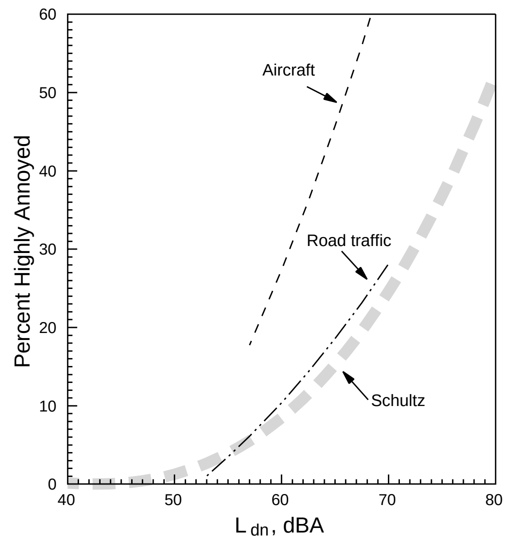

Figure 3.22. Percentages highly annoyed to road traffic and aircraft noise versus noise level compared to Schultz's curve.

In a later paper, Hall [81] reviewed a dozen papers that compared responses to several different types of community noise sources. He concluded that the overwhelming trend was that there were source specific differences in annoyance response curves. Annoyance response functions for train noise tend to be lower than those for road traffic noise, and annoyance response functions for aircraft noise tend to be higher than those for road traffic noise. Hall also pointed out that because of the uncertainties in survey results, there are still occasions where a single average annoyance response curve may be of some practical use.

Other studies have examined the combined effects of different types of noises. An early study by Bottom and Waters [76] produced one of the clearest sets of results of the combined effects of road traffic and aircraft noise. They interviewed subjects at nine sites that formed the combinations of three levels of aircraft noise and three levels of road traffic noise. Figure 3.23 shows regression lines and average responses to a question concerning annoyance to aircraft noise. Separate regression lines are given for sites with low, medium, and heavy road traffic, which is intended to be indicative of road traffic noise levels. There is a consistent effect that increasing road traffic noise reduces annoyance to aircraft noise independent of aircraft noise level.

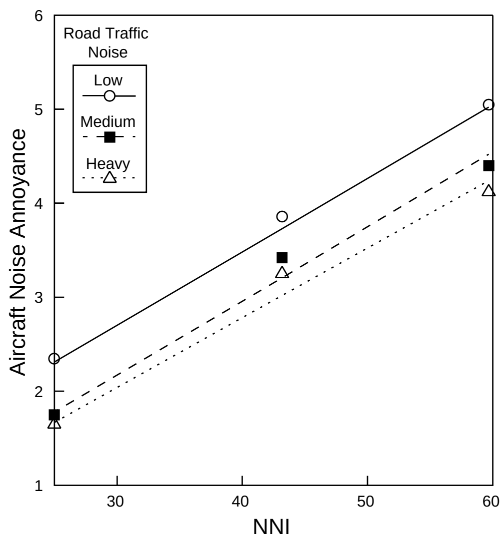

Figure 3.23. Annoyance to aircraft noise versus aircraft noise level for three levels of road traffic noise.

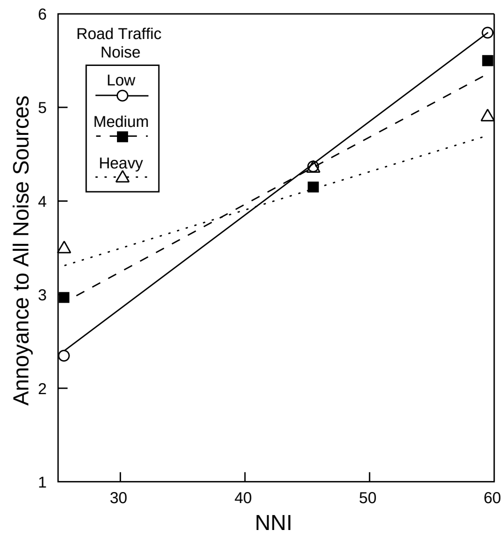

Figure 3.24. Annoyance to all noise sources versus aircraft noise level for three levels of road traffic noise.

When responses concerning annoyance to all noise sources are plotted in the same manner, the results shown in Fig. 3.24 were obtained. Here there is a clear interaction between the effects of road traffic noise and aircraft noise. General annoyance increases most rapidly with aircraft noise level when the road traffic noise level is lowest. The addition of more road traffic noise increases annoyance at lower aircraft noise levels and decreases it at higher aircraft noise levels.

More recently, Lawrence and Putra [79] also carried out a study of disturbance to combined aircraft and road traffic noise. All sites were in Sydney, Australia and the survey was carried out by mail. They too found that high levels of road traffic noise decreased annoyance to aircraft noise similar to the trend of Fig. 3.23.

Izumi [80] carried out extensive studies of the combined effects of train and road traffic noise. Both laboratory simulation experiments and field surveys of responses to combinations of both types of noise were carried out. Again, there were clear effects of the influence of one noise source on responses to the other. There were also results indicating interaction type effects similar to those in Fig. 3.24. Figure 3.25 shows one example of Izumi's results from his field survey. This figure shows regression lines to data from sites of medium road traffic noise level. Annoyance to train noise increased most with increasing train noise level. Annoyance with road traffic noise decreases with increasing train noise level even though all subjects were exposed to similar road traffic noise levels. The total noise annoyance increases with train noise level, but the increase is less than for the annoyance to train noise. Thus, the disturbing effects of the train noise were modified by the presence of road traffic noise.

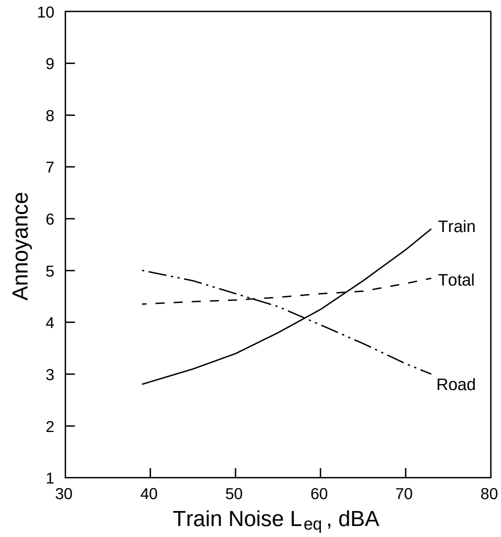

Figure 3.25. Annoyance to train, traffic and total noise versus train noise level for a constant level of road traffic noise.

In a recent aircraft noise survey, Gjestland et al. [70] specifically examined the effect of ambient noise levels from road traffic noise on annoyance to aircraft noise. They only found effects at a few sites with the highest aircraft noise levels, and the data was not adequate to describe a clear trend.

For residential air conditioner noise, clear effects of background noise levels on annoyance responses have been found [82]. For this type of more constant noise, it is much more likely that ambient noise could mask or make it difficult to hear the air conditioner noise. In the extreme, ambient background noise levels must influence annoyance to particular noises. That is, if one cannot hear the particular noise because of the high ambient level, then one cannot be annoyed by it. Because of the large fluctuations in aircraft noise levels, it is very unlikely that ambient noise levels will completely mask the sounds of aircraft fly-overs. Thus, one should expect small effects of ambient levels (as reported by Bottom [76]), or negligible effects (as reported by Gjestland [70]).

It seems quite clear that a single annoyance response curve cannot accurately describe the relationship between annoyance and noise level for different types of noise sources. Almost all studies that have addressed the problem have found source differences. There is even reasonable agreement that for similar noise levels, aircraft noise is more annoying than road traffic noise which is more annoying than train noise. There is further evidence that the effects of combined noise sources modify the responses to the individual sources. More precise descriptions of these effects will require large surveys focused on these specific problems.

3.5.4 Effects of Location Relative to the Flight Path

Some results suggest that even for similar noise exposures, annoyance responses are influenced by the subject’s location relative to the flight path. Hall et al. [77] suggested that subjects living directly under a flight path would tend to have increased fear of aircraft crashing on their homes and hence be more annoyed. However, they did not find increased fear of aircraft crashes at locations under the flight path even though these subjects were more annoyed. Their definition of being under the flight path was quite restrictive, being those homes within about 400 m of the centre of the flight path.

Gjestland [78] considered further the possibility of a flight path effect on responses to aircraft noise. He suggested that two sites in the United Kingdom survey [69] were more annoyed than other sites at similar noise levels because they were located directly under the flight path and not too far from the end of the runway. He also re-examined the Hall and Taylor data, re-defining under the flight path as within 750 m of the flight path, and separating the data into sites under the flight path and sites not under the flight path. The data from the subjects not under the flight path were then quite highly correlated with noise levels and formed a quite different trend than at the other sites. However, when the data were separated, the correlation between noise levels and the percentage annoyed did not improve for the sites under the flight path.

In the report on the Fornebu airport survey [70], Gjestland et al. separated sites into three categories: those under approach paths, those under take-off paths, and those not under flight paths. They were not able to find statistically significant differences between results from sites under take-off and sites under approach paths. Combining the under take-off and under approach path sites together led to differences relative to sites not under flight paths. The data from Fig. 22 of reference [70] is shown in Fig. 3.26. Subjects residing under flight paths were more highly annoyed. The regression lines to the two sets of data are displaced approximately 5 dB. However, Gjestland et al. pointed out that the confidence limits on this difference are quite large and hence there is considerable uncertainty over this value.

There does seem to be evidence of a separate influence on negative responses to aircraft noise that is related to the location of subject's home relative to the flight path. Because of the typical uncertainties in survey response data, it has been difficult to precisely define this effect. The best estimate is that it is equivalent to a 5 dB shift in noise levels and hence would seem to be important enough to warrant further study.

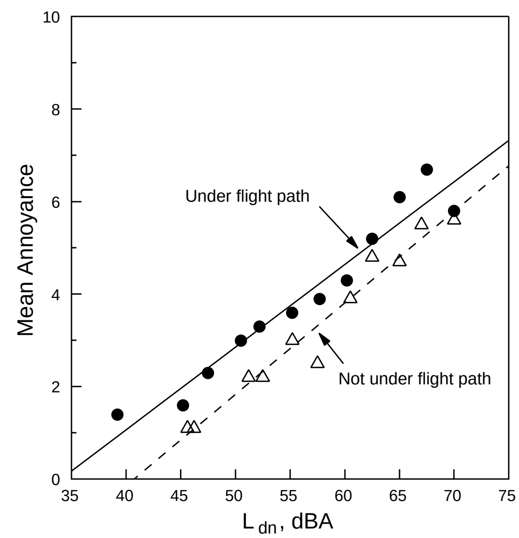

Figure 3.26. Comparison of mean annoyance score for residents living under the flight track or away from the flight track.

Several reasons for this effect have been suggested. It may be related to differences in the character of aircraft noise at sites under the flight path compared to those further away. This would include: directional effects, higher peak levels, and a more rapid rise and fall of levels at sites under the flight path. There could also be differences in non-acoustical variables such as the greater visibility of aircraft at homes under the flight path. It has also been suggested that the effect could be due to systematic errors in predicting noise levels using the INM model. (Both Hall and Taylor, and Gjestland et al. used the INM model to calculate noise levels.) This is a particularly interesting suggestion because an earlier part of the current review project did find systematic errors in the INM model. It was concluded that the ground attenuation calculation in the INM model was probably 2-3 dB too large. A simplistic analysis would then suggest that noise levels calculated by the INM model would be lower than measured at sites to the side of the flight paths. This would suggest that subjects located to the side of the flight path might be relatively more annoyed because they were actually exposed to higher noise levels than calculated. This is the opposite to the observed results.

The ground attenuation calculations or some other aspect of the INM model may contribute to explaining the flight path effect, but it will require a more detailed analysis including more detailed information on the location of homes and flight paths.

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4.0 SPECIFIC ISSUES

Transport Canada requested that a number of specific issues related to the basic differences between aircraft noise measures be considered in this project. These include the frequency weighting of sounds, the summation of multiple events, and time-of-day weightings. There are further specific issues concerning: whether responses to aircraft noise vary over time, the possible different reactions at smaller airports, and responses to very different aircraft types such as helicopters. Each section of this chapter examines one of these specific issues.

4.1 Frequency Weightings

The human hearing system is not equally sensitive to all frequencies of sound. When rating sounds that are a mix of various frequencies, it is therefore necessary to weight the relative importance of the different frequency components of the sounds. This has been done by calculation schemes as well as by electronic frequency weighting networks. The various schemes have been designed to approximate one of the sets of equal perception contours.

The first set of equal perception contours were the equal loudness contours. These are curves of sound levels versus frequency that represent a constant level of loudness; that is, they represent points of equal loudness. There is an agreed standard format of the equal loudness contours [1] and Fig. 4.1 illustrates one of these contours. This contour rises rapidly at lower frequencies to approximate the decreasing sensitivity of our hearing system. There is also a small increase in the contour at very high frequencies.

The system of equal loudness contours can be used to rate the loudness of single frequency sounds. More complex systems have been developed by Stevens [2, 3] and Zwicker [4] to determine the loudness of sounds that include a mixture of different frequencies. These loudness calculation schemes first require a 1/3 octave analysis of the frequency content of the sound in question. This must be followed by relatively

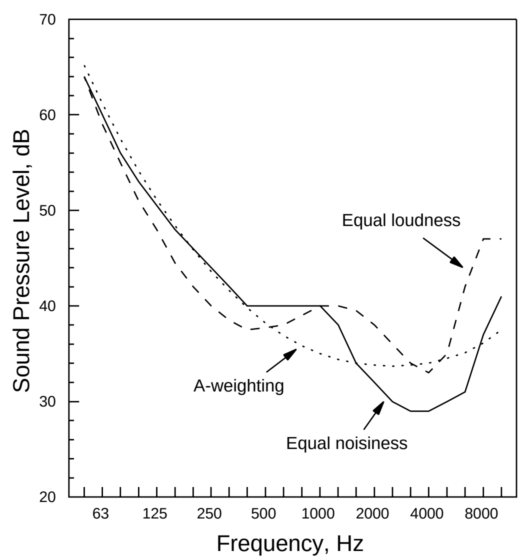

Figure 4.1. Comparison of an Equal Noisiness, and Equal Loudness, and the A-weighting contours.

complicated calculations from the individual 1/3 octave levels to determine the overall loudness of the sound.

Kryter [5] devised a similar system for rating the 'noisiness' of complex sounds. He first produced a set of equal noisiness contours that are quite similar to equal loudness contours. Figure 4.1 also includes an equal noisiness contour. Again, a 1/3 octave analysis of the sound is first necessary. From the 1/3 octave levels the noisiness of each band is determined, and from these the overall Perceived Noise Level, PNL, is calculated. The equal loudness contours and the equal noisiness contours are quite similar, but as Fig. 4.1 illustrates, there are differences. Critics have suggested that for every adjective describing sound there could be further sets of equal perception contours. For example, would equal annoyance contours be similar to equal noisiness contours?.

The calculation of Perceived Noise Levels has been extended to include tone corrections. These are based on the belief that noises with strong pure tone components are more annoying than noises with smoother spectra not having these discrete frequency components. Pure tone components are said to exist when the levels in a 1/3 octave band significantly exceed the levels in adjacent bands. The necessary calculations for the pure tone corrections add considerable further complexity to the calculation of perceived noise levels.

A simpler approach to the frequency weighting of sounds is to use a single frequency weighting network to electronically filter sounds. The oldest of these weighting networks is the A-weighting which dates from the 1930's and is intended to be an approximation to an equal loudness contour. The A-weighting contour is compared with the equal loudness and equal noisiness contours on Fig. 4.1. Although it has a simpler shape, it can be seen to be a reasonable approximation to the other two curves.

The major difference between the calculation schemes (such as PNL) and weighting networks (such as A-weighting) is that the shapes of the latter do not vary with sound level. The equal loudness and equal noisiness contours are not parallel, but get closer together at lower frequencies. This more correctly approximates the response of the hearing system and represents the changing frequency response of the hearing system with sound level. Ignoring this changing response with sound level could cause weighting networks to be less accurate predictors of negative responses to sounds. This would be most significant when considering sounds of widely varying overall sound level.

The A-weighting and B-weighting contours have both been in use for many years and were intended as approximations of two different equal loudness contours. Initially, the A-weighting contour was intended to evaluate quieter sounds and the B-weighting for higher level sounds. The A- and B-weighting frequency responses are compared in Fig. 4.2. In current practice, the A-weighting is almost universally used as a simple single number rating of all types of sounds and the B-weighting is rarely used.

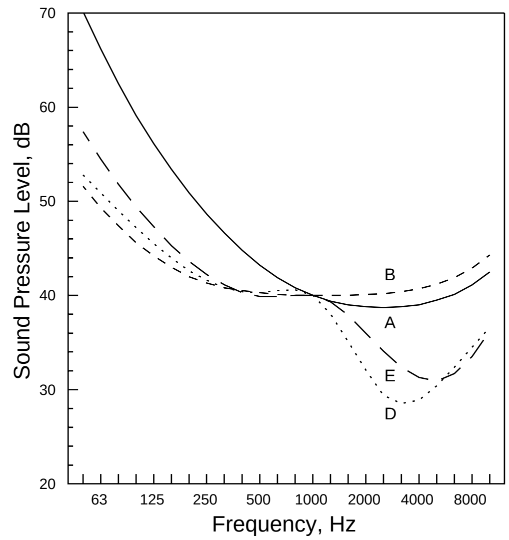

Figure 4.2. Comparison of the A-, B-, D- and E-weighting contours.

After the development of the equal noisiness contours, several attempts were made to develop new frequency weighting networks to approximate these contours. The resulting D- and E-weighting contours are compared with the A- and B-weighting contours in Fig. 4.2. Because the shapes of these weighting curves do not vary with sound level, they can only approximate some intermediate equal noisiness contour. It is not obvious whether they are better overall approximations than the more widely used A-weighting curve.

The relative merits of the various frequency weighting networks and calculation schemes have been considered in a number of studies. Because the Perceived Noise Level, calculated from equal noisiness contours, is a more complex procedure specifically developed to evaluate the noisiness of aircraft sounds, it is expected to more accurately predict negative responses to aircraft noise. On the other hand, using a frequency weighting network offers a much simpler method but usually with some reduction in the accuracy of rating negative responses. For groups of sounds with similar spectra and similar sound levels, the simpler weighting curves should be most successful.

Kryter's perceived noise level, PNL, and the A-weighting procedures are of most interest in this report. The NEF measure is based on the effective perceived noise level, EPNL, which is a tone and duration corrected PNL. The A-weighting is used in many aircraft noise measures such as SEL and L_{dn}.

A 1968 paper by Young et al. [6] compared the ability of various schemes to predict the judged noisiness of aircraft sounds. The authors concluded that using a simple A-weighting was as accurate as the use of the more complex Perceived Noise Level. In another early paper, Botsford [7] referred to the proliferation of so many different rating schemes as the "weighting game". He considered 953 different noise spectra with an emphasis on factory noises rather than aircraft noise. However, he too concluded that the A-weighting procedure was satisfactory for rating the negative aspects of noises. He argued that the correlation between human response and any noise measure is sufficiently low that the choice of the details of the noise rating scheme are often irrelevant.

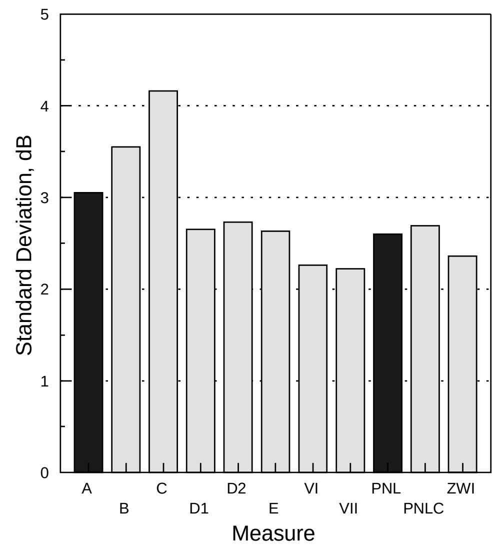

Figure 4.3. Comparison of the prediction accuracy of subjective judgments by various noise measures in terms of the related standard deviations. (A, A-weighted levels; B, B-weighted levels; C, C-weighted levels; D1 and D2, two variations of the D-weighting contour; E, E-weighted levels; VI, Stevens Mark VI loudness calculations; VII, Stevens Mark VII loudness calculations, PNL, Perceived noise levels; PNLC, tone corrected perceived noise levels; ZWI, Zwicker loudness calculations).

Schultz reviewed a number of comparisons of the various rating systems in his book “Community Noise Rating” [8]. He did not make definite conclusions, but pointed out the trade-offs between complex but slightly more accurate schemes, and slightly less accurate but simpler approaches. As Botsford has suggested, the statistical uncertainty in most subjective responses will often make it impossible to determine which measure is more accurate in a statistically significant manner.

Scharf and Hellman [9] carried out extensive comparisons of predictors of human response to noise. Taking data from 23 studies, they compared the prediction accuracy of six weighting curve measures and five calculation schemes. The data included the spectra of many different types of noise. They calculated the standard deviations of the predictions by each of the 11 noise measures. These standard deviations are given in Fig. 4.3. The B- and C-weighted measures were the least accurate predictors followed by the A-weighted levels. The D- and E-weightings and the Perceived Noise Levels form an intermediate group . The loudness measures were the most accurate predictors. If one accepts that loudness and noisiness are different subjective dimensions then it is possible that these results were influenced by the type of judgments in the original studies. These details are not specified by Scharf and Hellman.

Scharf and Hellman state that differences of 0.45 or greater between these standard deviations are significantly different at the $p < 0.05$ level or better. Thus, the Perceived Noise Level, PNL, is just significantly better than the A-weighted level for this group of noise spectra. (These two are highlighted in Fig. 4.3.) However, the magnitude of these differences may be so small as to be of little practical importance. It is also interesting to note that the addition of tone corrections to the Perceived Noise Levels, PNLC, degrade their prediction accuracy. Figure 4.3 shows that the standard deviation for the A-weighted results is only about 0.3 dB larger than for the PNLC results and therefore this difference is not quite statistically significant.

The NEF measure is based on tone corrected PNL values. These results suggest that the NEF measure could be improved by removing the tone corrections to the PNL values. However, Scharf and Hellman suggest that there may be some small benefit from tone corrections if restricted to higher noise levels.

In the special case of low-frequency noise, a number of authors have suggested that A-weighted level measurements underestimate human responses. Kjellberg et al. [10] concluded that both A-weighted levels and Perceived Noise Levels underestimated the annoyance of low-frequency noises and that C-weighted levels overestimated the annoyance and loudness of low-frequency noises. B- and D-weighting level measurements were said to be better but still underestimated the loudness and annoyance of low frequency noises. Persson and Björkman [11] also found that A-weighted levels underestimated the annoyance of low-frequency sounds and that the magnitude of this effect varied with sound level. Broner and Leventhall [12] improved the Perceived Noise Level calculations by extending them to lower frequencies. They found that simple A-weighted levels were more accurate predictors of annoyance to low-frequency noises than the original Perceived Noise Level system.

The application of the various rating systems to low-frequency noises may require some extensions or modifications to the original schemes. However, even in these extreme cases the evidence is not completely clear as to the relative accuracy of the various measurement schemes. The results probably depend on the particular noise spectra that are used.

A very recent study [13] compared various measures as predictors of the noisiness of road vehicle noise. Panels of listeners rated the noise of actual vehicle pass-bys while both indoors and outdoors. They concluded that A-weighted levels and calculated loudness were more accurate predictors of the judgments than were B- and C-weighted levels.

Integrated measures such as SEL were generally more accurate predictors than maximum levels. They also found that both outdoor and indoor subjective ratings were better explained by outdoor noise measures. This suggests that the normal practice of measuring noise levels outdoors in noise surveys is not only acceptable, it is better than trying to measure indoor noise levels.

The better prediction accuracy of the outdoor noise measures can be partly explained by the additional problems of trying to accurately assess noise exposures in rooms. Although this study included three indoor microphone positions, the data from only one of these positions was used in many of the analyses. The measurements of the predominantly low-frequency indoor noise from this single microphone position cannot accurately represent the individual noise exposures of all 20 subjects in the test room. This would lead to lower correlations between indoor noise measures and indoor subjective judgments as observed in this study.

On closer examination of this work, there seem to be other problems interpreting these data. Some plots of mean noisiness versus measured outdoor noise levels are included (e.g. Figs. 9, 12, and 13 of reference [13]) for A-weighted measurements. These results suggest vehicles were judged to be less noisy indoors, as would be expected, but the differences between indoors and outdoors were quite small. For heavy vehicles, the difference in noisiness judgments was equivalent to an approximate 8 dBA level difference. For mixed vehicles, the difference in noisiness judgments was equivalent to A-weighted level differences of 4-5 dBA. The paper makes no mention of the outdoor to indoor sound attenuation of the test building, but it is described as being built of brick with a single glazed window. One would expect the building facade attenuation to be much greater than the 4 to 8 dBA range suggested by the subjective results. These results seem to question either the experimental procedures of this experiment or the effectiveness of building sound insulation to reduce the indoor effects of noise. Unfortunately, there has been no comparable modern study to evaluate the various frequency weighting schemes for aircraft noises both indoors and outdoors.

There is still some uncertainty as to which measure is the most accurate predictor of responses in general and in particular of responses to aircraft noises. There seems to be a trend that Perceived Noise Levels are a little more accurate than A-weighted levels, but that tone corrections do not improve the prediction accuracy of Perceived Noise Levels. It is not clear that this small improvement in prediction accuracy is of practical importance or whether it is worth the added complexity of calculating Perceived Noise Levels. It is interesting to note that A-weighted and Perceived Noise Levels of Chapter 3 aircraft were found to be related to each other with a standard deviation of only 1.6 dB [14]. Thus, if one limited the question to the consideration of modern civil jet aircraft, the similarity of the noise spectra would probably lead to smaller differences in prediction accuracy between the various frequency weighting schemes.

For the precise certification of aircraft, it is arguable that the extra accuracy of the Perceived Noise Level frequency weighting system is justified. For the rating of noise levels in areas near airports, integrated A-weighted noise levels are surely sufficiently accurate. The difference in prediction accuracy between A-weighted levels and Perceived Noise Levels is 0.45 dB according to Scharf and Hellman [9], and even less when tone corrections are included. This error is much smaller than the accuracy of predicting noise levels around airports and quite tiny compared to the errors in predicting the expected annoyance of residents near airports. The 0.45 dB error may be an overestimate in that if only jet aircraft noise were considered, the standard deviation of predictions would be expected to be smaller.

4.2 Equal Energy Hypothesis

Residents near airports are exposed to varying numbers of aircraft, each producing different levels of noise at a particular resident's home. Many noise measures have been devised to predict the combined disturbance of these multiple aircraft noise events. The most common basic hypothesis is that annoyance is proportional to the total energy of the aircraft noise events. Thus, many noise measures are of a form similar to the following,

$$\text{\% Highly Annoyed} = SEL + K \bullet \log(N) \qquad [4.1]$$

where SEL is the integrated single event level for an average aircraft and N is the total number of such events.

If K is exactly 10, then the summation, $SEL+10 \bullet \log(N)$, corresponds to the total energy of the aircraft noise events.

Other values of K have been incorporated into aircraft noise measures. The Noise and Number Index, NNI, has a K value of 15. The German Störindex, Q, (now referred to as an aircraft noise equivalent level, L_{eq}(FLG)), includes a K of 13.3. Both were derived from early aircraft noise surveys and have been widely used. These K values greater than 10 suggest that increasing the number of operations would lead to larger increases in disturbance than a corresponding increase in the level of each aircraft.

The questions of deciding whether the above relationship, [4.1], is appropriate, and the correct value of K, have been considered in terms of both field and laboratory experiments. Laboratory experiments can provide more precise results than field studies, but cannot duplicate all of the influences of the real situation in the subject's home. While field studies can include realistic settings, they are notorious for producing subjective response data that are only weakly correlated with noise measures.

Rice [15] has carried out a comprehensive review of laboratory studies in the United States and the United Kingdom. His re-analysis of laboratory studies suggests that an equal energy approach could satisfactorily explain many of the results, but that it may not be the correct explanation. Initially, the original studies appeared to produce conflicting results. Rice explains these as due to the subjects lack of experience with a variety of aircraft noise exposure situations. That is, subjects cannot properly assess the overall trade-off relationship if they are exposed to quite limited combinations of numbers of events and noise

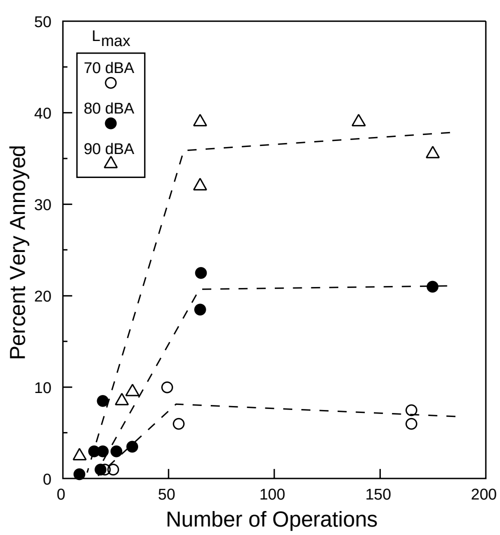

Figure 4.4. Percentage of respondents very annoyed by aircraft noise versus the number of operations per 24 hour period for three different categories of maximum aircraft noise levels. (from Rylander reference 16).

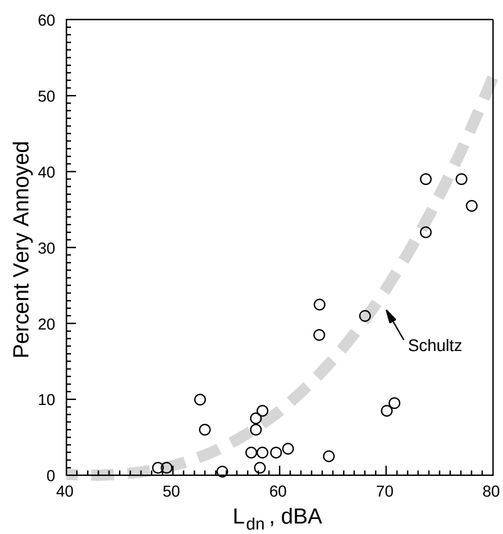

Figure 4.5. Rylander's data for percentage very annoyed plotted versus L_{dn}.

levels. For some cases of limited combinations of levels and numbers of events, the results did suggest an equal energy trade-off. However, when exposures were dominated by numbers of events the relationship became more complex. This may be due to the problem of not being able to produce completely realistic settings in laboratory experiments. Thus, when subjects realized that the number of events was being manipulated they, may have responded more strongly to changes in the number of events in an attempt to get the “right” answer. The problem can only be resolved by more realistic field studies.

Rylander et al. [16] has produced the most controversial field study results concerning the trade-off between levels and numbers of events. His results suggest that the percentage very annoyed increase with numbers of operations up to about 50 operations per 24 hours, and then does not vary for higher numbers of operations. His results are reproduced in Fig. 4.4. Although these results were based on a large number of survey responses, only quite limited noise measurements were possible. Also plotting responses versus a linear measure, that is the number of operations per 24 hours, tends to exaggerate the effects at the few points where there are larger numbers of operations.

Rylander’s data has been re-analyzed here by plotting responses versus estimated L_{dn} values in Fig. 4.5. L_{dn} values were estimated using the following relationship:

$$L_{dn} = L_{max} + 10 \bullet \log(N) + 10 \bullet \log\{20/(60 \bullet 60 \bullet 24)\} + 2 \qquad [4.2]$$

where N is the number of operations per 24 hours. Each pass-by was assumed to have an average effective duration of 20 s, and L_{dn} values were assumed to be 2 dBA greater than L_{eq24} values.

The conversion to L_{dn} values using equation [4.2] is only approximate because the real effective durations are not known and the 20 s value is just a reasonable guess. Therefore, one cannot be sure how well these data agree with the Schultz curve**.** However, Fig. 4.5 shows scatter of data points about the Schultz curve that is typical of most aircraft noise survey results. Rylander's data thus fit an equal energy model as well as most aircraft noise survey results. With such large uncertainty in the results, one cannot be sure of the trends illustrated in Fig. 4.4.

Fields [17] published a very extensive and detailed review of the results from 14 previous surveys of various types of noise. He calculated an optimum K value from the results of each of these surveys. His calculations resulted in K values varying from -3.7 to 23.8. The standard errors of these statistical estimates of the value of K were as a large as 21. Fields suggests that a mean of these studies would suggest a K value of about 5. However, the data are not precise enough to conclude that a K value of 10 is not optimum. Thus, the precision of most aircraft noise surveys is not sufficient to exactly determine the optimum value of K.

The NNI measure has been used in Switzerland for a number of years. This seems to be based on the use of NNI in the United Kingdom. The Swiss aircraft noise survey in 1971 [18] found a K value of 8 to be best. A more recent survey in the United Kingdom [19] was designed specifically to evaluate the relative merits of NNI and L_{eq} measures. It concluded that a K value of 9 or 10 would be best.

Thus, the original studies that led to measures such as NNI are no longer considered to be representative. Laboratory studies cannot predict absolute annoyance because they do not reproduce the complete realistic long term experience of living in a home exposed to aircraft noise. It is unlikely that field studies can be accurate enough to precisely define an optimum value of K. Thus, the practical solution is to use a K value of 10, because it is within the range of possible optimum values and because the simplicity of the equal energy approach is so appealing.

This lack of precise knowledge as to the correct value of K is important because of the expected changes in operations at Canadian airports. Both the average noise levels of aircraft and the numbers of operations are expected to change. With the introduction of quieter Chapter 3 aircraft, average aircraft noise levels will reduce. However, the expected increase in the numbers of operations will lead to increased noise levels. Whether or not the resulting combination of reduced aircraft noise levels and increased numbers of operations is acceptable will depend on the exact nature of the trade-off between the number of events and aircraft noise levels. We can only use the equal energy approach (K = 10) and hope that it is sufficiently close to the way people react to aircraft noise.

4.3 Time-of-Day Weightings

It has generally been assumed that noises during the evening and night-time hours are more disturbing and annoying than those during the day time. There is a long history of the addition of arbitrary time-of-day weightings to aircraft noise measures (see also Chapter 2). Although some early measures used a 5 dB night-time weighting, a 10 dB weighting has most commonly been used. Some measures have also incorporated a separate evening weighting that has typically been 5 dB. By assuming that the integrated exposure over the nine night-time hours should be 10 dB greater than the integrated exposure over the 15 day-time hours, the NEF measure obtained a 12.2 dB night-time weighting. None of these time-of-day weightings were derived from a rigorous scientific study of responses to noise.

The existing time-of-day weightings are simply a consensus of various “common sense” type arguments from groups responsible for the development of the various noise measures. For example, lower noise levels are assumed to be required at night because sleep is more sensitive to disturbance by noise than most day-time activities. While some have challenged these "common sense" type arguments, the evidence in the literature is not conclusive.

An early study by Fidell et al. [20] examined the importance of night-time operations by surveys before and after the cessation of night operations in an area near a major airport. There were 687 landings per 24-hour period and 50 of these had been at night. The cessation of the 50 night operations greatly reduced night-time noise levels but would have reduced L_{dn} values by only 2.5 dBA. Survey responses one month after the cessation of night operations were no different from those before the change. Fidell et al. also reported that a parallel study found no recovery in sleep patterns over the same period. These results suggest that night-time noise levels are not especially important. However, the change in overall L_{dn} was quite small and the recovery of sleep patterns and annoyance responses may take longer than the one month allowed in this study.

Ollerhead [21, 22] published reports concluding that there was no justification for a 10 dB night-time weighting, and suggesting that an evening weighting was perhaps more important. His pilot survey results indicated that people were most disturbed by aircraft noise during the evening and least disturbed at night. He suggested that there was little disturbance for most people at night because they were asleep and did not hear the noises. However, subjects who were disturbed at night considered the disturbance more severe than during the day time.

Bullen and Hede [23] analyzed the data from their five-airport Australian study specifically to determine optimum time-of-day weightings. They broke the 24-hour period into day (07:00-19:00), evening (19:00-23:00), and night (23:00-07:00). The percentage of subjects who were "Seriously Affected" on a composite response scale were correlated with NEF values for a range of evening and night-time weightings. An example of their results is shown in Fig. 4.6. As seen in this Figure, they varied both weightings from 0 to +12 dB. They also included cases where the night or evening noises were totally excluded (labeled -∞).

The correlation coefficients are relatively low as is usually found in such survey results. They do not vary greatly between adjacent combinations of time-of-day weightings. The maximum correlation occurred for a 0 dB night-time weighting and a 6 dB evening weighting. (This column on Fig. 4.6 is marked with an X). A number of the correlations for adjacent combinations of evening and night-time weightings were not significantly different from the maximum value. However, the correlation with responses for the standard NEF (0 dB evening and 12 dB night-time weighting) was much lower.

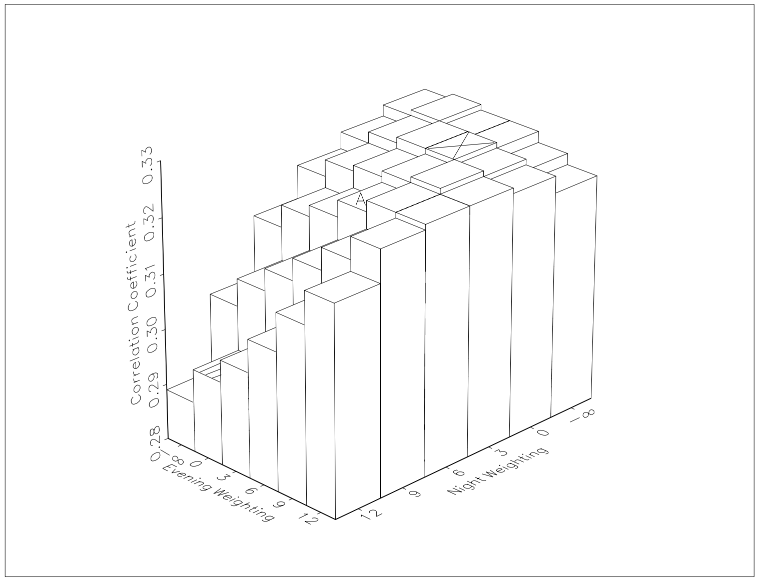

Figure 4.6. Results of correlations between 'Seriously Affected' Responses and NEF values with a range of both evening and night time weightings. The column marked with an 'X' represents the highest correlation (evening weighting = 6 dB, night weighting = 0 dB). The column marked with hatching represents the standard NEF (evening weighting = 0 dB, night weighting = 12 dB). The column marked with an 'A' corresponds to the Australian ANEF (evening weighting = 6 dB, night weighting = 6 dB).

These Australian results again suggest that evening weightings are more important than night-time weightings. Although they indicated that a 0 dB night time weighting is optimum, because of various practical considerations Bullen and Hede recommended a 6 dB weighting for both the evening and night-time periods. This proposal is now incorporated in the Australian NEF measure.

Fields [24, 25] reviewed and re-analyzed a large number of surveys in an attempt to determine the most appropriate time-of-day weightings. He analyzed the various approaches to determining time-of-day weightings and the results of these previous analyses. He explains that there are four different forms of time-of-day weighting models, and there are four different methods for estimating the time-of-day weightings. From 11 studies, he found 15 estimates of time-of-day weightings. However, results from the various surveys were not consistent; each survey tended to produce a different night-time weighting. There was a general tendency for night-time noises to be more annoying, and for a night-time weighting to be beneficial. However, there were also a number of surveys where results suggested that no night-time weighting was best.

The results of surveys are limited by their input data. In particular, at almost all locations night-time noise levels are highly correlated with day-time noise levels. At the same time, responses are usually only weakly correlated with noise measures. Thus, it is usually not possible to accurately determine the combination of day and night-time noise levels that best predicts responses. From an analysis of airport operations, Fields concluded that it would be impossible to find measurement sites that would enable more precise definitions of optimum night-time weightings.

Various practical and "common sense" arguments suggest that some time-of-day weightings are necessary. Existing survey results tend to confirm that some form of time-of-day weighting is required. There are several studies that suggest that an evening weighting is more important than a night-time weighting, and that relatively small night-time weightings are acceptable. The night-time weighting in the NEF measure is larger than in other aircraft noise measures. However, existing survey results do not lead to a precise unique definition of any time-of-day weighting, and Fields has concluded that future surveys are unlikely to do so because of the limited variations in noise exposures around actual airports.

4.4 Changes Over Time

Annoyance to aircraft noise may change over time due to changes in the noise environment, changes in attitudes, or a combination of both factors. There is only limited experimental evidence describing these effects.

Two examples were found of repeated studies at the same airport or airports. Ollerhead [21] compared the results of the first two major surveys at London's Heathrow airport with his own results. His comparisons are repeated here in Fig. 4.7. This plot of mean annoyance versus noise level shows that mean annoyance for a given noise level did not change over the 17-year interval between the three surveys. These results suggest that there were no systematic changes in attitudes to noise around Heathrow airport over this time period.

A survey of aircraft noise around major Swiss airports carried out in 1971 was repeated in 1991. A comparison of the results of the two surveys was made by Oliva et al. [26] and is reproduced here in Fig. 4.8. Again, there is no evidence of any systematic change in attitudes to aircraft noise even over a 20-year period.

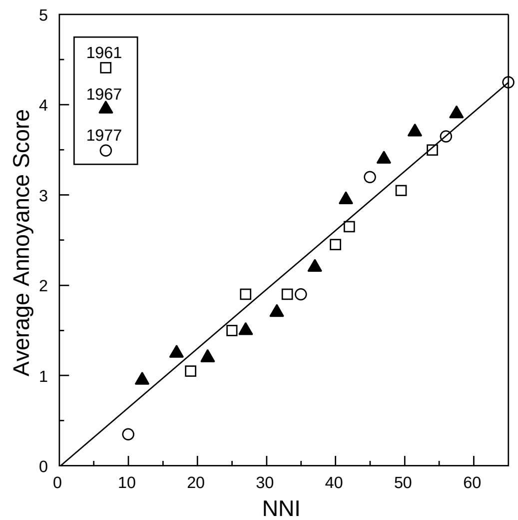

Figure 4.7. Comparison of mean annoyance versus aircraft noise level for three different surveys near Heathrow airport.

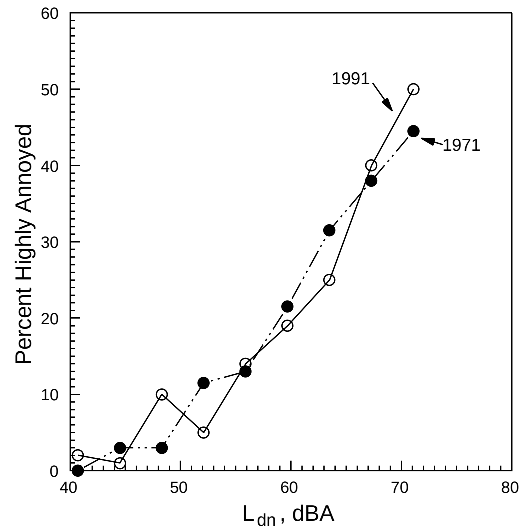

Figure 4.8. Comparison of percentage highly annoyed responses from two surveys near major Swiss airports.

No evidence was found to support the idea that attitudes to aircraft noise are changing. Although people may be more aware of environmental issues and may or may not be more sensitive to aircraft noise, this was not reflected in these two examples of repeated studies.

Other studies have looked at the case of responses to changing noise environments. In section 4.3 above, Fidell et al.'s [20] study of the influence of the cessation of night flights was mentioned. In that study there was no measured change in responses, but the reduction in overall noise climate was quite small.

From studies of road traffic noise, Langdon and Griffiths [27] re-examined data for residents near a road where levels of traffic noise were greatly reduced by diversions of traffic to a new road. They concluded that the reduction in noise levels led to considerably reduced responses. They also found that the change in responses were greater than would be predicted from typical dose response curves based on non-changing noise environments. In other words, the actual change led to a further reduction in annoyance than would have been expected from just the change in noise levels. However, they also mentioned a German road traffic study where the effects tended to be the opposite. In the German study, the noise level reductions were achieved by building traffic noise barriers. Subjectively, this does not seem to be as effective as re-routing the traffic to another road.

Fidell et al. [28] carried out a unique study on the sensitivity of residents to changes in aircraft noise levels caused by runway repairs at a single airport. He surveyed neighbourhoods where noise levels were temporarily increased and others where levels were temporarily decreased. Noise measurements and interviews were carried out at various times before and after the changes in noise levels. They found distinct changes in the percentage of residents who were highly annoyed as a result of the changing noise levels. Figure 4.9(a) shows their results for a site where aircraft noise levels were reduced by over 15 dBA. Annoyance due to aircraft noise over the past week dropped very abruptly with the reduction in noise levels. Annoyance due to aircraft noise over the past year decreased more gradually.

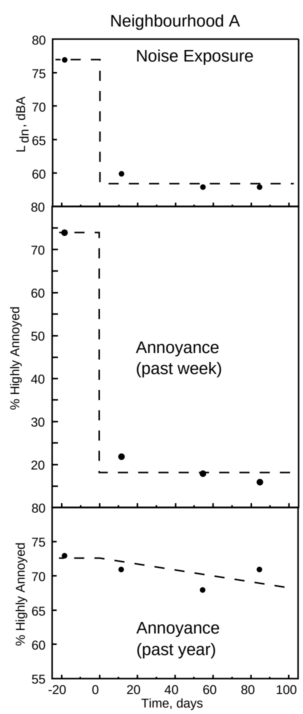

Figure 4.9(a). Comparison of changes in noise levels, short term, and long term annoyance for neighbourhood A where noise levels decreased.

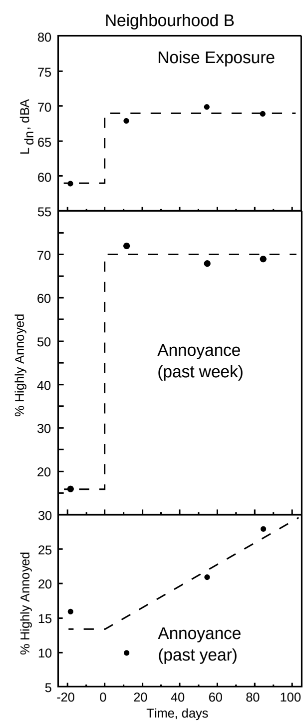

Figure 4.9(b). Comparison of changes in noise levels, short term, and long term annoyance for neighbourhood B where noise levels increased.

Figure 4.9(b) shows Fidell et al.'s results for a site where noise levels increased by approximately 10 dBA. Again, annoyance to aircraft noise over the past week increased quite abruptly with the increase in actual noise levels. Annoyance to aircraft noise over the past year increased more gradually. Thus, the changes in annoyance closely reflected the changes in aircraft noise levels. Fidell et al. also point out that a period of at least two months is required for responses to stabilize after a change in the noise environment.

Raw and Griffiths [29] further analyzed the data of Fidell et al. They found larger changes in responses than would be expected from just the differences in noise levels. That is, the increase in noise levels apparently led to some extra annoyance just because of the negative change, and a reduction in noise levels led to some reduction in annoyance just because of the positive change. This parallels Langdon and Griffith's [27] earlier results for road traffic noise. Thus, predicting the expected annoyance after modifications to an airport may underestimate the change in annoyance if predictions are simply based on dose response curves of annoyance versus noise level.

4.5 Smaller Airports and General Aviation

Most major studies of adverse response to aircraft noise have been carried out near major airports in large cities. The type of aircraft operations and the overall noise environment in these studies would be quite different from situations in smaller cities or neighbourhoods near general aviation airports. Although it is frequently suggested that these factors may influence judgments of aircraft noise, the limited available information does not give an unequivocal description of the effects of airport and community size on responses to aircraft noise.

A study of road traffic noise [30], sponsored by Transport Canada, specifically examined the effects of community size. Annoyance to road traffic noise was less in very small communities than in medium and larger cities at the same noise level. Patterson et al. [31] reported a community size effect for responses to aircraft noise. They quoted results that showed lower percentages of highly annoyed residents near airports in small cities than in larger cities and at the same noise levels. The authors suggested that the differences may be due to social differences that lead to different attitudes to noise in smaller communities, or to seasonal differences. Apparently, the surveys in the larger cities were carried out in the summer months and those in the small cities in winter months. It is not possible to reject either suggestion; both are possible explanations of the observed community size effect.

There is a major difference between the city sizes of the aircraft noise study and the traffic noise study mentioned above. In the traffic noise study, the decreased annoyance was only found in very small rural communities having populations of a few thousand people or less. In the aircraft noise study, the smaller cities were of medium size (Reno and Chattanooga). Thus, it is not clear that the two studies demonstrate similar results.

The study of annoyance around five Australian airports [23] included smaller cities and smaller airports. The percentages very annoyed from this survey were seen to be lower than for the other major surveys considered in Fig. 3.21. For similar noise levels, there tended to be greater annoyance at sites in Sydney than at sites near the smaller airports.

There have been several studies of general aviation airports. Of course, these vary from very small airports with only general aviation activity to larger airports with a mixture of aircraft operations. Because there is not a clear division between the extremes, it is to be expected that studies will provide a range of different results related to the particular mix of operations at the airport studied.

There seems to be a general belief that general aviation activities are more annoying than the same noise level from airline activities. For example, Danish aircraft noise restrictions [32] have lower noise limits at smaller airfields. A study by Harris [33] suggested that noise exposure limits should be 10 dBA lower for general aviation operations than for air carrier operations. He suggested a further 5 dBA reduction for touch-and-go training operations.

Taylor et al. [35] surveyed responses to general aviation operations at Oshawa airport and compared results with those from residents near Toronto airport. There was not a consistent difference between the two situations. Some negative responses were greater at Toronto and others were greater at Oshawa. The authors explained the results by suggesting that a single dose response relationship cannot exist for all airport situations. Differences in the combinations of average peak levels, numbers of operations, and numbers of night-time operations were thought to explain the observed differences.

Schomer's [34] study at Decatur, Illinois, produced results that were said to agree with the Schultz synthesis curve. Thus, Schomer concluded that responses to general aviation operations were the same as for major air carrier operations. Although Decatur is a smaller airport, there were some commercial and military jet aircraft operations and so it represents a mixture of types of operation. The results of Fig. 3.21 suggest that agreeing with the Schultz curve may not indicate similarity with responses at most large airports.

Fidell et al. [36] reported a quite extensive survey of annoyance to mixed types of operations at three smaller airports. They reported greater percentages of highly annoyed subjects than would be predicted by the Schultz synthesis curve. Figure 4.10 compares their best fit linear regression line to the Schultz synthesis and the mean curve of several aircraft surveys from Fig. 3.21. These results indicate greater percentages of highly annoyed subjects than would be found in most studies of large airports.

Ollerhead [37] compared the results of British studies of general aviation operation with air carrier operations at major airports. His data are re-plotted in Fig. 4.11. The percentage of highly annoyed residents near small general aviation airports is seen to be greater than found near major airports in the United Kingdom. The results from the British major airports study were already shown to indicate greater annoyance than the Schultz curve in Figs. 3.17 and 3.21. Thus, these British data seem to be in general agreement with the U.S. data of Fidell et al.

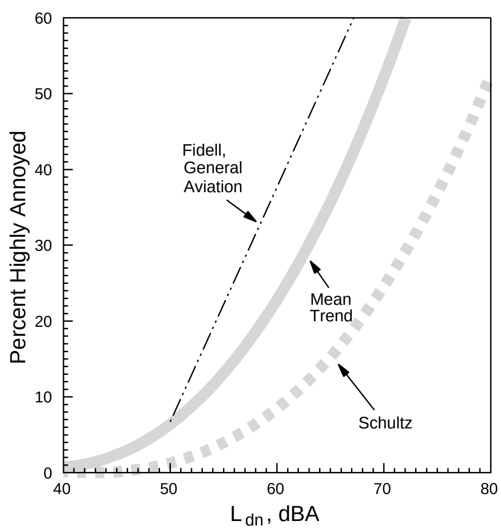

Figure 4.10. Comparison of the percentage highly annoyed from Fidell's general aviation airports with the Schultz curve and the Mean Trend aircraft curve from Fig. 3.21.

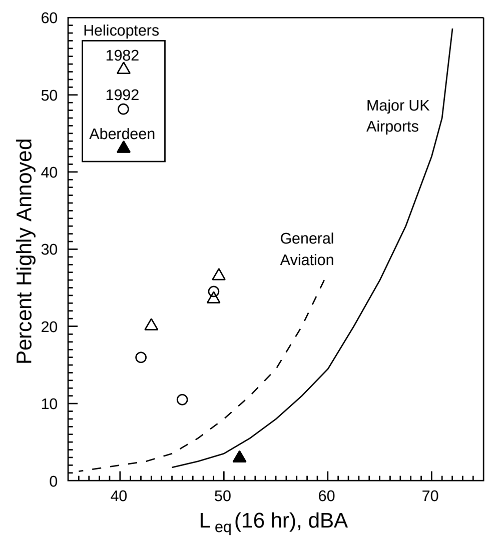

Figure 4.11. Ollerhead's comparison of percentages highly annoyed from surveys near British airports.

In one of the British studies [38], it is stated that there is only a systematic effect of general aviation noise on annoyance to aircraft noise at or above a 16-hour L_{eq} of 50 dBA. Below this level there is a degree of annoyance but it does not correlate with noise levels. Thus, general aviation noise causes some additional annoyance because of people's attitudes to this activity.

Although all studies are not in complete agreement, there is reasonable agreement that general aviation noise is more annoying than noise from air carrier operations. The results of Figs. 4.10 and 4.11 suggest that the difference is equivalent to approximately a 5 dBA difference in levels relative to the Mean Trend results for large airports derived in this report. If the Schultz curve is used as a reference, then the difference will appear to be closer to 15 dBA. However, it is also possible that annoyance to scheduled airline activities at smaller airports is less than at larger airports. Thus, there may be opposite effects of increased annoyance to general aviation activity and decreased annoyance to scheduled airline operations at smaller airports. At smaller airports that combine both types of operations, the two effects may tend to cancel each other. This may explain results such as Taylor's for Oshawa airport.

4.6 Helicopters

Helicopters have noise and operational characteristics that are quite different from those of conventional aircraft, and because of this it is often suggested that the noise that they produce is more annoying. Although there is some evidence to support this idea, other results suggest that helicopters produce similar levels of annoyance at equivalent noise levels.

In Fig. 4.11 comparing British annoyance survey results for general aviation and major airports, data were also included for helicopter noise. The responses to helicopter noise were taken from several studies. The results shown as open circles and open triangles were obtained in areas near London where relatively high socio-economic status subjects were exposed to helicopter traffic between Heathrow and Gatwick airports. This situation led to larger percentages of very annoyed responses than occurred for subjects exposed to the noise from general aviation or the

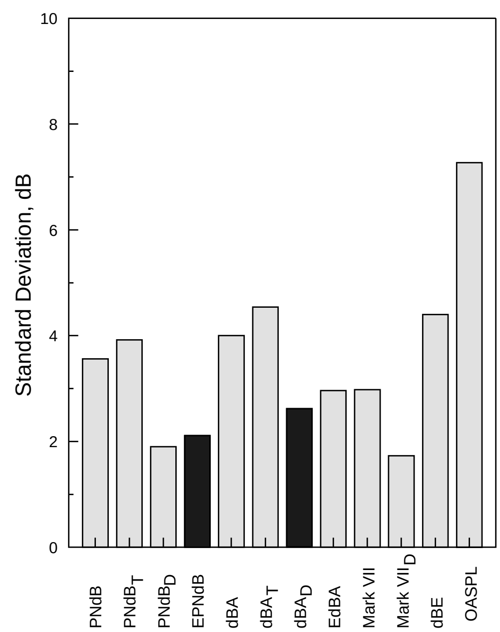

Figure 4.12. Standard deviations of the predictions of annoyance responses by various noise measures. (PNdB, perceived noise level; $PNdB_T$, tone-corrected perceived noise level; $PNdB_D$, perceived noise level with duration correction; EPNdB, effective perceived noise level; dBA, A-weighted sound level; dBA_T, tone corrected A-weighted sound level; dBA_D, A-weighted sound level with duration correction; EdBA, A-weighted sound level with tone and duration corrections; Mark VII, Stevens Mark VII loudness calculation; Mark VII_D, Stevens loudness calculation with added duration correction; dBE, E-Weighted sound level; OASPL, overall sound pressure level).

noise from major airports. However, the survey carried out near Aberdeen (solid triangle symbol) produced quite different results These subjects were much less annoyed than the other subjects exposed to helicopter noise. The helicopter noise in Aberdeen was due to traffic to the North Sea oil platforms. Because work on the North Sea oil platforms was a major economic stimulus to the area, the noise from the helicopters was probably viewed in a much more positive light. Thus, response to helicopter noise may be strongly influenced by non-noise factors that significantly influence attitudes and responses.

Several laboratory studies have examined the question of predicting annoyance to helicopter noise. Figure 4.12 compares standard deviations of the prediction of subjective ratings of helicopter noise by 12 different noise measures from one such study [39]. Perceived noise levels with duration corrections, $PNdB_D$ were the best predictor of subjective judgments. A-weighted levels with duration corrections were slightly less accurate, but the difference was not statistically significant. Duration corrections were always important and loudness calculations, Mark VII; A-weighted levels, dBA; and perceived noise levels, PNdB; all improved with the addition of duration corrections based on a simple energy summation model. On the other hand, tone corrections decreased the accuracy of the predictions when applied to PNdB and dBA measures.

The key results are the comparison of the EPNdB and the duration corrected A-weighted levels, dBA_D (dBA_D would be equivalent to an SEL). These are high lighted in Fig. 4.12. The difference between the prediction accuracy of these two measures for helicopter noise (approximately 0.5 dB) is about the same as for other types of noises shown in Fig. 4.3.

The study also found that the low-frequency content of the helicopter noise and the rotational speed (beats per minute) did not influence annoyance responses. They found that there was no need for a “blade slap” correction, because the characteristic “slapping” sound produced by helicopters increased integrated levels appropriately.

Ollerhead [40] concluded that PNdB, A-weighted and D-weighted levels were similarly successful predictors of responses to helicopter noise. He also found conventional duration corrections to be highly significant to judged annoyance. As in the previous study, no impulsive correction was found to be necessary to explain extra annoyance due to blade slap sounds. Annoyance to helicopter noise was similar to annoyance to conventional aircraft noise when the helicopter noise levels were slightly lower than the conventional aircraft noise levels. Noise measures predicted response to helicopter noise less accurately than annoyance to fixed wing aircraft noise.

Fields [41] confirmed some of these results in a field study of response to helicopter noise. Subjects were surveyed on several occasions and were unaware that the number of helicopter operations were varied as part of the experiment. The effects of levels, number of operations, and the duration of events on annoyance responses were found to be consistent with integrated noise measures such as L_{eq}. After statistically removing the effects of noise level and duration, there were no important differences between annoyance to helicopter noise with blade slap and helicopter noise without blade slap.

In a Norwegian study, Gjestland [42] found that, on average, the annoyance to helicopter noise was similar to the annoyance to civil jet aircraft. However, the annoyance to large helicopters was less than the annoyance to smaller helicopters at the same noise levels. The difference in annoyance responses to large and small helicopters was equivalent to a 4-5 dBA difference in levels. Annoyance to civil jet aircraft sounds was intermediate to that for the two types of helicopters. All events were of the same duration so no information on duration effects was presented.

The bulk of the results in the literature suggest that the disturbance from helicopter noise can be treated similarly to that from conventional fixed wing aircraft. A-weighted levels and PNdB are acceptable noise measures as long as they include duration corrections. Level, duration and number of events should be combined on an energy summation basis. Tone corrections are not helpful. Predicted annoyance may be less accurate than for civil jet aircraft noise and the inclusion of other details of helicopter noise may be able to improve future prediction accuracy.

Work has also progressed on characterizing the noise output from helicopters and the development of prediction models for helicopter noise. Galloway [43] produced helicopter noise level data as a function of distance for a variety of operating conditions. Transport Canada [44] has published a database of helicopter noise levels to be used in noise level predictions. The US FAA [45] has recently produced a Helicopter Noise Model, HNM, for predicting helicopter noise contours. It is not clear how accurate this computer prediction program is or whether it includes details such as the reverberant increase in sound levels in urban environments [46]. ICAO has developed a noise certification procedure for helicopter noise [47], and Cooper [48] suggests that proposed helicopter noise standards in Australia are so restrictive they will "exterminate" the helicopter industry. Where some helicopter operations are mixed with regular air traffic operations, they may not influence calculated NEF values, although they will have significant localized effects. It would seem more appropriate to consider helicopters in terms of single event type noise measures.

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5.0 COUNTER MEASURES

5.1 Source Reduction

Since the initial introduction of commercial jet aircraft, great strides have been made in reducing the noise levels that they produce [1, 2]. Jet noise has been reduced by the introduction of first low- and then high-bypass ratio turbofan engines. In these engines, a large fan at the intake to the engine causes some air to by-pass around the central combustion chambers of the engine. By including this intermediate speed layer of air that by-passes the combustion chambers, turbulence in the engine exhaust and the resulting jet noise are reduced. Another major change has been the introduction of special sound absorbing materials into jet engines. The result has been a reduction of certification noise levels by typically 20 EPNdB since the initial introduction of civil jet aircraft.

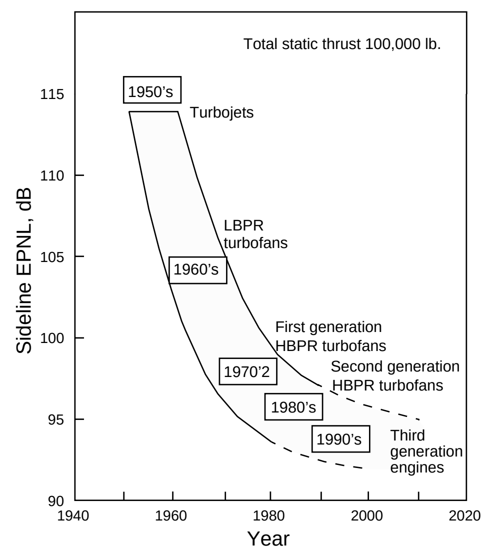

Figure 5.1. General trend of reductions in sideline noise levels of civil jet aircraft (LBPR, low by-pass ratio; HBPR, high by-pass ratio).

Figure 5.1 illustrates [3] the general trend of reduced noise levels plotted in terms of sideline levels measured at a distance of 1500 ft (457 m). Although there was a very rapid initial decrease in aircraft noise levels, the rate of decrease has become much less in recent years. Manufacturers argue strongly that further dramatic reductions are not possible. Because there is no evidence of new basic approaches to obtaining further reductions, one can only expect small improvements as a result of refinements to present design procedures over the next decade. Some small improvements are possible and some European interests have already suggested that the current Chapter 3 limits should be made 3 dB more restrictive for new aircraft. There are differences among current Chapter 3 aircraft and it is possible to have further small reductions in aircraft noise levels by using only the quieter of currently available aircraft as this European initiative would require.

Some Chapter 2 aircraft are being modified to comply with Chapter 3 limits by the addition of Hush Kits. These engine modifications are usually cheaper than complete engine replacements. There is the fear that in some cases the resulting hush-kitted aircraft will only just meet current Chapter 3 limits. This would not be in accord with the general trend to lower noise levels and in particular with the desire for a more restrictive Chapter 3 limit.

Internationally accepted limits for certification noise levels have been the major source of reduced aircraft noise levels. It is important that the process of setting realistic lower future limits for manufacturers continue so that the maximum possible source level reductions can be achieved. The costly research and development of quieter engines will not happen unless it is necessary to meet lower internationally accepted noise limits in order to sell aircraft. While a 3 dB change seems like a small improvement, it is equivalent to re-routing half of the aircraft over-flying a particular area. Even a 3 dB reduction is much more readily achieved and more widely appreciated when it is a reduction in the levels of the source.

It is impossible to guess the magnitude of noise level reductions that may be possible over the longer term. We must first do the research to develop new basic approaches to the problem. At the same time, aircraft engines will evolve to improve their performance and fuel efficiency. The very high by-pass ratio engine has already been tested and, if introduced into regular service, will produce some new types of noise problems. Much larger and possibly more noisy aircraft are also possible. Regulating continuing small reductions in source levels will keep research teams active in this area and this is most likely to stimulate new developments to further reduce source levels.

5.2 Noise Abatement Procedures

Noise reduction at the source is usually the most effective method of obtaining reduced noise levels, but the development of quieter aircraft can take several years. Aircraft can be in service for 25 years or more. Other techniques are required to provide more immediate solutions and to add to the benefits of lower source levels. Many different techniques have been tried. They include various restrictions on aircraft operations, modifications to operational procedures and flight tracks, and restrictions on the use of land near airports. Frequently there are trade-offs between reducing noise exposures and safety considerations. There are also trade-offs between the quality of life of residents near the airport and the commercial interests of nearby communities. The profitability of new residential developments can put extreme pressure on land use restrictions intended to ensure the long term viability of the airport.

Cline [4] has listed strategies for the control of aircraft noise from a survey of a large number of airports. Other references have discussed the approaches at particular airports [5]. Twenty-three different noise control strategies are listed below grouped into five different categories.

5.2.1 Laws and Plans

1. Laws - Various local, provincial, or federal laws can be used to restrict operations and to control noise levels and the use of land near airports.

2. Plans - Airports can develop plans to manage their noise problems. These could include limits on operations, and land use restrictions in areas near the airport. Some airports have developed noise management plans that include a noise budget system [6, 7]. The noise produced by each aircraft type is evaluated and the total contribution of all operations by each airline is calculated. The contribution of each airline to the total noise exposure is restricted to limit the total noise exposure around the airport. This encourages the use of quieter aircraft so that more operations are possible within the same total noise budget. A gradually decreasing total annual noise budget can be used to reduce the overall impact of aircraft noise in cooperation with the airlines using the airport.

3. Noise Contour Maps - The calculation of noise contour maps for both present and future situations is an important element in understanding and controlling airport noise problems.

4. Noise Monitoring - The continuous monitoring of noise levels near airports is important to verify the details of current noise levels and to identify particular problems. The combination of noise monitors and flight track radar information can be a powerful tool for verifying compliance with various noise reducing operational procedures.

5.2.2 Ground Noise

5. Auxiliary Power Units (APU) -Auxiliary power units can be a source of annoyance to residents near the airport[8]. It is important to consider their use when locating terminal areas close to the airport boundary. Noise barriers and buildings acting as noise barriers can often be located to reduce the impact of these noises.

6. Ground Run-Up Noise - After maintenance, jet engines are tested for extended periods while the aircraft is on the ground. This can cause disturbing levels of noise in nearby communities [9]. It is important that these operations be located as far away from nearby residents as possible. In some cases, night-time ground run-up operations may be

banned, but this would in general interfere with efficient maintenance operations. Some airports, such as Orly in Paris, have special noise monitoring systems to help to regulate ground run-up noise.

Ground run-up noise can be significantly reduced by the use of special mufflers or by special noise reducing test hangars [10]. However, airport authorities usually describe these solutions as too expensive. Even the use of screens and enclosures of the test area can be helpful in reducing noise levels.

7. Taxiing and Terminal Operations - Where terminals or taxi ways are close to the airport boundary, noise levels may be disturbing at nearby residences. Barriers or screens can be erected to reduce noise levels, but are often of limited effectiveness. In general, levels will be reduced by only a few decibels and only in areas well inside the acoustical shadow of the screen. They usually have no effect for receiver locations far from the screens [9].

5.2.3 <u>Operations</u>

8. Limit Numbers of Operations - The number of operations can be restricted according to: the time of day, the day of the week or even the season. Such restrictions can limit the most extreme noise exposures near an airport. Orly airport near Paris has a limit on the total annual number of operations.

9. Night-Time Limits and Curfews - Because people are assumed to be particularly sensitive to noise at night, many airports have some form of night-time restriction. In some cases there are complete night-time curfews on operations during specific night-time hours, such as at Zurich in Switzerland and Sydney, Australia. There may be different time periods for limits on landings and take-offs and there may be intermediate time periods where restrictions are phased in each night. Other night-time restrictions are based on the noise output of the particular aircraft.

10. Limits by Aircraft Type or Noise Level - The most obvious example of limits by aircraft noise levels are the various national regulations related to ICAO certification categories. In most western countries, the older and noisier Chapter 1 jet aircraft are no longer permitted. Similarly, Chapter 2 aircraft will be phased out in Canada by the year 2002 . In some European countries, there are already demands for more

restrictive standards than the current Chapter 3 limits. In particular, a 3 dB increase in the Chapter 3 limit is being proposed for new aircraft purchases. Chapter 3 aircraft already in operation would not be affected.

More specific limits are possible such as the banning of supersonic aircraft and level dependent night-time limits. The new British scheme for night-time restrictions at London airports [11] is a noise budget type scheme based on the certified noise levels of each aircraft type. Each aircraft type is assigned a number of points that relate to the noise energy produced by the aircraft. Quotas are assigned to each airline, and night-time operations are limited by these quotas. The British system excludes quieter aircraft from the quotas and hence encourages the use of quieter aircraft rather than limiting the total number of night-time operations.

Several European airports already have night-time restrictions based on maximum A-weighted levels at noise monitor locations. Copenhagen has an 85 dBA L_{max} night-time limit. At Düsseldorf, 79 dBA L_{max} must not be exceeded more than five times per night, and at Münich 75 dBA must not be exceeded more than six times per night. These L_{max} limits may vary according to the distance of the measurement location from the flight track.

11. Noise Weighted Landing Fees - A number of European airports have noise- weighted landing fees. By this scheme, noisier aircraft pay increased landing fees to discourage the use of these noisier aircraft. Although the extra fees are usually relatively small, they add up for large numbers of operations and seem to be a significant influence on airlines.

5.2.4 Flight Tracks and Runway Use

12. Preferential Runways - Runways with approach and departure tracks that do not cross noise sensitive areas can be used preferentially to minimize noise impact. The use of these runways may be limited from time to time by wind direction and other safety concerns.

13. Flight Track Routing - At many airports, departure flight tracks can be modified so that aircraft avoid flying over noise sensitive areas. For example, a turn shortly after take off might avoid flying over a nearby residential area. Such flight track modifications are limited by safety concerns and

complex multiple turns are not usually acceptable. Landing tracks are usually limited to a straight in approach that follows the direction of the runway. In the future, new microwave air traffic control systems may make it possible to safely carry out more complex approach tracks.

14. Displaced Runway Threshold - In some cases, the effective length of the runway has been reduced by displacing the threshold. This is another way of restricting use by larger aircraft.

15. Runway Rotation - By rotating the use of runways, residential areas get periods of relief from the higher levels of aircraft noise. This is a particularly obvious technique where there are parallel runways, and where take-offs and landings can be rotated between the two runways. The result is to share the noise exposure among a larger number of people and to reduce the average noise level of the most severely exposed people.

16. Take Off Climb Modification - Different procedures have been implemented to modify the rate of climb of aircraft after take off so that noise exposures are reduced. In some cases, a maximum safe climb rate is specified so that aircraft gain height as quickly as possible. This would increase noise levels close to the airport but could reduce levels further away. In other cases, thrust reduction is specified at some point close to the airport. The aircraft then climbs more gradually, but produces less noise.

    The most beneficial scheme depends on the details of the airport and the location of noise sensitive areas. For airports with greater numbers of operations, higher noise areas spread out further from the airport. Thus, the point where thrust reduction may be most beneficial will be further from the end of the runway. Proposed noise reducing take off procedures must therefore be thoroughly evaluated in terms of conditions at the airport in question to verify their expected success.

17. Reverse Thrust Limitation - At some airports, such as at Zurich in Switzerland, and Copenhagen in Denmark the use of thrust reversal to slow down landing aircraft is discouraged by local airport regulations. Of course, these limitations can be ignored for safety reasons.

18. Flight Training Restrictions - The repetitive nature of training operations can be particularly annoying to local residents. Limiting these to certain time periods or to less sensitive areas can reduce community response without impeding the regular operations of the airport.

5.2.5 <u>Areas Near the Airport</u>

19. Zoning and Land Use Planning - Land use planning to zone areas near the airport for non-noise sensitive use is intended to minimize the disturbance of the aircraft noise. Some such schemes follow either current or future noise contours precisely, while others draw "sensible" boxes around the actual contours. To avoid the uncertainties of future changes in operations, some are calculated for the maximum capacity of the airport rather than the expected operations of a particular year.

20. Purchase of Land - In extremely noisy areas very close to the airport, noise problems can be solved by purchasing the land and using it for non-noise sensitive activities. Limited numbers of such land purchases have occurred at a number of major international airports.

21. Building Code Restriction - It is possible to have building code type restrictions that require extra noise control features in buildings in areas of higher aircraft noise close to airports.

22. Noise Easements - Such limits on property rights would at least serve to warn purchasers of land near airports that a potential noise problem exists.

23. Extra Sound Insulation - Extra sound insulation can be used to reduce indoor aircraft noise levels. In many cases, airports or government agencies have provided significant financial support for added sound insulation of existing homes and schools in higher noise areas.

5.3 Sound Insulation of Buildings

The upgrading of the sound insulation of buildings is widely accepted as a useful technique for reducing the negative impact of aircraft noise. In many countries, sound insulation programs have been carried out to improve the sound insulation of homes, schools, and hospitals near airports. The cost of the added insulation is usually paid for by revenues from the airport such as from noise penalties added to landing fees. These insulation programs are usually well received by residents near the airport and it is generally considered to be a good public relations gesture as well as a good way to reduce indoor noise levels. There is the added benefit that the extra insulation usually also increases the thermal insulation of the building and hence reduces the costs of heating and/or cooling the building.

Many measurement studies have been made of building sound insulation against aircraft noise. An SAE report [12] summarized the results of measurements of the sound insulation of existing homes in both warmer and colder parts of the United States for cases with windows open and closed. The homes classified as from warmer climates were located in California and Florida. The cold climate homes were located near Boston and New York. Thus, the cold climate homes may be typical of many Canadian homes. The average results given in Table 5.1 show that even with windows closed, noise reductions averaged only 26 dBA. The distribution of measured A-weighted noise reductions for the cold climate homes are given in Fig. 5.2.

	Windows	
Climate	Open	Closed
Warm	11.1	22.4
Cold	17.4	26.4

Table 5.1. Average A-weighted noise reduction for windows open or closed and for both warm and cold climate regions of the United States.

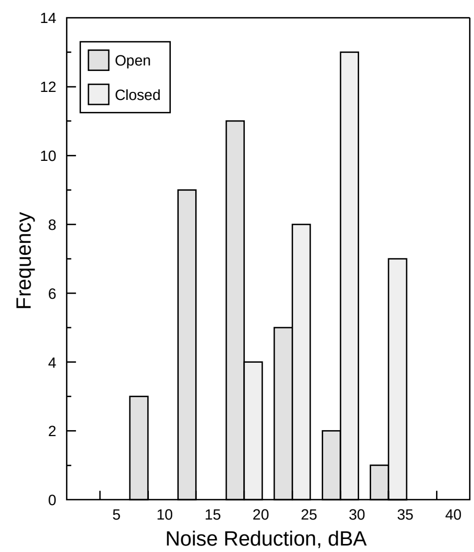

Figure 5.2. Distribution of measured noise reductions of aircraft noise for homes in cold climates with windows open or closed.

In another study [13], measurements of the sound insulation of schools and hospitals found noise reductions of 13.4 to 31.8 dBA with an average of 22.7 dBA. The authors concluded that 10 to 20 dBA increases would be possible in many schools and hospitals. However, the larger

20 dBA improvements would require quite extreme changes such as the complete filling-in of windows. More recent measurements of schools near Pearson airport at Toronto obtained similar results [14]. The noise reductions of aircraft noise in 18 schools were measured. The average A-weighted noise reductions were 15.4 dBA with windows open and 28.3 dBA with windows closed.

A demonstration project in St. Louis, Missouri [15] evaluated the addition of "improved" sound insulation to six single family homes. Measurements of noise reductions of aircraft noise were made both before and after the retrofits of these homes. The measured improvements were in terms of the differences between indoor and outdoor SEL values. Changes in noise reductions varied from -4.0 to +8.3 dBA, with an average of 3.3 dBA. That is, in some cases the noise reductions of the homes were decreased and not increased by the modifications. Apparently, these negative improvements were achieved by replacing older storm windows, having a large air space between the two layers of glass, with double glazing, having a very small space between the two panes of glass. Thus, optimizing thermal performance may not always optimize acoustical performance. Even the most successful retrofits did not produce very large increases in noise reductions, and the authors concluded that a maximum practical noise reduction for wood frame single family homes would be about 30 dBA.

The most common standard test of the sound transmissibility of building partitions is that between two reverberation chambers [16, 17]. In this type of test, sound is incident on the partition more or less equally from all directions. The sound transmission loss of the partition is obtained in each 1/3 octave band and these numbers are compared to a standard reference contour to obtain a single Sound Transmission Class (STC) for the partition. This type of test has been said to be inappropriate for external partitions because outdoor sound is not usually incident equally from all angles, and because these ratings are intended for internal partitions and do not work well for environmental noises with relatively high levels of low frequency sound.

Accordingly, other types of tests have been proposed to supplement the standard laboratory tests. The most realistic approach is to measure the sound attenuation of the building using the real environmental noise source. The Scandinavian countries have this type of standard procedure for measuring the sound insulation of homes against aircraft noise [18]. It involves making integrated measurements of aircraft fly-overs simultaneously inside and outside the building. Other tests use a loudspeaker source to measure the attenuation of the building facade at particular angles of incidence. Jonasson and Carlsson found that an angle of 60 degrees gave the best agreement with laboratory test results for windows [19].

From an extensive series of measurements of facade attenuations of a test house, Quirt [20] found small differences between laboratory measurements and his field tests using aircraft as the sound source. Thus, when measurements are made by integrating over a complete aircraft pass-by, the results seem to agree with laboratory tests within 2 to 3 dB.

When the facade attenuation is examined in more detail as a function of the angle of incidence, larger effects can be found. Quirt reported [20] that the facade attenuation could vary by up to 10 dB with incident angle and that the minimum attenuation occurred for incident angles between 70 and 80 degrees. Hall and Bechrakis [21] made measurements on a number of homes near Pearson Airport and concluded that angle of incidence effects led, on average, to variations of approximately 5 dB in facade attenuation during aircraft flyovers.

Because most facade constructions provide the least attenuation at lower frequencies, indoor noise levels can be influenced by the spectrum of the aircraft noise and in particular the relative amount of low-frequency sound energy [21].

The attenuation of facades varies considerably with the area of open windows. Quirt [22] has shown that this is largely related to the percentage of open area formed by the open window relative to the area of the total partition. Thus, a 10 dB noise reduction would be expected to correspond to 10% of the facade area being open windows. Of course, when the percentage of open window area is quite small it may be necessary to correctly add the transmission loss of the various elements of the facade.

Various single number rating schemes have been proposed to improve on the suspected deficiencies of the STC system intended for internal partitions. The Exterior Wall Rating system (EWR) is similar to the standard STC approach but uses a different set of reference contours [23]. These contours were developed to better include the effects of low-frequency environmental noise and were based on a source spectrum that was intermediate to aircraft and road traffic noise.

The Outdoor-Indoor Transmission Class (OITC) approach has recently been standardized in the United States [24]. This procedure uses a specific source spectrum and measured 1/3 octave transmission loss values to calculate the expected indoor A-weighted sound level. The source spectrum is quite different to that used to develop the EWR measure and doesn't seem to be representative of aircraft noise. This source spectrum is compared with the average of measurements near Pearson Airport [14] and the source spectrum used in the CMHC document [25] in Fig. 5.3. The spectra in this figure were normalized at 1000 Hz to the value of the CMHC document spectrum to permit an easy comparison. The OITC spectrum is similar to the measured aircraft noise spectrum at intermediate frequencies but indicates higher levels at both high and low frequencies than found for typical modern jet aircraft noise spectra.

A simpler method for accounting for the source spectrum was proposed by Quirt [26]. This procedure includes a table of corrections to be added to laboratory measurements of STC values to account for various typical source spectra.

None of these single number rating systems is widely used. In many cases, only A-weighted level reductions are used to rate external facades.

In Australia, there is a national standard procedure [27] for calculating the amount of noise intrusion into buildings sited in high levels of aircraft noise. Similarly, in Canada the CMHC document "New Housing and Airport Noise" [25] has been widely used to design improved sound insulation against airport noise. This guide was one result of a collaborative effort of the National Research Council, Central Mortgage and Housing, and Transport Canada over 20 years ago.

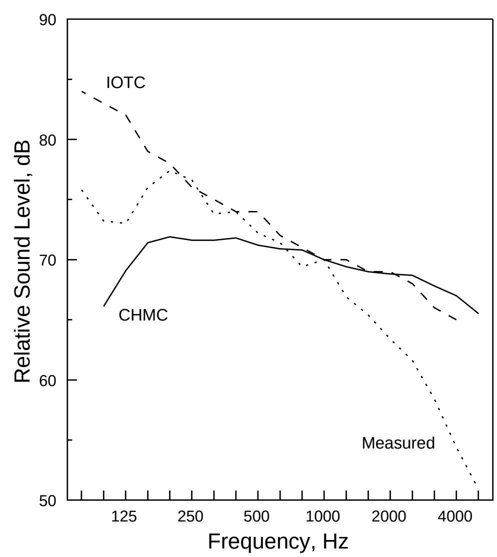

Figure 5.3. Comparison of aircraft noise spectra from the CMHC guide [25], from the OITC standard [24], and from measurements at Pearson Airport [14].

Although the CMHC guide has been a valuable tool for the design of improved building attenuation, it is now out of date and very much in need of being revised. The source spectrum used in the document is shown in Fig. 5.3 and clearly does not correspond to modern aircraft noise spectra. Although modern jet aircraft tend to be quieter, they do tend to have relatively higher low-frequency levels than indicated by the older CMHC guide source spectrum. Because building facades offer the least attenuation at low frequencies, the low-frequency details of the source spectrum can be quite important. The CMHC guide also needs revising because it does not reflect modern building trends. Many types of facade construction that are common today are not included and these include lighter weight constructions that would have lower sound attenuation values. A further problem with the CMHC guide is that the procedures have never been verified by measurements on actual houses near Canadian airports.

Although many studies have reported objective measurements of the sound insulation of buildings, there have been very few studies of the perceived effectiveness of added sound insulation on long term responses such as annoyance. In a laboratory study, Flindell [28] had subjects evaluate the effects of added sound insulation. He found that the subjective evaluations of the effects of storm windows were less than would have been expected from the reduction in A-weighted noise levels. However, it is not possible for a laboratory study to completely evaluate the long-term benefits of added home insulation.

Langdon's [29] traffic noise studies suggested that reducing traffic noise by re-routing the traffic was more effective than the same reduction achieved by adding noise barriers. Solberg et al. [30] compared the effects of noise barriers and added insulation. Their studies were carried out in Norway on residents of homes exposed to road traffic noise. Figure 5.4 reproduces their plot of the reduction in annoyance versus the reduction in noise levels. The regression line shows the average trend for noise reduction using noise barriers. The data points for the cases of added insulation all fall on or above this line. Thus, for the same noise reduction, added sound insulation led to greater reductions in annoyance. This tends to parallel Langdon's conclusions for road traffic noise and suggest that added sound insulation is more effective than noise barriers for road traffic noise.

Fidell [31] carried out a field survey of the effectiveness of added sound insulation for homes exposed to aircraft noise. Residents in homes both with and without added sound insulation were interviewed in areas exposed to higher levels of aircraft noise. Fidell's results are seen in Fig. 5.5 compared to the Schultz curve. The new data points, for both insulated and non-insulated homes, lie above the Schultz curve similar to the other airport noise studies shown in Fig. 3.21. Fidell concluded, "…no clear benefit of home insulation was observed in terms of lowered prevalence of annoyance to aircraft noise…" There was no overall, statistically significant, reduction in annoyance due to added home sound insulation.

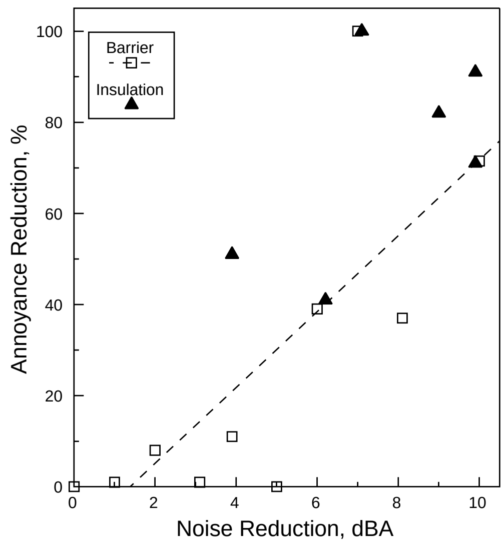

Figure 5.4. Comparison of the reduction in road traffic noise levels and the related reduction in annoyance.

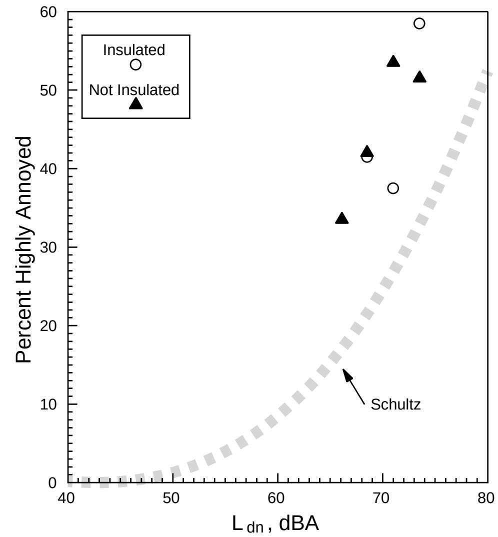

Figure 5.5. Percentage highly annoyed by aircraft noise for homes with and without added sound insulation.

In a study of the effects of aircraft noise on students in schools exposed to aircraft noise, Cohen et al. [32] considered the effects of added sound insulation to some of the classrooms. Peak aircraft noise levels were said to be reduced by 20 dBA, but no details of the added insulation were given. Children in treated classrooms reported fewer problems hearing their teachers and performed better on school achievement tests than children in non-treated classrooms.

Combining all of the available information suggests that added sound insulation is at best only a partially successful solution. Large reductions in indoor noise levels are difficult to achieve. Probably, a careful analysis of each home is first required by knowledgeable experts in order to achieve substantial additional noise reductions. The added sound insulation can only be effective while all windows and doors are kept closed. Special noise attenuating ventilation systems will also be required, and in climates with warm summers air conditioning may be an essential part of the added sound insulation package. In more temperate climates, where windows are normally kept open and air conditioning is not in wide spread use, added sound insulation may not be a practical alternative for reducing indoor aircraft noise levels. Of course, there can be no improvement to the outdoor environment.

Added sound insulation can improve only the indoor environment and may have no significant reduction on long-term annoyance to aircraft noise. Annoyance is presumably influenced by outdoor noise levels as well as indoor levels. In extreme cases, where indoor aircraft noise levels are so high that they interfere with speech communication, the benefits of added sound insulation become more obvious.

5.4 Land Use Planning

Land use planning is an obvious and almost universally accepted technique for minimizing the negative impact of airport noise in areas adjacent to airports. It is an especially appropriate approach in a country like Canada where large areas of land are not developed and there is space to take a rational planning approach. However, what seems so rational and simple does not always happen.

Land use planning near airports requires the division of land areas near airports into zones according to noise levels and the choice of acceptable uses in each of these zones. Although land use planning to minimize airport noise impact is widespread, there are many different noise measures, many different procedures for selecting zone boundaries, and many different acceptability criteria. It is usually quite difficult to determine in detail how the various regulations are applied in each country. Some apparently strict noise criteria can be quite ineffective if not adequately enforced.

Although various countries use different noise measures to characterize aircraft noise, the noise measures are almost always integrated measures that sum the total noise exposure over at least a number of days. Such measures would include, NEF, L_{dn}, and L_{eq}. Noise level contour maps are usually calculated to describe the noise environment around an airport in terms of one of these integrated noise measures. It is usually possible to make approximate conversions between the various integrated measures to compare planning limits in various countries. In some cases, additional single event measures such as peak noise level limits are also used such as in Norway [33]. Peak levels are more difficult to estimate for future situations, but it is easier to establish acceptable limits in terms of single event measures.

There are various methods for drawing boundaries to land use zones, but they all usually start from the calculated noise level contours. The noise level contours can be intended to reflect: current conditions, conditions at some future date, or conditions for the maximum capacity of the airport. The zone boundaries can exactly follow one of the calculated noise contours or they can be the result of some practical approximation to the noise contours. For example, rather than follow the exact course of a noise contour, they can be expanded to follow roads or some other obvious land division.

As a planning tool, basing land use zone boundaries on current conditions seems unacceptable. One must plan for the future. However, setting up boundaries based on expected conditions for a particular date in the future can also lead to problems. The number of aircraft operations and the resulting noise levels may increase after that date and residential areas might then become unacceptably noisy. Setting planning limits that are based on the maximum capacity of an airport might seem to avoid these problems, but only if the maximum capacity is not exceeded. Of course, this often occurs when airport facilities are expanded.

Setting up zone boundaries that exactly follow noise level contours will lead to numerous arguments over the development of properties on or close to the zone boundaries. It is much more practical to have zone boundaries that follow some logical land division such as a road and at the same time are outside the actual noise level contour. Such a practical alignment of zone boundaries should make administering the system of planning zones much easier.

There is a basic problem with the concept of basing zone boundaries on the aircraft operations expected on some particular future date. Such an approach corresponds to continually changing boundaries to planning zones. This is particularly relevant over the next few years as quieter Chapter 3 aircraft are phased in. Initially, the introduction of quieter aircraft will cause noise contours to shrink. However, as the number of operations increase, the noise level contours will grow larger again. Thus, it would be possible to set zone boundaries based on a future date corresponding to the minimum contour areas. Such a scenario could lead to noise-sensitive developments in areas that would subsequently become excessively noisy.

It would be better for long-term planning commitments if land use boundaries around airports were considered to be fixed to meet the long-term needs of both airport and adjacent communities. The airport would then have the responsibility of managing its operations to meet the fixed noise level limits at each zone boundary. Operations could be increased by introducing quieter aircraft or by re-routing flights, but the boundaries and noise level limits would be considered fixed. It would be the airport's responsibility to ensure that planning limits were not exceeded and the communities' responsibility to regulate the use of land near the airport. In exceptional cases, where there is a need to expand the airport beyond the planning limits, then this modification of the planning limits should be based on negotiations with the local community. The trade off between expanded commercial benefits to the community and the costs of increased noise exposures should be reflected in financial support for solving the new noise problems that are created. For example, the airport might pay the cost of additional sound insulation for homes in areas that would become too noisy, and where there would be significant noise level increases the airport might buy homes and convert them to some non-noise sensitive use.

Because land use planning is a local and provincial concern, and aircraft noise is produced at federally operated airports, there is a need for considerable inter-governmental co-operation. Developing this co-operation in a uniform manner across the country is the only way to develop a coherent approach to airport noise problems in Canada.

Land use near airports has also been considered in terms of the reduced value of homes due to their proximity to the airport. Levesque [34] reviewed several studies and found an average 0.63% reduction in the value of homes per NEF unit. A study near Winnipeg airport [35] found a 0.65% reduction per NEF unit. These figures would suggest that a $100,000. home at NEF 25 would be worth $6,500. less at NEF 35. This is a readily quantifiable negative effect of the airport and the resulting aircraft noise. It might be used to assess property tax values, or the amount of compensation that the owner is due, but it is not useful for setting land use planning limits. These limits are better based on the effects of noise on people.

Land use planning limits vary from country to country but usually include specific mention of conditions acceptable for residential areas. Typically, there is a lower noise level limit below which residential construction and almost any other noise-sensitive use is allowed. There is usually an intermediate range of noise levels where residential construction is allowed if it includes extra sound insulation. Finally, there is an inner high noise zone in which only non-noise sensitive activities are allowed.

Transport Canada recommends [36] that residential construction only be allowed at noise levels of NEF_{CAN} 30 or less. This is approximately equivalent to Ldn 61 and is a little lower than the L_{dn} 65 limit in the US FAR Part 150 regulations [37]. The equivalent recommendations in the UK correspond to approximately NEF_{CAN} 30 [38] and in Denmark [39] and Australia [40] to NEF_{CAN} 24. Thus, there is a range of limits and Canada is towards the top of this range. In the review of the derivation of the NEF measure and the associated limiting values in Chapter 2, it was seen that the Canadian limits are not based on a comprehensive scientific study, but evolved from various consulting case studies in the U.S.A. If land use planning is to be seriously considered, the question of noise level limits needs to be thoroughly re-examined.

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6.0 AIRPORT NOISE IN OTHER COUNTRIES

6.1 Overview

Although airport noise problems are caused by the same types of aircraft throughout the world, the approaches to controlling these problems vary considerably from country to country. Almost every country uses a different noise measure and different levels of acceptability. In some countries procedures are included in national laws, while in others aircraft noise regulations are merely guidelines that should be followed or only apply to a few airports.

Much of the information presented in this chapter was obtained from personal contacts with various people during a number of technical visits carried out as part of this project. Appendix 1 gives a complete list of all technical contacts. The various noise measures were completely defined and compared in an appendix of a previous report [1]

Country	Noise Index	Contours Major Airports	Outer Contour	NEF_{CAN} Equiv.	Prediction Models	Noise Monitor	Flight Track Info.
Australia	ANEF	Yes	20	24	Mod. INM	Yes	Yes
Canada	NEF_{CAN}	Yes	30	30	NEF_1.7	Yes	
Denmark	Lden	Yes	55[3]	23	DANSIM	Yes	No
France	I_p	Yes	78	28	several	Yes	No
Germany	L_{eq}(FLG)	Yes	67	38	several[1]	Yes	No
Japan	WECPNL[4]	Yes	70	26	several	Yes	Yes[2]
Netherlands	K_e	Yes	35	-		Yes	
Norway	EFN	Yes	55	24	INM	Yes	
Switzerland	NNI_s[5]	Yes	45	35	simulation	Yes	Yes
United Kingdom	L_{eq}(16 hr)	Yes	60	32	several	Yes	
United States	L_{dn}	Yes	65	34	INM, NOISEMAP	Yes	

Notes

1. Calculation details specified in German law.
2. System of acoustical tracking used at Tokyo Narita airport.
3. Lower for small airports.
4. Use L_{den} at small airfields.
5. Use L_{eq} at small airfields.

Table 6.1. Summary of approaches to aircraft noise in 11 countries.

Table 6.1 summarizes some aspects of the regulation and monitoring of aircraft noise in 11 countries. Each of the 11 countries uses a different noise measure although some are closely related. All countries in Table 6.1 do calculate noise level contours around major airports, but acceptable noise levels vary considerably. The noise level of the lowest noise contour represents the boundary where aircraft noise is considered to begin to be a significant problem. These are given in Table 6.1 and are also converted to approximate NEF_{CAN} values [1]. The estimated NEF_{CAN} values of the outer contours vary from 23 to 38. The highest value (NEF_{CAN} 38) is for Germany where aircraft noise is regulated strictly by a national law. The lowest value (NEF_{CAN} 23) is for Denmark where the regulations do not apply to the major airport at Copenhagen.

All of these countries use aircraft noise prediction programs to calculate expected noise levels. Several countries use the American Integrated Noise Model, INM, or at least a modification of it. Most countries have their own models and often there are several different models in use in each country. Noise monitoring systems exist in all 11 countries but vary considerably in extent and degree of sophistication. Only a few countries have systems that routinely combine flight track information.

The following sections summarize in more detail the approaches to aircraft noise in various countries.

6.2 Australia

6.2.1 Description of Noise Measures

Australia uses a modified version of the NEF metric referred to as the ANEF [2]. It is the same as the original NEF measure used in Canada except for different time-of-day weightings. Day-time, from 7:00 to 19:00 hours, receives no weighting; the evening, from 19:00 to 22:00 hours, and night-time, from 22:00 to 7:00 hours, both receive a 6 dB weighting. (Noise measures are more completely defined in reference [1].)

The ANEF measure was a result of a large survey of residents near major Australian airports. The survey concluded that people were more disturbed by aircraft during the evening period and that a reduced night-time weighting was acceptable. Because it is incorporated in a National Standard and has been thoroughly validated in Australia, the ANEF is well accepted as a satisfactory measure of the negative impact of aircraft noise.

6.2.2 Limits

Australian standard AS 2021-1985, "Acoustics -Aircraft Noise Intrusion - Building Siting and Construction" contains clear land use planning limits. Below ANEF 20, all types of construction are acceptable. Between ANEF 20 and 25, construction of noise-sensitive types of buildings such as homes, schools, and hospitals are required to have satisfactory sound insulation. Above ANEF 35, no types of new buildings are accepted.

Because these limits are in a national standard, they are considered to apply to all Australian airports. Thus, there is a uniform system of limits throughout Australia.

Australia has a separate standard for helicopter noise, AS 2363 - 1990, "Assessment of Noise from Helicopter Landing Sites". It prescribes limits in terms of L_{eq} values for busier helipads and in terms of maximum levels for less frequently used sites. This a new standard that is quite controversial in Australia [3].

6.2.3 Noise Monitoring Systems

Sydney and Brisbane airports have new and quite sophisticated noise monitoring systems with integrated flight track radar information. It is planned to expand the systems to other major airports. The system is seen to be an invaluable tool for monitoring the causes of airport noise problems and providing detailed information to respond to complaints about unusually noisy events. They also plan to carry out studies of the relative contributions to the total noise levels by aircraft type and by airline to look for ways of improving the noise environment.

6.2.4 Remedial Measures and Added Sound Insulation Programs

Financial support for added sound insulation and the buying of homes in exceptionally noisy areas near Sydney airport has been used to minimize the impact of aircraft noise. As a part of the construction of a proposed new third runway, residents newly exposed to aircraft noise levels exceeding 20 ANEF will receive compensation to improve the sound insulation of their homes.

6.2.5 Computer Models

The Australian Civil Aviation Authority uses a modified version of the American INM computer program. They have modified the source code to incorporate the ANEF evening and night weightings. The Civil Aviation Authority calculates contours for almost all major Australian airports because this modified version of the INM model is not readily available.

These calculated ANEF contours are used to determine the suitability of land near airports for noise sensitive developments.

6.3 Denmark

6.3.1 Description of Noise Measures

Denmark uses L_{den} which is an integrated energy equivalent A-weighted measure similar to L_{dn}, but with a 5 dB evening weighting in addition to the 10 dB night-time weighting. Thus, day-time extends from 07:00 to 19:00 with no weighting, evening from 19:00 to 22:00 with a 5 dB weighting, and night-time from 22:00 to 07:00 with a 10 dB weighting.

6.3.2 Limits

In Denmark, there are planning guidelines or recommendations that specify acceptable land use relative to aircraft noise levels [4]. For major airports, housing is not permitted in areas with L_{den} > 55 dBA. This is approximately equivalent to L_{dn} 54 dBA or NEF 19. For medium sized airports, this reduces to 50 L_{den} (approximately NEF 14), and for small general aviation airports the maximum is only 45 dBA (approximately NEF 9). While these limits are used to restrict the construction of new housing, in-fill construction of housing in noisier areas is usually allowed, and these limits do not apply to the major airport at Copenhagen.

Copenhagen airport is very much a special case in that it is much busier than other airports and there are serious noise problems with houses close to the airport. Copenhagen does not have a night-time curfew, but there is an 85 dBA L_{max} limit at night. Thus, any aircraft that exceeds this level at night at monitoring locations in the nearby community is not permitted.

There is also a special restriction on the use of full thrust reversal at Copenhagen airport. There is a monitoring location at the end of the runway to verify that full thrust reversal is not used except when safety requires it, such as under slippery runway conditions.

In Denmark, they are now considering further more restrictive limits at airports with particularly annoying activities. These include the flying of ultra-lights, glider towing, training, and instruction flights, etc. These will have new more restrictive time-of-day penalties. Now L_{den} includes a 5 dB evening and a 10 dB night-time weighting penalty. The new proposal would have a 10 dB evening weighting and a 15 dB night weighting. Also, there would be a 10 dB day-time weighting on the weekend. This would mean that new airports intended for these activities would have a larger buffer of land around them before the construction of housing is permitted.

6.3.3 Noise Monitoring Systems

At Copenhagen airport, there is a noise monitoring system with ten microphones located in the nearby communities. The system is fully automatic and includes flight track radar data. They are thus able to check the causes of excessive noise levels. They also use the system to verify that night-time limits are not exceeded (i.e. the 85 dBA L_{max} limit mentioned above).

6.3.4 Remedial Measures and Added Sound Insulation Programs

Denmark has not undertaken large schemes to buy houses in very noisy areas. (with a few exceptions near Copenhagen airport).

There has been a large home insulation program in the vicinity of Copenhagen airport (130 million DKR or approximately $26 million Canadian were spent). Homes close to the airport received 90% of the costs of adding sound insulation. This usually included double glazing and added material in the roof or ceiling of homes. Homes further from the airport received less financial support, decreasing to 50%. There is a general feeling that this insulation was well received, but there have never been any annoyance studies in Denmark. Thus, there is no concrete evidence that people are more or less annoyed. Added acoustical insulation includes the added benefit that the homes became thermally better insulated (in a country where it costs about four times as much to heat a house as it does in Ottawa).

6.3.5 Computer Models

DANSIM is the current name of the Danish airport noise prediction model [5]. It was developed by the Danish Acoustical Institute and seems to be the only model currently used in Denmark. They claim that their model is different and better because it uses a simulation technique. That is, at each measurement grid point on the ground the energy from each aircraft is summed as the aircraft is moved in steps along the flight path. (Models such as INM consider the energy from each aircraft at only the point of closest approach to the measuring grid points.) The DANSIM calculations are performed for the average number of operations during the busiest three months.

6.4 France

6.4.1 Description of Noise Measures

In France, the integrated noise measure for airports is called the Psophique index, I_p. It is calculated from the mean PNL_{max} and the number of events on an energy summation basis. I_p is described in a national law governing airport noise in France. This 1986 law is a replacement of an older law, and thus the I_p index is well established in France. Because the I_p index is described in a national law that is referred to by other laws, there is little interest in changing to some other noise measure. There is no attempt to measure I_p values. These are only to be predicted for future situations.

6.4.2 Limits

The Aéroport de Paris authority is responsible for all airports within 50 km of Paris. A national government agency is responsible for all other airports. The Paris airports together handle ten times the traffic of the next largest airport (50 million versus 5 million passengers per year). While noise is a serious concern at the Paris airports, such concerns are said to be less developed at the other French airports.

The national airport noise law overrides local land-use planning. The law and associated regulations describe the steps involved in first developing and getting approval for a master plan. After other technical studies and noise contour calculations, the predicted I_p contours are divided into three zones:

Zone	I_p	approx. NEF	Comments
A	> 96	43	for airport use only
B	> 89	35	industrial use only, no new houses
C	≥84	30	new houses allowed but insulation
	≥78	22	for ≥35 dBA noise reduction required

The outer limit of the C zone is “negotiable” from 84 to 78 I_p. Houses within the C zone must have a noise reduction of ≥35 dBA. Only detached single homes can be built in zone C to minimize the density of people living in this area. Immediately outside the C zone it is recommended that houses have a noise reduction of at least 30 dBA.

Orly airport near Paris has residential areas up to the airport boundary, and many of them are inside the B zone. As a result, there are many serious noise problems. There is a special limit on the total number of operations at Orly airport. Because of the combination of this limit and decreasing aircraft noise levels, there is hope for improvements in the future. Orly has a night-time curfew from 23:30-06:00. It used to exclude aircraft carrying mail, but these are now routed to Charles de Gaulle airport. Charles de Gaulle airport was located away from the urban areas of Paris to avoid noise problems. However, as the airport and new housing areas expand, noise problems may develop there too.

6.4.3 Noise Monitoring Systems

At Orly airport, they have a small (two-microphone) monitoring system to check on night-time ground run-up noise levels. They have a problem getting airlines to use an existing muffler when performing night-time ground run-ups to verify that engines are working properly after maintenance. One microphone is located close to the maintenance area and the other close to airport boundary. By comparing these they can identify noise peaks near local houses that were due to ground run-up activities. The level of the noise in the maintenance area tells them if the muffler was used. It provides 10-15 dB attenuation.

Orly airport is now in the process of installing an automatic noise monitoring system to monitor aircraft noise levels in the adjacent community. No other French airport has a noise monitoring system. There will eventually be 12 microphone locations in the community surrounding the airport and under the flight paths. They will be located as far out as the outer marker. The system will use Bruel and Kjaer hardware and French software to link the noise data with flight track radar data. The software is now being developed.

The main purpose of the noise monitoring system is for public relations. There will be active public display boards showing the noise levels at each monitoring station. Their team of five public relations people spends much of its time responding to complaints and working with the local communities. These people will have access to both the noise and flight track data when the new system is up and running later this year. Thus, they will be able to use this information to respond to complaints.

The monitoring system will measure A-weighted levels. There is no intention that the system be used to verify the noise prediction model. It is not likely that they would regularly monitor the flight tracks for examples of large deviations from the central track as done at Zurich. This would infringe on the independence of the air traffic control group.

6.4.4 Remedial Measures and Added Sound Insulation Programs

There is a system of graduated landing fees that provides a fund of money that is used to buy homes in extremely noisy areas and to provide support for extra home sound insulation. The noise component of the landing fee is approximately 10% of the total fee. Where a home is entitled to extra sound insulation, the airport pays 80% of the costs. This is usually given to existing homes in zone B. They base decisions on next year's noise contours and not on the future maximum planning contours.

The details of the required added sound insulation are determined by an airport employee, expert in noise insulation techniques, who goes to each home to prescribe a solution. This usually consists of replacing windows and doors. The noise insulating windows include heavy plastic construction with steel channels inside the plastic, multiple rubber seals and heavy double glazing (e.g. 10 mm glass - 6 mm air gap - 5 mm glass). The airport noise staff actually go out and measure the noise reduction of a few homes to verify that the program is working well. This is done with real aircraft noise by simultaneously measuring integrated A-weighted levels both inside and outside the home during a fly-over. The measured attenuation is an A-weighted measure that is corrected for the reverberation time of the receiving room.

6.4.5 Computer Models

Several groups have computer models to calculate contours of the Psophique Index. I_p is based on the PNL_{max} values of each fly-over. The PNL_{max} data are obtained from certification measurements. The I_p contours are intended for land use planning purposes.

The contours are predictions for the maximum expected future traffic. Thus at Charles de Gaulle airport, predictions are for 2015, when it is expected that the current two runways will be expanded to five. At Orly, there is a limit to the number of operations that are allowed. They expect after 2002, when all Chapter 2 aircraft are banned, that the noise climate should remain nearly constant for some time (unless aircraft continue to get quieter). Thus, at Orly predictions are for the year 2005.

6.5 Germany

6.5.1 Description of Noise Measures

Germany uses an index that used to be referred to as the Störindex or Disturbance Index and was given the symbol Q. They now refer to it as an equivalent level, L_{eq}(FLG). However, this is a little confusing because it is not an energy equivalent level as it includes a 13.3•log(N) term. Apparently, the 13.3 factor was the result of noise surveys in the 1960's in which annoyance seemed to increase by an amount equivalent to 4 dB for each doubling of the number of flights. This resulted in the 13.3•log(N) term which is actually quite close to the NNI measure that includes a 15•log(N) term corresponding to a 4.5 dB increase per doubling of the number of operations.

The L_{eq}(FLG) index must be calculated for two cases: a daytime only case, and a full day and night case. The greater of the two values is used as the final result. For the day only case, the levels for the day-time period are increased to represent the overall levels that would result if this day-time noise continued through the night. The German index is defined in a national law.

6.5.2 <u>Limits</u>

There are firm regulations in German law that prevent any building where L_{eq}(FLG) > 75 dBA (approximately NEF 42), and prevent some noise sensitive activities such as schools where L_{eq}(FLG) > 67 dBA [6] (approximately NEF 34). However, the building of houses in areas where L_{eq}(FLG) > 67 dB is not prohibited, but the airport may provide compensation for the addition of sound insulation to homes.

In Germany, most airports have night-time curfews. Night time is usually defined as 22:00 to 06:00. However, the details of the curfews vary with aircraft type and also from airport to airport.

At Düsseldorf, there are local night time limits in terms of L_{max}. The local authorities specify that L_{max} must not exceed 79 dBA more than five times each night. However, in Münich there is a different local night-time limit of 75 dBA six times a night. Thus, the use of the L_{eq}(FLG) index is standardized throughout Germany, but night-time limits and curfews are not.

6.5.3 <u>Noise Monitoring Systems</u>

The major airports are all said to have automatic noise monitoring systems. These accumulate data to verify the changing noise climate and presumably to verify that measured noise levels do not exceed the official noise contour levels. They do not have the related radar flight track information.

Düsseldorf has a very sophisticated automatic noise monitoring system. There are about 12 microphone locations throughout the nearby community and two more locations are soon to be added. Each station measures noise levels every 10 ms and transmits an average, a maximum, and wind information to the central system each 0.5 seconds. There is a threshold of about 65 dBA below which the remote stations do not transmit measured noise data.

6.5.4 <u>Remedial Measures and Added Sound Insulation Programs</u>

Within the 67 dBA L_{eq}(FLG) contour, airports may provide compensation for the addition of insulation to homes. Homes have to be in an area where aircraft noise predominates and where the insulation will have a significant effect. They usually improve mostly windows and doors, and again these also have thermal benefits for the residents. The goal is to reduce aircraft noise indoors to an L_{max} of no more than 50 to 55 dBA.

In Germany, there is a differential system of landing charges based on the noise output of aircraft. There are categories for Chapter 3, Chapter 2, propeller, and non-classified aircraft, etc. At Düsseldorf, this approach is carried further so that noisier Chapter 3 aircraft pay more than the quieter Chapter 3 aircraft. The differences in landing fees are said to be significant enough to encourage airlines to buy quieter aircraft. This is intended to put pressure on the manufacturers to produce quieter aircraft.

6.5.5 Computer Models

The Max Planck Institut does work on aircraft noise prediction and they have their own noise prediction program. The details of the calculation method are specified in German law, and other programs exist to make airport noise contour predictions. The law includes all equations and source spectra, and completely specifies how the airport noise calculations are to be made. The Ministry of the Environment has a noise prediction program that is used for the official predictions of noise contours at major airports. Since all programs follow the detailed specifications in the German law, they should all agree.

The input database that is used is in terms of aircraft type groups and not by specific aircraft and engine types as in the American INM program. The type groups include Chapter 2, Chapter 3, propeller, etc. and for various weight groupings. The technique starts from the maximum A-weighted level at the point of closest approach. Some other models use SEL values at the point of closest approach. Calculations are performed in octave bands and the octave band source spectra are given in the German specification regulations. Ground attenuation is said to be less than the SAE 1751 procedure used in the INM.

6.6 Japan

6.6.1 Description of Noise Measures

Japan uses an A-weighted version of the WECPNL measure proposed by ICAO [7]. There is assumed to be a 13 dB difference between perceived noise levels and A-weighted levels. The Japanese WECPNL is a combination of the average maximum A-weighted noise levels and a weighted total number of events. The number of events include both evening and night-time weightings. During the evening period from 19:00 to 22:00 hours, the number of events is weighted by a factor of 3, and during the night time period from 22:00 to 7:00 by a factor of 10. One can approximately convert from WECPNL values to NEF values by subtracting 48 from the WECPNL values.

There is a new proposal to use the L_{den} measure to characterize noise near helipads and other very small airports. The L_{den} measure would include a 5 dBA evening weighting and a 10 dBA night weighting.

6.6.2 Limits

The "Environmental Quality Standards for Aircraft Noise" regulations issued in December 1973 set out targets for airports to preserve the living environment and to contribute to protecting people’s health for areas near 16 major airports. These regulations present goals for two land use categories: I, WECPNL < 70 (approximately NEF 22) suitable as residential areas, and II, WECPNL < 75 (approximately NEF 27) where normal living conditions must be preserved. Target dates were set to meet these goals but in most cases were not completely met. Efforts are continuing to meet these goals. For example, at Tokyo’s Haneda airport, runways are being relocated to minimize levels in residential areas to attempt to meet these goals.

These regulations do not apply to Tokyo’s new Narita airport. Near Narita, schools and hospitals are sound-proofed and anti-flutter television antennas are provided in areas where WECPNL > 70 dBA. For areas where WECPNL > 75 dBA, homes are insulated. The construction of new homes is prohibited in very noisy areas.

A new law was passed in 1990 for helipads in terms of L_{den} values. For areas near helipads and very small airports, category I areas should have L_{den} < 60 dBA and < 65 dBA in category II areas.

All but four of Japan’s 20 major airports have night-time curfews. Almost all of the major airports have restrictions on take-off and landing procedures to minimize noise levels.

6.6.3 Noise Monitoring Systems

Both Tokyo airports have noise monitoring systems. The one at Narita airport is quite sophisticated and includes a unique acoustical tracking system. It was successfully used to determine that one airline was not following the required maximum safe climb departure intended to minimize noise impact on areas under the take off path. The older system at Haneda airport will soon be replaced with the same type of system as at Narita.

6.6.4 Remedial Measures and Added Sound Insulation Programs

At Tokyo's Narita airport, homes are insulated in areas where WECPNL > 75 dBA. At Tokyo's Haneda airport, runways are being relocated to reduce the impact on nearby residential areas. The new airport at Osaka is located on reclaimed land in Osaka bay. The equivalent of approximately $273,000,000. was spent on compensation schemes in Japan during 1992.

6.6.5 Computer Models

Various groups seem to have their own aircraft noise prediction programs.

6.7 Switzerland

6.7.1 Description of Noise Measures

Airport noise at the three major Swiss airports, Zurich, Basel, and Geneva, is regulated in terms of NNI_s. However, the Swiss NNI_s is an A-weighted measure. They assume that PNL_{max} values are approximately 12 dBA greater than the corresponding L_{max} values.

According to the new noise protection law, at lesser airfields noise levels are regulated in terms of L_{eq} values for an average day from the busiest six months.

6.7.2 Limits

Switzerland has three different levels of noise limits: (1) a planning level, (2) an immission level, and (3) a level of alarm. Planning levels are lowest and alarm levels are highest. For large airports, the planning level and the immission level are both NNI_s 45 (approximately NEF 31). Within this level, you cannot build new houses without extra sound insulation. For NNI_s levels greater than 55 (approximately NEF 38), no new houses are permitted.

The noise protection law of 1987 regulates noise from most kinds of environmental sources in terms of an L_{eq} plus a correction K to account for possible differences in the disturbance caused by similar levels of different types of noises. This includes noise from lesser airfields. There are tables of acceptable noise levels in terms of: (1) planning levels, (2) immission levels, and (3) alarm levels. There are also corresponding tables of L_{max} values. The basic concept is that the source of the noise should pay, i.e. the polluter pays.

The planning level for housing is L_r = 55 dBA. This is used to limit the areas that can be zoned for housing in future zoning changes. This does not apply to existing areas.

The immission level for housing is L_r = 60 dBA. This implies that a potential problem is recognized and will be further investigated. This does not seem to imply that there will be any concrete action to remedy the problem. For example, they might check to see if extra insulation or some other modification might help. However, if it seems that noise levels may decrease with time, they will do nothing. Similarly, if the expected changes would result in only very small improvements, again no action would be taken.

The level of alarm for housing areas is L_r = 70 dBA. This is said to indicate a serious problem and something must be done.

They have night-time curfews that ban landings from 24:00 to 05:00 and take-offs from 24:00 to 06:00 with some tolerance for late arrivals. However, they define day as 06:00 to 22:00. Thus, NNI_s contours are calculated for only the day-time traffic, and the traffic between 22:00 and 24:00 is ignored.

They have a regulation that specifies that full thrust reversal should not be used except where runway conditions require it for safety. At Zurich, they also specify that approaches be made in an optimum clean configuration with no flaps.

6.7.3 Noise Monitoring Systems

Zurich airport has a quite sophisticated automatic noise monitoring system with a total of nine microphones generally located quite close to the ends of the runways. The maximum distance from the ends of the runways to the microphones is about 4 km. The airport is required by law to have a noise monitoring system. The airport seems very serious about aircraft noise and compiles mountains of statistics and monthly bulletins listing all noise offenders.

Zurich has a FANAMOS flight track radar system, but it is not automatically coupled to the noise monitoring system. They are currently in the process of buying a new system that will combine noise measurements and flight track monitoring.

At Zurich, they use the system to refute claims that the noise environment is getting worse. They go into great detail and identify aircraft that either stray from the accepted flight paths or exceed maximum noise levels specified for each microphone location. After problems have been verified to be pilot errors, the airline gets a letter asking for an explanation.

6.7.4 Remedial Measures and Added Sound Insulation Programs

Noise penalties are included in landing fees. Aircraft are divided into noise groups and there is a graduated scale of increasing penalties for noisier aircraft types. Currently, Chapter 3 aircraft pay nothing and Chapter 2 pay a 135 SF penalty. Although this seems like a modest penalty, Swissair objects to these charges.

6.7.5 Computer Models

The EMPA institute has the official airport noise prediction program for estimating NNI_s contours at large Swiss airports. It is a simulation type model that starts from the octave band levels and directivities of individual aircraft types. The reported 50 hours of calculation time on a modern VAX computer is indicative of the cost of the improved accuracy of the simulation technique.

To improve the model, they recently completed measurements of 500 fly-overs at Zurich airport to get better level and directivity data relevant to Zurich. This would avoid the problems of using the INM database derived from certification data.

6.8 United Kingdom

6.8.1 Description of Noise Measures

The United Kingdom used to use the NNI_{UK} measure, but a few years ago converted to a 16-hour day-time L_{eq} measure. The day is from 07:00-23:00.

They have a table of NNI_{UK} to L_{eq16} equivalents.

NNI_{UK}	L_{eq16}
35	57
40	60
45	63
50	66
55	69
60	72

Table 4.2. British L_{eq16} equivalents to NNI_{UK} values.

6.8.2 Limits

The airports at Gatwick, Stanstead, and Heathrow come under Department of Transport scrutiny and hence there are noise contours, noise limits, night time quotas and noise monitoring systems, etc. These are not found at other airports that do not come directly under the Department of Transport. At Manchester, the third largest airport, there are some such activities but they are all locally motivated in order to remain in reasonably cooperative relations with the surrounding communities.

The U.K. Ministry of the Environment, “Circular 10/73” [8] gives recommended criteria the for the control of development in areas affected by aircraft noise. This is an old document, dating from 1973, which specifies limits in terms of NNI_{UK} values. No major new developments are recommended for areas of NNI_{UK} ≥40 (approximately NEF 27). In-filling is to be permitted only with appropriate additional sound insulation. For less noisy areas, NNI_{UK} 35-39 (approximately NEF 23-26) permission to build dwellings is not to be refused on noise grounds alone. There is no mention of any extra insulation for dwellings in these areas. However, schools in these areas are recommended to have sufficient sound insulation. Local planning authorities have considerable freedom in interpreting the Department of the Environment Guidelines. They can adopt more or less restrictive land use planning schemes.

There are no night-time events included in either the old NNI_{UK} measure or the new L_{eq16} noise measure. Thus, noise contours are not influenced by night-time events. Night-time restrictions are handled separately. They now have a complicated system of quotas based on the areas of 95 PNdB contours for aircraft. When the quotas are exceeded, the penalty is to reduce the quota during the next time period. There are separate quota periods for summer and winter. They also have maximum noise limits at monitoring stations of 102 PNdB at night and 110 PNdB during the day time that have been converted to 89 and 97 dBA. These are monitored at stations close to the runway.

There is a new proposal for night-time limits that is based on the certification noise levels of both take off and landings. The quietest aircraft get a 0 rating and are exempt from the quotas. Increasingly noisy aircraft get 1, 2, 4, 8, and 16 ratings . Thus, one “4” rated aircraft is counted as equivalent to four “1” rated aircraft. The scheme may be adopted in the near future and the British hope that other European countries may adopt this system.

British Airports Authority was completely privatized in 1987 and operates seven U.K. airports that include about 70% of the U.K. air traffic. These include: Heathrow, Gatwick, Stanstead, Southampton, Aberdeen, and Glasgow. They try to be a responsible neighbour that takes noise problems seriously. They would like to see quieter aircraft, because this would help to solve their problems with local communities. Their attempts to reduce the noise impact on nearby communities are limited by their need to compete for business with other European airports.

They do have a differential landing fee scheme. Chapter 2 aircraft have no penalty, Chapter 3 have a 10% reduction, and others pay a 40% increase.

6.8.3 Noise Monitoring Systems

Heathrow, Gatwick and Stanstead are getting new noise monitoring systems with integrated flight track radar information. They will soon be programmed to measure EPNdB so that they can verify the rank ordering of aircraft noise levels for the new night time quota system that is based on certification noise levels.

The systems will have a limited number of permanent monitor locations at each of the three London airports and a centralized control system. At Gatwick there will only be two fixed locations to monitor take-off levels. There will be no locations at Gatwick to monitor landing levels. They will also have 24 portable monitoring systems that can accumulate data for a week or so . These will be used to investigate specific problems. They seem to appreciate the significant public relations benefit of putting these portable monitors out in the community in response to particular complaints.

6.8.4 Remedial Measures and Added Sound Insulation Programs

There have been sound insulation programs around Heathrow and Gatwick that have been funded by the airports. These have been specific programs with finite periods of activity. They were not general to other airports.

Traffic is increasing at Stanstead, London's third airport, and it is expected to grow from the current 2 million passengers per year to 8 million per year. As a part of planning for this expansion, there is a current sound insulation scheme at Stanstead. Approximately 600 homes are eligible for secondary glazing. They expect about 45% of them will accept the offer. The airport would pay 100% of the costs. People must sign up within two years and get the work done within another three years. The secondary glazing is not double glazing and is added on the inside, making much mess. A number of factors are used to determine eligibility. One is if the home is within the L_{eq16} = 66 dBA contour. Another is based on the footprint of a relatively noisy 737-200.

6.8.5 Computer Models

The Civil Aviation Authority do have a computer program for predicting noise contours and do this for Gatwick, Stanstead, and Heathrow airports. The Civil Aviation Authority does the calculations and the Department of Transport approves and sells them to local authorities.

They seem to be mainly intended to check year-to-year variations in noise levels. They try and calculate contours each year based on current traffic. Predictions for the future are also done but that is not the main purpose of the procedure.

6.9 United States

6.9.1 Description of Noise Measures

The day-night sound level, L_{dn}, is used throughout the United States to characterize environmental noise including aircraft noise. It is an integrated energy equivalent A-weighted measure with a 10 dBA night-time weighting. The night-time period is from 22:00 to 7:00 hours.

The CNEL measure has been used in California. It is identical to L_{den}, used in Denmark, and is an A-weighted measure like L_{dn} but with an additional 5 dB evening weighting.

6.9.2 Limits

The federal FAR Part 150 regulation [9] is used to provide financial support for remedial measures at airports throughout the United States. Areas with L_{dn} values less than 65 dBA are considered to be not seriously impacted and do not automatically qualify for financial support. However, specific local needs may result in noise abatement in areas below L_{dn} 65. Areas between L_{dn} 65 and 75 are usually considered eligible for additional home insulation. Areas above L_{dn} 75 are considered not suitable for residential use.

6.9.3 Noise Monitoring Systems

Many airports have noise monitoring systems that are used as an integral part of noise management programs. These usually do not have access to flight track radar information. Coleman and Eldred [10] refer to a new system to be installed at Boston’s Logan airport that will include 29 microphone locations and flight track data. With the very large number and variety of airports in the United States, it is difficult to present a brief summary.

6.9.4 Remedial Measures and Added Sound Insulation Programs

The FAR Part 150 program provides federal funds for increased home sound insulation as part of an overall noise management plan at a particular airport. The details of sound insulation and other remedial measures vary from airport to airport. As one example, Carroll [11] describes a variety of remedial measures undertaken at Atlanta airport under the federal FAR Part 150 program.

6.9.5 Computer Models

The Integrated Noise Model, INM, is the standard model for predicting aircraft noise levels in the United States. It is readily available at low cost and so is in very widespread use. The United States Air Force program, NOISEMAP, has been shown to produce similar results to the INM program and is also commonly used.

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7.0 AIRCRAFT NOISE LEVEL CRITERIA

7.1 Limits in Terms of NEF Values

Early estimates of acceptable levels of aircraft noise were determined from consulting experience with limited case studies of community noise. These early limits have been discussed in Chapter 2. Both Transport Canada [1] and Canada Mortgage and Housing Corporation [2] have used these early limits as land use planning guidelines. The material reviewed in this report suggests more substantial evidence for setting such airport noise level criteria. It is hoped that a balanced interpretation of this data will provide a more substantial basis for establishing airport noise level criteria

Acceptable limits can be set in terms of the onset of various unwanted negative effects of aircraft noise. Information on each of these unwanted effects has already been reviewed in earlier chapters of this report. Such unwanted effects would include hearing impairment, sleep disturbance, medical effects, speech interference, and annoyance responses. In addition, acceptable land use planning limits from other countries can be considered for comparison purposes.

In this chapter all noise levels are converted to NEF_{CAN} values, (that is, NEF values equivalent to those produced by the Transport Canada NEF_1.7 program). NEF_{CAN} values are thought to be greater than related measured average NEF values. The excess ground attenuation calculation in the NEF_1.7 program overestimates NEF values by approximately 2 dB [3]. There is a further overestimate of expected average measured values of approximately 2 dB because NEF_{CAN} values are based on a 95th percentile day (Peak Planning Day) rather than an average day. Thus, it is estimated that NEF_{CAN} values are approximately 4 dB greater than measured average NEF values.

Figure 7.1 summarises the approximate aircraft noise levels at which these various unwanted negative effects commence. The methods of obtaining each

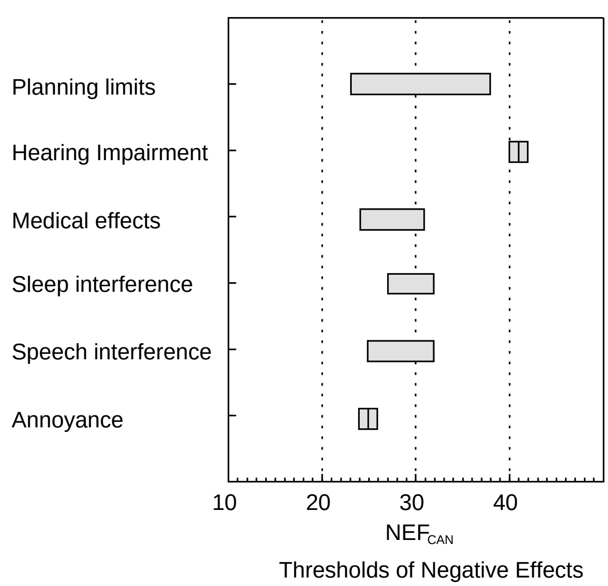

Figure 7.1. Summary of the thresholds of the onset of various negative effects of aircraft noise in terms of NEF_{CAN} values.

of these results and the techniques for approximately converting critical levels to NEF_{CAN} values will be explained for each example.

The first horizontal bar of Figure 7.1 summarises the range of planning limits from various countries. These were taken from Table 6.1 and represent the level below which aircraft noise is not considered to be a serious problem. The lowest limits of NEF_{CAN} 23 and 24 are from Denmark and Australia, respectively. The highest limit, equivalent to NEF_{CAN} 38, is from Germany and is probably high because above this level German law requires action must be taken.

In Section 3.1, hearing impairment was seen to be possible above a 24-hour L_{eq} of 70 dBA. This is approximately equivalent NEF_{CAN} 41. Above this level, permanent damage to the hearing system is possible.

Section 3.2 reviewed various non-auditory effects of aircraft noise. Knipschild's various studies of populations near Amsterdam's Schipol airport suggest that above about L_{dn} 55-62 dBA, various unwanted medical effects are possible. This range would correspond to NEF_{CAN} 24-31.

The onset of sleep interference is better documented but more difficult to convert to equivalent NEF values. Griefahn's review (see Fig. 3.5) suggested that below indoor maximum levels of approximately 54 dBA, subjects were unlikely to be awakened. Using the average noise reduction value of 26 dBA for well insulated wood frame construction with closed windows from Table 5.1, this would correspond to an outdoor L_{max} of 80 dBA. Thus, outdoor noise peaks above 80 dBA will cause awakenings indoors. Although it is perhaps better to treat this as a single event limit, one can estimate an equivalent NEF_{CAN} using Fig. 7.1 of [3] (modified to NEF_{CAN} values) shown here as Fig. 7.2. This shows the NEF_{CAN} values related to combinations of L_{max} values and numbers of operations. Figure 7.2 also shows that an L_{max} of 80 would correspond approximately to NEF_{CAN} 32 for a total of 100 operations per day. Of course, there is not one unique conversion between L_{max} values

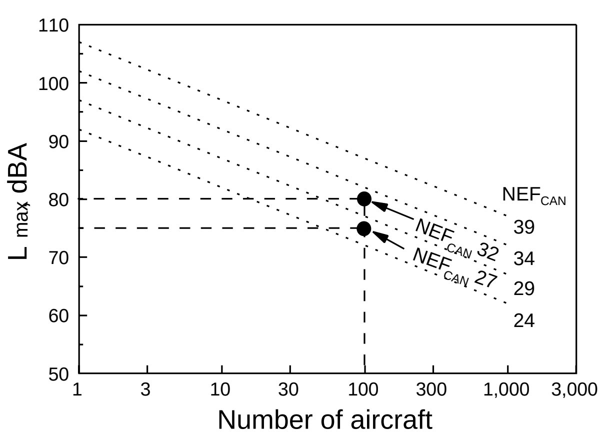

Figure 7.2. Relationship between maximum levels, L_{max}, numbers of operations, and the resulting NEF_{CAN} values. Also illustrated is the approximate conversion of 100 operations per day with an L_{max} of 80 dBA to an NEF_{CAN} value of 32.

and NEF_{CAN} values. For example, a conversion point assuming fewer operations per day would result in a lower NEF_{CAN} value. Other combinations can be obtained from Fig. 7.2. However, the approximate equivalence to NEF_{CAN} 32 is satisfactory for the purposes of the current overview.

Figure 3.7, from Ollerhead's field study of sleep disturbance, indicated arousals due to aircraft noise above L_{max} values of 75-80. Using Fig. 7.2, an L_{max} of 75 dBA, and assuming a conversion point of 100 operations per day, suggests the onset of sleep disturbance could occur as low as NEF 27. Thus, the range from NEF 27 to NEF 32 shown in Fig. 7.1 best indicates the area of the onset of sleep disturbance.

In Section 3.4, it was calculated that the indoor aircraft noise SEL should not exceed 64 dBA to avoid speech interference. Using the same average building facade noise reduction of 26 dBA for a well insulated home with closed windows, would lead to a maximum outdoor aircraft noise SEL of 90 dBA. Thus, outdoor aircraft noise that produces an SEL of greater than 90 dBA will cause significant speech interference inside the home. Again, it is not possible to convert this to a unique NEF_{CAN} value. Figure 7.3 (from Fig. 7.2, reference [3]) shows combinations of SEL values and numbers of operations that lead to particular NEF_{CAN} values. From Figure 7.3 it is seen that an SEL of 90 dBA and 100 operations per day would correspond to an NEF_{CAN} of 32. These calculations were based on a 'normal' voice level. If they were repeated for a 'casual' voice level, typical of conversations in homes, the resulting equivalent NEF_{CAN} would be reduced from 32 to 25.

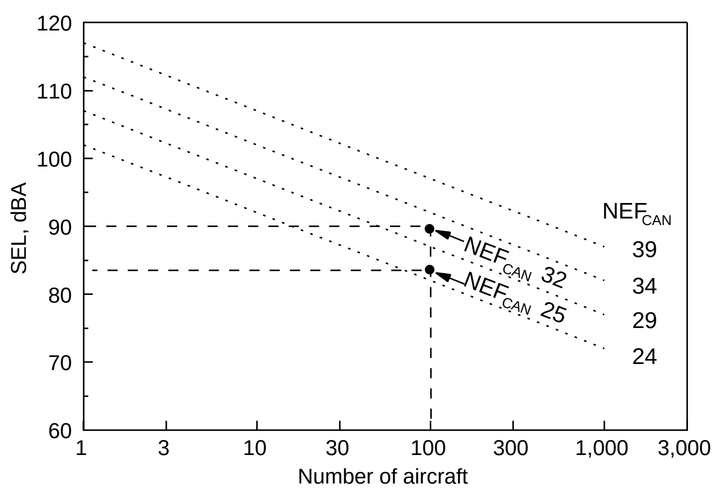

Figure 7.3. Relationship between integrated single event levels, SEL, numbers of operations and the resulting NEF_{CAN} values. Also illustrated is the approximate conversion of 100 operations per day with SEL values of 84 and 90 to NEF_{CAN} values of 25 and 32, respectively.

In setting the US FAR Part 150 limits of an L_{dn} of 65 dBA, the Schultz curve is often referenced. Using the Schultz curve, an L_{dn} of 65 corresponds to approximately 15% of the population being highly annoyed. If the new 'Mean' curve of Fig. 3.21 is used, then 15% of the population would be highly annoyed at an L_{dn} value of 56 dBA. This would correspond to an NEF_{CAN} of 25 and is also shown on Fig. 7.1.

Almost all of the thresholds of negative effects included in Fig. 7.1 start in the NEF_{CAN} 25 to NEF_{CAN} 30 range. Most of the planning limits also start in this same range. Thus, it is only below this range that one can avoid the negative effects of aircraft noise. NEF_{CAN} 25 should be regarded as the threshold of negative effects of aircraft noise.

At NEF_{CAN} 30, the various negative effects are established and growing. By NEF_{CAN} 35, the negative effects of aircraft noise are very significant. These comparisons suggest that areas with noise levels greater than NEF_{CAN} 35 are not suitable for residential development, and that in areas above NEF_{CAN} 30 all homes must have extra sound insulation. Without substantial sound insulation, the negative effects would commence at significantly lower aircraft noise levels. The calculated onset of sleep and speech interference included a 26 dBA building facade noise reduction. If sealed homes with extra insulation are not acceptable, then there should be no homes.

At approximately NEF_{CAN} 41 and greater, permanent hearing impairment starts to become possible. At NEF_{CAN} 40, both speech and sleep impairment will be very significant and almost half of the population will be highly annoyed. Such high noise levels are clearly not suitable for use as residential areas.

These various thresholds of acceptability are all presented in Fig. 7.4. They are similar to those accepted in many communities today. They are essentially the same as Transport Canada’s recommended guidelines[4]. Because these recommendations are based on very extensive analyses of current knowledge of the effects of aircraft noise on people, they add to the credibility of the Transport Canada guidelines.

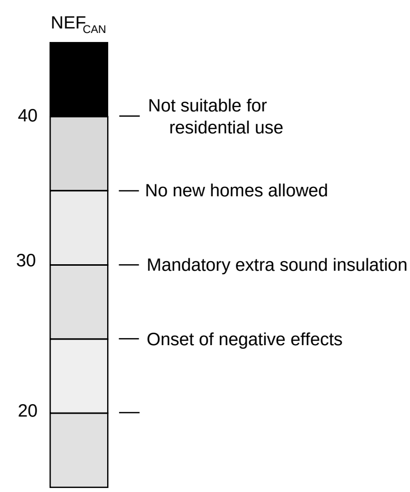

Figure 7.4. Summary of the thresholds of acceptability of aircraft noise.

7.2 Limits in Terms of Single Event Noise Measures

In some cases, disturbance is related to the intensity of each noise event and not directly to some long-term average measure such as NEF. This is true for sleep and speech disturbance by aircraft noise. Thus, it is not completely satisfactory to consider only integrated measures such as NEF values. This becomes particularly true in some more extreme cases such as where there are relatively small numbers of quite noisy events. Some examples would include a small number of relatively noisy operations of military aircraft at a smaller airport or the operation of helicopters. For these cases, speech or sleep could be quite severely disturbed even though NEF values are quite low.

It is therefore necessary to consider acceptable single event limits in addition to those given in Fig. 7.4 in terms of NEF_{CAN} values. From the discussion of sleep disturbance above and in Section 3.3, maximum outdoor night-time levels should not exceed 80 dBA to avoid disturbance of sleep. The discussions of speech interference above and in Section 3.4 suggest a limit of 90 dBA for the outdoor SEL of individual aircraft fly-overs to avoid significant disruption of speech communication. In some European countries with night-time single event limits, a small number of operations are allowed to exceed the limit each night.

The use of these single event limits in addition to the NEF limits should ensure that the general noise environment and particular worst case situations are both acceptable and the negative effects of aircraft noise on people are negligible. It is suggsted that single event limits should restrict maximum levels of single events at smaller airports so that they do not exceed those experienced near larger airports.

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8.0 CONCLUSIONS

8.1 Introduction

This chapter is intended to provide a comprehensive summary and conclusions for the entire report. The concluding and summary remarks are presented on a chapter-by-chapter basis and the section sub-headings of these conclusions are the same as the report chapter titles.

8.2 History of Airport Noise Measures

The NEF measure evolved from the earlier CNR measure intended initially for all types of community noise. Except for the development of Kryter's Perceived Noise level, the development never included any scientific measures of responses to aircraft noise. The basic principles of the NEF measure were developed on an intuitive basis from a limited number of practical consulting studies.

There has never been any true calibration of the NEF measure in terms of the expected response to various levels of aircraft noise. Currently accepted land use planning limits developed from general impressions of community responses in various practical consulting studies.

8.3 Effects of Noise on People

8.3.1 Noise-Induced Hearing Impairment

The results of many studies of hearing impairment from long term exposures to industrial noise have established a lower bound on integrated noise levels likely to permanently impair hearing. Below a 24-hour L_{eq} of 70 dBA (approximately NEF_{CAN} 41), permanent hearing impairment is very unlikely. No studies were found with evidence of hearing impairment due to aircraft noise in residential areas near airports.

8.3.2 Non-Auditory Effects of Aircraft Noise

Extensive studies of possible psychiatric effects have failed to provide consistent evidence of a definite relationship with aircraft noise. Loud sounds can cause basic responses in our cardiovascular system but there is no evidence that these are harmful. Studies of populations near Amsterdam's Schipol airport suggest there are increased numbers of medical visits and increased use of anti-hypertensive drugs for cardiovascular problems in higher aircraft noise areas. There have not been similar studies around other major airports to corroborate these results.

8.3.3 Sleep Interference

Griefahn has concluded from a review of many studies of sleep disturbance that below maximum indoor levels of about 54 dBA, very few people will be awakened. A major recent field study in homes near several British airports found no evidence of sleep disturbance below maximum outdoor levels of approximately 75-80 dBA. For well-insulated homes with closed windows, these results are more or less equivalent. Many details of how sleep is disturbed by noise are not so well understood. This would include the effects of age, habituation to long-term exposures, effects of changes in noise exposures, and the long-term effects of sleep disturbance on health. There is evidence that questionnaire responses do not provide an accurate measure of sleep disturbance.

8.3.4 Speech Interference

There are a wide range of acceptable background noise levels for good speech communication because many of these incorporate some form of practical compromise. Ideal maximum background levels for near perfect speech communication are readily derived from average speech levels. Such calculations indicate that with a ‘normal’ vocal effort, the background noise level should not exceed 35 dBA. Lower background levels would be required for lower levels of vocal effort or in large meeting rooms and auditoria.

New calculations demonstrate the inappropriateness of using integrated noise measures such as L_{eq} or NEF to predict the speech interference of aircraft noise. The expected speech interference is more accurately predicted from point-by-point speech intelligibility calculations over a complete aircraft pass-by. In many cases, the new calculations suggest less speech interference than estimates from L_{eq} values would suggest. The new results allow one to calculate the expected speech interference from the outdoor SEL of an aircraft fly-over and the A-weighted noise prediction of the building facade.

8.3.5 Annoyance

Schultz’s synthesis curve relating the percentage highly annoyed to L_{dn} values has become a widely accepted single dose-response curve for all types of environmental noises. A re-analysis of a number of major modern airport noise surveys, including a Toronto survey, failed to show close agreement with the Schultz curve. The results of these large airport surveys clustered together quite well and indicated considerably greater percentages of highly annoyed people than suggested by the Schultz curve. The Schultz curve was concluded to considerably underestimate the actual percentage of highly annoyed residents living near major airports. A new Mean curve can be used to more accurately estimate the expected percentages of highly annoyed residents as a function of aircraft noise level.

There is considerable evidence to question the appropriateness of any one dose-response curve for all types of community noise. There is a general trend that for equivalent noise levels, aircraft noise is more annoying than road traffic noise which is more annoying than train noise.

8.4 Specific Issues

8.4.1 Frequency Weightings

Laboratory studies have compared the merits of various frequency weighting schemes to predict responses to noise. Where many different types of noise are included with quite different spectra, it is more important that the frequency weighting scheme correctly models the response of our hearing system. If the noises all have similar spectral characteristics, such as various samples of jet aircraft noise, then the differences of various frequency weighting schemes are not so important. In general, the various loudness calculation schemes and the Perceived Noise Level scheme, that is included in the NEF measure, tend to predict responses more accurately than the simple A-weighting system. However, the improvement in prediction accuracy is typically only 0.5 dB.

8.4.2 Energy Summation

There is growing international support for integrated noise measures that combine noise levels and numbers of events on a simple energy summation basis. The United Kingdom has recently converted from the NNI measure to an L_{eq} measure. Older measures, such as British NNI and the German Q, that do not include a simple energy summation, were based on analyses of particular older survey results. Re-analysis of these results and newer results suggest that an energy summation type noise measure is at least equally adequate.

Because survey responses include a considerable amount of scatter, it is not likely to be possible to precisely define the exact optimum form of relationship. However, it is also very unlikely that one could prove a relationship other than energy summation to be significantly better.

8.4.3 Time-of-Day Weightings

Many different time-of-day weightings are in use in various countries. These include differences in the time periods assigned additional weightings and differences in the magnitude of the weightings. Some countries simply ignore night-time noise levels. Again, the scatter in survey response data makes it impossible to precisely define the optimum evening or night-time weighting. However, the 12 dB night-time weighting in the NEF measure is the largest in common use. There is evidence to suggest that evening weightings are at least equally important and that weightings smaller than the 12 dB included in the current NEF would be appropriate.

8.4.4 Changes Over Time

No evidence could be found of attitudes to similar noise levels changing over time. Studies around London's Heathrow airport and around major Swiss airports suggest that attitudes relative to a particular noise level have been remarkably constant over time. That is, dose-response curves of the percentage highly annoyed versus noise level have not change over 10 years or longer.

There have also been studies of responses to changing noise levels. These results suggest that responses may change more than would be predicted from steady state noise conditions at different noise levels.

8.4.5 Smaller Airports

There have been quite limited studies at smaller airports. These studies have tended to confuse differences in types of operations and differences in airport size. General aviation activities are probably more annoying than the same level of noise from other aviation activities. The activities of smaller airports are probably less annoying than larger airports. Many smaller airports include considerable general aviation activity and so both effects would be combined. No study has attempted to carefully separate these two effects.

8.4.6 Helicopters

Although helicopters are usually assumed to be a more annoying source of noise, there is not much evidence to support this idea. British studies have shown that annoyance to helicopter noise is strongly dependent on the importance of the helicopters to the local community. Other studies have suggested they lead to about the same annoyance as similar levels of other types of aircraft noise. Because helicopter noise does not usually significantly effect long term average noise measures such as NEF, there are arguments that helicopter noise should be considered in terms of single event measures.

8.5 Counter Measures

8.5.1 Source Reduction

The most effective counter measure to control the negative effects of aircraft noise is noise reduction at the source. Reducing the noise output of each source guarantees reduced noise levels in all areas around all airports and both indoors and outdoors. Although only small reductions can be expected over the next few years, it is important to apply continuing regulatory pressure on aircraft manufacturers to ensure that these reductions are achieved and that research teams continue to tackle this very important problem.

8.5.2 Noise Abatement

While the development of quieter aircraft can reduce future noise levels, various noise abatement procedures can help to reduce noise levels immediately. There is a long list of techniques that can help airports to manage noise problems. These could include noise management plans to limit noise exposures backed up by noise contour calculations and noise monitoring of actual noise levels. Adjustments to flight tracks, take-off procedures and ground operations can minimize the impact on nearby residential areas.

8.5.3 Building Insulation

Extra sound insulation is often prescribed as a solution to aircraft noise problems in residential areas near major airports. Measured building facade noise reductions are often quite disappointing. An average well insulated wood frame home with closed windows has a noise reduction of about 26 dBA. Of course, building insulation does not improve the outdoor environment and there is no evidence that long term annoyance to aircraft noise is reduced by adding sound insulation to homes.

8.5.4 Land Use Planning

Some form of land use planning is routinely practiced in areas around most major airports. However, successful planning requires a stable, long-term goal. Basing land use on changing noise contours is not an acceptable approach for long-term planning.

A better approach would be to have fixed land use boundaries as part of a noise budget management system. The limits would be based on clear national standards but the means of achieving them could be negotiated locally. Airports could increase operations as quieter aircraft are introduced as long as the total noise climate stays within the fixed limits.

8.6 Airport Noise in Other Countries

The details of how airport noise is managed vary from country to country. Almost every country uses different noise measures that include different time-of-day weightings or that even ignore night-time noise levels. Most are now based on A-weighted measures and combine events on an energy summation basis. When converted to equivalent NEF values, the limits of acceptability vary considerably from country to country. Most countries calculate noise contours around airports and have automatic noise measuring systems to monitor actual noise levels near airports. However, not all can make full use of the noise data by relating it to flight track information. Most countries have used a variety of common counter measures to control airport noise problems such as modified aircraft operations and the addition of insulation to homes near major airports.

8.7 Aircraft Noise Level Criteria

Currently accepted land use planning limits in Canada have evolved with the NEF measure from experience from several practical consulting projects. A new set of criteria for aircraft noise were developed from this review of current knowledge of aircraft noise and its effects on people. Significant negative effects to aircraft noise start at NEF_{CAN} 25 and higher. Above NEF_{CAN} 30, homes should have extra insulation to ensure an acceptable indoor environment. No new homes should be permitted above NEF_{CAN} 35 Additional single event limits are required in situations where there are a small number of unusually noisy events. (This would include many situations with helicopters). The night-time L_{max} should not exceed 80 dBA to minimize disturbance of sleep. The SEL of individual aircraft fly-overs should not exceed 90 to avoid significant speech interference.

8.8 Recommendations

There are a number of areas where we do not adequately understand the details of the negative effects of aircraft noise.

Canada has a large number of smaller airfields and bases for aircraft operations into remote areas. There is very little information concerning the negative impact of smaller airports and the effects of airport size are usually confused with the effects of different types of operations.

One of the most significant differences between the NEF measure and other integrated noise measures relates to different time-of-day weightings. The benefits of other night-time weightings and the addition of evening weightings should be further evaluated.

To be sure of the long-term validity of acceptable noise level limits, the constancy of responses to aircraft noise around Canadian airports should be verified.

It is important to verify that the new 'Mean' dose response curve accurately represents the response to aircraft noise near major Canadian airports. It is also important to determine whether this same curve is valid for smaller airports and for different kinds of aircraft operations.

All of the above needs could be pursued in a major survey of responses to aircraft noise around airports of varied size coupled with comprehensive noise measurements.

The new procedure for calculating the expected speech interference from aircraft noise must be validated using laboratory speech intelligibility tests and recordings of actual aircraft fly-overs.

Extra sound insulation is often recommended to reduce the negative effects of aviation noise. Modern information on the aircraft noise reduction of building facades and detailed design procedures for providing improved sound insulation in Canadian buildings are urgently needed. There is no evidence that added insulation reduces long term annoyance to aviation noise. Studies are needed to evaluate the perceived long-term benefits of added sound insulation in different climatic regions of Canada.

APPENDIX 1. PRINCIPAL TECHNICAL CONTACTS

This Appendix lists the names of people who were personally contacted to gain information for the work on the NEF validation project.

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APPENDIX 2. SUMMARIES OF OTHER REPORTS

A2.1 NEF Validation Study: (1) Issues Related to the Calculation of Airport Noise Contours

This was the first of three reports containing the results of an NEF validation study for Transport Canada

The NEF_1.7 program is a critical part of the management of airport noise in Canada, and it is extremely important that its validity and accuracy be as good as is reasonably possible. The use of millions of dollars worth of land near airport is determined by the noise level contours from this program. Similarly, the acceptability of land near airports for residential use is determined from the calculated noise contours produced by the NEF_1.7 program. The analyses of this report suggest that improving the detail of the flight path description and developing a more correct excess ground attenuation calculation procedure would considerably improve the NEF_1.7 program. It is therefore essential that the required continuing development of the NEF_1.7 program receive the necessary financial and technical support.

The analyses of this report were focused on the errors associated with predicting noise levels around airports. The related problems of determining acceptable noise level limits and the practical application of these limits will be considered in a second report. These two reports will form the technical background for a final report evaluating the use of the NEF measure to quantify airport noise levels near Canadian airports.

Some of the major technical findings of this report are as follows:

- The NEF_1.7 program is similar to other models such as the Integrated Noise Model (INM) and NoiseMap used in U.S.A. Compared to these two models, NEF_1.7 uses simpler flight path descriptions and a different excess ground attenuation calculation. More sophisticated simulation type models are now being developed that are potentially more accurate, such as the Swiss model.

- Comparisons of the NEF_1.7 program with the INM and NoiseMap programs using the same input data from four Canadian airports showed that the NEF contours from the NEF_1.7 program were 60 to 80% larger and NEF values at particular locations were 3 to 4 dB higher. However, it is not known which prediction model agrees best with measured aircraft noise levels. When the complete Canadian approach of using a Peak Planning Day with the NEF_1.7 program was compared with the American approach of using a mean planning day and the INM model, even larger differences resulted.

- Errors in estimating the expected future total aircraft operations could typically lead to 1 dB errors in NEF values and 12% errors in contour areas. Errors from estimating the number of night-time operations would usually be about half as large. Other errors in the estimated input data for future conditions would have smaller overall effects but often quite significant local effects.

- The detail in which the horizontal ground track and the vertical profile of the flight path are described influence the accuracy of the predictions. It is particularly important that the expected horizontal dispersion of aircraft about the nominal flight track be included in airport noise contour predictions.

- The major cause of differences between the contours produced by the NEF_1.7 program and those from the two American programs is their calculation of excess ground attenuation. Evidence from European research and limited measurements of modern civil aircraft suggest that the most appropriate excess ground attenuation is intermediate to the NEF_1.7 procedure and the SAE procedure used in the INM and NoiseMap. Data from more extensive experimental studies are required to determine a better excess ground attenuation calculation procedure. Performing calculations in octave bands would permit more accurate estimates of the propagation of aircraft noise.

- A systematic procedure for relating single event noise measures to combined measures for many aircraft is presented.

- A-weighted SEL values and PNL weighted EPNL values can be related with standard errors of less than 2 dB. Ldn and NEF values were found to relate with errors of less than 1 dB.

- Approximate conversions between various airport noise measures were systematically derived. The largest scatter in these relationships is caused by differences in frequency weightings and time of day weightings.

A2.2 NEF Validation Study: (3) Final Report

This is the summary of the final report of a project to evaluate the validity of the NEF measure of aircraft noise. This final report is intended to directly respond to the specific requirements of the original proposal. A database of references and two technical reports have already been sent to Transport Canada as part of this project. Summaries of the previous technical reports are included in the Introduction of this report. The highlights of this final report include:

General Recommendations

- Upgrade (and provide ongoing support for) the continuing development of the NEF_1.7 program.

- Establish and publish noise criteria for all major Canadian airports in terms of NEF values with supplementary single event noise criteria.

- Undertake a major Canadian survey of response to aircraft noise to include: isolated single event type problems, various smaller airport situations, tests of various time-of-day weightings, evaluation of the long term effectiveness of additional home insulation, and to provide a comprehensive calibration of the NEF measure.

- Support updating of the CMHC document on new housing and aircraft noise.

- Consider adopting an A-weighted NEF measure.
- Encourage a uniform national approach to the management of airport noise in Canada.

Acceptable Aircraft Noise Level Criteria

- It is proposed that the following noise level criteria thresholds be adopted in terms of NEF_{CAN} values: NEF_{CAN} 25, the onset of negative effects of aircraft noise; NEF_{CAN} 30, homes should include additional sound insulation; NEF_{CAN} 35, no new homes should be built; NEF_{CAN} 40, limit for existing homes. (NEF_{CAN} refers to NEF values predicted by Transport Canada's NEF_1.7 program.

- Supplementary single event noise criteria should also be adopted to control noise problems involving small numbers of unusually loud events. Initial proposals were based on previous sleep interference studies and new considerations of speech interference by aircraft noise.

Historical Development of the NEF Measure

- The NEF measure evolved from the older CNR measure, initially intended for general community noise problems.

- The development was based on a pragmatic common sense approach using specific consulting community noise case studies.

- The basic concepts did not come from systematic studies and there was never any thorough attempt to calibrate the NEF measure in terms of negative human responses.

Details of the NEF Measure

- The equal energy principle for adding multiple events that is incorporated in the NEF measure is widely accepted and is used in almost all other aircraft noise measures.

- The EPNL metric, which determines the frequency response of the NEF measure, is probably a slightly more accurate predictor of adverse human responses, but it makes NEF values more difficult to measure and hence it is more difficult to validate NEF predictions.

- The NEF measure incorporates the largest night-time weighting in common use. There are arguments for a smaller night-time weighting and for the addition of an evening weighting.

- The prediction of the number of operations for future Peak Planning Days could be improved. Errors in forecasting future operations could lead to errors of up to 2 dB in NEF_{CAN} values and up to 30% in contour areas. Smaller errors would more typically occur.

- The NEF_1.7 program has archaic input and output procedures, needs to be thoroughly validated, and needs ongoing support for both technical improvements and for improving the user friendliness of the software in coordination with the improvements of computer hardware.

Users' Evaluations

- Most users seem to be familiar and comfortable with the NEF measure.

- Many users say that the NEF_1.7 program is not user friendly and lacks sufficient detail in the description of flight paths.

- We do not know how to combine the impact of aircraft noise with other types of community noise such as road traffic noise.

- Too much attention to complaint data can distract us from a rational approach to aircraft noise management.

- Because Transport Canada does not have authority over all aspects of the problem, there is a need for a coordinated effort to manage airport noise that includes all levels of government and is carried out uniformly across the country.

Changes and Special Cases

- Excess ground attenuation algorithms in the NEF_1.7 program are in need of modification and lead to significant errors in the calculated NEF contours. New procedures must be based on, or validated in terms of, the measured attenuations of aircraft noise.

- There is a need to be able to include more complex approach and departure flight paths to correctly model current operations as well as to include the normal dispersion about the nominal flight path in the NEF_1.7 program.

- There is only limited information on changes of responses to aircraft noise over time from European studies. These show no change of reponses as a function of noise levels.

- Although there are many smaller airports in Canada, the negative impact of these airports on residents is not well understood. The evidence suggests that disturbance may be less at smaller airports but larger where there are significant numbers of general aviation operations.

Land use planning needs to be in terms of more stable maximum long term goals. It should be based on standard noise level criteria and it should be applied in a coordinated manner by all levels of government.