

## Effects of Aircraft Noise: Research Update on Select Topics

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AIRPORT COOPERATIVE RESEARCH PROGRAM

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## ACRP SYNTHESIS 9

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# Effects of Aircraft Noise: Research Update on Selected Topics

*A Synthesis of Airport Practice*

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**SUBJECT AREAS**

Aviation

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Research Sponsored by the Federal Aviation Administration

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**TRANSPORTATION RESEARCH BOARD**

WASHINGTON, D.C.

2008

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## **FOREWORD**

*By Gail Staba  
Senior Program Officer  
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Airport operators, service providers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to the airport industry. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire airport community, the Airport Cooperative Research Program authorized the Transportation Research Board to undertake a continuing project. This project, ACRP Project 11-03, "Synthesis of Information Related to Airport Practices," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an ACRP report series, *Synthesis of Airport Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

## **PREFACE**

This synthesis study is intended to inform airport operators, stakeholders, and policy makers of updated information about aviation noise effects. In the decades since FAA Report No. FAA-EE-85-2 "Aviation Noise Effects" was first published in 1985 much has changed in the understanding of this complex issue. Increased air travel, new and quieter aircraft, increased awareness of land use planning and aviation noise, and mitigation of previously incompatible land uses are just a few of the changes. Knowledge of the effects of aviation noise has also changed. The greatest increases in knowledge have come in the areas of health effects, annoyance, sleep disturbance, and potential effects on children's learning abilities in schools.

This document is intended to synthesize research since 1985 to update and compliment the original FAA report, primarily by providing an annotated bibliography and summary of new research in selected topic areas. Although research inquiry has progressed in many areas, there is still much to be learned. The reader is encouraged to review each chapter for additional information and to be directed to source material.

Vince Mestre, Mestre Greve Associates, Laguna Niguel, California, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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# EFFECTS OF AIRCRAFT NOISE: RESEARCH UPDATE ON SELECTED TOPICS

**SUMMARY** In the years since *Aviation Noise Effects* (FAA Report No. FAA-EE-85-2) was published in 1985, much has changed in the aviation world. Quieter jets, increased air travel, new breeds of aircraft types, increased awareness of proper land-use planning, and mitigation of previously incompatible land uses are just a few of the changes. Our knowledge of the effects of aviation noise has also changed. The greatest increases in knowledge are in the areas of health effects, annoyance, sleep disturbance, and potential effects on children's learning abilities in schools.

This document is intended to update and complement the original document, primarily by focusing on the latest research efforts and conclusions. Considerable research, review of previous research with new thought, new independent research, and collaborative efforts have been compiled in this report. Although we have progressed in many areas, there is still much to be learned. This synthesis provides a condensed review of selected research, with detailed discussions appearing in Appendix A, which the reader is highly encouraged to review thoroughly.

- Chapter One—Introduction and Methodology

After a complete review of FAA's 1985 *Aviation Noise Effects* report, a literature search was undertaken, with representative studies completed since 1985 being selected, annotated, and categorized for each of the 11 chapter topic areas outlined. For ease of use, each chapter has its own discussion and summary, and is immediately followed by an annotated bibliography.

- Chapter Two—Health Effects of Aviation Noise

In the 20-plus years since publication of the FAA's *Aviation Noise Effects*, considerable research, review of previous research with new thought, and new independent research, as well as collaborative efforts to identify health effects related to aviation noise, have been completed. Some studies have identified a potential correlation between aviation or road noise above certain noise thresholds, typically a day-night average noise level (DNL) value of 70 dBA, and increased hypertension; however, other studies contradict such findings. Occupational noise is also an intricate concern. Health effects on children, particularly those with decreased cognitive abilities, mental disturbances, or other psychological stressors, and studies of pregnancy and low infant birth weights, all indicate either little correlation or conflicting results of relationships between aviation noise and childhood psychiatric disorders, environmental factors, or low infant birth weights. Additionally, recent studies conclude that aviation noise does not pose a risk factor for child or teenage hearing loss. Because aviation and typical community noise levels near airports are not comparable to the occupational or recreational noise exposures associated with hearing loss, hearing impairment resulting from community aviation noise has not been identified. However, newer studies suggest there may be a potential relationship between aviation noise levels and hypertension or ischemic heart disease at noise levels as low as 50 dBA  $L_{eq}$ .

Despite decades of research, including review of old data and multiple new research efforts, health effects of aviation noise continue to be complicated and the need for additional

research is crucial to understanding. This synthesis report includes annotation of 21 recent reports on health and hearing.

- Chapter Three—Annoyance and Aviation Noise

Annoyance remains the single most significant effect associated with aviation noise. Community annoyance is the aggregate community response to long-term, steady-state exposure conditions. However, to adequately support government noise policy-making efforts, it is necessary to synthesize the large amount of data contained in journal articles and technical reports to develop a useful exposure-response relationship.

Significant research has occurred since the 1985 aviation effects report was published. There is no current research to suggest that there is a better metric than DNL to relate to annoyance. However, there remains significant controversy over the use of the dose-response annoyance curve first developed by Schultz and then updated by others. Although the curve is presented as a smooth definitive relationship between DNL and annoyance, there is an extraordinary amount of scatter in the data used to develop the curve. Investigations that report a distinct percentage of the population that will be highly annoyed at a given DNL may incorrectly be interpreted as having a more precise meaning than should be assumed from the data, given such a large amount of scatter. Furthermore, more recent research tends to support the idea that the dose-response curves are different for aircraft, road, and rail noise sources. An area of research that remains to be investigated is the relationship between single-event noise levels and annoyance. The expanding use of airport noise monitoring systems, flight tracking systems, and geographic information systems (GIS) may make the evaluation of annoyance and single-event noise a prime area for examination. This synthesis report includes annotation of 12 recent reports on annoyance and aviation noise.

- Chapter Four—Sleep Disturbance and Aviation Noise

Sleep disturbance is a common effect described by most noise-exposed populations and their complaints are often very strong, especially in the vicinity of airports. Protection of a particular sleep period is necessary for overall quality of life. Sleep may be quite sensitive to environmental factors, especially noise, because external stimuli are still processed by the sleeper sensory functions, although there may be no conscious perception of their presence.

The large amount of research published during the last 30 years has produced considerable variability of results, some of which is controversial. As in establishing the health effect of aviation noise, the absence of one internationally accepted “exposure-effect” or “dose-response” relationship is largely the result of the lack of one obvious “best choice” research methodology, as well as the complex interactions of the many factors that influence sleep disturbance. These include the differences of the noise source and the context of the living environment, to name one example. Current exposure-response relationships use either “awakenings” or “body movements” to describe sleep disturbance.

Although the most common metrics for assessing the impacts of community noise, DNL, and Day-Evening-Night Average Sound Level ( $L_{den}$  or CNEL), already contain a 10-dB penalty for nighttime noises, there are circumstances where a separate analysis of the impacts of nighttime transportation noise is warranted. There are, however, different definitions of sleep disturbance and different ways to measure it, different exposure metrics that can be used, and consistent differences in the results of laboratory versus field studies. At the present time, very little is known about how, why, and how often people are awakened during the night, although it is generally acknowledged that the “meaning of the sound” to the individual, such as a child crying, is a strong predictor of awakening. Although the Integrated Noise Model can estimate the various metrics referenced in this discussion of sleep disturbance, there is substantial controversy associated with how to apply and interpret these studies.

Since 1985, research has focused on measuring in-home sleep disturbance using techniques not available before that time. A review of in-home sleep disturbance studies has clearly shown that it requires more noise to cause awakenings than was originally thought based on laboratory sleep disturbance studies. In the context of attempting to estimate the population awakened for a specific airport environment, or the difference in population awakened for a given change in an airport environment, the sleep disturbance research may not yet have sufficient specificity to warrant such an estimate. This synthesis report includes annotation of 14 recent reports on sleep disturbance and aviation noise.

- Chapter Five—Speech Interference and Aviation Noise

Speech interference (SI) is an important component in annoyance response. SI has been well researched over the years and there have been few new research papers dealing specifically with aircraft noise published on this topic since 1985. However, most SI studies and guidelines deal with steady-state noises. Aircraft noise, however, is an intermittent noise, and therefore the SI literature is inadequate with respect to intermittent noise (the 1974 EPA levels document briefly addresses the issue of intermittent noise). There is a need for more research on the effect of intermittent noise, such as an aircraft flyover, on speech. This synthesis report includes annotation of four recent reports on SI and aviation noise.

- Chapter Six—Effects of Aviation Noise on Schools

The research on the effects of aviation noise on schools has focused on identifying noise as an important issue in the classroom. However, there has been little work done on establishing a dose-response relationship between aviation noise and classroom effects. This lack of a reliable dose-response relationship between aircraft noise and classroom effects makes the evaluation of aircraft noise on schools and setting policy very difficult.

Although it is clear that at high enough noise levels speech communication is virtually impossible, there is no clear threshold for when aircraft noise begins to effect schools. Much of the research has focused on the use of standardized test scores and stress hormone measurement in cross-sectional studies. There is a clear need for additional research on the effects of aviation noise on schools and these studies need to include in-classroom noise measurements and observation of student responses to aircraft activity. This synthesis report includes annotation of 13 recent reports on aviation noise and schools.

- Chapter Seven—Effects of Aviation Noise on Parks, Open Space, and Wilderness Areas

National parks have been a focus of park and open space noise research in the United States. Preserving the natural quiet is a controversial topic, one that is subject to Congressional mandate. The FAA has developed specific analytical tools included as part of the most recent version of the Integrated Noise Model for use in analyzing aviation noise affects in national parks. Little research has been done on the effect of aviation, or any other kinds of noise, on the more common urban and suburban parks. The research on urban parks that has been done in Europe indicates that users consider noise a very important factor in park enjoyment, but that park users judge sounds differently based on whether the noise is an expected or unexpected part of the park environment. This synthesis report includes annotation of nine recent reports on aviation noise and parks, open space, and wilderness.

- Chapter Eight—Aviation Low-Frequency Noise and Vibration

Low frequency noise is an issue for observers located near an airport runway where jet noise at the start of takeoff roll and/or the thrust reversers may cause low frequency noise impacts not common to other parts of the airport environs. Low frequency noise is unique in that it may not be adequately described by the A-weighted decibel, and may cause structural

vibration that could lead to increased annoyance owing to the rattling of windows or bric-a-brac on shelves or hanging on walls. Low frequency noise studies have proven to be controversial and ongoing research is attempting to address the low frequency noise issues. Among the outstanding issues are what metrics to use to describe low frequency noise and what noise levels are compatible with residential land uses. This synthesis report includes annotation of eight recent reports on aviation low frequency noise and vibration.

- Chapter Nine—Aviation Noise Effects on Wildlife and Domestic Animals

The effects of aviation noise on animals have been studied rather extensively over the past 20 years, with much of the work being conducted by U.S. Air Force-sponsored researchers. The studies have revealed that the effects are highly species-dependent and that the degree of the effect may vary widely. Responses of animals to aircraft noise vary from almost no reaction to virtually no tolerance of the sound. The question of how adaptable animals are remains largely unanswered. Both wild and domesticated animals have been studied, although more research has centered on domesticated or laboratory animals (such as rats and mice).

Although noise is often defined as unwanted sound for humans, it has been suggested that it is also so for animals. “Noise” is best defined as any sound that (1) causes hearing loss; (2) masks signals needed for communication, navigation, prey detection, predator avoidance, and environmental monitoring; (3) effects non-auditory health; (4) effects biologically significant changes in behavior; and (5) alters population including declines in abundance, changes in distribution, or reproductive failures.

Although it is not possible to generalize a dose-response relationship for all wildlife and farm animals, the reader is referred to specific tables in chapter nine for a summary of the findings of effects of aircraft noise and sonic booms. Of noteworthy reference is the National Park Service’s comprehensive annotated bibliography, “Impacts and Noise and Overflights on Wildlife,” published in 2005. The report also includes 76 documents divided into categories. Although it is impossible to generalize or summarize the results of such a broad range of studies in this synthesis, it is clear that some reports found dramatic effects, whereas others discovered that other factors overwhelm the noise effects. This synthesis report includes annotation of six recent reports on aviation noise and wildlife and domestic animals.

- Chapter Ten—Aviation Noise Effects on Property Values

The studies of the effects of aviation noise on property values are highly complex owing to the differences in methodologies, airport and community environments, market conditions, and demand variables involved. Whereas most studies concluded that aviation noise effects on property value range from some negative impacts to significant negative impacts, some studies combined airport noise and proximity and concluded that the net effect on property value was positive. Prospective homebuyers were at times not well-informed about the noise levels of aircraft operations near the property of interest. Lacking information often led to high bid prices and possible disappointment after purchase. However, once noise levels stabilized, the next homeowner was compensated once the property value adjusted as the result of the effects of noise. Lastly, the technology available to analyze data has improved throughout the years. The spatial nature of aircraft operations, noise contours, and property location will continue to prompt studies founded in geographic information system analysis that will improve our understanding of the effects of aviation noise on property value. This synthesis report includes annotation of 12 recent reports on aviation noise and property values.

- Chapter Eleven—Effect of Meteorology on Aviation Noise

Meteorology plays a very important role in the propagation of sound. Simply put, air absorbs sound. As sound travels through the atmosphere it is attenuated by this absorption. Complicating matters is that air absorption varies with temperature and humidity and the frequency of the sound. Sound travels downwind better than upwind. In the real atmosphere the temperature, humidity, and wind speed and direction are not homogeneous, but are changing constantly. Temperature and/or wind gradients cause refraction (bending) of sound waves.

One of the consequences of the complex way weather affects sound propagation is that noise models are limited to estimating noise levels for average conditions. Comparing noise model predictions with short-term noise measurements is meaningless, as atmospheric effects are not adequately accounted for in the model. However, long-term measurements will produce an average noise level in which atmospheric effects will tend to average out and comparison with noise model results will be much more meaningful. This caution should be noted for any short-term measurement program.

Current research includes highly technically complex studies analyzing how sound levels increase as the refractive curvature goes from negative to positive values; ground effects on propagation and infrasound propagation. Research indicates that large-scale turbulence is a significant cause of acoustic signal fluctuations, particularly in the signal phase. Other, more site-specific research evaluates the influence of a pine forest on sound propagation, finding high frequency attenuation owing to the forest that increases with distance. This synthesis report includes annotation of seven recent reports on meteorology and aviation noise.

- Chapter Twelve—Effect of Topography and Ground Absorption on Aviation Noise

Aircraft sound heard by an observer can be influenced by a number of factors. As previously stated, meteorology is one such factor. Another factor is the propagation of sound over the ground and as affected by terrain. When an aircraft is directly overhead, the sound experienced by an observer is only affected by meteorology. However, as the aircraft passes by or is at lower elevation angles, the sound heard by an observer is both the sound that travels in a straight line from the aircraft plus the sound reflected off the ground. Although the interaction of sound traveling over the ground is quite complex, recent research has provided new insight.

Although FHWA's 1978 report on highway noise prediction model was prepared before 1985, it still presents one of the best descriptions of how to include noise barrier effects in transportation modeling. It includes detailed methodologies to computer noise barrier effects. This synthesis report includes annotation of seven recent reports on topography, ground absorption, and aviation noise.

## INTRODUCTION AND METHODOLOGY

In 1985, the FAA published *Aviation Noise Effects*, Report No. FAA-EE-85-2, to summarize and synthesize the effects of aviation noise in several topical areas. The report provides summaries of critical research, conclusions of pertinent research, and, when possible, conclusions, criteria, or perspectives for the reader. This document has been a valuable resource for the airport community for more than 23 years. Because the literature on the topics reviewed in the 1985 report has expanded, it was determined that the time was right to supplement it with an up-to-date synthesis.

After a complete review of this landmark FAA report, a literature search was undertaken. The most representative studies completed since 1985 were selected, annotated, and categorized for each of the following topic areas:

1. Health effects of aviation noise,
2. Annoyance and aviation noise,
3. Sleep disturbance and aviation noise,
4. Speech interference and aviation noise,
5. Effects of aviation noise on schools,
6. Effects of aviation noise on parks, open space, and wilderness areas,
7. Aviation low-frequency noise and vibration,
8. Aviation noise effects on wildlife and domestic animals,
9. Aviation noise effects on property values,
10. Effect of meteorology on aviation noise, and
11. Effect of topography and ground absorption on aviation noise.

These 11 topic areas are outlined in the following 11 chapters, which lead to a section of conclusions. For the reader's ease, each of these chapters has its own discussion, summary, and annotated bibliography in Appendix A. An extensive reference list, glossary, and key word index complete the report. The goal of ACRP Synthesis S02-01 is to provide a supplemental report on the current state of knowledge and practice in the selected topical areas regarding the effects of aircraft noise.

In addition to the 1985 FAA report, the reader should be aware of an EPA report, mandated by Congress, *Information on Levels of Environmental Noise Requisite to Protect Public Health and Welfare with an Adequate Margin of Safety* (1974). This report is commonly referred to as the EPA *Levels Document*. The *Levels Document* is significant because it presents a comprehensive background on the effects of noise in many of the topic areas discussed in this synthesis. Even though the document is now more than 30 years old, and some of the information has been updated (particularly with respect to sleep disturbance), it is still a valuable reference.

## HEALTH EFFECTS OF AVIATION NOISE

Trying to identify, measure, and quantify any potential effects of aviation noise on health is a complex and difficult field of study. Variations on how to identify and/or measure the noise exposure itself (single dose, long-term average, number of events above a certain level, etc.), and attempting to separate the effects from other life events are difficult at best. For example, lifestyles, life's stressors, hereditary factors, and genetic composition are just a few factors that may distort potential results of an aviation noise health effects study.

Given this complexity, the large amount of research published during the past 30 years has produced considerable variability of results; often, some are quite controversial. The absence of one internationally acceptable "exposure-effect" or "dose-response" relationship is largely the result of the lack of one obvious "best choice" research methodology.

After reviewing all new research, reviewing previous research with new thought, and collaborative efforts to identify health effects related solely to aviation noise were completed, four main subject areas were identified: cardiovascular effects, aviation noise effects and children, aviation noise effects on hospitals and care facilities, and potential hearing impairment. Each is discussed separately here.

### CARDIOVASCULAR EFFECTS

Several recent studies have reviewed previous literature, either through compilation or re-review of original data, which suggest that increased hypertension or other cardiovascular effects may be associated with particular long-term noise exposure. For example, in 2000 at a World Health Organization expert task force meeting, a weak association between long-term environmental noise exposure and hypertension was suggested, but no dose-response relationship could be established (*Guidelines for Community Noise* 2000). It concluded that cardiovascular effects may be associated with long-term exposure; however, the associations are weak and the effect is somewhat stronger for ischemic heart disease than for hypertension. Another example, a study by Passchier-Vermeer and Passchier (2000) reviewed existing literature that stated there was sufficient scientific evidence that noise exposure can induce hearing impairment, hypertension, and ischemic heart disease. It concluded there were no obvious effects from noise exposure on mean diastolic and

mean systolic blood pressure; however, some effects were observed in terms of an increase in the percentage of individuals with hypertension.

Most reviewers concluded that previous reviews were not carried out in a systematic way, which makes them prone to bias. Reviewers pointed out the tendency for some studies to inadequately report noise exposure data. In 2002, for example, Van Kempen et al. concluded that whereas "noise exposure can contribute to the prevalence of cardiovascular disease, the evidence for a relation between noise exposure and ischemic heart disease is still inconclusive, because of the limitations of exposure characterization, adjustment for important confounders, and occurrence of publication bias."

No differences in systolic and diastolic blood pressure have been found in cross-sectional studies comparing areas near an airport with calm, suburban areas; therefore, aircraft noise levels were not a factor in these two subject areas. One should note that cross-sectional studies are notoriously difficult to interpret. They often report conflicting results, generally do not identify a cause and effect relationship, and often do not report a dose-response relationship between the cause and effect.

### AVIATION NOISE EFFECTS AND CHILDREN

Another particular concern over the last 30 years is the potential health effect on children owing to exposure to or interference from aviation noise. Published studies include the effects of aircraft noise and mental disturbances by means of a cross-sectional study in two contrasting geographical regions. Although noise levels were not reported, they are likely to be very high, as military aircraft fly as low as 75 m with very high onset rates. Neither psychiatric disorders nor environmental factors showed any relationship to noise; however, psychophysiological parameters (e.g., heart rate and muscle tension) did demonstrate some relationship to noise.

Other recent studies have focused on relationships between noise exposure during pregnancy and low birth weights; however, no association was found between personal noise exposure (measured in decibels) and birth weight (Wu et al. 1996; Passchier-Vermeer and Passchier 2000). Other possible noises (e.g., occupational, traffic noise, and history of listening to amplified music) also showed no effect on infant birth

weights. The reader is also referred to chapter six, “Effects of Aviation Noise on Schools” for additional information.

### HOSPITALS AND CARE FACILITIES

A careful search for research regarding aviation noise and hospitals and care facilities did not identify any studies that address this particular issue. Most airport noise and land-use compatibility guidelines list hospitals and care facilities as noise-sensitive uses, although there are no studies that have identified health effects associated with aviation noise. However, there are numerous studies that identify problems with internal hospital noises.

### HEARING IMPAIRMENT

Although aviation noise exposure and potential hearing impairment during all ages of life are common research areas, the research is much more definitive, usually owing to adequate controls, data, and identifiable conclusions. For example, in 1999, a study by Ludlow and Sixsmith reviewed nine studies undertaken in the vicinity of seven civil and military airports, and two laboratory studies, finding that “the laboratory studies suggest that permanent threshold shifts are unlikely to be induced by exposures to aircraft noise thought to be typical of real life.” The reviewed studies concluded “environmental noise does not appear to approach recognized occupational noise limits. Furthermore, it may be that the intermittency of environmental noise itself may protect hearing from damage” (Ludlow and Sixsmith 1999). These conclusions are echoed in several other studies as well, because environmental noise does not approximate occupational noise levels or recreational noise exposures (e.g., personal listening devices, concerts, or motorcycles), as it does not have an effect on hearing threshold levels. Lastly, studies have also shown that early noise exposure as a child on military jet aircraft bases does not make one more susceptible to noise-induced hearing loss.

In conclusion, in the more than 23 years since publication of *Aviation Noise Effects* (Newman and Beattie 1985)

considerable research, review of previous research with new thought, and new independent research, as well as collaborative efforts to identify health effects related to aviation noise have been completed. Some studies have identified a potential correlation between increased hypertension and aviation or road noise above certain noise thresholds; however, other studies contradict such findings. Occupational noise often becomes an intricate concern. Health effects on children, particularly those with decreased cognitive abilities, mental disturbances, or other psychological stressors, and studies of pregnancy and low infant-birth weights, all indicate there is no correlation between aviation noise and childhood psychiatric disorders, environmental factors, or low infant-birth weights. Additionally, recent studies conclude aviation noise does not pose a risk factor for child or adolescent hearing loss, but perhaps other noise sources (personal music devices, concerts, motorcycles, or night clubs) are a main risk factor. Because aviation and typical community noise levels near airports are not comparable to the occupational or recreational noise exposures associated with hearing loss, hearing impairment resulting from community aviation noise has not been identified.

Although newer studies suggest there may be a potential relationship between aviation noise levels and hypertension or ischemic heart disease at noise levels as low as 50 dBA  $L_{eq}$  (equivalent sound level), further research is necessary. One such study only found that effect for night aircraft noise (Eriksson et al. 2007). Among the confounding factors in studies of hypertension and aircraft noise is that aircraft noise exposure is taken from noise model estimates without regard to ambient noise levels. The ambient noise levels in urban areas and most suburban areas exceed 50 dBA  $L_{eq}$ . Further, only a handful of recent studies attempted to segregate health effects of noise from that of air pollution near airports.

Despite decades of research, including review of old data and new research efforts, health effects of aviation noise continue to be an enigma. Most, if not all, current research concludes that it is as yet impossible to determine causal relations between health disorders and noise exposure, despite well-founded hypotheses.



## ANNOYANCE AND AVIATION NOISE

Annoyance remains the single most significant effect associated with aviation noise. Community annoyance is the aggregate community response to long-term, steady-state exposure conditions. However, to adequately support government noise policy-making efforts, it is necessary to synthesize the large amount of data contained in journal articles and technical reports to develop a useful exposure-response relationship.

In his seminal journal article, Schultz (1978) reviewed data from social surveys concerning the noise of aircraft, street and expressway traffic, and railroads. Going back to the original published data, the various survey noise ratings were translated to Day-Night Average Noise Level (DNL) and, where a choice was needed, an independent judgment was made as to which respondents should be counted as “highly annoyed.” According to Schultz “. . . the basic rule adopted was to count as ‘highly annoyed’ the people who responded on the upper 27% to 29% of the annoyance scale . . .” (Schultz 1978).

For decades, environmental planners have relied heavily on the Schultz Curve for predicting the community annoyance produced by noise from transportation noise sources. Notwithstanding the methodological questions, errors in measurement of both noise exposure and reported annoyance, data interpretation differences, and the problem of community response bias, Schultz’s recommended relationship has historically been the most widely accepted interpretation of the social survey literature on transportation noise-induced annoyance.

Beginning with the publication of this original exposure-response curve, work has continued in many countries to conduct new field studies, develop databases with the results of dozens of new social surveys, and explore whether separate curves are needed to describe community responses to aircraft, street traffic, and railway noise. Based on an updating of the Schultz curve by Fidell et al. (1991), the Technical Section of the Federal Interagency Committee on Noise (FICON), stated in 1992 that there were no new descriptors or metrics of sufficient scientific standing to substitute for the present DNL cumulative noise exposure metric (Federal Interagency Committee on Noise 1992). The dose-response relationship, as represented by DNL, and the percentage of persons “highly annoyed” remains the best available approach for analyzing overall health and welfare impacts for the vast majority of transportation noise analyses. In later years, Fidell goes on to criticize the use of this type of simplistic

curve such as the one in FICON, in light of the high data variability, the effect of low- and high-noise exposure levels on the curve fit, and the lack of consideration of other variables in community response to noise.

A comprehensive review and critique of the Fidell et al. update was later published by Fields (1994) that raises questions about the use of the synthesis data to develop the commonly used annoyance/DNL dose-response relationship. The report arrives at several conclusions, including “the curve is NOT a measurement of the relationship between DNL and the percentage of the population that would describe themselves as ‘highly annoyed’” and “if it is necessary to estimate the dose/response relationship . . . a single constituent survey provides a better estimate” (Fields 1994).

Fidell et al.’s expansion of the existing community annoyance research database and their revised prediction curve provided a considerable extension of the original Schultz meta-analysis (Fidell et al. 1991). However, because there were several debatable methodological issues involved in this update, Finegold et al. (1994) reanalyzed the Fidell et al. data focusing primarily on the choice of screening criteria for selecting which studies to include in the final database and the choice of a data fitting algorithm.

Using the new data set, a new logistic fit curve as the prediction curve of choice was developed and adopted by FICON in 1992 for use by federal agencies in aircraft noise-related environmental impact analyses (Federal Interagency Committee on Noise 1992). It was also adopted as part of the American National Standards Institute (ANSI) Standard on community responses to environmental noises (Acoustical Society of American 2006). Finegold et al. (1994) showed that if the data are broken down into separate curves for various types of transportation noises (aircraft, roadway, and rail noise) aircraft noise appears to be more annoying at the same DNL than road or rail noise.

Over the past decade, Miedema and Vos (1998) have compiled the most comprehensive database of community annoyance data yet available, and several studies have been published on the results of their analyses. It is a comprehensive review of an issue—separate, non-identical curves for aircraft, road traffic, and railway noise—that has been the subject of much debate since Shultz published his data in 1978. Caution should be exercised, however, when drawing

conclusions about the state of knowledge regarding the relationship between various transportation noise sources and community annoyance.

The European Commission position on annoyance is based on a report recommending the percentage of persons “highly annoyed” be used as the descriptor for noise annoyance. Similar to Miedema and Vos (1999) the report distinguishes between aircraft, road, and rail traffic noise; recommends use of a separate pair of curves (“annoyed” and “highly annoyed”) for each; and clearly shows a tendency to treat aircraft, road, and rail noise as unique when estimating population that will be “annoyed” or “highly annoyed” by noise (Miedema and Vos 1999).

In their 1999 paper, Miedema and Vos further studied the effects of demographic variables (sex, age, education level, occupational status, size of household, dependency on the noise source, use of the noise source, etc.) and two attitudinal variables (noise sensitivity and fear of the noise source) on annoyance. The results are very interesting and suggest that fear and noise sensitivity has a large impact on annoyance. Additionally, in a 2002 report by Fidell et al., it is suggested that a good part of the excess annoyance is attributable to the net influence of non-acoustic factors.

Some of the most interesting research comes from Fidell’s “The Schultz Curve 25 Years Later: A Research Perspective” (2003). It presents the argument that although federal adoption of an annoyance-based rationale for regulatory policy has made this approach a familiar one, it is only one of several historical perspectives, and not necessarily the most useful for all purposes. This tutorial article traces the development of the dosage-effect relationship on which FICON currently relies and identifies areas in which advances in genuine understanding

might lead to improved means for predicting community response to transportation noise. It provides an important summary of how the annoyance synthesis was developed, and the inherent weakness of the DNL/dose-response relationship that was developed. Fidell is highly critical of U.S. policy that relies solely on the synthesized dose-response relationship.

Fidell and Silvati (2004) identified shortcomings of a fitting function endorsed by FICON for predicting annoyance in populations exposed to aircraft noise that are well-understood and well-documented. The authors argue that the U.S. National Environmental Policy Act (NEPA) (1969) requires the use of the best-available technology for disclosure of noise impacts of major federal actions, even though reliance on the FICON curve for meeting NEPA requirements does not use the best available technology.

To summarize, significant research has occurred since the 1985 aviation effects report was published. Although no current research suggests there is a better metric than DNL to relate to annoyance, there still remains significant controversy over the use of the dose-response annoyance curve first developed by Schultz and then updated by others. Further, investigations that report a distinct percentage of the populations that will be highly annoyed at a given DNL may be incorrectly interpreted as to having a more precise meaning than should be taken from the data. Lastly, a relatively new concept is that more research tends to support the idea that dose-response curves are different for aircraft, road, and rail noise sources. Areas of research that remain to be investigated include the relationship between single-event noise levels and annoyance. The expanding use of airport noise monitoring systems, flight-tracking systems, and geographic information systems may make the evaluation of annoyance and single-event noise rich for examination.

## SLEEP DISTURBANCE AND AVIATION NOISE

Most noise-exposed populations especially in the vicinity of airports cite sleep disturbance as a common complaint. Protection of a particular sleep period is necessary for overall quality of life. Sleep may be quite sensitive to environmental factors, especially noise, because external stimuli are still processed by the sleeper's sensory functions, although there may be no conscious perception of their presence.

The large amount of research published during the last 30 years has produced considerable variability and often controversial results. For example, in establishing the effect of aviation noise on health, the absence of one internationally accepted exposure-effect or dose-response relationship is largely the result of a lack of one obvious "best choice" research methodology, as well as to the complex interactions of many factors that influence sleep disturbance, including the differences of the noise source and the context of the living environment. Current exposure-response relationships use either awakenings or body movements to describe sleep disturbance.

Several studies suggest that either sound exposure level (SEL) or maximum noise level ( $L_{\max}$ ) are better predictors of sleep disturbance than long-term weighted averages [equivalent sound level ( $L_{\text{eq}}$ )], day-evening-night average noise levels ( $L_{\text{den}}$ ), community noise equivalent level (CNEL), DNL, or equivalent noise level for night ( $L_{\text{night}}$ ). A survey of the literature also shows large differences between results from numerous laboratory studies and those from epidemiological or experimental studies made in real, in-home situations. The landmark study by Ollerhead et al. (1992) clearly identified a difference between laboratory and in-home studies of sleep disturbance, with the in-home data showing it takes considerably more noise to awaken people than data collected in the laboratory studies, and that the agreement between actimetrically determined arousals and electroencephalogram (EEG)-measured arousals were very good (Ollerhead et al 1992). It summarized by stating that "once asleep, very few people living near airports are at risk of any substantial sleep disturbance resulting from aircraft noise, even at the highest event noise levels."

Later studies by Horne et al. (1994) document a landmark in-home field study that demonstrated dose-response curves based on laboratory data greatly overestimated the actual awakening rates for aircraft noise events. In 1995, Fidell found that SELs of individual noise intrusions were much more

closely associated with awakenings than long-term noise exposures (Fidell et al. 1995). These findings do not resemble those of laboratory studies of noise-induced sleep interference, but agree with the results of other field studies. Importantly, the study also concludes the relationship observed

... between noise metrics and behavioral awakening responses suggest instead that noise induced awakening may be usefully viewed as an event-detection process. Put another way, an awakening can be viewed as the outcome of a de facto decision that a change of sufficient import has occurred in the short-term noise environment to warrant a decision to awaken (Fidell et al. 1995).

This is an important observation that leads to suspicion of any assumption about the independence of noise events made in the pursuit of estimating total awakenings.

In 1989, a comprehensive database representing 25 years of both laboratory and field research on noise-induced sleep disturbance was the basis for an interim curve to predict the percent of exposed individuals awakened as a function of indoor A-weighted SEL (Finegold et al. 1992). This curve was adopted by FICON in 1992. Since publication of the FICON report (Federal Interagency Committee on Noise 1992), substantial field research in the area of sleep disturbance has been completed. The data from these studies show a consistent pattern, with considerably less percent of the exposed population expected to be behaviorally awakened than laboratory studies had demonstrated. As a result, the Federal Interagency Committee on Aviation Noise (FICAN) published a new recommendation in 1997. Interestingly, the FICAN curve does not represent a best fit of the study data, but rather is constructed to represent the out boundary of the data (FICAN 1997).

In summary, although the most common metrics for assessing the impacts of DNL,  $L_{\text{den}}$ , or CNEL already contain a 10-dB penalty for night-time noises, there are circumstances where a separate analysis of the impacts of night-time transportation noise is warranted. There are, however, different definitions of sleep disturbance and different ways to measure it, different exposure metrics that can be used, and consistent differences in the results of laboratory versus field studies. At the present time, very little is known about how, why, and how often people are awakened during the night, although it is generally acknowledged that the "meaning of the sound" to the individual, such as a child crying, is a strong predictor of awakening. Although different models can estimate various metrics, there is substantial controversy associated with how to

apply and interpret these studies. Current research has focused on measuring in-home sleep disturbance using techniques not available in 1985. In-home sleep disturbance studies clearly demonstrate that it requires more noise to cause awakenings than was previously theorized based on laboratory sleep disturbance studies. Recent studies have cautioned about the

over-interpretation of the data. This is contrasted with recent efforts to estimate the population that will be awakened by aircraft noise around airports. Research may not yet have sufficient specificity to estimate the population awakened for a specific airport environment or the difference in population awakened for a given change in an airport environment.

## SPEECH INTERFERENCE AND AVIATION NOISE

SI is a principal factor in human annoyance response. Activities where speech intelligibility is critical include classroom instruction, personal communication, and leisure listening endeavors such as television, radio, and the like. SI can also be a critical factor in situations requiring a high degree of intelligibility essential to safety. Factors that can influence SI include location (outdoor or indoor), transmission loss (acoustical isolation) of structure, vocal effort, vocal frequency content (such as male or female), listening skill, hearing acuity noise frequency, and noise temporal characteristics.

Most of the SI research involves steady-state or constant noise masking well-defined speech signals. The majority of this research was published well before 1985 and has not been expanded significantly since then.

In 1999, the World Health Organization (WHO) published noise guidelines that included discussion of SI (*Guidelines for Community Noise* 1999). The guidelines do not discuss aircraft noise and SI expressly, but address the problems associated with speech comprehension, which result in a large number of personal disabilities and behavioral effects. WHO conclusions are applicable to steady-state noise, but do not address intermittent noise such as an aircraft flyover.

SI is most rigorously defined using metrics that analyze signal-to-noise relationships defined in specific frequency bands. The Articulation Index and a related methodology, the Speech Interference Level, have been used since the 1950s for this purpose. In addition, the A-weighted sound level has

proven to be a good predictor of speech intelligibility and has often been employed in research findings. To that end, the ANSI has published a standard in terms of A-weighted decibels for rating noise with respect to speech (ANSI S12.65-2006).

FICON, in a federal review of noise issues in 1992, explained that where speech communication is an issue, certain specific analyses, such as the Time Above metric or the SEL, and/or the maximum A-weighted noise level ( $L_{\max}$ ) may be useful (Federal Interagency Committee on Noise 1992). These metrics may be estimated using the Integrated Noise Model.

The EPA Levels Document published in 1974 is one of the few documents to address the effect of intermittent noise on SI. The EPA questioned whether the results of SI relative to steady-state noise would apply to sounds that have fluctuating levels. The results demonstrate that, for 95% sentence intelligibility, normal vocal effort and a 2-m separation between talker and listener outdoors, the maximum  $L_{\text{eq}}$  value associated with continuous noise is less than the maximum value for an environmental noise whose magnitude varies with time, such as an aircraft flyover. Therefore, when interpreting the amount of SI using the ANSI method or the guidelines of FICON or WHO, these methods will overestimate that amount of SI.

Little research has been published since 1985 on intermittent noise such as aircraft noise and its influences on speech; therefore, more research is needed.

## EFFECTS OF AVIATION NOISE ON SCHOOLS

Some of the most promising research has been in the area of aviation noise effects on school children. Recent studies indicate a potential link between increased aviation noise and both reading comprehension and learning motivation, particularly for those students already scholastically challenged.

The effect of aviation noise on children's learning ability and retention of information in schools is of critical concern worldwide, with several new and potentially conclusive studies having been completed in the last few years. Most of the new research and related results have taken place either in Munich (using the old and new Munich airports before and after the closing of one and opening of the other) or the United States through FICAN. Most types of school effect studies utilize a binary definition; that is, describing two subject environments of noise exposure, a high-noise setting and a low-noise setting, which make it difficult to define a dose-response curve. However, it is usually clear that noise levels above a certain  $L_{eq}$  affect a child's learning experiences.

In 1995 and again in 1998, Evans et al., studying school children living in the vicinity of the Munich airport and a quiet suburban area, demonstrated that children within high-noise areas showed evidence of poor persistence on challenging tasks, and reported considerable annoyance with community noise levels, adjusted for individual differences in rating criteria for annoyance judgments (Evans et al. 1995, 1998). Other studies by Hygge et al. (2002) examined aviation noise effects on children in the area around the old and new Munich airports. They reported that three data waves were collected, pre- and post-switching of the airports. Long-term memory and reading were impaired in the noise group at the new airport, although there was improvement in the formerly noise-exposed group at the old airport. Short-term memory also improved in the latter group after the airport was closed. Speech perception was impaired in the newly noise-exposed group.

Other interesting and unexpected differences in the effects of aviation noise on classroom learning experiences come from Hygge's study where children aged 12 to 14 years were tested for recall and recognition of a text exactly one week later (Hygge 2003). Overall, there was a strong noise effect on recall, and a smaller but significant effect on recognition. Using a sound source located in the classroom, the single-source studies—aircraft and road traffic—impaired recall at both noise levels, yet train noise and verbal noise did not

affect recognition or recall. Given that road noise and verbal noise were relatively constant sources and the aircraft and train noise were event-type sources, these observed differences were not expected.

In 2000, FICAN published a position paper regarding effects of aircraft noise on classroom learning. It summarized research on its effects, and indicated that aircraft noise can interfere with learning in the areas of reading, motivation, language, speech acquisition, and memory. The strongest findings are in the area of reading, where more than 20 studies have shown that children in noise-impact zones are negatively affected by aircraft. Research has confirmed conclusions from studies completed in the 1970s that show a decline in reading when outdoor noise levels equal or exceed  $L_{eq}$  of 65 dBA.

Recently released and not yet fully reviewed is FICAN's initial study involving 35 public schools in Texas and Illinois near three airports ("Findings of the FICAN Pilot Study . . ." 2007). Results of the study indicate that the

Student failure rate may be due to impaired learning in the classroom, perhaps caused in part by noise stress. To the extent that noise stress contributes to student failure, then failing students are the ones most likely to benefit from noise reduction. In contrast, top-score students are less likely to benefit. Such a rationale is consistent with the results of this study.

This study's analysis is not yet fully reviewed.

Regarding indoor classroom acoustical performance criteria, two main works stand out that additionally complement each other. The Acoustical Society of America provides performance criteria, design requirements, and design guidelines for new school classrooms and other learning spaces ("Acoustical Performance Criteria . . ." 2002). These criteria are keyed to the acoustical qualities needed to achieve a high degree of speech intelligibility in learning spaces, and the standard is a very good guideline for best practices in classroom acoustical design. The second publication is a very technical comparison of speech intelligibility metrics in the classroom based on various background noise (Bistafa and Bradley 2000). The study, consistent with the ANSI standard recommendation for steady-state noise, recommends ideal and acceptable background noise levels of classrooms, but does not address intermittent noise such as noise from outdoor transportation.

## EFFECTS OF AVIATION NOISE ON PARKS, OPEN SPACE, AND WILDERNESS AREAS

In considering the effects of aviation noise on parks in relation to both animals and humans, there have been new and interesting issues not previously considered, particularly concerning restoring and/or maintaining natural quiet in U.S. national parks and Native American tribal lands. Given the often extremely low ambient noise of the parks, aviation noise from high-altitude aircraft passby or lower-altitude tour operations can be heard for miles. Trying to define the natural soundscape can often be as challenging as defining the noise intrusion and potential effects.

### NATIONAL PARKS AND NATIVE AMERICAN TRIBAL LANDS

The study of aviation noise effects on national parks and Native American tribal lands began in 1985. Because this is a completely new research area, a brief history of its development and oversight responsibilities is warranted. With the passage of the National Parks Overflight Act of 1987, the FAA and the National Park Service were tasked to join forces and begin the process of restoring natural quiet to the nation's parks. In 2000, the National Parks Air Tour Management Act required commercial tour operators to develop air tour management plans (ATMP) and obtain FAA approval to conduct operations over parks or tribal lands. Any ATMP for a national park may prohibit commercial air tour operations, and may establish conditions or restrictions of operations, including noise restrictions, visual restrictions, or other impacts. The National Parks Air Tour Management Act does not provide specific noise limits to be considered as part of the ATMP. Additionally, the National Park Service's "Soundscape Preservation and Noise Management" Director's Order #47 that expired in 2000 articulated National Park Service operational policies that required, to the fullest extent practicable, the protection, maintenance, or restoration of the natural soundscape resource in a condition unimpaired by inappropriate or excessive noise sources ("Soundscape Preservation and Noise Management" 2000–2004). In this Order, an outline of the park director's responsibilities included natural soundscape preservation as part of the operating policies of the park. The Order provided a broad structure for consideration of soundscape preservation in the park facilities planning process, but it did not address specific noise level goals or specific programs.

In 2005, the FAA published a report that summarizes the findings of all known aircraft noise (dose) and visitor annoyance

(response) data previously collected in the national parks (Rapoza et al. 2005). The accumulated data consist of almost 2,500 visitor interviews and simultaneous acoustical measurements collected at four different national parks between 1992 and 1999, including two major FAA dose-response measurement programs in 1997 (short-hike) and 1998 (overlook).

The dose-response data obtained from these studies can be used to determine the relationships between aircraft noise and visitor response for purposes of assessing aircraft noise in the national parks. Important results from that 2005 report included the finding that the vast majority of visitors' (92% to 94%) rate annoyance is equal to or higher than interference with enjoyment. Visitors appear to be less sensitive to high-altitude jet overflight noise as compared with noise from tour aircraft. However, the data do not show this with statistical certainty and no definitive conclusions can be drawn. Visitor response to tour overflight noise differs between overlooks and short hikes. In addition, it appears that a respondent's familiarity with the site can influence visitor response to aircraft noise; that is, repeat visitors generally are more annoyed.

Some of the most provocative new research is by Horonjeff (2005) who provides a good summary background of the efforts to define methods to quantify the natural soundscape of the wilderness park environment. The author defines the soundscape in terms of duration of quiet time and time a visitor has to wait until he or she experiences quiet times of certain durations. In terms of defining periods of natural quiet for purposes of analyzing transportation projects near parks, the author concludes that the use of computer models is the only efficient means by which noise effects may be evaluated over large areas.

### URBAN PARKS

Very little recent research has been completed that discusses noise in urban parks; however, it does indicate that noise is an important urban park characteristic, but not as important as other criteria, such as safety and cleanliness. Results from noise surveys and laboratory listening tests showed that the subject's expectation to hear a sound in a specific environment influences the corresponding annoyance. Furthermore, the acceptability of the non-natural sound increases with decreasing levels and detectability. These findings are significant as they point out that loudness of a noise source is

not the most important aspect of its acceptance. Natural sounds expected in a park setting are deemed acceptable no matter what their sound level, although unexpected sounds such as aircraft and road noise are judged as annoying.

Another evaluation of noise pollution in urban parks was conducted in Brazil (Zannin et al. 2006). Measured noise

levels were compared with locally permitted levels, and were classified as “acoustically polluted or unpolluted.” Measured values were also evaluated according to international legislation from Rome, Germany, WHO, and the U.S. EPA. Noise levels in the test parks do not satisfy any of the standards used. The study provides a useful comparison of various international noise limits that may be applied to parks.



## AVIATION LOW-FREQUENCY NOISE AND VIBRATION

Another new area of study not addressed in the original 1985 document is low-frequency noise (LFN). LFN represents a special issue because outdoor A-weighted noise measurements may not appropriately reflect LFN levels that can induce potentially annoying secondary emissions inside residences near runways where the jet noise at the start of take-off roll and/or the jet noise from thrust reversers may cause LFN levels that are not typical of other areas in the airport environs. LFN is not absorbed by the atmosphere or blocked by terrain and buildings as well as higher frequencies. Therefore, LFN can sometimes be audible at farther distances than higher frequency noise.

LFN has been studied at a small number of airports where community concern has been acute. The general conclusion from these studies is that LFN can induce structural building response that may cause rattle of windows, fixtures, pictures, and the like, causing annoyance well beyond the annoyance expected based on noise level alone. An Expert Panel convened by the communities around the Minneapolis–St. Paul

International Airport produced a controversial report of which FICAN was highly critical that described a new noise metric and dose-response relationship for LFN (*FICAN on the Findings . . . 2002*).

At the present time there is no universally accepted method of describing LFN and its impact on communities around airports. Some efforts to use the C-weighting for this purpose have been noted; however, this approach represents a poor surrogate for making octave or one-third octave measurements at the lower frequencies because the C-weighting will include sounds in frequencies above those that induce rattle.

Current studies done under the Partner/COE (Center of Excellence) programs under sponsorship of the FAA and NASA shed more light on the levels of low-frequency sound needed to induce rattle effects. The results remain controversial. The results of the Partner/COE Project 1 low-frequency noise study were released in April 2007 (Partnership for Air Transportation Noise & Emissions Reduction 2007).

## AVIATION NOISE EFFECTS ON WILDLIFE AND DOMESTIC ANIMALS

The effects of aviation noise on animals have been studied extensively over the past 20 years, with much of the work being conducted by U.S. Air Force-sponsored researchers. The studies have revealed that the effects are highly species-dependent and that the degree of the effect may vary widely. Responses of animals to aircraft noise vary from almost no reaction to virtually no tolerance of the sound. The question of how adaptable animals are remains largely unanswered. Both wild and domesticated animals have been studied, although more research has centered on domesticated or laboratory animals such as rats and mice.

Although noise is often defined as unwanted sound for humans, it has been suggested that it is also the same for animals. “Noise” is best defined as any sound that (1) causes hearing loss; (2) masks signals needed for communication, navigation, prey detection, predator avoidance, and environmental monitoring; (3) effects non-auditory health; (4) effects

biologically significant changes in behavior; and (5) alters population, including declines in abundance, changes in distribution, or reproductive failures.

Although it is not possible to generalize a dose-response relationship for all wildlife and farm animals, the reader is referred to specific Tables A1 through A4 in chapter nine of Appendix A for a summary of findings of effects of aircraft noise and sonic booms. Of noteworthy reference is the National Park Service’s annotated bibliography on impacts of noise and overflights on wildlife (“Annotated Bibliography . . .” 2005). It is a comprehensive annotated bibliography, with results presented in three-column format. The report also includes 76 documents divided into categories. Although it is impossible to generalize or summarize the results of such a broad range of studies in this synthesis, it is clear that some reports found dramatic effects, whereas others found that other factors overwhelm the noise effects.

## AVIATION NOISE EFFECTS ON PROPERTY VALUES

Aviation noise has a direct effect on property value. The effects of aviation noise on the buyer and seller determine the value of properties within proximity to aircraft operations. The noise level at a given property location becomes one of many property features and amenities (number of rooms, crime rate, schools) that make up the total value of that property.

Research conducted on the effects of aviation noise on property value used several different methodologies resulting in outcomes ranging from effects of substantial negative impact to effects of no impact. Most studies attempted to control for and measure the noise variable alone. However, some studies coupled aviation noise with airport proximity, and therefore measured the positive and negative impacts of two variables that essentially could not be present without the other (or that were dependent on each other). Recent studies used GIS not only to analyze large amounts of data, but also to integrate spatial autocorrelation to analyze the relationships among residential properties and other features in proximity; that is, other homes, airports, schools, roads, etc. Looking at future research, one can expect that the powerful GIS tool will facilitate a better understanding of this topic.

In contrast to most results, a study conducted in the city of College Park, Georgia, concluded that noise did not significantly affect the values of residential properties (Lipscomb 2003). Unique community demographics and characteristics attributed to this finding; specifically, many community residents were employed in airport-related occupations so distance from the airport (short work commute) was given greater importance during the home purchasing process.

Results from a survey of 200 realtors and 70 appraisers in 35 suburban communities near Chicago O'Hare International Airport found that a significant segment of buyers lack adequate information about the noise environment, resulting in inflated bid prices and likely in disappointment after purchase (Frankel 1991). The author continued by classifying noise-affected property owners into two groups: those who came to their location when the location was quiet and later became the subject of aircraft noise and those who purchased the property near an operational airport from a previous

owner. The report stated that it was the members of the first group who bore the true burden of airport noise.

If noise exposure decreases property value, one could reasonably presume the second group was compensated for the existing noise exposure once they willingly purchased properties that sold at a market-discounted price. This has led to the description of aircraft noise as a one-time effect on property value.

A study conducted around Manchester Airport, England, showed that when using the Noise and Number Index (similar to DNL and no longer used), results revealed no significant negative relationship between noise and property value (Tomkins et al. 1998). Quite interesting, however, is their finding that when the  $L_{eq}$  measure is substituted, and even though it defines a smaller core of properties, it also displays both a greater accuracy in identifying those "which are truly noise-blighted." Proximity to the airport also had significant impacts, but at a decreasing rate. The net impact was that property location in close proximity to the airport was a more important factor of property value than noise.

In summary, the studies of the effects of aviation noise on property values are highly complex owing to the differences in methodologies, airport/community environments, market conditions, and demand variables involved. Whereas most studies concluded that aviation noise effects on property value range from some negative impacts to significant negative impacts, some studies combined airport noise and proximity and concluded that the net effect on property value was positive. Prospective homebuyers were at times not well-informed about the noise levels of aircraft operations near the property of interest. Lack of information often led to high bid prices and possible disappointment after purchase. Homeowners that experienced an increase in noise levels bore the burden of aviation noise. However, once noise levels stabilized, the next homeowner was compensated once the property value adjusted owing to the effects of noise. Lastly, the technology available to analyze data has improved throughout the years. The spatial nature of aircraft operations, noise contours, and property location will continue to prompt studies founded in GIS analysis that will improve our understanding of the effects of aviation noise on property value.

## EFFECT OF METEOROLOGY ON AVIATION NOISE

Meteorology plays a very important role in the propagation of sound. Simply put, air absorbs sound. As sound travels through the atmosphere it is attenuated by this absorption. Complicating matters is that air absorption varies with temperature, humidity, and the frequency of the sound. Sound travels downwind better than upwind. Temperature, humidity, and wind speed and direction are not homogeneous in the real atmosphere, but are changing constantly. Temperature and/or wind gradients cause refraction (bending) of sound waves.

The Integrated Noise Model (INM), Version 7, includes the effect of meteorology in two ways (*INM Users Guide 2007*). First, temperature is used to calculate aircraft performance; that is, an aircraft climbs much better in cool weather than in hot weather. INM 7 now includes an option to match atmospheric sound propagation to aircraft performance. That is the second way INM can use temperature. The INM uses noise data in the form of a noise-power-distance (NPD) curve based on standard temperature and humidity. This version includes options to adjust the NPD curves to the user-selected average temperature and humidity. The European Civil Aviation Conference provides technical routines to adjust the NPD curves to the actual temperature and humidity from standard conditions (*Report on Standard Method . . . 2005*). For temperatures near standard conditions or at distances near the airport, this

adjustment is small. However, at large propagation distances the effects are non-trivial. Even this correction is somewhat simplistic, in that it is based on a homogeneous atmosphere; that is, constant temperature and humidity and does not attempt to correct for temperature gradients.

One of the consequences of the complex way weather affects sound propagation is that noise models are limited to estimating noise levels for average conditions. Comparing noise model predictions with short-term noise measurements is meaningless, as atmospheric effects are not adequately accounted for in the model. However, long-term measurements will produce an average noise level in which atmospheric effects will tend to average out making comparison with noise model results much more meaningful.

Current research includes highly technically complex studies analyzing how sound levels increase as the refractive curvature goes from negative to positive values and ground effects have complex effects on propagation over long distances. Research indicates large-scale turbulence is a significant cause of acoustic signal fluctuations, particularly in the signal phase. Other more site-specific research evaluates the influence of a pine forest on sound propagation, finding high-frequency attenuation owing to the forest that increases with distance.

## EFFECT OF TOPOGRAPHY AND GROUND ABSORPTION ON AVIATION NOISE

Aircraft sound heard by an observer can be influenced by a number of factors. As previously stated, meteorology is one such factor. Another factor is the propagation of sound over the ground and as it is affected by terrain. When an aircraft is directly overhead, the sound experienced by an observer is only affected by meteorology. However, as the aircraft passes by or is at lower elevation angles, the sound heard by an observer is both the sound that travels in a straight line from the aircraft plus the sound reflected off the ground. Although the interaction of sound traveling over the ground is quite complex, recent research has provided new insight.

The FHWA's 1978 report on highway noise prediction model presents one of the best descriptions of how to include noise barrier effects in transportation modeling, and includes detailed methodologies to computer noise barrier effects.

Another noise modeling program is NOISEMAP, typically used by the Air Force and other organizations to compute environmental noise around airbases and airports. NOISEMAP presumes the ground is flat, level, and at the same altitude as the airbase and runways, limiting the effect of ground absorption. Although usually applicable, there are situations where these variables should be adjusted to improve model accuracy. Plotkin et al. (1992) present detailed descriptions on how NOISEMAP would have to be modified to accommodate variations in topography.

The NATO/CCMS 1994 Working Group identifies various modeling techniques used in different countries and describes issues associated with topographic effects on modeled aviation noise (NATO/CCMS Working Group Study 1994). The report discusses the effect of topography on slant range distance and the effects of shielding owing to topography. Shielding, which is usually not important when an aircraft is overhead, may be very important when an aircraft is at low-elevation angles. The report presents recommendations for including topographic effects in aviation modeling.

New research completed in 2000 (Senzig et al. 2000) examined the applicability of available mathematical models of lateral attenuation. Analysis of the data revealed that lateral attenuation is a function of aircraft geometry. For example, lateral attenuation of aircraft with tail-mounted engines was found to agree with published literature, whereas wing-mounted engine aircraft types were found to be less than predicted in the model, resulting in an under-prediction of sideline noise levels. Similarly, in 2006, the Society of Automotive Engineers provided detailed calculation methods to compute lateral attenuation (*Method for Predicting . . .* 2006). Integrated Noise Model Version 7 includes the methodology specified for such calculation. Shielding calculations are also available in Integrated Noise Model Version 6.2 and later, allowing the Integrated Noise Model to work better near airports that have nearby hills or steep valleys.

## CONCLUSIONS

Nearly every aspect of aviation, and related technology, has changed since the 1985 publication of FAA's *Aviation Noise Effects*. Although much has been learned, both technically and socially, the process of identifying, quantifying, and alleviating noise effects of aviation remains an art. We now know that because aviation noise does not approximate those of occupational health criteria, hearing loss is unlikely; aviation noise effects do not influence newborn birth weight, and annoyance may be largely influenced by non-acoustic factors. Sleep interference, with great variability between laboratory and in-home studies, occurs much less than previously thought. We have also learned that cross-sectional studies are notoriously difficult to interpret, often report conflicting results, and do not result in dose-response relationships.

Investigations that report a distinct percentage of the population who are "highly annoyed" at any given day-night average noise level may be incorrectly interpreted as having a more precise meaning than should be taken from the data. Areas of annoyance that remain to be investigated include the relationship between single-event noise levels and annoyance. Use of data not previously available, including airport noise monitoring systems, flight tracking systems, and geographic information systems, may prove to be a rich source of data in understanding annoyance and meteorological and topographical effects.

Aviation noise effects on schools and school children have been well-researched and documented. Recent studies indicate a potential link between aviation noise and both

reading comprehension and learning motivation, particularly for those children who are already scholastically challenged. Other studies indicate increased stress levels for children in high-noise environments. New best practices designs for interior classroom acoustics and speech intelligibility have been completed, but do not address intermittent noise such as aviation noise. Some research has indicated that effects of aviation noise may differ from the effects of other transportation noises. Speech interference, although quite important, has not had the benefit of research as related to intermittent noise sources.

New definitions and criteria for natural soundscape in national parks and Native American tribe lands are being established, and new dose-response relationships may be used to guide important policy decisions. Low frequency noise with its related vibration, meteorological, and topological data continue to drive modeling improvements, and correct some limited under-predictions of sideline-noise levels. Home property values may have limited relationship to noise levels, and future research linked with powerful geographic information system tools may provide new insights. Although long-term averages are typically used in conjunction with land use planning and residential property location, new research indicates that the use of  $L_{eq}$  (equivalent sound level) may display a greater accuracy in identifying areas most affected by aviation noise.

In conclusion, despite decades of research and new, well-documented information, aviation noise effects continue to be an enigma waiting to be solved.

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## GLOSSARY

**A-weighting**—a frequency-weighting network used to account for changes in human auditory sensitivity as a function of frequency.

**Actigraph**—a watch-sized device that records human movement and can provide an indication of sleep.

**Annoyance**—any bothersome or irritating occurrence.

**Anxiety**—a feeling of apprehension, uncertainty, and fear without apparent stimulus. It is associated with physiological changes (tachycardia, sweating, tremor, etc.), the source of which is often nonspecific or unknown to the individual.

**Arrhythmia**—any irregularity in the rhythm of the heart's beating.

**Audiometry**—the measurement and testing of hearing, including aspects other than hearing sensitivity.

**Auditory threshold**—the minimum audible perceived sound.

**Back-country visitor**—a visitor to wilderness areas or national parks who ventures into the so-called back-country areas; that is, those undeveloped areas of the park that do not have developed camp grounds, picnic areas, and where solitude and quiet are an expected amenity (see front-country visitor for contrast).

**Cardiovascular**—a term used when referring to the heart and blood vessels.

**Change in aircraft SEL (sound level exposure)**—is a noise metric developed for analyzing noise impacts in national parks and is abbreviated  $\Delta L_{AE,Tac}$ .

**CNEL (community-noise equivalent level)**—a term used in California and nearly identical to DNL (day-night average sound level), except that CNEL includes a 5 dB penalty for the evening time period from 7 p.m. to 10 p.m.

**Cross-sectional**—those data collected by observing many subjects (such as individuals) at the same point of time. Analysis of cross-sectional data usually consists of comparing the differences among the subjects. For example, in airport noise studies, a cross-sectional study compares responses in one group with another group in a different location. Cross-sectional data differ from longitudinal data, which follow one subject's changes over the course of time.

**Curvilinear**—in the context used in this synthesis, refers to a particular statistical method of plotting a smooth curve through scattered data.

**Day-Night Average Sound Level (DNL, denoted by the symbol  $L_{dn}$ )**—the 24-h average sound level for a given day, after addition of 10 db to levels from midnight to 0700 hours and from 2200 hours to midnight.  $L_{dn}$  is computed as follows:

$$L_{dn} = L_{AE} + 10 \cdot \log_{10}(N_{day} + 10 \cdot N_{night}) - 49.4 \text{ (dB)}$$

where:

$L_{AE}$  = Sound exposure level in dB (also known as SEL);

$N_{day}$  = Number of vehicle passbys between 0700 and 2200 hours, local time;

$N_{night}$  = Number of vehicle passbys between 2200 and 0700 hours, local time; and

49.4 = A normalization constant which spreads the acoustic energy associated with highway vehicle passbys over a 24-h period; that is,  $10 \cdot \log_{10}(86,400 \text{ s per day}) = 49.4 \text{ dB}$ .

**Decibel (dB)**—a unit of sound level when the base of the logarithm is the tenth root of ten and the quantities are proportional to power.

**Dose-response**—the dose-response relationship is one that describes the change in effect on an organism caused by differing levels of exposure to a stressor, in this case, noise.

**Epinephrine**—a hormone secreted by the adrenal medulla (inner or central portion of an organ) in response to stimulation of the sympathetic nervous system.

**Equivalent sound level (TEQ, denoted by the symbol  $L_{AeqT}$  or  $L_{eq}$ )**—Equivalent sound level is 10 times the logarithm to the base 10 of the ratio of time-mean-squared instantaneous A-weighted sound pressure, during a stated time interval  $T$ , to the square of the standard reference sound pressure.  $L_{AeqT}$  is related to  $L_{AE}$  by the following equation:

$$L_{AeqT} = L_{AE} - 10 \cdot \log_{10}(t_2 - t_1) \text{ (dB)}$$

where:

$L_{AE}$  = Sound exposure level in dB.

**FICAN (Federal Interagency Committee on Aircraft Noise)**—a federal committee organized to coordinate federal research and policies on aircraft noise (see [www.FICAN.org](http://www.FICAN.org)).

**FICON (Federal Interagency Committee on Noise)**—is a federal committee organized to coordinate federal policies on noise.

**Front-country visitor**—a visitor to a park who utilizes the developed camp grounds, picnic area, day-use areas (see back-country visitor for contrast).

**GIS (geographic information systems)**—a computer software program used to analyze spatial data that can be especially useful in examining noise distribution over a geographic area.

**Ground absorption**—as sound propagates near the ground, ground absorption is the interaction of the sound wave with the ground that results in attenuation of the sound.

**Hard ground**, such as water, has less attenuation than soft ground (most other surfaces). (Also known as lateral attenuation.

**Hearing impairment**—decreased ability to perceive sounds as compared with what the individual or examiner would regard as normal; the result is an increase in the threshold of hearing.

**Hearing threshold**—for a given listener and specified signal, a hearing threshold is the minimum: sound pressure level

- or force level that is capable of evoking an auditory sensation in a specified function of trials.
- Hedonic—a term used by both economists and other scientists. Basically, it means that one item or measure is judged better than another. Hedonic studies are commonly used for estimating the impact of aircraft noise on property values. Noise is considered as one of the many variables that may affect property values.
- Hertz (Hz)—a unit of frequency representing the number of times a phenomenon repeats itself in a unit of time.
- ICBEN (International Commission on Biological Effects of Noise)—a commission that meets and publishes a report every five years.
- INM (Integrated Noise Model)—an FAA-developed computer program used to compute noise contours around an airport.
- Ischemic—a medical term that refers to a restriction in blood supply, generally owing to factors in the blood vessels, with resultant damage or dysfunction of tissue.
- $L_{AE}$  (see sound exposure level).
- Lateral attenuation—as sound propagates near the ground lateral attenuation is the interaction of the sound wave with the ground resulting in attenuation of the sound. Hard ground, such as water, has less attenuation than soft ground (most other surfaces). Also known as ground absorption.
- $L_{den}$ —Similar to day-night noise level (DNL), but includes an evening weighting period like CNEL.
- $L_{dn}$  (see day-night average sound level).
- $L_{Aeq}$  (see equivalent sound level).
- $L_{eq}$  (see equivalent sound level).
- Longitudinal—a longitudinal study is one that follows one subject's or group's changes over the course of time. It differs from a cross-sectional study in that the effect of a change in exposure is measured in the same subjects, whereas with a cross-sectional study the differences are observed by comparing different subjects. Longitudinal studies are superior to cross-sectional studies.
- $L_{max}$  (maximum noise level)—the maximum noise level, in A-weighted decibels, that occurs during an aircraft flyover.
- $L_{night}$ —the equivalent noise level ( $L_{eq}$ ), computed for night-time hours, 10 p.m. to 7 a.m.
- Maximum noise level ( $L_{max}$ )—the maximum noise level, in A-weighted decibels, that occurs during an aircraft flyover.
- Meta-analysis—in statistics, a meta-analysis is an analysis of data that combines the results of several studies that address a set of related research hypotheses.
- NDI (Noise Depreciation Index)—a common method used to report the change in property value as a function of noise exposure.
- Neuroendocrine—a clinical term referring to a specialized group of nerve cells (neurons) that produce hormones.
- Noise—any unwanted sound.
- Noise-induced temporary threshold shift—temporary hearing impairment occurring as a result of noise exposure, often phrased temporary threshold shift.
- Noise-induced permanent threshold shift—permanent hearing impairment occurring as a result of noise exposure, often phrased permanent threshold shift.
- Norepinephrine—a hormone produced by the adrenal medulla similar in chemical and pharmacological properties to epinephrine, but chiefly a vasoconstrictor with little effect on cardiac output.
- NPD (Noise Power Distance)—NPD curves are the basic data used in the Integrated Noise Model to define the source noise levels for different aircraft types. It defines the noise level as a function of distance and engine power setting.
- Paracusis—any hearing abnormality or disorder.
- Peak-sound pressure level—peak-sound pressure level is the level of peak-sound pressure with stated frequency weighting, within a stated time interval.
- Parsimonious—a term signifying an unwillingness to spend money or resources; stinginess or frugality.
- Pathological—any condition that is a deviation from the normal.
- Percent Time Above Ambient (%TAA)—a noise metric developed for use in analyzing noise levels in national parks.
- Psychological morbidity—an incidence of mental health illness, including but not limited to depression and anxiety.
- Physiological—refers to the branch of biology dealing with the functions and vital processes of living organisms or their parts and organs.
- Presbycusis, Presbycusis—a condition referring to hearing deterioration occurring after middle age.
- Psychophysiological—a term describing the promotion of or combination of the normal or healthy functioning of the mind or mental processes.
- Recruitment (loudness)—refers to abnormal loudness perception.
- Reverberation—a sound that persists in an enclosed space, as a result of repeated reflection or scattering, after the source has stopped.
- Reverberation time—reverberation time of an enclosure, for a stated frequency or frequency band, is the time that would be required for the level of time-mean-square sound pressure in the enclosure to decrease by 60 dB, after the sound source has stopped.
- Schultz Curve—the dose-response relation curve that relates DNL to the percentage of the population who are “highly annoyed.” It is named for Theodore Schultz, who first proposed and developed this curve. The curve has been updated by others and the updated curves are often also referred to as the Schultz Curve in honor of the original author.
- Sound exposure level (SEL; denoted by the symbol  $L_{AE}$ )—over a stated time interval,  $T$  (where  $T = t_2 - t_1$ ), is 10 times the base-10 logarithm of the ratio of a given time integral of squared instantaneous A-weighted sound pressure, and the product of the reference sound pressure of 20 micropascals, the threshold of human hearing, and the reference duration of 1 s. The time interval,  $T$ , must be long enough to include a majority of the sound source's acoustic energy.

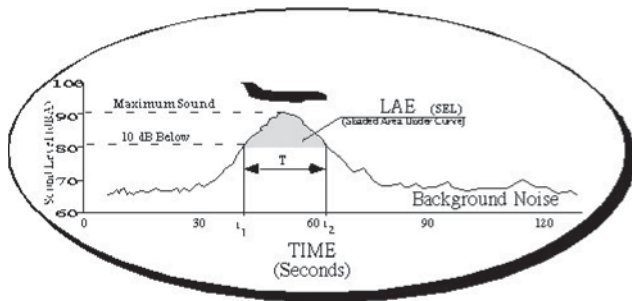


FIGURE 1 Schematic diagram of aircraft flyover noise metrics (Mestre Greve Associates 2007).

As a minimum, this interval should encompass the 10 dB down points (see Figure 1). In addition,  $L_{AE}$  is related to  $L_{AeqT}$  by the following equation:

$$L_{AE} = L_{AeqT} + 10 \cdot \log_{10}(t_2 - t_1) \text{ (dB)}$$

where:

$L_{AeqT}$  = Equivalent sound level in dB (see definition above, also known as  $L_{eq}$ ).

Sound pressure level (SPL)—SPL is 10 times the base-10 logarithm of the ratio of the time-mean-square pressure of a sound, in a stated frequency band, to the square of the reference sound pressure in gases of 20 micropascals.

Steady-state—steady-state noise is a continuous, constant noise as compared with a noise that varies over time.

Stress—the sum of the biological reactions to any adverse stimulus (physical, mental, or emotional, internal, or external) that tends to disturb the organism's state of stability.

Threshold of hearing—(see hearing threshold).

Tinnitus—a condition that causes a sound of ringing or whistling in the ears, excluding hallucinations of voices. It is an otological condition in which sound is perceived by a person without an external auditory stimulation.

Vasoconstriction—a tightening or compressing of the blood vessels.

WECPNL (Weighted Equivalent Continuous Perceived Noise Level)—is a noise metric commonly used in Japan, it is similar in concept to DNL, but uses a different algorithm to compute and includes an evening weighting similar to CNEL and  $L_{den}$ .

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## APPENDIX A

### Discussion of Topic Issues

#### CHAPTER TWO: HEALTH EFFECTS OF AVIATION NOISE

Determination of the effects of aviation noise on health is an intricately complex and notoriously difficult field of study. Variations on how to identify and/or measure the noise exposure (single dose, long-term average, number of events above a certain level, etc.) and attempting to separate these effects from other life events is a difficult task. For example, lifestyles, life's stressors, hereditary factors, and genetic composition are just a few factors that may distort potential results of an aviation noise health effects study.

Given this complexity, the large amount of research published during the last 30 years has produced considerable variability of results; often, some are quite controversial. The absence of one internationally accepted "exposure-effect" (or "dose-response") relationship is largely the result of a lack of one obvious "best choice" research methodology, as well as to the complex interactions of the many factors that influence aviation noise effects. These include differences in the characteristics of the noise itself, differences in individual sensitivities, differences in attitudinal biases toward the noise source, and variations in living environments.

Considerable research, review of previous research with new thought, new independent research, and collaborative efforts to identify health effects related solely to aviation noise have been completed; most can be condensed into impacts in three primary categories: the cardiovascular system, children, and hearing impairment.

#### Cardiovascular Effects

Several recent studies have reviewed previous literature, either through compilation or re-review of original data, which suggests that increased hypertension or other cardiovascular effects may be associated with particular long-term noise exposure. For example, the World Health Organization's (WHO's) *Guidelines for Community Noise* (2000), presented at the WHO Expert Task Force meeting, finds that:

... the overall evidence suggests a weak association between long-term environmental noise exposure and hypertension, and no dose-response relationships could be established ... The overall conclusion is that cardiovascular effects are associated with long-term exposure to  $L_{Aeq}$  24 h values in the range of 65–70 dB or more, for both air- and road traffic noise. However, the

associations are weak and the effect is somewhat stronger for ischemic heart disease than for hypertension. Nevertheless, such small risks are potentially important because a large number of persons are currently exposed to these noise levels, or are likely to be exposed in the future.

Another example is a study by Passchier-Vermeer and Passchier (2000) that reviewed existing literature and states that there is sufficient scientific evidence that noise exposure can induce hearing impairment, hypertension, and ischemic heart disease. The authors concluded that there are "no obvious effects from noise exposure on mean diastolic and mean systolic blood pressure, but some effects were observed in terms of an increase in the percentage of people with hypertension (including those who use medication for hypertension)" (Passchier-Wermeer and Passchier 2000). The observation threshold for hypertension is estimated to correspond to an  $L_{dn}$  value of 70 dB(A) for environmental noise exposure.

Most reviewers concluded that previous reviews were not carried out in a systematic way, which makes them prone to bias. Reviewers point out the tendency for some studies to inadequately report noise exposure data. With respect to the association between noise exposure and blood pressure, small blood pressure differences were evident. Van Kempen et al. (2002) stated: "Although we can conclude that noise exposure can contribute to the prevalence of cardiovascular disease, the evidence for a relation between noise exposure and ischemic heart disease is still inconclusive because of the limitations of exposure characterization, adjustment for important confounders, and the occurrence of publication bias."

Cross-sectional studies, such as that by Goto and Kaneko (2002), who observed blood pressure in general health examination data from around a city airport and then compared the data with that from a calm suburban area of the city, showed that systolic and diastolic blood pressure was not associated with aircraft noise levels in the area.

Recent studies by Eriksson et al. (2007) and Järup et al. (2007) have reported higher rates of hypertension with increasing aircraft noise levels. The HYENA study identified that the effect occurred only for night-time aircraft noise.

It should be noted that cross-sectional studies are notoriously difficult to interpret, because they often report conflicting results, generally do not identify a cause and effect

relationship, and often do not report a dose-response relationship between the cause and effect.

### Aviation Noise Effects and Children

Another particular concern over the past 30 years is the potential health effect on children resulting from exposure to or interference from aviation noise. One cross-sectional study by Poustka et al. (1992) studies psychiatric disorders on children aged 4 to 16 years in two contrasting geographic regions using cross-sectional analyses of the two regions. Although noise levels were not reported, they are likely to be very high because military aircraft fly as low as 75 m with very high onset rates. Neither psychiatric disorders nor environmental factors showed any relationship to noise; however, psychophysiological parameters (e.g., heart rate and muscle tension) demonstrated some relationship to noise.

Other recent studies have focused on the relationships between noise exposure during pregnancy and low birth weights. Wu et al. (1996) analyzed the effect of total noise exposure during pregnancy on infant birth rate. No association between personal noise exposure measured in decibels (less than 85 dBA  $L_{eq}$  during pregnancy) and birth weight was found. Possible occupational noise, traffic noise exposure, or a history of listening to amplified music using personal listening devices during pregnancy also showed no effect on infant birth weight.

### Hospitals and Care Facilities

A careful search of recent research regarding aviation noise and hospitals and care facilities identified no studies that addressed this specific issue. It is common for airport noise/land-use compatibility guidelines to list hospitals and care facilities as noise-sensitive uses, although there are no studies that have identified health effects associated with aviation noise. There are numerous studies that identify problems with internal hospital noises such as warning alarms, pagers, gurney collisions with doors, talking, etc.; however, none that addressed aviation or roadway noise. WHO included a discussion of hospital noise in its *Guidelines for Community Noise* (2000) (Section 4.3.3 of WHO *Guidelines* addresses hospital noise levels in general terms and does not provide any specific guidance relative to aircraft noise).

### Hearing Impairment

Aviation noise exposure and potential hearing impairment during all ages of life are also a common research effort. Research in this area is much more definitive, often owing to adequate controls, data, and identifiable conclusions. One study, Sixsmith and Wheeler (1999) on auditory impact, reviewed nine studies done in the vicinity of seven civil and military airports and two laboratory studies.

The laboratory studies suggest that permanent threshold shifts are unlikely to be induced by exposures to aircraft noise thought to be typical of real life. . . . In the main, these studies have been

conducted where environmental noise does not appear to approach recognized occupational noise limits. Further, it may be that the intermittency of environmental noise itself may protect hearing from damage (Sixsmith and Wheeler 1999).

The conclusion that environmental noise does not have an effect on hearing threshold levels, particularly that environmental noise does not approximate occupational noise levels or recreational noise exposures (e.g., personal listening devices, discotheques, motorcycles, and pop concerts) is also echoed in several other studies. Lastly, studies have also shown that early noise exposure as a child on military jet aircraft bases does not make one more susceptible to noise-induced hearing loss. Ludlow and Sixsmith (1999) state that “this study has found no evidence that RAF personnel who have lived on or near fast jet stations while very young display raised hearing threshold levels associated with noise-induced hearing loss.”

### Summary

In the more than 20 years since publication of the FAA’s *Aviation Noise Effects* document there has been considerable research, review of previous research with new thought, and new independent research, as well as collaborative efforts to identify health effects related to aviation noise. Some studies have identified a potential correlation between increased hypertension and aviation or road noise above certain noise thresholds [typically a day-night average noise level (DNL) value of 70 dBA]; however, other studies contradict such findings. Occupational noise often becomes an intricate concern. Health effects on children, particularly those with decreased cognitive abilities, mental disturbances, or other psychological stressors, and studies of pregnancy and low infant birth weights, all indicate there is no correlation between aviation noise and childhood psychiatric disorders, environmental factors, or low infant birth weights. Additionally, recent studies have concluded that aviation noise does not pose a risk factor for child or teenage hearing loss, but perhaps other noise sources (e.g., personal music devices, concerts, motorcycles, and night clubs) are a primary risk factor. Because aviation and typical community noise levels near airports are not comparable to the occupational or recreational noise exposures associated with hearing loss, hearing impairment resulting from community aviation noise has not been identified.

Although newer studies suggest there may be a potential relationship between aviation noise levels and hypertension or ischemic heart disease at noise levels as low as 50 dBA  $L_{eq}$  (Eriksson et al. 2007), further research is necessary. Among the confounding factors in studies of hypertension and aircraft noise is that aircraft noise exposure is taken from noise model estimates without regard to ambient noise levels. The ambient noise levels in urban areas and most suburban areas exceed 50 dBA  $L_{eq}$ . Furthermore, only a handful of recent studies of populations near airports attempted to segregate health effects of noise from that of air pollution.

Despite decades of research, including reviews of old data and multiple new research efforts, health effects of aviation noise continue to be an enigma. Most, if not all, current research concludes that despite well-founded hypotheses it is as yet impossible to determine causal relations between health disorders and noise exposure.

#### **Annotated Bibliography—Health Effects of Aviation Noise**

**Babisch, W.,** *Transportation Noise and Cardiovascular Risk, Federal Environmental Agency, Berlin, Germany, 2006, 113 pp.*

This German Federal Environmental Agency study presents a comprehensive review of transportation noise and cardiovascular risk. The study uses published reports and presents no new study data. The author states that according to the general stress concept, repeated autonomic and endocrine responses can result in permanent functional and metabolic changes of the organism in chronically exposed subjects. Epidemiological studies suggest a higher risk of cardiovascular diseases including high blood pressure and myocardial infarction in subjects chronically exposed to high levels of road or air-traffic noise. Sixty-one epidemiological noise studies were evaluated regarding the relationship between transportation noise and cardiovascular outcomes. The author is careful to separate studies and results for road noise from those that included aircraft noise. “With respect to aircraft noise and hypertension, studies consistently show higher risks in higher exposed areas.” The data for these studies tend to show that the effect threshold is a DNL of 60 dBA. “With regard to ischemic heart disease [IHD], the evidence of an association between community noise and IHD risk has increased since a previous review. There is not much indication of a higher IHD risk for subjects who live in areas with a daytime average sound pressure level of less than 60 dBA.” The author notes that “statistical significance was rarely achieved.”

**Eriksson, C., M. Rosenlund, G. Pershagen, A. Hilding, C. Ostenson, and G. Bluhm,** “Aircraft Noise and Incidence of Hypertension,” *Epidemiology*, Vol. 18, No. 6, 2007, pp. 716–721.

This study of hypertension near Stockholm Arland Airport was conducted from 1992 through 1994 and again with the same subjects from 2002 through 2004. The study group was based on the Stockholm Diabetes Preventive Program; half of the study subjects had a family history of diabetes. Residential aircraft noise exposure (expressed as time-weighted equal energy and maximal noise levels) was assessed by geographical information systems (GIS) techniques among those living near the airport. Incident cases of hypertension were identified by physical examinations, including blood pressure measurements, and questionnaires in which subjects reported treatment or diagnosis of hypertension and information on cardiovascular risk factors.

The results showed that “for subjects exposed to energy-averaged levels above 50 dB(A) the adjusted relative risk for hypertension was 1.19. . . . Maximum aircraft noise levels presented similar results, with a relative risk of 1.20 . . . for those exposed above 70 dB(A).” The authors went on to conclude that “these findings suggest that long-term aircraft noise exposure may increase the risk for hypertension.” The authors also state that this type of longitudinal study would tend to be more reliable than the typical cross-sectional study on hypertension. However, although it is true that the study included the same subjects in the 1992–1994 and 2002–2004 surveys, the results for subjects near the airport were compared with subjects farther from the airport. The study is subject to the problems of a cross-sectional study in which subjects in one area of noise exposure are compared with subjects in a different area of noise exposure. Furthermore, the study results identified increased hypertension at noise levels as low as 50 dBA  $L_{eq}$ , which is lower than typical ambient noise levels in urban areas and lower than ambient noise levels in many suburban areas.

**Finegold, L.S., S. Job, R. de Jong, and B. Griefahn,** “The Effect of Noise on Public Health: International Congress Explores Global Impact,” *The ASHA Leader*, Oct. 5, 2004, pp. 6–7, 13.

This is a two-part series describing the research and findings presented at the Eighth International Congress in Rotterdam, The Netherlands, in 2004 on Noise as a Public Health Problem. The Congress, which is held every five years, is sponsored by the International Commission on Biological Effects of Noise and is organized into nine noise teams. The team on non-auditory physiological effects reported on current studies. Recent years have focused on cardiovascular research and on the effects of noise on children. Studies of environmental noise appear to predict both hypertension and coronary heart disease, although self-report outcomes are probably insufficient in this area. Further consideration is needed in assessing environmental stressors such as air pollution, which frequently accompanies noise pollution.

**Franssen, E.A.M., C.M.A.G. van Wiechen, N.J.D. Nagelkerke, and E. Lebrecht,** “Aircraft Noise Around a Large International Airport and Its Impact on General Health and Medication Use,” *Journal of Occupational and Environmental Medicine*, Vol. 61, 2004, pp. 405–413.

The authors assess the prevalence of general health status, use of sleep medication, and use of medication for cardiovascular diseases, and study their relation to aircraft noise exposure around Schipol Airport (Amsterdam). These health indicators were measured by a cross-sectional survey (self-report questionnaire) among 11,812 respondents living within a radius of 25 km of the airport. The authors calculated the odds ratio for each effect and associated an increasing effect with increasing  $L_{den}$  [DNL with a 5 dBA evening weighting, identical to the community noise equivalent level (CNEL) metric used in



California]. The associations were statistically significant for all indicators, except for use of prescribed sleep medication or sedatives and frequent use of this medication. None of the health indicators were associated with aircraft noise exposure during the night, but use of non-prescribed sleep medication or sedatives was associated with aircraft noise exposure during the late evening. Vitality-related health complaints such as tiredness and headache were associated with aircraft noise, whereas most other physical complaints were not. A small fraction of the prevalence of poor self-rated health (13%), medication for cardiovascular diseases or increased blood pressure (8%), and sleep medication or sedatives (22%) might be attributed to aircraft noise. Although the authors concluded that the results suggest an association between community exposure to aircraft noise and indicators of poor general health status, use of sleep medication, and use of medication for cardiovascular diseases, the data are more complex than this conclusion indicates. For example, the odds ratios for cardiovascular diseases or increased blood pressure medication increase for populations exposed to  $L_{den}$  levels in the 50 to 55 dBA range; it increases yet again for populations in the 55 to 60 dBA range, but decreases for the population above 60  $L_{den}$ . When the populations were divided into two groups, one with noise exposures less than 51  $L_{den}$  and the other with noise exposures more than 59  $L_{den}$ , percentages of the population reporting a health effect were identical or different by only 1% for each group. The method that the authors used to segregate out the fraction of the population reporting a health effect that is associated with aircraft noise is unclear.

**Goto, K. and T. Kaneko, "Distribution of Blood Pressure Data from People Living near an Airport," *Journal of Sound and Vibration*, Vol. 250, No. 1, 2002, pp. 145–149.**

This cross-sectional study observed blood pressure in general health examination data in the vicinity of a city airport and compared the data with those from a calm suburban area of the city. Information was also collected on the short-term history of medication and lifestyle including smoking, drinking, and eating salty foods. This cross-sectional study on 469 women showed that systolic and diastolic blood pressure was not associated with aircraft noise levels in the area, even after controlling for variables regarding anti-hypertension treatment and lifestyle factors. A comparative study on 469 women from an area around an airport and 1,177 women from a suburban control area showed no significant difference between blood pressure and other medical tests controlling for the variables of medication and lifestyle. Changes in blood pressure after 8 years were observed in 183 women around the airport. No significant differences among three zones with different levels of aircraft noise were found. The three noise zones used in the study were less than 75 WECPNL (Weighted Equivalent Continuous Perceived Noise Level) (~60 DNL), between 75 and 90 WECPNL (~60 and ~77 DNL), and greater than 90 WECPNL (~77 DNL). The authors do not provide noise level data for the control group in the suburban control area.

**Griefahn, B., "Noise-Induced Extraaural Effects," *The Journal of the Acoustical Society of Japan (E)*, Vol. 21, 2000, pp. 307–317.**

The paper presents a state-of-the-art summary concerning the extraaural effects of noise. The study is based on a review of other studies and no new research data are presented. The analysis is presented in terms of primary effects that occur during the period of noise exposure [e.g., speech interference (SI), sleep disorders, and altered autonomous functions], secondary effects (e.g., annoyance, degraded well-being, and performance), and tertiary effects (long-term health effects; e.g., hypertension or cardiovascular diseases). The study concludes that it was as yet impossible to determine causal relations between health disorders and noise exposures despite well-founded hypotheses. The author identified studies that show the threshold for higher risk for hypertension to be "day-time outdoor levels of considerably more than 80 dBA," although "the reviewers determined the respective thresholds of at least 70 dBA for hypertension and between 65 and 70 dBA for ischemic heart diseases." The author noted that difficulties to determine causal relations increase with the time lag between the onset of noise exposure and the manifestation of an effect in question. Another important factor is habituation, which causes a reduction of primary and secondary responses with time. The significance of these contributors in view of the hypothesized health effects must be elucidated in future studies. Other topics for future research are discussed as well.

***Guidelines for Community Noise, Presented at the WHO–Expert Task Force Meeting, B. Berglund, T. Lindvall and D.H. Schwela, eds., London, United Kingdom, 2000.***

In 2000, the WHO published its *Guidelines for Community Noise*, which was assembled by a team of international experts including two members from the United States. It includes chapters on noise sources and noise measurement, adverse health effects of noise, guideline values, noise management strategies, and conclusions. The report addresses all forms of noise including industrial, transportation, construction, domestic activities, and leisure activities. The *Guidelines* describe various noise metrics and their application. In terms of health effects, it describes hearing loss, interference with speech, sleep disturbance, cardiovascular and physiological effects, mental health effects, performance effects, and annoyance. The report does not contain any original research, but is a comprehensive review of available literature available as of April 1999. In terms of cardiovascular and physiological effects the report finds

... only a few studies on environmental noise have shown that populations living in noisy areas around airports and on noisy streets have an increased risk for hypertension. The overall evidence suggests a weak association between long-term environmental noise exposure and hypertension, and no dose-response relationships could be established. . . . The overall conclusion is that cardiovascular effects are associated with long-term exposure to  $L_{Aeq}$ , 24h values in the range of 65–70 dB or more, for both air and

road traffic noise. However, the associations are weak and the effect is somewhat stronger for ischemic heart disease than for hypertension. Nevertheless, such small risks are potentially important because a large number of persons are currently exposed to these noise levels, or are likely to be exposed in the future. Furthermore, only the average risk is considered and sensitive subgroups of the populations have not been sufficiently characterized. Other observed psychophysiological effects, such as changes in stress hormones, magnesium levels, immunological indicators, and gastrointestinal disturbances are too inconsistent for conclusions to be drawn about the influence of noise pollution.

**Harris, C., *The Effects of Noise on Health*, U.S. Air Force, Armstrong Laboratory, Wright-Patterson Air Force Base, Ohio, 1997, 56 pp.**

This is a comprehensive report on the health effects of noise. Both environmental noise and occupational noise exposure are examined. It contains no original research, but is a very good compilation of research done through 1997 and includes extensive critical review of the available literature. The author comments on the extent and quality of health-related research and finds much of the research to be lacking. After some expert opinion on the health effects of noise, there is an attempt to convey the complexity of the difficulties in forming a perspective on noise research. This is followed, in turn, by a discussion of some of the early research sponsored by the EPA. Next is a discussion of noise-induced physiological changes, noise as a stressor, and some specialized topics regarding the effects of impulsive acoustic stimuli, the effects on sleep, on hearing, and on people living under military training routes. Finally, an attempt is made to summarize, evaluate, and take a position relative to health effects of noise. The author identified a number of studies that focus on the relationship between cardiovascular disease and noise exposure, which identify the inconsistency of the results. The author points out that the only two effects that result directly from aircraft noise are hypertension and ischemic heart disease." The relative risk of ischemic heart disease and of hypertension starts to increase for persons living in areas with road or air-traffic noise at equivalent sound levels above 70 dB(A)."

**Järup, L., et al., "Hypertension and Exposure to Noise near Airports—The HYENA Study," *Environmental Health Perspectives*, Vol. 116, No. 3, pp. 329–333 [Online]. Available: doi:10.1289/ehp.10775 (available at <http://dx.doi.org/>), Dec. 11, 2007.**

This study measured blood pressure and collected data on health, socioeconomic, and life-style factors, including diet and physical activity, for 4,861 persons aged 45 to 70 years who had lived at least five years near any of six major European airports. Noise exposure was assessed using noise models with a resolution of 1 dB (5 dB for UK road traffic noise). The authors found significant exposure-response relationships between night-time aircraft noise as well as average daily road traffic noise exposure and risk of hypertension after adjustment for major confounders. Note that the HYENA study data analysis is ongoing and that air pollution as a confounder was not analyzed

in the first study reports. For night-time aircraft noise, a 10 dB increase in exposure was associated with an odds ratio (OR) of 1.14. OR is computed from the odds of one group having a condition to the odds of another group having that condition. The exposure-response relationships were similar for road traffic noise and stronger for men. The results indicate excess risks of hypertension related to long-term noise exposure, primarily for night-time aircraft noise and daily average road traffic noise. A closer review of the HYENA data for night-time aircraft noise raises some questions about the data. Figure A1 shows the OR plotted as a function of the night-time aircraft  $L_{eq}$ . The dashed line is the trendline. The highest OR occurs in the range of night  $L_{eq}$  from 40 to 44 dBA and decreases at higher exposures. Note that the first two data points, OR values near 1 (no effect on hypertension) at noise exposures less than 40 dBA, have a significant effect on the trendline. If the first two no-effect data points are eliminated from the regression analysis, the trendline reverses slope (decreasing odds of hypertension with increasing noise level), a result not addressed by the authors. Note that the authors used modeled noise levels for this study and report night-time outdoor noise levels as low as 30 dBA. This is the aircraft contribution to the overall ambient noise level and the ambient noise level is most likely higher than this. This may explain the OR values near 1 (meaning no effect on hypertension) at the lower noise levels.

**Järup, L., M.L. Dudley, W. Babisch, D. Houthuijs, W. Swart, and G. Pershagen, "Hypertension and Exposure to Noise near Airports (HYENA): Study Design and Noise Exposure Assessment," *Environmental Health Perspectives*, Vol. 113, No. 11, Nov. 2005, pp. 1473–1478.**

The Hypertension and Exposure to Noise near Airports (HYENA) project aims to assess the impact of airport-related noise exposure on blood pressure and cardiovascular disease using a cross-sectional study design. The study includes 6,000 persons (45 to 70 years old) who had lived for at least five years near one of six major European airports. Modeled aircraft noise contours were used with the intent of maximizing exposure contrast. Automated blood pressure instruments were used to reduce observer error. A standardized questionnaire was used to collect data on annoyance, noise disturbance, and major confounders. Cortisol in saliva was collected in a subsample of the study population ( $n = 500$ ) stratified by noise exposure level. To investigate short-term noise effects on blood pressure and possible effects on night-time blood pressure dipping, 24-h blood pressure was measured and assessed with continuous noise models in another subsample ( $n = 200$ ). To ensure comparability between countries, common noise models were used to assess individual noise exposure, with a resolution of 1 dBA. Modifiers of individual exposure, such as the orientation of living rooms and bedrooms toward roads, window-opening habits, and sound insulation, were assessed by the questionnaire. For four airports, estimated exposure to air pollution was used to explore modifying effects of air pollution on cardiovascular disease. The project assesses exposure to traffic-related air pollutants, primarily using data

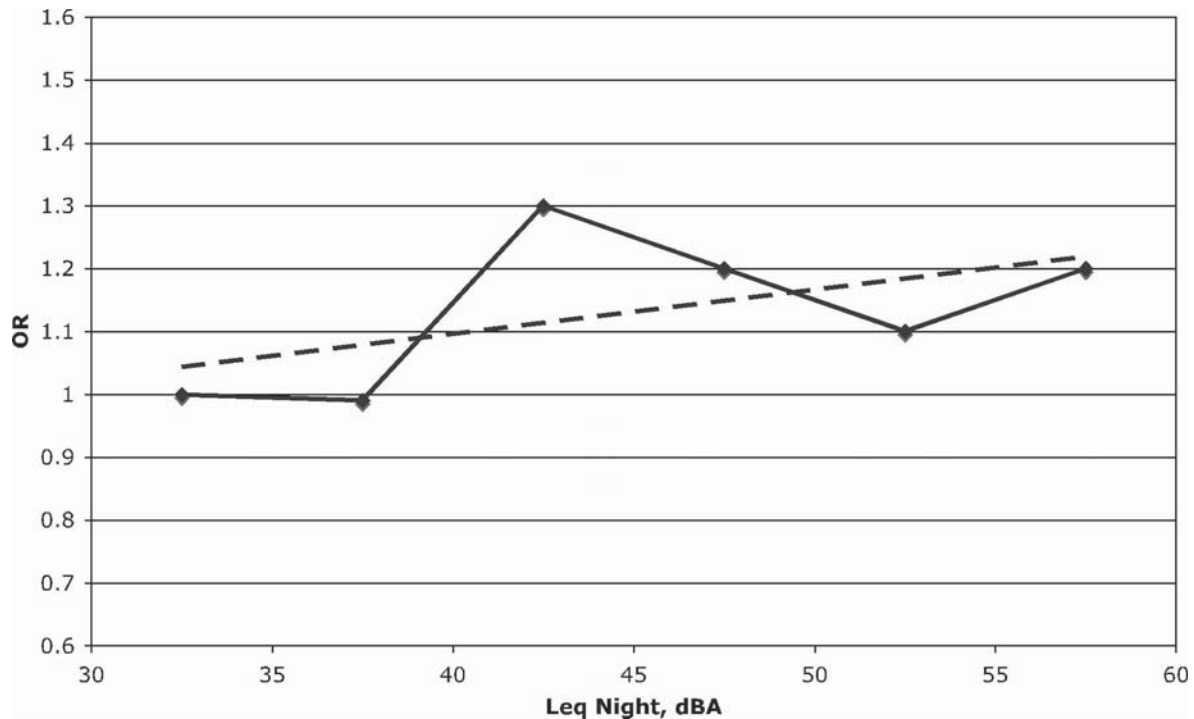


FIGURE A1 Odds ratio for hypertension versus night-time aircraft noise (adapted from Figure 2 of HYENA Study, Jarup et al. 2007).

from another project funded by the European Union. This study is one of the very few attempting to segregate the health effects caused by noise or air pollution near airports. The study results were scheduled to be published in the fall of 2007.

Two HYENA studies were published in early 2008, too late for full consideration in this synthesis. These studies (Jarup et al. 2007 and Haralabidis et al. 2008) present results indicating “excess risks of hypertension related to long-term noise exposure primarily for night-time aircraft noise and daily average road traffic noise” (Jarup et al. 2008). “Effects of noise exposure on elevated subsequent BP measurements were clearly shown. The effect size of the noise level appears to be independent of the noise source” (Haralabidis et al. 2008).

**Lee, C.S.Y. and G.G. Fleming, *General Health Effects of Transportation Noise*, U.S. Department of Transportation, Washington, D.C., June 2002, 44 pp.**

The FRA sponsored the preparation of this report to support a rulemaking process about the use of locomotive horns and the accompanying environmental impact statement. This document reviews select current and past research on the effect of transportation noise on the physiological and psychological health of both people and wildlife. This is a short and easy-to-read report that does not contain any original research, but rather relies on reports published through the year 2000. The subjects covered include annoyance, SI, effects on performance, interference with recreational activities, hearing loss, sleep disturbance, muscular effects, cardiovascular effects,

mental health effects, and effects on wildlife. In terms of health effects, the report concludes that most studies include limited data with no definitive conclusions. With respect to cardiovascular effects, the report concludes that such effects are associated with long-term exposure to daily equivalent sound levels greater than 65 dB.

**Passchier-Vermeer, W. and W.F. Passchier, “Noise Exposure and Public Health,” *Environmental Health Perspectives*, Vol. 108, No. 1, Mar. 2000, pp. 123–131.**

This journal article presents a broad discussion of existing literature on the health effects of noise, including environmental and occupational exposures. The authors report that there is sufficient scientific evidence that noise exposure can induce hearing impairment, hypertension, ischemic heart disease, annoyance, sleep disturbance, and decreased school performance. The evidence is limited for other effects, such as changes in the immune system and birth defects. A subject for further research is the elucidation of the mechanisms underlying noise-induced cardiovascular disorders and the relationship of noise with annoyance and non-acoustical factors modifying health outcomes. A high-priority study subject is the effect of noise on children, including cognitive effects, and its reversibility. With respect to aircraft and road noise and hypertension and ischemic heart disease, the authors conclude that there are “no obvious effects from noise exposure on mean diastolic and mean systolic blood pressure, but some effects were observed in terms of an increase in the percentage of people with hypertension (including those who use medication

for hypertension). The observation threshold for hypertension is estimated to correspond to an  $L_{dn}$  value of 70 dB(A) for environmental noise exposure.” Studies of the cardiovascular effects of noise on children are less clear; therefore, the authors recommend further study. The authors also cite studies on the effects of noise on birth weight and conclude that noise exposure is not related to birth weight.

**Rosenlund, M., N. Berglund, G. Pershagen, L. Järup, and G. Bluhm, “Increased Prevalence of Hypertension in a Population Exposed to Aircraft Noise,” *Journal of Occupational and Environmental Medicine*, Vol. 58, 2001, pp. 769–773.**

This study used a cross-sectional analysis to investigate whether there is a relation between residential exposure to aircraft noise and hypertension. The study was done by the Department of Environmental Health, Stockholm County Council, Sweden. The study population was comprised of two random samples of subjects aged 19 to 80 years, one including 266 residents in the vicinity of Stockholm Arlanda airport and another comprising 2,693 inhabitants in other parts of Stockholm County. The subjects were classified according to the time weighted equal energy and maximum aircraft noise levels at their residence. A questionnaire provided information on individual characteristics including history of hypertension. The prevalence odds ratio for hypertension adjusted for age, sex, smoking, and education was higher among those with energy-averaged aircraft noise levels exceeding 55 dBA, and among those with maximum aircraft noise levels exceeding 72 dBA. An exposure-response relation was suggested for both exposure measures. The exposure to aircraft noise appeared to be particularly important for older subjects and for those not reporting impaired hearing ability. The study concludes that community exposure to aircraft noise may be associated with hypertension.

**Van Kempen, E., H. Kruize, H.C. Boshuizen, C.B. Ameling, B. Staatsen, and A. de Hollander, “The Association Between Noise Exposure and Blood Pressure and Ischemic Heart Disease: A Meta-Analysis,” *Environmental Health Perspectives*, Vol. 110, No. 3, Mar. 2002, pp. 307–317.**

The authors conducted a meta-analysis of 43 epidemiological studies published between 1970 and 1999 that investigated the relation between noise exposure (both occupational and community) and blood pressure and/or ischemic heart disease. It has been suggested that noise exposure is associated with blood pressure changes and ischemic heart disease risk, but epidemiological evidence is still limited. Most reviews investigating these relations were not carried out in a systematic way, which makes them more prone to bias. The authors studied a wide range of effects, from blood pressure changes to myocardial infarction. They pointed out the tendency for some studies to inadequately report noise exposure data; therefore, they included an evaluation of the noise exposure data and

made adjustments is needed. With respect to the association between noise exposure and blood pressure, small blood pressure differences were evident. The meta-analysis showed a significant association for both occupational noise exposure and air-traffic noise exposure and hypertension, although the conclusion, with respect to air traffic, was derived from a single study done in 1976. Occupational exposure to noise and hypertension was identified in numerous studies. Air traffic noise exposure was positively associated with the consultation of a general practitioner or specialist, the use of cardiovascular medicines, and angina pectoris. In cross-sectional studies, road traffic noise exposure increases the risk of myocardial infarction and total ischemic heart disease. Only 2 of the 43 studies attempted to quantify the relation between noise and cardiovascular disease. “Although we can conclude that noise exposure can contribute to the prevalence of cardiovascular disease, the evidence for a relation between noise exposure and ischemic heart disease is still inconclusive because of the limitations of exposure characterization, adjustment for important confounders, and the occurrence of publication bias.” The authors recommended further study.

#### **Aviation Noise Effects and Children**

**Poustka, F., P. Eckermann, and K. Schmeck, “Effect of Aircraft Noise and Psychosocial Stressors on Mental Disturbances of Children and Adolescents: An Epidemiological Survey in Westphalia,” In *Developmental Psychopathology*, H. Remschmidt and M.H. Schmidt, eds. Hogrefe and Huber Publishers, 1992, pp. 83–96.**

In this chapter the authors report on psychiatric disorders in children aged 4 to 16 years. The children were studied in two contrasting geographic regions using a cross-sectional analysis of two regions. These regions differed according to the noise made by jetfighters exercising frequently at low altitude. Noise levels are not reported, but are likely very high because these military aircraft fly as low as 75 m with very high onset rates. Psychosocial and individual variables known to act as potential risk factors for psychiatric disorders correlate highly with psychiatric disorders. The correlation between adverse factors and symptoms differed between age and gender samples. Neither psychiatric disorders nor environmental factors showed any relationship to noise; however, psychophysiological parameters (e.g., heart rate and muscle tension) demonstrated some relationship to noise. Their meaning is uncertain and warrants further research.

**Wu, T.N., L.J. Chen, J.S. Lai, G.N. Jo, C.Y. Shen, and P.Y. Chang, “Prospective Study of Noise Exposure During Pregnancy on Birth Weight,” *American Journal of Epidemiology*, Vol. 143, No. 8, 1996, pp. 792–796.**

This study does not address aircraft noise specifically, but the total noise exposure to all noise sources during the day. To examine the effect of noise exposure during pregnancy on infant birth weight, a well-characterized cohort of 200 pregnant

women in the first trimester participating in a prenatal care clinic was followed throughout gestation in Taiwan in 1991. Individual 24-h noise exposure of all women was prospectively measured using a personal dosimeter, and information regarding possible noise exposure from traffic and occupation was also obtained. Noise exposure during pregnancy was correlated with the birth weights of the women's babies. No association between personal noise exposure measured in decibels (less than 85 dBA  $L_{eq}$  during pregnancy) and birth weight was found. Possible occupational noise exposure (indicated by working in a manual job), traffic noise exposure (indicated by the distance between the home and main streets), and a history of listening to amplified music and using personal listening devices during pregnancy also showed no effect on infant birth weight. Maternal weight, maternal weight gained during pregnancy, gestational age, and the infant's sex were the four factors that correlated significantly with birth weight. The study concluded that the noise exposure experienced by women during pregnancy may not be great enough to affect their infants' birth weight.

#### Hospitals and Care Facilities

See WHO, *Guidelines for Community Noise* (2000) in previous section.

#### Hearing Impairment

**Finegold, L.S., A. Muzet, B.F. Berry, and M.S. Finegold, *Effects of Aircraft Noise on Communities: Sleep Disturbance and Hearing Loss*, Japan Defense Forces Environmental Improvements Association (DFEIA), Tokyo, Japan, 2003, 47 pp.**

The Japan Defense Facilities Environment Improvement Association initiated this study in 2003 to provide information on the effects of aircraft overflight noise on communities, based mainly on research conducted in the United States and Europe. The document contains the Final Report on this project and has two major sections addressing sleep disturbance resulting from aircraft noise exposure and hearing loss owing to aircraft noise exposure. In the study, the authors provide detailed reviews and annotations for 22 recent relevant studies. In terms of hearing loss, the study concludes that there is no evidence of raised threshold shifts in populations in the vicinity of civil or military airports.

**International Standards, "Acoustics—Determination of Occupational Noise Exposure and Estimation of Noise-Induced Hearing Impairment," *ISO 1999*, 2nd. ed., 1990-01-15 (E), 17 pp.**

This International Standard presents, in statistical terms, the relationship between noise exposure and the "noise-induced permanent threshold shift" in people of various ages. It provides procedures for estimating the hearing impairment resulting from noise exposure of populations free from auditory

impairment other than that owing to noise (with allowance for the effects of age) or of unscreened populations whose hearing capability has been measured or estimated. The standard specifies a method of calculating the expected noise-induced permanent threshold shift in the hearing threshold levels of adult populations resulting from various levels and durations of noise exposure. The standard does not address specific noise sources such as aircraft noise. The methodology employed is somewhat complex, but is useful for considering the potential for hearing loss from environmental exposure to aircraft noise. Typical community noise levels near an airport are not comparable to the occupational or recreational noise exposures that are associated with hearing loss.

**Ludlow, B. and K. Sixsmith, "Long-Term Effects of Military Jet Aircraft Noise Exposure During Childhood on Hearing Threshold Levels," *Noise and Health*, Vol. 5, 1999, pp. 33–39.**

This study evaluates suggestions that young children may be relatively more susceptible to noise-induced hearing loss than adults, and that the unique noise footprint associated with military jet aircraft is particularly damaging to hearing. This pilot study looked for evidence of noise-induced hearing loss in adults who have been exposed to military jet noise in early childhood, while living in married quarters on active Royal Air Force fast jet stations. Many of the subjects lived in quarters that lie within 70 dBA  $L_{eq}$  contours, with a few in 83 dBA  $L_{eq}$  contours. A cross-sectional pilot study was undertaken to examine the hypothesis that military jet noise exposure early in life is associated with raised hearing thresholds. The authors' concluded that "this study has found no evidence that RAF personnel who have lived on or near fast jet stations while very young display raised hearing threshold levels associated with noise-induced hearing loss."

**Passchier-Vermeer, W., *Noise and Health of Children*, TNO Prevention and Health Report, Netherlands Organization for Applied Scientific Research, Leiden, the Netherlands, 2000, pp. 52.**

This report gives an overview of the adverse effects of noise exposure on the health of children and covers a broad range of topics, including hearing impairment. The author considers hearing impairment in the fetus, pre-term and full-term babies, pre-school and school children, and teenagers. The studies are not limited to aircraft or environmental noise but all noise sources. Occupational noise exposure was the only risk factor identified for the fetus, although high levels of noise in the neonatal intensive care unit and incubator noise was identified as the major risk factor for pre-term babies. With respect to pre-school and school-age children, the author concluded that "The investigations undertaken so far show that environmental noise exposure does not have an effect on hearing threshold levels of children, with the exception of exposure to noise from extremely low flying military aircraft." With respect to teenagers, the author

concluded that firecrackers, tractors, snowmobiles, hunting equipment, power tools, musical instruments, portable music players, boom-cars, night clubs, rock concerts, motorcycles, and occupational or technical schools are the main risk factors for hearing loss in teenagers. Environmental noise was not considered a risk factor for teenage hearing loss.

**Sixsmith, K. and P. Wheeler, “Auditory Impact of Aircraft Noise on Civilian Populations: Examination of the Scientific Literature for Evidence,” Presented at the Inter-Noise Symposium, Fort Lauderdale, Fla., Dec. 6–8, 1999.**

This review examines the scientific literature for any evidence that jet aircraft noise may be associated with hearing impairment in populations surrounding civil and military airfields, as measured at frequencies up to 8 kHz. Papers were found using MEDLINE and by searching recent international conference proceedings. The study includes a review of nine studies done in the vicinity of seven civil or military airports and two laboratory studies. The studies reviewed included noise levels as high as 130 dBA ( $L_{max}$ ) and 95 dB WECPNL (~82 DNL). “The laboratory studies suggest that permanent threshold shifts are unlikely to be induced by exposures to aircraft noise thought to be typical of real life.” The authors summarized the results: “In the main, these studies have been conducted where environmental noise does not appear to approach recognized occupational noise limits. Further, it may be that the intermittency of environmental noise may itself protect hearing from damage.”

**CHAPTER THREE: ANNOYANCE AND AVIATION NOISE**

Before addressing recent studies related to exposure-response relationships between transportation noise and community annoyance, a brief historical overview is warranted. With the development of jet aircraft technology in the early 1950s, concern about exposure to noise from transportation sources led to the publication of the initial scientific studies of aircraft noise exposure and the responses of communities in the vicinity of airports and, later, for road traffic and railway noise. The concept of “community annoyance” was developed to provide one comprehensive term to describe the overall community response to noise, including both degradation of outdoor activities and interference with indoor activities. There are two general assumptions: (1) that the noise exposures of interest for policy-making purposes occur over a period of at least a month, and (2) that the population has had between 2 and 6 months to habituate to major changes in their community-wide noise exposure. Community annoyance is therefore the aggregate community response to long-term, steady-state exposure conditions. However, to adequately support government noise policy-making efforts, it is necessary to synthesize the large amount of data contained in journal articles and technical reports to develop a useful exposure-response relationship. Statistical data meta-analysis techniques are used to accomplish this.

In his seminal article, Schultz (1978) reviewed the data from social surveys concerning the noise of aircraft, street and expressway traffic, and railroads. Returning to the original published data, the various survey noise ratings were translated to DNL, and where a choice was needed, an independent judgment was made as to which respondents should be counted as “highly annoyed.” According to Schultz, “. . . the basic rule adopted was to count as ‘highly annoyed’ the people who responded on the upper 27%–29% of the annoyance scale. . . .” (Schultz 1978). The results of 11 of the reviewed surveys showed a remarkable consistency—the so-called “clustering surveys.” In performing his analysis, Schultz used a third-order polynomial function to fit the 161 data points contained in the 11 “clustering” surveys.

For decades, environmental planners have relied heavily on the Schultz curve for predicting community annoyance from transportation noise sources. Notwithstanding the methodological questions, errors in measurement of both noise exposure and reported annoyance, data interpretation differences, and the problem of community response bias, Schultz’s recommended relationship has historically been the most widely accepted interpretation of the social survey literature on transportation noise-induced annoyance.

Beginning with the 1978 publication of Schultz’s original exposure-response curve, work has continued in many countries to conduct field studies, to develop databases with the results of new social surveys, and to explore whether separate curves are needed to describe community responses to aircraft, street traffic, and railway noise. The conclusions of several major meta-analyses of these data will be reviewed and possible future directions for this line of research will be discussed.

In 1992, Federal Interagency Committee on Noise (FICON) reported that there were no new descriptors or metrics of sufficient scientific standing to substitute for the present DNL cumulative noise exposure metric (*Federal Agency Review . . .* 1992). The dose-response relationship, as represented by DNL, and the percentage of “highly annoyed” remains the best available approach for analyzing overall health and welfare affects for the vast majority of transportation noise analyses.

Fidell et al. (1991) were commissioned by the U.S. Air Force to update this important curve. That update, along with the Schultz curve, is the basis of the FICON recommendation and the basis for most U.S. policy on aviation noise. The result of this major database update was the inclusion of 292 additional data points to the original 161 data points for a new total of 453 data points. The result nearly tripled the size of the database for predicting annoyance owing to general transportation noise exposure as compared with the original Schultz Curve. As shown in Figure A2, even though the data points nearly tripled, the 1978 relationship still provides a reasonable fit to the data. Although the article published the widely used “updated Schultz curve,” it also carefully showed the individual data points that went into the synthesis of the curve

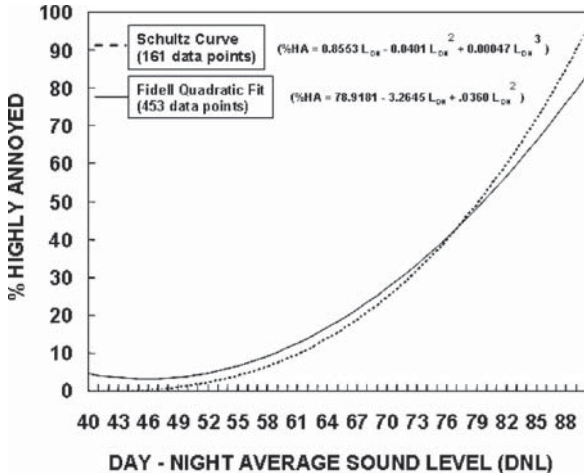


FIGURE A2 Prediction curve from Fidell compared with original Schultz Curve (adapted from Fidell et al. 1991).

(see Figure A3; the percentage of “highly annoyed” ranges from about 5% to more than 70% at 65 DNL). In later years, the primary author criticized the use of this simplistic curve, in light of the high data variability, the effect of low- and high-noise exposure levels on the curve fit, and the lack of consideration of other variables in community response to noise.

A comprehensive review and critique of Fidell et al.’s update (1991) was later published by Fields (1994), where the

author raises questions about the use of the synthesis data to develop the commonly used annoyance/DNL dose-response relationship. The report arrives at several conclusions, including “the curve is NOT a measurement of the relationship between DNL and the percentage of the population that would describe themselves as ‘highly annoyed’ and if it is necessary to estimate the dose/response relationship . . . a single constituent survey provides a better estimate” (Fields 1994).

The Fidell et al. (1991) expansion of the existing community annoyance research database and their revised prediction curve provided a considerable extension of the original Schultz meta-analysis. However, because there were several debatable methodological issues involved in this update, Finegold et al. (1994) reanalyzed the Fidell et al. data and published the results of this additional meta-analysis. Their re-analysis focused primarily on the choice of screening criteria for the selection of which studies to include in the final database and the choice of a data fitting algorithm. Use of more stringent study selection criteria resulted in a 12% loss of the original data points.

Using the new data set, a new logistic fit curve as the prediction curve of choice was developed and adopted by FICON in 1992 for use by federal agencies in aircraft noise-related environmental impact analyses. It was also adopted as part of the ANSI Standard on community responses to

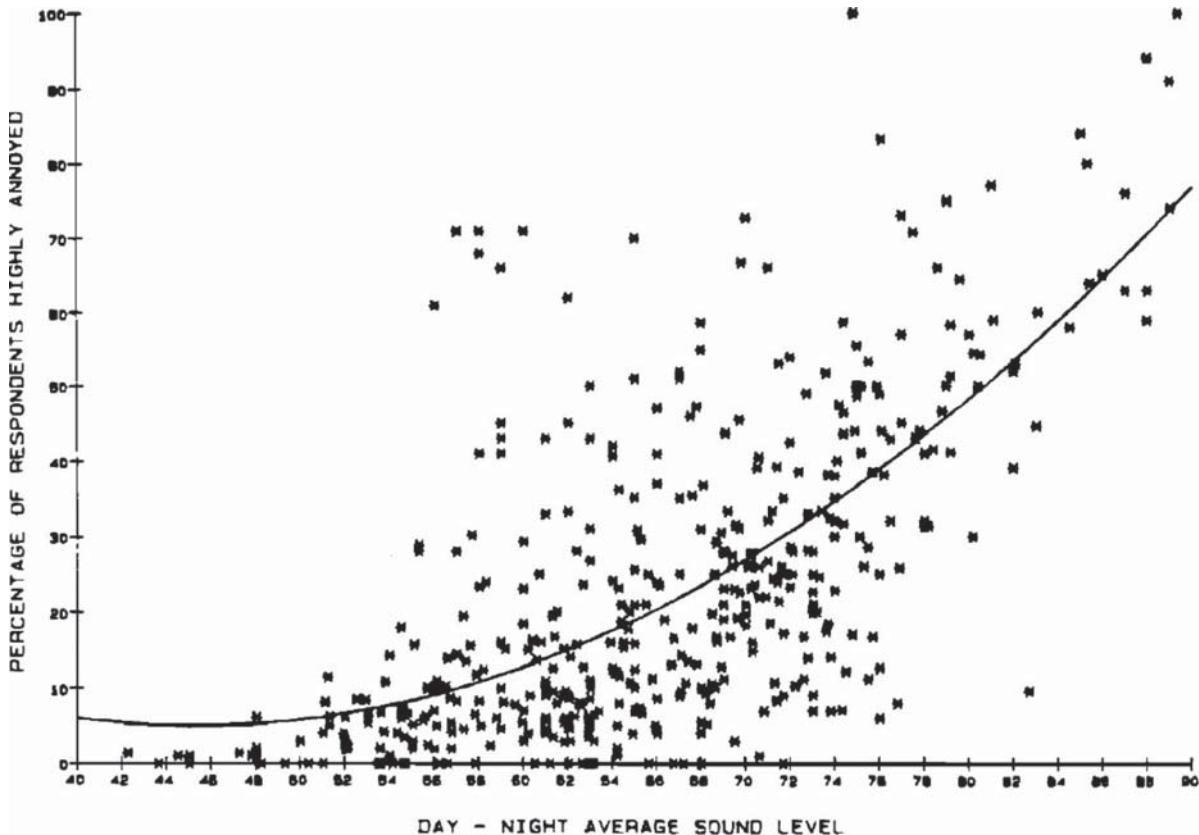


FIGURE A3 All 453 datapoints used in updated dose-response curve (adapted from Fidell et al. 1991).

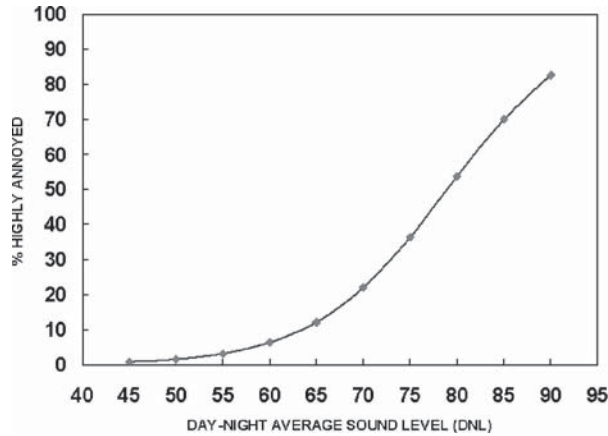


FIGURE A4 Community annoyance prediction curve (Finegold et al. 1994).

environmental noises. Figure A4 presents the Finegold et al. (1994) curve, which shows that if the data are broken down into separate curves for various types of transportation noises (aircraft, roadway, rail noise), aircraft noise appears to be more annoying at the same DNL than either road or rail noise (see Figure A5).

Over the past decade, Miedema and Vos (1998, 1999) have compiled the most comprehensive database of community annoyance data yet available, and several studies have been published on the results of their meta-analyses. It is a comprehensive review of an issue that has been contentious ever since Schultz published his data in 1978. Separate, non-identical curves were found for aircraft, road traffic, and railway noise. Aircraft is shown to be more annoying than road or rail noise. Miedema and Vos used three different curves to describe the data for the three noise categories—aircraft, road traffic, and railway noise, as shown in Figure A6. However, no data were found describing the statistical significance of these differences. One should exercise caution in drawing firm conclusions about the state of knowledge concerning the

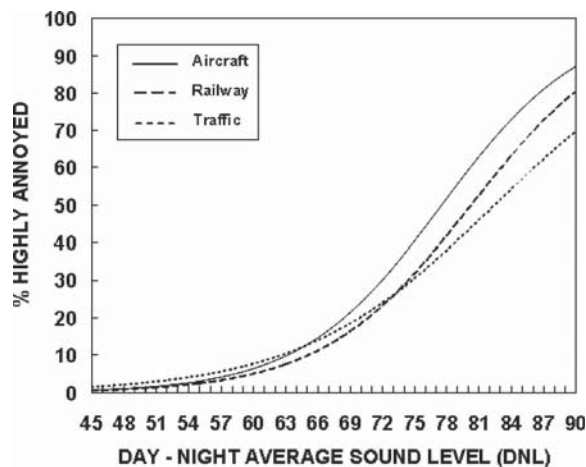


FIGURE A5 Curves for three transportation noise sources (Finegold et al. 1994).

relationship between the various transportation noise sources and community annoyance.

The European Union position on annoyance is based on its report in 2002 that recommends that the percentage of persons “annoyed” or percentage of persons “highly annoyed” be used as the descriptor for noise annoyance. Similar to Miedema and Vos, the position paper distinguishes between aircraft, road, and rail traffic noise; recommends use of a separate pair of curves (“annoyed” and “highly annoyed”) for each; and clearly shows a tendency to treat aircraft, road, and rail noise as unique when estimating the percentage of the population who will be “annoyed” or “highly annoyed” by noise.

Miedema and Vos (1999) further studied the effects of demographic variables (e.g., sex, age, education level, occupational status, size of household, dependency on the noise source, and use of the noise source) and two attitudinal variables (noise sensitivity and fear of the noise source) on annoyance. The results are very interesting and suggest that fear and noise sensitivity have a large impact on annoyance. Additionally, Fidell et al. (2002) suggest that a good part of the excess annoyance is attributable to the net influence of non-acoustic factors. “A disproportionately large and long-term increase was observed in the prevalence of self-reported high annoyance long after a step increase in aircraft noise exposure . . . The greater than predicted increase in the prevalence of annoyance cannot be attributed to changes in noise exposure alone” (Fidell et al. 2002).

Some of the most interesting research comes from Fidell in two papers. In “The Shultz Curve 25 Years Later: A Research Perspective,” he argues that although federal adoption of an annoyance-based rationale for regulatory policy has made this approach a familiar one, it is only one of several historical perspectives, and not necessarily the most useful for all purposes (Fidell 2003). This tutorial article traces the development of the dosage-effect relationship on which FICON currently relies, and identifies areas in which advances in genuine understanding might lead to improved means for predicting community response to transportation noise. It provides an important summary of how the annoyance synthesis was developed and the inherent weakness of the DNL/dose-response relationship. In summary, Fidell is highly critical of U.S. policy that relies solely on the synthesized dose-response relationship.

In the second paper, Fidell and Silvati identified shortcomings of a fitting function endorsed by FICON for predicting prevalence rates of annoyance in populations exposed to aircraft noise that are well-understood and well-documented (Fidell and Silvati 2004). The authors argue that the U.S. National Environmental Policy Act (NEPA) requires the use of best-available technology for disclosure of noise impacts of major federal actions; however, the authors’ underlying concern is that the reliance on the FICON curve for meeting NEPA requirements does not use the best available



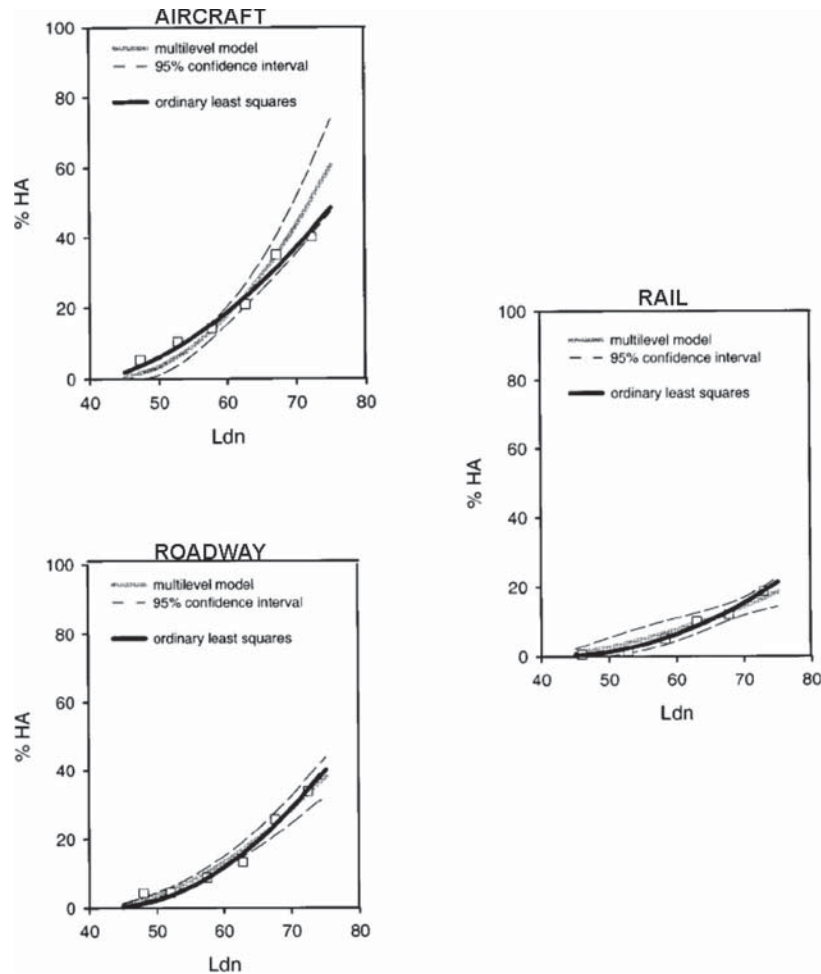


FIGURE A6 Community annoyance prediction curves for aircraft, road, and rail noise (Miedema and Vos 1998).

technology. They state that although fitting functions more accurate and reliable than that of FICON can be identified by regression analyses of the findings of more than two dozen studies of aircraft noise annoyance, alternative approaches to characterizing annoyance resulting from aircraft noise are more readily defensible for basic policy-related purposes, “No useful prediction of the prevalence of annoyance engendered by aircraft noise that is based solely on cumulative exposure is likely to account for more than half of the variance in field measurements” (Fidell and Silvati 2004).

### Summary

Significant research has occurred since the 1985 aviation effects report was published. There is no current research to suggest that there is a better metric than DNL to relate to annoyance. However, there remains significant controversy over the use of the dose-response annoyance curve first developed by Schultz and then updated by others. Although the curve is presented as a smooth definitive relationship between DNL and annoyance, there is an extraordinary amount of scatter in the data used to develop the curve. Investigations that report a distinct percentage of the population

that will be “highly annoyed” at a given DNL may incorrectly be interpreted as having a more precise meaning than should be derived from the data. Furthermore, more recent research tends to support the idea that the dose-response curves are different for aircraft, road, and rail noise sources. An area of research that remains to be investigated is the relationship between single-event noise levels and annoyance. The expanding use of airport noise monitoring systems, flight tracking systems, and GIS, may make the evaluation of annoyance and single-event noise rich for examination.

### Annotated Bibliography—Annoyance and Aviation Noise

**European Union, *Position Paper on Dose Response Relationships Between Transportation Noise and Annoyance, EU Future Noise Policy, WG2—Dose/Effect, Feb. 20, 2002, 40 pp.***

This position paper forms the basis for a European Union position on annoyance. The paper recommends that the percentage of persons “annoyed” or percentage of persons “highly annoyed” be used as the descriptor for noise annoyance.

Initially, it was proposed that percentage “annoyed” be used because it is more sensitive to changes in DNL; however, in the final paper both percentage “annoyed” and percentage “highly annoyed” were included. The position paper distinguishes between aircraft, road, and rail traffic and recommends a separate pair of curves (“annoyed” and “highly annoyed”) for each. At 65 DNL the percentage of “highly annoyed” for aircraft is 26%, roadway 16%, and 9% for rail noise. European practice is clearly showing a tendency to treat aircraft, road, and rail noise as unique when estimating population that will be “annoyed” or “highly annoyed” by noise.

**Federal Interagency Committee on Noise, “Federal Agency Review of Selected Airport Noise Analysis Issues,” Aug. 1992, 203 pp.**

Although the FICON report consists of two parts (policy and technical), only the technical part was reviewed for this annotated bibliography. The technical conclusions relative to annoyance state that there are no new descriptors or metrics of sufficient scientific standing to substitute for the present DNL cumulative-noise exposure metric. The dose-response relationship, as represented by DNL, and percentage of “highly annoyed” remains the best available approach for analyzing overall health and welfare impacts for the vast majority of transportation noise analyses. Annoyance is a summary measure of people’s general adverse reaction to living in noisy environments with the resulting effects causing SI; sleep disturbance; desire for a tranquil environment; and the inability to use the telephone, radio, or television satisfactorily.

**Fidell, S., “The Schultz Curve 25 Years Later: A Research Perspective,” *The Journal of the Acoustical Society of America*, Vol. 114, No. 6, Dec. 2003, pp. 3007–3015.**

The contemporary technical rationale for assessing effects (impacts) of transportation noise on communities rests in large part on a purely descriptive dosage-effect relationship of the sort first synthesized by Schultz (1978). The author argues that although U.S. federal adoption of an annoyance-based rationale for regulatory policy has made this approach a familiar one, it is only one of several historical perspectives, and not necessarily the most useful for all purposes. Last reviewed 10 years ago by FICON, the accuracy and precision of estimates of the prevalence of a consequential degree of noise-induced annoyance yielded by functions of noise exposure leave much to be desired. This tutorial article traces the development of the dosage-effect relationship on which FICON currently relies in a wider historical context of efforts to understand and predict community response to transportation noise. It also identifies areas in which advances in genuine understanding might lead to improved means for predicting community response to transportation noise. There is an important summary of how the annoyance synthesis was developed and the inherent weakness of the DNL/dose-response relationship that developed. The author pointedly notes that the dose-response curve fit was highly influenced

by annoyance data at the very high and the very low end of the exposure scale. This leads to the conclusion that approximately 12% of the population is “highly annoyed” at 65 DNL. If one looked solely at data between 60 and 70 DNL and did a similar analysis, the conclusion would be that more than twice that number are “highly annoyed” at 65 DNL. Importantly, Fidell is highly critical of U.S. policy that relies solely on the synthesized dose-response relationship.

**Fidell, S., D. Barber, and T. Schultz, “Updating a Dosage-Effect Relationship for the Prevalence of Annoyance due to General Transportation Noise,” *The Journal of the Acoustical Society of America*, Vol. 89, No. 1, Jan. 1991, pp. 221–233.**

This important article along with the Schultz Curve forms the basis of the FICON recommendation and most of the U.S. policy on aviation noise. It was written more than a decade after Schultz synthesized the findings from a dozen social surveys and reported on the relationship between community noise exposure and the prevalence of annoyance. This quantitative dosage-effect relationship has been adopted as a standard means for predicting noise-induced annoyance in environmental assessment documents. The present effort updates the 1978 relationship with findings of social surveys conducted since its publication. Although the number of data points from which a new relationship was inferred more than tripled, the 1978 relationship still provides a reasonable fit to the data. Although the article publishes the widely used “updated Schultz curve,” it also carefully shows the individual data points that went into the synthesis of the curve. Notably, some communities have data points that fall on or near the synthesis curve and others have data points that are well off the curve. In later years, Fidell criticized the simplistic use of this curve in light of the high data variability, the effect of low- and high-noise exposure levels on the curve fit (and that effect on suppressing the estimate of the number of people “highly annoyed” at 65 DNL), and the lack of consideration of other variables in community response to noise.

**Fidell, S. and L. Silvati, “Parsimonious Alternatives to Regression Analysis for Characterizing Prevalence Rates of Aircraft Noise Annoyance,” *Noise Control Engineering Journal*, Vol. 52, No. 2, Mar.–Apr. 2004, pp. 56–68.**

The authors identified shortcomings of a fitting function endorsed by FICON for predicting prevalence rates of annoyance in populations exposed to aircraft noise that are well-understood and well-documented. These shortcomings include: (1) substantial underestimation of measured prevalence rates of aircraft noise annoyance in the exposure range of greatest practical interest, (2) the burden of analytic assumptions made in logistic regression, and (3) the limited amount of variance for which a generic (non-source specific) function for all forms of transportation noise accounts in the relationship between cumulative noise exposure and measured prevalence rates of aircraft noise annoyance. Plots of the synthesized dose-response curves

are provided with plots of the underlying data points that were used to synthesize the curves. The amount of data scatter is striking compared with the smooth curves. Fidell and Silvati (2004) argued that NEPA requires use of best-available technology for disclosure of noise impacts of major federal actions such as construction of airport infrastructure and that a review was undertaken of the FICON relationship that considers additional information that has become available in the last decade. The authors' underlying concern is that reliance on the FICON curve for meeting NEPA requirements does not meet the test of using the best available technology. The authors reported that although fitting functions more accurate and reliable than that of FICON can be identified by regression analyses of the findings of more than two dozen studies of aircraft noise annoyance, alternative approaches to characterizing annoyance resulting from aircraft noise are more readily defensible for basic policy-related purposes, "No useful prediction of the prevalence of annoyance engendered by aircraft noise that is based solely on cumulative exposure is likely to account for more than half of the variance in field measurements."

**Fidell, S., L. Silvati, and E. Haboly, "Social Survey of Community Response to a Step Change in Aircraft Noise Exposure," *The Journal of the Acoustical Society of America*, Vol. 111, No. 1, Jan. 2002, pp. 200–209.**

Community response to a step change in aircraft noise exposure associated with the opening of a new runway at Vancouver International Airport was documented in two rounds of telephone interviews. One round of interviews was conducted 15 months before the start of operations on the new runway, with a second round of interviews undertaken 21 months after the start of operations. The proportion of respondents who described themselves as "very annoyed" or "extremely annoyed" in a residential area with increased aircraft noise exposure after the runway opening was markedly greater than that predictable from well-known dosage-response relationships. Data in the report show that in one neighborhood where the noise level increased from 46 to 49 DNL, the reported percentage of "highly annoyed" increased from 0% to 18%. In another neighborhood where the DNL increased from 54 to 61, the reported percentage of "highly annoyed" increased from 11% to 52%. Analysis suggests that a good part of the "excess" annoyance is attributable to the net influence of non-acoustic factors. "A disproportionately large and long-term increase was observed in the prevalence of self-reported high annoyance long after a step increase in aircraft noise exposure. . . . The greater-than-predicted increase in the prevalence of annoyance cannot be attributed to changes in noise exposure alone."

**Fields, J.M., "A Review of the Updated Synthesis of Noise/Annoyance Relationships," *NASA High-Number CR 194950*, July 1994.**

This 1994 report completed for NASA evaluates the evidence supporting the "dosage-effect relationship for the

prevalence of annoyance resulting from general transportation noise" that was originally presented in 1978 and more recently updated in 1991. The synthesis methods and many of the constituent studies' reports are examined. The weaknesses of the synthesis are identified and found to be partly the result of the synthesis methodology, but fundamentally to the lack of comparability in the constituent studies' methodologies and reporting procedures. Several suggested improvements to survey, analysis, and synthesis techniques are proposed. This report is important because it raises questions about the use of synthesized data to develop the annoyance/DNL dose-response relationship. As a result of the different methodologies used in the various studies that were synthesized into a single curve, the author arrives at several conclusions. For the purposes of this synthesis, the most important conclusions are that "the curve is NOT a measurement of the relationship between DNL and the percentage of the population that would describe themselves as 'highly annoyed'" and "if it is necessary to estimate the dose/response relationship for a particular annoyance question or survey condition that is present in one of the constituent surveys, a single constituent survey provides a better estimate of a dose/response relationship than does the vaguely defined dose/response relationship defined by the synthesis."

**Finegold, L.S. and M.S. Finegold, "Development of Exposure-Response Relationships between Transportation Noise and Community Annoyance," Presented at the Japan Net-Symposium on Annoyance, Stress, and Health Effects of Environmental Noise, Nov.–Dec. 2002.**

Finegold and Finegold present an excellent history of the development and controversies associated with developing the annoyance dose-response curve relationship. Much of this discussion is summarized in the papers described earlier. Notably, the authors weigh in on separating aircraft noise annoyance from road and rail noise. They describe a policy in the United States where a single dose-response curve is selected for setting policy because the separate curves do not differ by more than 5 dB. Examining the scatter in the data used to develop the dose-response curves, the authors suggest that curves for separate sources are justified only if the curves differ by more than 10 dB and conclude that the scatter in the data and the underlying uncertainty associated with that scatter do not justify a separate aircraft dose-response curve.

**Finegold, L.S., C.S. Harris, and H.E. von Gierke, "Community Annoyance and Sleep Disturbance: Updated Criteria for Assessing the Impacts of General Transportation Noise on People," *Noise Control Engineering Journal*, Vol. 42, No. 1, Jan.–Feb. 1994, pp. 25–30.**

The question of prediction of sleep disturbance and annoyance resulting from transportation noise is addressed in this study. With respect to annoyance, two sets of previously published data have been re-analyzed. This project was initiated

as part of a long-term U.S. Air Force research program on the effects of aircraft noise on humans. It concludes that DNL is still the most adequate noise descriptor for use in environmental impact analyses to assess the annoyance and overall impact of noise from general transportation, including civilian and military aircraft operations. A new logistic curve adopted in 1992 for general use by federal agencies is recommended for use in environmental impact statements as the nominal relationship between DNL and the percentage of a general residential population predicted to be “highly annoyed” by the noise. A power curve, using A-weighted sound exposure level, is recommended for predicting nighttime sleep disturbance from general transportation noise. This revised curve fit based on re-evaluation of the data sets to be used and a new mathematical curve fit results in a curve similar to the two previous curves. Finegold et al. show that if the data are broken down into separate curves for aircraft, roadway, and rail noise, the aircraft annoyance appears to be more annoying at the same DNL than road or rail noise. However, they caution that there are relatively fewer data points in the areas of the curves where the sources differ and that further studies should address this issue.

**Green, D. and S. Fidell, “Variability in the Criterion for Reporting Annoyance in Community Noise Surveys,” *The Journal of the Acoustical Society of America*, Vol. 89, No. 1, Jan. 1991, pp. 234–243.**

Green and Fidell identify a number of issues associated with the curve fitting of community survey data from multiple sources into a single dose-response curve. The article shows plots of the original data scatter on a synthesized curve and discusses the very large variation in the data and the associated complexity of attempts to collapse the data into a single curve. Independent estimates of the contributions of acoustic and non-acoustic factors to the prevalence of annoyance observed in 32 surveys of reactions to transportation noise are made by means of a previously described probabilistic model. The surveys show considerable variation in the level of noise exposure required to elicit self-reports of consequential degrees of annoyance. The distributions of the criteria for reporting annoyance with aircraft and with other noise sources overlap considerably, but the mean value of the criterion for reporting annoyance is about 5 dB more tolerant of non-aircraft exposure. Errors of estimates in quantifying noise exposure and human response in field studies are also assessed.

**Miedema, H.M.E. and H. Vos, “Exposure-Response Relationships for Transportation Noise,” *The Journal of Acoustical Society of America*, Vol. 104, No. 6, Dec. 1998, pp. 3432–3445.**

This article presents synthesis curves for the relationship between DNL and percentage of “highly annoyed” for three transportation noise sources: aircraft, roadway, and railway noise. It is a comprehensive review of an issue that

has been contentious ever since Schultz published his data in 1978. The results are based on all 21 data sets examined by Schultz in 1978, and Fidell et al. in 1991 for which acceptable DNL and the percentage of “highly annoyed” measure could be derived and augmented with 34 data sets. Separate, non-identical curves were found for aircraft, road traffic, and railway noise. Aircraft is shown to be more annoying than roadway, and roadway more annoying than railway noise at the same DNL. At 65 DNL the percentage of “highly annoyed” for these sources are 27%, 19%, and 10%, respectively. A difference between sources was found using data for all studies combined as well as for those studies in which respondents only evaluated two sources. Miedema and Vos conclude that the latter outcome strengthens the conclusion that the differences between sources cannot be explained by difference in study methodology.

**Miedema, H.M. and H. Vos, “Demographic and Attitudinal Factors That Modify Annoyance from Transportation Noise,” *The Journal of the Acoustical Society of America*, Vol. 105, No. 6, June 1999, pp. 3336–3344.**

The effect of demographic variables (e.g., sex, age, education level, occupational status, size of household, homeownership, dependency on the noise source, and use of the noise source) and two attitudinal variables (noise sensitivity and fear of the noise source) on noise annoyance is investigated. The results are very interesting and suggest that whereas some demographic variables are not important, there are a few that are very important. It is found that fear and noise sensitivity have a large impact on annoyance (a highly fearful individual reacts as though the DNL were 19 dBA higher than the actual DNL). Additionally, those that identified themselves as highly noise sensitive had a response that was equivalent to a DNL 11 dB higher than the actual DNL. Demographic factors are much less important. Noise annoyance was shown not to be related to gender. Age was shown to have an effect. For those under 20 the response was as though the DNL was 4 dB lower and for those more than 70, the response was as though the DNL was 3 dB lower. The effects of the other demographic factors on noise annoyance are small. The results are based on analyses of the original data from various previous field surveys of response to noise from transportation sources.

## **CHAPTER FOUR: SLEEP DISTURBANCE AND AVIATION NOISE**

### **Introduction**

Sleep disturbance is a common effect described by most noise-exposed populations whose complaints are often very strong, especially those in the vicinity of airports. Protection of this rest period is necessary for a good quality of life, because daytime well-being often depends on sleep quality and efficiency. Reduction or disruption of sleep is detrimental in the

long term because chronic partial sleep deprivation induces marked tiredness, increases a state of low vigilance, and reduces both daytime performance and the overall quality of life. Sleep appears to be quite sensitive to environmental factors, especially noise, because external stimuli are still processed by the sleeper's sensory functions, although there may be no conscious perception of their presence. The large amount of research published on this subject during the last 30 years has produced considerable variability of results, some of which are quite controversial. The absence of one internationally accepted exposure-effect (or dose-response) relationship is largely owing to (1) the lack of one obvious "best choice" research methodology, and (2) the complex interactions of the many factors that influence sleep disturbance. These factors include differences in the characteristics of the noise itself, differences in individual sensitivities, differences in attitudinal biases toward the noise source, and the context of the living environment. Current exposure-response relationships use either "awakenings" or "body movements" to describe sleep disturbance.

## Noise Exposure

### *Different Metrics and Noise Characteristics*

Noise is present everywhere in our everyday life and sleep disturbance resulting from excessive noise has been studied in a variety of environments; however, the effects of transportation noise have been studied the most. Different indices have been used to describe various community noise exposures, and there is no general agreement on which should be preferred among the various integrated energy indices (e.g.,  $L_{eq}$ ,  $L_{den}$ /CNEL, DNL, and  $L_{night}$ ), or event indices [e.g.,  $L_{max}$  Sound Exposure Level (SEL)]. Even for sleep disturbance resulting from transportation noise exposure, there is no single generally accepted noise exposure metric or measurement approach. One important review of the sleep disturbance literature (*Effects of Aviation Noise on Awakenings from Sleep* 1997) showed that, overall, SEL was a better predictor of sleep disturbance across the various studies. The community noise guidelines published by the WHO in 2000 proposes the use of either  $L_{max}$  or SEL.

### *Laboratory Versus In-Home Field Studies*

Survey of the literature shows large differences between results obtained in numerous laboratory studies and those issued from epidemiological or experimental studies made in real in-home situations. This difference is shown rather dramatically in the curves published by FICAN and shown in Figure A7. In this figure, the 1992 FICON dashed curve is based on laboratory studies. This research firmly established the significant differences observed between laboratory and in-home field studies, with nocturnal awakenings being much greater in laboratory studies. It would certainly be the case that a certain degree of habituation occurs in people's

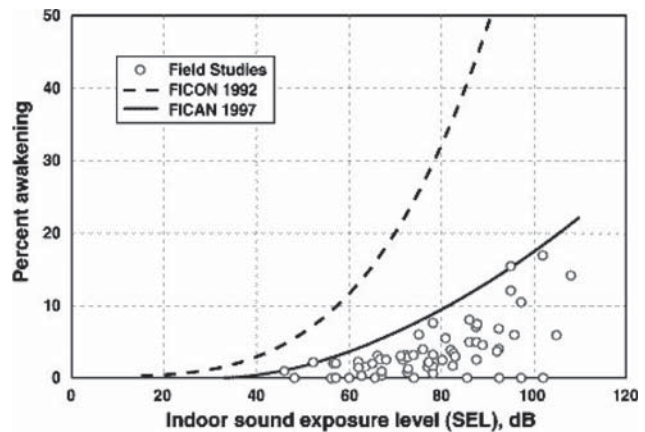


FIGURE A7 FICAN recommended sleep disturbance dose-response relationship (*Effects of Aviation Noise on Awakenings from Sleep* 1997).

own homes. On the other hand, modifications in sleep stage architecture (i.e., number of sleep stage changes) appear to habituate less with time, although purely autonomic (involuntary) responses do not habituate at all over extended periods of time.

### *Different Sleep Disturbance Measurement Approaches*

A variety of different research methodologies have historically been used in sleep disturbance research. For example, sleep stage change analyses were sometimes made every 10, 20, 30, or 60 s in various published studies. The results of these studies—and especially those about the number of awakenings, sleep stage changes, and sleep architecture—should therefore be expected to be quite different from each other, as indeed they are. Some of the most-cited field studies present limited sleep disturbance indices with the use of a controversial choice of measurement methods and sleep disturbance indicators. This is particularly the case for studies using either behavioral awakening, as indicated by pushing a button when awakened (Fidell et al. 1995) and/or body motility (i.e., body movement as measured by an actimeter) as indicators of nocturnal awakening (Ollerhead et al. 1992; Horne et al. 1994). Pushing a button when being awakened during the night is only a rough conservative technique to evaluate sleep disturbance, although it is an obvious indicator of awakening and should be easily understood by the public. However, changes in sleep architecture, including sleep stage changes and short-lasting awakenings as determined by electroencephalographic (EEG) recordings are more subtle and would often be totally missed by both the button-press and the actimetry research techniques. In addition, body movements during sleep are quite normal physiological events; only a small amount of them result in behavioral awakenings. Most night-time body movements do not result in awakening. Therefore, measuring bodily movement by actimetric

techniques during sleep is considered by some to be a relatively poor way of predicting awakenings (Basner et al. 2006).

Complicating factors in current sleep research include the many cases of sleep disturbance in the vicinity of major airports. Given this, aircraft noise is not the most frequent cause of awakening (Horne 1994).

Figure A8 shows the cause of awakening (6,457 total awakenings) for study participants in the vicinity of four U.K. airports.

*How to Assess Sleep Disturbance*

The effects of noise on sleep can be measured immediately or be evaluated afterward, at the end of the night or during the following day. Thus, immediate effects are mainly measured by objective data recorded during sleep, which show how the sleeper is reacting to noise. Afterward, effects are measured at the end of the night by subjective evaluations or by some

objective biochemical data (such as levels of stress hormones) or by performance levels during the following day. The following list includes some of the various objective physiological, biochemical, and behavioral measures used to assess the immediate effects of night-time noise:

- EEG arousal responses,
- Sleep stage changes,
- Nocturnal awakenings,
- Total waking time, and
- Autonomic responses.

*After Effect Measures*

Other measures made after night-time noise exposure include daytime performance and cognitive function deterioration analyses. In addition, the excretion of stress hormones in the morning urine flow can be measured to evaluate the impact of noise exposure at night. However, these types of measurements are quite difficult to perform in field situations and only a few studies have included them in the recent years.

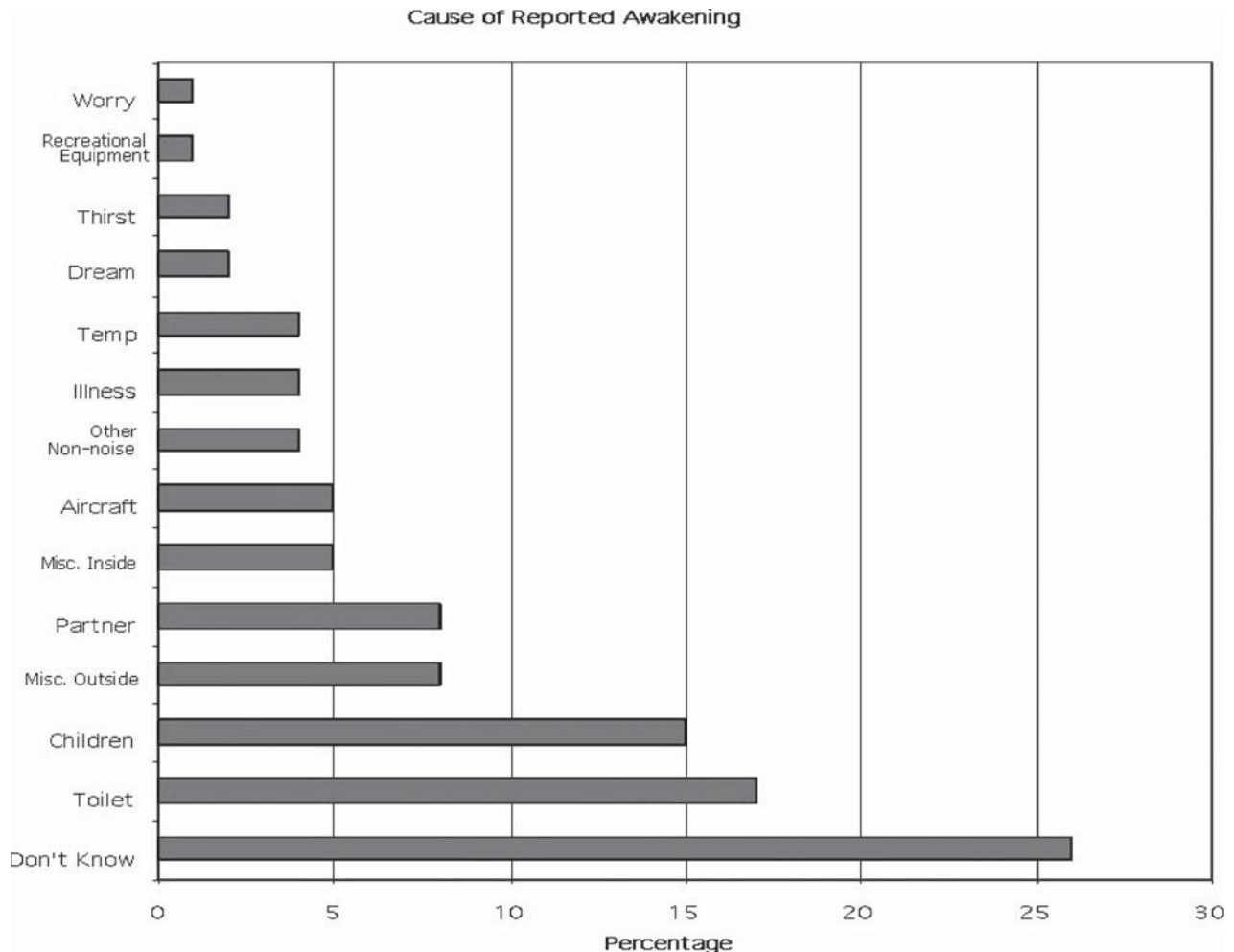


FIGURE A8 Causes and prevalence of all awakenings reported in morning sleep logs for all nights, by gender and age (Horne 1993).

### Subjective Evaluation of Sleep Disturbance

Subjective evaluation of sleep quality using a morning-after questionnaire is an easier and less costly way of collecting field data, whereas recordings of objective sleep disturbance data can be too costly and difficult to use with large samples of the population or when research funding is scarce. Sleep disturbance can be assessed from complaints about bad sleep quality and nocturnal awakenings, which are often accompanied by impaired quality of the subsequent daytime period with increased tiredness, daytime sleepiness, and the need for compensatory resting periods. However, subjective complaints are quite different than objective (instrumental) measures. There are many factors that influence a person's subjective evaluation of his or her own sleep quality. It has been very difficult for researchers to find a clear relationship between subjective complaints and actual noise exposure levels. In general, subjective self-reports of awakenings do not correlate well with more objective measures of sleep disturbance (Finegold et al. 2006).

### Current Exposure-Response Relationships for Sleep Disturbance

#### Europe

The European Union contracted with the Netherlands Organisation for Applied Scientific Research (TNO) to derive exposure-response relationships between  $L_{\text{night}}$  and sleep disturbance for transportation noise (Passchier-Vermeer 2003). TNO recognized that outdoor night-time noise exposure at the most exposed facade of a dwelling ( $L_{\text{night}}$ ) is not the only acoustical factor that influences sleep disturbance. Therefore, attention is being given to the role of other factors, notably the actual noise exposure at the facade of the bedroom, and the difference between outdoor and indoor noise levels (sound insulation) of bedrooms. There is also concern about whether using only a metric that describes the whole night exposure, such as  $L_{\text{night}}$ , is sufficient or whether an individual event metric such as  $L_{\text{max}}$  or SEL is also needed (Michaud et al. 2007).

In the TNO analysis, relationships were developed between noise-induced increase in motility or noise-induced increase in onset of motility in the 15-s interval following the maximum noise level of an overflight, using indoor exposure levels ( $L_{\text{max}}$  or SEL). Although the TNO reports contain several versions of the derived exposure-response relationships, for simplicity only one is presented here. Figure A9 shows a plot of the probability of (aircraft) noise-induced motility in the 15-s interval at which indoor maximum noise level occurs as a function of  $L_{\text{max}}$  for various levels of long-term aircraft noise during sleep periods ( $L_{\text{night}}$ ). Other determinants of the relationships between instantaneous motility and  $L_{\text{max}}$  or SEL are the point of time in the night and time since sleep onset; for example, after 7 h of sleep, noise-induced motility is about 1.3 larger than in the first hour of sleep. Age has only

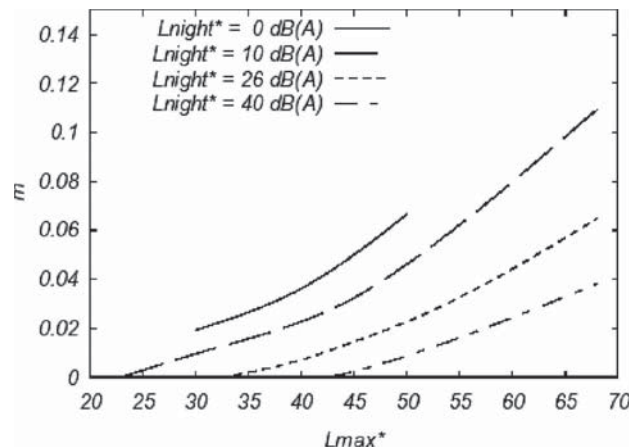


FIGURE A9 Probability of (aircraft) noise-induced motility ( $m$ ) in the 15-s interval at which indoor maximum noise level occurs as a function of  $L_{\text{max}}$ , for various levels of long-term aircraft noise during sleep period ( $L_{\text{night}}$ ) (Passchier-Vermeer et al. 2002).

a slight effect on noise-induced motility, with younger and older people showing a lower motility response than persons in the age range of 40 to 50 years. Discussion will continue for some time concerning the use of single-event versus whole-night exposure indicators and whether the time of night also needs to be considered (Finegold et al. 2006).

In the TNO analysis “no relationship could be assessed between  $L_{\text{night}}$  and *self-reported sleep disturbance* on the basis of the analysis of aircraft noise surveys” [Emphasis added] (Passchier-Vermeer 2003). Therefore, future use of self-reports of movement, awakenings, or other effects needs serious reconsideration because of the questionable validity of self-report data for predicting actual responses to noise events.

#### United States

Since 1985, a series of field sleep studies have been conducted in the United Kingdom and the United States to further investigate noise-induced sleep disturbance from transportation noise sources, primarily aircraft noise, in various residential settings. Based on this series of field studies, FICAN published its recommended sleep disturbance dose-response curve as shown in Figure A7. Finegold and Elias (2002) published a dose-response curve based on an analysis of the published sleep studies (see Figure A10). An important difference between the FICAN curve and the Finegold and Elias curve is the approach to fitting a curve with the data. FICAN took the approach that a maximum awakening could be drawn by using the outer boundary of the curve. This was done at a time when the field sleep studies had first shown that the older laboratory sleep studies had overstated sleep disturbance. The latter curve is fitted through the data to represent a best estimate of sleep disturbance.

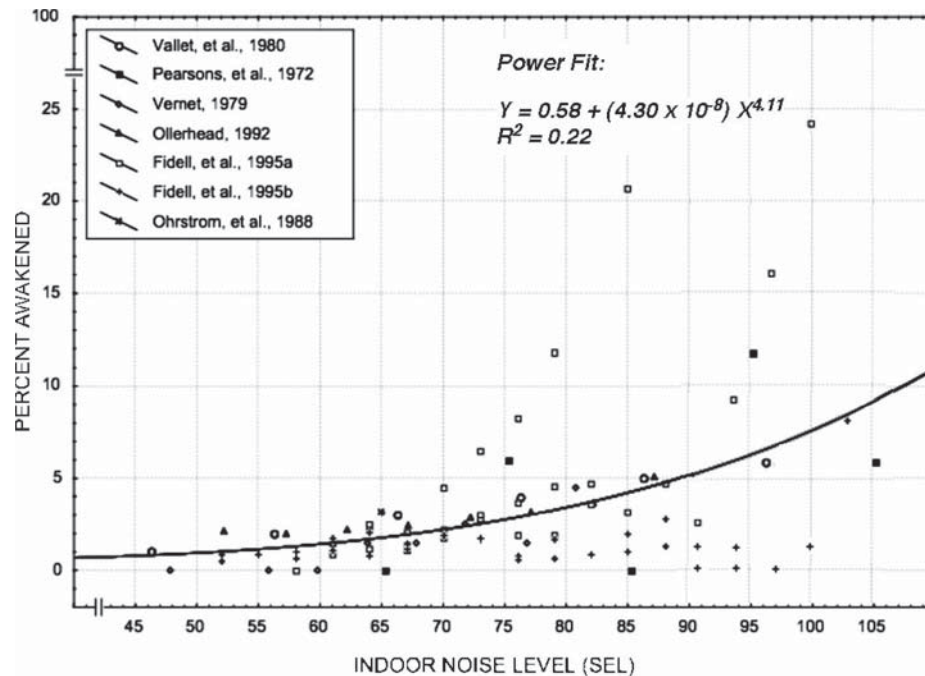


FIGURE A10 Finegold and Elias sleep curve with data points identified by source study (adapted from Finegold and Elias 2002).

## Summary

Although the most common metrics for assessing the impacts of community noise, DNL,  $L_{den}$ , or CNEL, already contain a 10-dB penalty for night-time noises, there are circumstances where a separate analysis of the impacts of night-time transportation noise is warranted. There are, however, different definitions of sleep disturbance and different ways to measure it, different exposure metrics that can be used, and consistent differences in the results of laboratory versus field studies. At the present time, very little is known about how, why, and how often people are awakened during the night, although it is generally acknowledged that the “meaning of the sound” to the individual, such as a child crying, is a strong predictor of awakening. Although the INM can estimate the various metrics referenced in this discussion of sleep disturbance, there is substantial controversy associated with how to apply and interpret these studies. Current research has focused on measuring in-home sleep disturbance using techniques that were not available in 1985. In-home sleep disturbance studies clearly show that it requires more noise to cause awakenings than was thought based on laboratory sleep disturbance studies. Recent studies have cautioned about the over-interpretation of the data (Michaud et al. 2007). This is contrasted with recent efforts to estimate the population that will be awakened by aircraft noise around airports (Anderson and Miller 2005). The technique proposed by Anderson and Miller and a similar approach used in Germany by Basner et al. (2006) are based on statistical assumptions about the probability of awakening (or not awakening) that conflict with some field data (Fidell et al. 1995); specifically, whether sleep disturbance is a product of independent statistical factors for each event, or, as stated by Fidell:

The relationship observed in the present study between noise metrics and behavioral awakening responses suggest instead that noise-induced awakening may be usefully viewed as an event-detection process. Put another way, an awakening can be viewed as the outcome of a de facto decision that a change of sufficient import has occurred in the short-term noise environment to warrant a decision to awaken.

In the context of attempting to estimate the population awakened for a specific airport environment or the difference in population awakened for a given change in an airport environment, the sleep disturbance research may not yet have sufficient specificity to warrant such an estimate.

## Annotated Bibliography—Sleep Disturbance and Aviation Noise

**Anderson, G. and N.P. Miller, “A Pragmatic Re-Analysis of Sleep Disturbance Data,” Presented at the Noise-Con Symposium, Minneapolis, Minn., Oct. 17–19, 2005.**

This paper attempts to extend the sleep dose-response relationship published by FICAN into a methodology for estimating the number of awakenings per night in a population using grid data from the INM, before dose-response relationships for behavioral awakening were first generalized to account for multiple aircraft during the night. Later, they were further generalized to account for person-to-person variation. Both of these generalizations were made on original data from one of the field studies summarized by FICAN. Key to the proposed methodology is the assumption that aircraft flyovers are independent events, “that successive chances of awakening during the night are mutually independent.” This is an



extremely critical assumption for the methodology to work. The authors then state that, "It is possible that this is not strictly true." Given the critical nature of this assumption, the question is why the validity of this assumption was not tested using the field data that are available. The authors give the following example, "with multiple SELs of 90 dBA, the chance of sleeping through the first aircraft is 95%. Therefore, the chance of sleeping through both the first and second is .95 multiplied by .95 (95% of 95%), which equals 90%." The third flyover results in a chance of sleeping through all three aircraft of 86% and so on. The authors do not consider that sleep disturbance may be a threshold critical event and that if a person sleeps through one 90 SEL event he or she may sleep through all 90 SEL events. This may occur owing to habituation to the noise. The authors further attempt to address the issue that people may be in different sleep states during different portions of the night and that awakening may be more likely in some of these sleep states than in others. The authors go on to assume that, "the mathematics in this section assumes that any such departures from independence will average out of the night." Again, this is a critical assumption that is not tested against the field sleep disturbance data. The methodology proposed is highly sensitive to the number of noise events, meaning the more events the larger the population that will be awakened. Large numbers of relatively quiet events that the FICAN curve shows have a low probability of awakening will still generate a large estimate of awakened population. Testing this methodology at low SEL values is particularly important. The effect of habituation, in and of itself, raises questions about the assumption of each aircraft being an independent event. This methodology should be further tested before adoption as a method of estimating the population awakened by night-time noise.

**Basner, M., A. Samel, and U. Isermann, "Aircraft Noise Effects on Sleep: Application of the Results of a Large Polysomnographic Field Study," *The Journal of the Acoustical Society of America*, Vol. 119, No. 5, May 2006, pp. 2772–2784.**

The Institute of Aerospace Medicine at the German Aerospace Center (DLR) investigated the influence of nocturnal aircraft noise on sleep in polysomnographic (includes brain wave, eye movements, and muscle tension) laboratory and field studies between 1999 and 2004. The results of the field studies were used by the Regional Council of Leipzig (Germany) for the establishment of a noise protection plan in the official approval process for the expansion of Leipzig/Halle airport. Methods and results of the DLR field study are described in detail. Special attention is given to the dose-response relationship between the maximum sound pressure level of an aircraft noise event and the probability to wake up, which was used to establish noise protection zones directly related to the effects of noise on sleep. The noise protection plan for Leipzig/Halle airport is presented and substantiated: (1) on average, there should be less than one additional awakening induced by aircraft noise, (2) awakenings recalled in the

morning should be avoided as much as possible, and (3) aircraft noise should interfere as little as possible with the process of falling asleep again. Issues concerned with the representation of the study sample are discussed. The dose-response curve presented in this paper is very similar to that published by FICON (Federal Interagency Committee on Noise 1992). The estimate of awakenings in the population assumes independence of events and sums up the probability of awakening. The authors conclude that the number of events above threshold is not adequate, nor is night-time equivalent noise level adequate, but that a combination of each is best. The number of events above threshold limit may result in a small number (less than the limit) that is well above the threshold and induce a high percentage of awakenings. A night  $L_{eq}$  limit includes an implicit 3 dB increase for a doubling of events and underestimates the change in number of awakenings. Using criteria containing both metrics, the downsides of each are eliminated and the goal is achieved.

**Brink, M., K. Wirth, and Ch. Schierz, "A Long-Term Field Experiment on Aircraft Noise and Sleep Quality at the Beginning and End of the Night," Presented at the Inter-Noise Symposium, Prague, Czech Republic, Dec. 22–25, 2004.**

The handling of takeoffs and landings during the night is restricted in some form at most airports in Switzerland. Therefore, at Swiss airports, evenings and mornings were investigated for sleep disturbances by aircraft noise. This field study focuses on the sleep quality impact of aircraft noise at sleep onset in the evening and before wakeup in the morning. Aircraft noise is administered using prerecorded noise events and played back in the subjects' bedrooms. Experiments run for 30 consecutive nights for each subject. Sixty-four subjects are contributing to a total of 1,920 nights, each experiencing timely distribution of noise (evening versus morning), maximum sound pressure level ( $L_{max}$  of 50 versus 60 dBA), and number of noise events (8 versus 16). Either at the beginning or toward the end of the night, within a 90-min period, aircraft noise events are played back from a loudspeaker in the bedroom. The nightly sequence of factor combinations is balanced over all subjects and each subject is administered the same total amount of noise. Physiological as well as self-reported psychological reaction patterns are measured as dependent variables. A non-intrusive recording system for sleep physiology (e.g., actimetry, cardiac, and respiratory parameters) has been developed. The measuring principle is based on the vibrations cause by the cardiac and respiratory system that propagate through the body and are coupled to the mattress and the bed. These signals are recorded using pressure sensors installed below the bed posts. The study was not complete at the time of the paper's publication, but the authors had noted that the "preliminary results show that for most subjects, noise in the evening was equally annoying to noise in the morning. And surprisingly, subjects so far judged aircraft noise (10 mentions) to be less annoying than street traffic noise (17 mentions) of the same sound pressure level."

***Effects of Aviation Noise on Awakenings from Sleep, Federal Interagency Committee on Aviation Noise, June 1997, 6 pp.***

In 1992, the Federal Interagency Committee on Noise (FICON) recommended an interim dose-response curve to predict the percentage of the exposed population expected to be awakened as a function of the exposure to single-event noise levels expressed in terms of SEL. Since the adoption of FICON's interim curve in 1992, substantial field research in the area of sleep disturbance has been completed. The data from these studies show a consistent pattern, with a considerably smaller percentage of the exposed population expected to be behaviorally awakened than had been shown with laboratory studies. As a result of this observation, FICON published a recommended new dose-response curve for predicting awakening, based on the more recent field data. FICON considered eight field studies in adopting the new dose-response curve. Interestingly, the FICON curve does not represent a best fit of the study data, but is constructed to represent the outer boundary of the data. "The committee takes the conservative position that, because the adopted curve represents the upper limit of the data presented, it should be interpreted as predicting the maximum percent of the exposed population expected to be behaviorally awakened, or the maximum percent awakened."

***Fidell, S., K. Pearsons, B. Tabachnick, R. Howe, L. Silvati, and D.S. Barber, "Field Study of Noise-Induced Sleep Disturbance," The Journal of the Acoustical Society of America, Vol. 98, No. 2, Aug. 1995, pp. 1025–1033.***

Behaviorally confirmed awakenings were recorded during night-time hours for periods of approximately one month in 45 homes of 82 test participants. Measurements of awakening and of both indoor and outdoor noise exposure were made for a total of 632 subject nights near a military airfield, 783 subject nights near a civil airport, and 472 subject nights in neighborhoods with community noise exposure of non-aircraft origin. Sound exposure levels of individual noise intrusions were much more closely associated with awakenings than long-term noise exposure levels. The slope of the relationship between awakening and sound exposure level was rather shallow, however. The findings do not resemble those of laboratory studies of noise-induced sleep interference, but they agree with the results of other field studies. With respect to using long-term average noise levels, the report concludes, "The failure of analyses based on 'entire night' noise measurements (that is, total noise exposure from retiring to last awakening) to account for appreciable variance in the awakening data indicates that cumulative noise exposure metrics such as DNL are ill-suited to prediction of noise-induced sleep disturbance." Importantly, this study also concludes that, cumulative

... the relationship observed in the present study between noise metrics and behavioral awakening responses suggest instead that noise-induced awakening may be usefully viewed as an

event-detection process. Put another way, an awakening can be viewed as the outcome of a de facto decision that a change of sufficient import has occurred in the short-term noise environment to warrant a decision to awaken.

This is a very important observation and leads to suspicion of any assumption about the independence of noise events made in the pursuit of estimating total awakenings.

***Fidell, S., K. Pearsons, B.G. Tabachnick, and R. Howe, "Effects on Sleep Disturbance of Changes in Aircraft Noise near Three Airports," The Journal of the Acoustical Society of America, Vol. 107, No. 5, May 2000, pp. 2535–2547.***

Field measurements were conducted on potential sleep disturbance associated with changes in night-time aircraft noise exposure near three airports. One study was conducted near Stapleton International Airport (DEN) and Denver International Airport (DIA) in anticipation of the closure of the former and the opening of the latter. Sleep behavior was monitored in 57 homes located near runway ends at the two airports. A second study was conducted in the vicinity of DeKalb–Peachtree Airport (PDK), a large general aviation airport that expected increased night-time flight operations resulting from the Olympic Games in July and August of 1996. Similar methods of measuring night-time noise levels and sleep disturbance in the two studies were maintained over the course of 2,717 and 686 subject-nights of observations, respectively. Interestingly, the study found no major differences in noise-induced sleep disturbance when observed as a function of changes in night-time aircraft noise exposure. "The present findings may appear counterintuitive, in that they suggest that the sleep of residents of neighborhoods near airports is not highly sensitive to night-time disturbance by aircraft noise. Instead, the results indicate that relatively few night-time noise intrusions disturb sleep, and that residential populations near airports appear well-adapted to night-time noise intrusions." This study and its conclusions are significant and raise good questions about the assumption used in other studies of each flyover being an independent event when considering dose-response curves for sleep awakening.

***Finegold, L.S. and B. Elias, "A Predictive Model of Noise Induced Awakenings from Transportation Noise Sources," Presented at the Inter-Noise Symposium, Dearborn, Mich., Aug. 19–21, 2002.***

A primary consideration in the assessment of noise impacts from transportation noise sources is the degree to which the noise interferes with normal sleep behavior. EEG recordings; motility measurements; behavioral awakenings; or self-report of sleep duration, awakenings, and subjective sleep quality are used to measure sleep behavior. For the purposes of assessing the impact of environmental noise from transportation sources on sleep in field settings, behavioral awakenings

are recommended as the metric of choice because of researchers' capabilities to measure and record behavioral awakenings relatively unobtrusively and the lack of ambiguity in interpreting measures of such awakenings. Over the past 25 years, several field studies have been performed assessing the relationship between single-event noise levels attributable to transportation noise sources and behavioral awakenings. The findings of these studies have been compiled and analyzed using meta-analytic techniques to derive a predictive model of noise-induced awakenings from transportation noise sources. The predictive model is based on a curvilinear power function fit through the data points defining the percentage of study participants awakened at given indoor SELs. This curvilinear power function fit provides a better description of the relationship between indoor noise levels and awakenings than the linear regression fit through the data points advocated by others. The curvilinear power function fit is also a different approach used by FICAN, which chose to recommend a curve that represented the outer boundary of the data. In this paper, Finegold and Elias recommend the curve that they represent as the best fit of a curve through the field data.

**Finegold, L.S., A. Muzet, B.F. Berry, and M.S. Finegold, *Effects of Aircraft Noise on Communities: Sleep Disturbance and Hearing Loss, Japan Defense Forces Environmental Improvements Association (DFEIA), Tokyo, Japan, 2003, 47 pp.***

A.N. Kankyo-Bunka Labs., Inc., in Tokyo was awarded a contract by the Japan Defense Facilities Environment Improvement Association in April 2003 to provide information on the effects of aircraft overflight noise on communities, based mainly on research conducted in the United States and Europe. The two major sections of this report address sleep disturbance and hearing loss resulting from aircraft noise exposure. The report includes a comprehensive review of noise-induced sleep disturbance studies. The authors present a description of the various metrics used to measure sleep disturbance as well as the current state of policy on various metrics. Based on the research available at the time of the study, a recommended dose-response curve for sleep disturbance is provided based on the indoor SEL. It is a fit through the data from seven published studies and in that way differs significantly from the FICAN curve that represents the outer boundary of study data points.

**Griefahn, B., A. Marks, and S. Robens, "Noise Emitted from Road, Rail, and Air Traffic and Their Effects on Sleep," *Journal of Sound and Vibration*, Vol. 296, Dec. 2005, pp. 129–140.**

This study compared the effects of road, rail, and aircraft noise and tested the applicability of the equivalent noise level for the evaluation of sleep disturbances. Sixteen women and 16 men (ages 19 to 28) slept during three consecutive weeks in the laboratory. Eight persons slept in quiet throughout.

Twenty-four persons were exposed to road, rail, or aircraft noise. Each week consisted of a random sequence of a quiet night (32 dBA) and three nights with equivalent noise levels of 39, 44, and 50 dBA, and maximum levels of 50 to 62 dBA, 56 to 68 dBA, and 62 to 74 dBA, respectively. The polysomnogram was recorded during all nights, sleep quality was assessed, and performance tests were completed in the morning. Subjectively evaluated sleep quality decreased and reaction time increased gradually with noise levels, whereas most physiological variables revealed the same reactions with considerably stronger reactions to the night noise load. Aircraft noise, rail, and road traffic noise cause similar after-effects; however, physiological sleep parameters were most severely affected by rail noise. The authors concluded that the equivalent noise level appeared to be a suitable predictor for subjectively evaluated sleep quality, but not for physiological sleep disturbances.

**Health Council of the Netherlands, *The Influence of Night-Time Noise on Sleep and Health*, The Hague: Health Council of the Netherlands, 2004, 196 pp.**

The Health Council of the Netherlands completed this comprehensive review of the effect of night-time noise on sleep in response to a request for advice from the government. As with other countries, the Netherlands has regulations designed to limit public exposure to environmental noise, primarily with a view to managing the associated nuisance. Most of the limits related to exposure over a complete 24-h period and therefore do not focus specifically on the period during which most people sleep. However, European Union regulations are presently being prepared that concentrate on night-time noise exposure. The European Union has adopted a night-time noise metric,  $L_{\text{night}}$ , for use in describing night-time noise impacts on sleep.  $L_{\text{night}}$  is the  $L_{\text{eq}}$  from hours of 11 p.m. to 7 a.m. averaged over a full year. Against this background, the State Secretary of Housing, Spatial Planning, and the Environment wrote to the Health Council on February 3, 2003, asking for its advice regarding the influence of night-time noise on sleep, health, and well-being. This report, compiled by the Council's Noise, Sleep, and Health Committee, addresses the questions posed by the State Secretary. Among the conclusions contained in the report are that the observation threshold for EEG awakening and motility onset is an SEL of 40 dBA. The threshold for heart-beat acceleration is less than 40 dBA, and the threshold for subject-registered awakening is an SEL of 54 dBA. The threshold for EEG-detected sleep stage is probably lower than an SEL of 40 dBA. The study also concludes that almost no research data are available regarding the acute effects of night-time noise on children. The report repeats an important conclusion found in many of the sleep studies: "The committee believes it is reasonable to assume that, broadly speaking, between 1.5 and two times and ten to twelve times per night, a person is sufficiently conscious to coincidentally hear a noise event that has not actually awoken him or her. This may help to explain the extent of night-time noise-related annoyance."

**Horne, J.A., F.L. Pankhurst, L.A. Reyner, K. Hume, and I.D. Diamond, "A Field Study of Sleep Disturbance: Effects of Aircraft Noise and Other Factors on 5,742 Nights of Actimetrically Monitored Sleep in a Large Subject Sample,"** *Sleep*, Vol. 17, No. 2, 1994, pp. 146–195.

This study documents a landmark in-home field study that demonstrated that dose-response curves based on laboratory data greatly overestimated the actual awakening rates for aircraft noise events. This field study assessed the effects of night-time aircraft noise on actimetrically measured sleep in 400 people (211 women and 189 men; ages 20 to 70; one per household) habitually living at eight sites adjacent to four U.K. airports, each with different levels of night flying. Subjects wore wrist-actimeters for 15 nights and completed morning sleep logs. A sample of 178 nights of sleep using EEGs was recorded synchronously with actigrams. The EEG was used to develop filters for the raw actigrams to estimate sleep onset and compare actigrams with aircraft noise events (ANEs). Actigrams, filtered to detect the onset of discrete movements, were able to detect 88% of all EEG-determined periods of interim wakefulness of >15 s and periods of movement time of >10 s. The main findings were: (1) actimetry and self-reports showed that only a minority of ANEs affected sleep and, for most subjects, that domestic and idiosyncratic factors had much greater effects; (2) despite large between-site variations in ANEs, the difference between sites in overall sleep disturbance was not significant; (3) there was a diminished actimetric response to ANEs in the first hour of sleep and, apparently, also in the last hour of sleep; and (4) men had significantly more discrete movements than women and were more likely to respond to ANEs.

**Michaud, D.S., S. Fidell, K. Pearsons, K.C. Campbell, and S.E. Keith, "Review of Field Studies of Aircraft Noise-Induced Sleep Disturbance,"** *The Journal of the Acoustical Society of America*, Vol. 121, No. 1, Jan. 2007, pp. 32–41.

This article is a comprehensive and critical review of the most recent field studies of aircraft noise-induced sleep disturbance (AN-ISD). The article finds that reliable generalization of findings to population-level effects is complicated by individual differences among subjects, methodological and analytic differences among studies, and predictive relationships that account for only a small fraction (20%) of the variance in the relationship between noise exposure and sleep disturbance. It is nonetheless apparent in the studied circumstances of residential exposure that sleep disturbance effects of night-time aircraft noise intrusions are not dramatic on a per-event basis, and that linkages between outdoor aircraft noise exposure and sleep disturbance are tenuous. It is also apparent that AN-ISD occurs more often during later than earlier parts of the night; that indoor sound levels are more closely associated with sleep disturbance than outdoor measures; and that spontaneous awakenings, or awakenings

attributable to non-aircraft indoor noises, occur more often than awakenings attributed to aircraft noise. "As such, single event metrics do not by themselves, provide robust guidance for regulatory purposes." Predictions of sleep disturbance owing to aircraft noise should not be based on oversimplifications of the findings of the reviewed studies, and these reports should be treated with caution in developing regulatory policies for aircraft noise.

**Ollerhead, J.B., C.J. Jones, R.E. Cadoux, A. Woodley, B.J. Atkinson, and J.A. Horne, Report of a Field Study of Aircraft Noise and Sleep Disturbance, U.K. Department of Transport, London, 123 pp.**

This report prepared for the U.K. Civil Aviation Authority was a landmark study that clearly identified a difference between laboratory and in-home studies of sleep disturbance. The in-home data showed that it takes considerably more noise to awaken people than had data collected in laboratory studies. The in-home data were collected from 400 subjects in 8 study areas located near London's four major airports. Actimetry (movement) measurements were the primary tool, although a portion of the sample was monitored with EEG in addition to actimetry: "the agreement between actimetrically determined arousals and EEG-measured arousals was very good." The report concluded that, "All subjective reactions to noise vary greatly from person to person and from time to time and sleep disturbance is no exception; deviations from the average can be very large. Even so, this study indicates that, once asleep, very few people living near airports are at risk of any substantial sleep disturbance resulting from aircraft noise, even at the highest event noise levels," And further, "At outdoor event levels below 90 dBA SEL (80 dBA  $L_{max}$ ), average sleep disturbance rates are unlikely to be affected by aircraft noise."

**Passchier-Vermeer, W., Night-Time Noise Events and Awakening, TNO Inro Institute for Traffic and Transport, Logistics and Spatial Development, Delft, the Netherlands, July 2003, 59 pp.**

This report presents an analysis to obtain relationships between probability of behavioral awakening resulting from noise events and an indoor noise metric (SEL). The database used in the analysis consists of data derived from eight field studies. In the report a relationship for commercial aircraft noise events has been assessed based on 175,000 such events. No general applicable relationship could be established for military aircraft, railway, and other ambient noise events. The author presents dose-response curves based on SEL data as well as  $L_{night}$ , the night-time equivalent noise level. The  $L_{night}$  presentation is interesting because the author uses it to estimate the total awakenings in one year for an individual. The authors consider background awakenings (awakenings that occurred in absence of an aircraft noise events) in the study and report the number of additional awakenings per year resulting from aircraft noise events.

## CHAPTER FIVE: SPEECH INTERFERENCE AND AVIATION NOISE

SI is a principal factor in human-annoyance response. Activities where SI is critical include classroom instruction; personal communication; and television, radio, and other leisure listening endeavors. SI can also be a critical factor in situations requiring a high degree of intelligibility essential to safety. In addition, annoyance response is often triggered by SI. Factors influencing SI include location (indoor or outdoor), transmission loss (acoustical isolation) of structure, vocal effort, vocal frequency content (male or female), listening skill, hearing acuity, noise frequency, and noise temporal characteristics.

Intrusive background noises can mask speech, degrading intelligibility and disrupting communication. Frequent SI typically triggers annoyance and, in a small percentage of cases, complaints. Most of the research in SI involves steady-state or constant noise masking well-defined speech signals. The research on SI has not been expanded a great deal since 1985 and the greater body of this work was published well before 1985.

In 2000, the WHO published noise guidelines that included a discussion of SI. The WHO guidelines do not discuss aircraft noise and SI expressly, but do address the problems associated with SI, including interference with speech comprehension that result in a large number of personal disabilities, handicaps, and behavioral effects. This includes problems with concentration, fatigue, uncertainty, self-confidence, irritation, misunderstandings, decreased working capacity, problems in human relations, and a number of stress reactions. The WHO guidelines conclude,

It is usually possible to express the relationship between noise levels and speech intelligibility in a single diagram, based on the following assumptions and empirical observations, and for speaker-to-listener distance of about 1 m: a. Speech in relaxed conversation is 100% intelligible in background noise levels of about 35 dBA, and can be understood fairly well in background levels of 45 dBA. b. Speech with more vocal effort can be understood when the background sound pressure level is about 65 dBA.

Note that the WHO statement applies to a steady-state noise and does not address intermittent noise such as an aircraft flyover.

SI is most rigorously defined using metrics that analyze signal-to-noise relationships defined in specific frequency bands. The Articulation Index (AI) and a related methodology, the Speech Interference Level (SIL), have been used since the 1950s for this purpose. In addition, the A-weighted sound level has proven to be a good predictor of SI and has often been employed in research findings. To that end, the American National Standards Institute (ANSI S12.65-2006) has published a standard in terms of the A-weighted decibel for rating noise with respect to speech. This standard defines

a simple numerical method for rating the expected speech-interfering aspects of noise using acoustical measurements of the noise. The intelligibility of speech in noise is dependent on many factors, including:

1. *Acoustic factors*, such as the level of the speech signal (at the listener's ear), the level of the interfering noise, the frequency spectrum of the speech signal, the frequency spectrum of the noise, the temporal pattern of the speech and noise, differences in the spatial relationship of the speech and noise sources, and reverberation effects.
2. *Non-acoustic factors*, such as size of message set, a priori probability of occurrence of each message or unit of speech, the listener's motivation and familiarity with the speech material, the role of visual cues, and the talker's speech habits.
3. *Random or quasi-random factors*, such as individual differences between talkers and listeners, day-to-day variations in a listener's ability or a talker's effectiveness, effects of randomization in the choice of test material, and random sampling errors.

The deleterious effect of noise on SI may be greater for elderly listeners or listeners with sensory neural hearing impairments. The standard includes a commonly published plot of talker-to-listener distances for normal, raised, very loud, and shout voice levels (see Figure A11). The region below each curve shows the talker-to-listener and noise-level combination for which just-reliable face-to-face communication is possible. The parameter on each curve indicates the relative voice level. The data show that SI for face-to-face conversation at a distance of 3 ft for normal voice is prevalent at 60 dBA. Although references indicate that this is for a steady noise, the standard does not. Intermittent noise, such as an aircraft flyover event, is not addressed in the standard.

In 1992, FICON published a federal review of noise issues that concluded,

From a technical perspective, whenever intrusive noise exceeds approximately 60 dB indoors, there will be interference with speech communication . . . Increasing the indoor level of

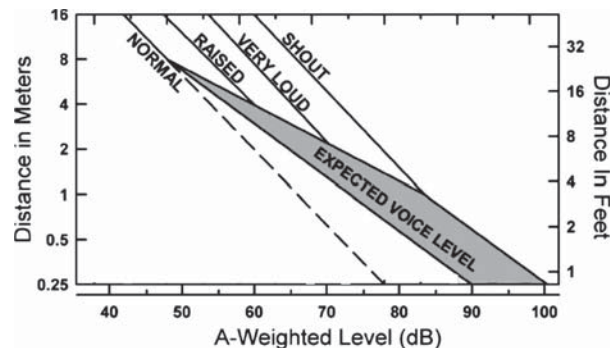


FIGURE A11 Talker-to-listener distances for just-reliable communication (adapted from ANSI S12.65-2006).

intrusive noise to 80 dB reduces intelligibility to near zero, even if a loud voice is used. . . . some degree of indoor speech interference would be expected whenever exterior noise levels exceed 75 dB to 85 dB (windows open and closed, respectively) (Federal Interagency Committee on Noise 1992).

FICON goes on to explain that where speech communication is an issue, certain specific analyses, such as the TA metric, or SEL, and/or the maximum A-weighted noise level ( $L_{\max}$ ), may be useful. These metrics may be estimated using the INM.

The EPA *Levels* document (*Information on Levels of Environmental Noise . . . 1974*), although not published after 1985, is one of the few documents that address the effect of intermittent noise on SI. The EPA questioned whether the results of SI relative to steady-state noise would apply to sounds that have fluctuating levels. For example, when intermittent noise intrusions, such as those from aircraft flyovers are superimposed on a steady-noise background, the equivalent sound level is greater than the level of the background alone. Appendix D in the EPA document addresses this issue in detail. The results demonstrate that for 95% sentence intelligibility, normal vocal effort, and 2-m separation between talker and listener outdoors the maximum  $L_{\text{eq}}$  value associated with continuous noise is less than the maximum value for an environmental noise whose magnitude varies with time, such as an aircraft flyover. The EPA states, “It is therefore concluded that almost all time-varying environmental noises with the same  $L_{\text{eq}}$  would lead, averaged over long time periods, to better intelligibility than the intelligibility for the same  $L_{\text{eq}}$  values of continuous noise” (*Information on Levels of Environmental Noise . . . 1974*). Therefore, when interpreting the amount of SI using the ANSI method or the guidelines of FICON or WHO, these methods will overestimate that amount of SI.

### Summary

SI is an important component in annoyance response. SI has been well researched over the years, but there have been few new research papers dealing specifically with aircraft noise published on this topic since 1985. Most SI studies and guidelines deal with steady-state noises; however, because aircraft noise is an intermittent noise, SI literature is lacking (the 1974 EPA *Levels* document briefly addresses the issue of intermittent noise). There is a need for more research on the effect of intermittent noise, such as an aircraft flyover, on speech.

### Annotated Bibliography—Speech Interference and Aviation Noise

**Acoustical Society of America, “For Rating Noise with Respect to Speech Interference,” Acoustical National Standard, Accredited Standards Committee S12, New York, N.Y., Feb. 2006, 20 pp.**

This standard defines a simple numerical method for rating the expected speech-interfering aspects of noise using acoustical

measurements. The intelligibility of speech in noise is dependent on many factors. These include:

1. *Acoustic factors*, such as the level of the speech signal (at the listener’s ear), the level of the interfering noise, the frequency spectrum of the speech signal, the frequency spectrum of the noise, the temporal pattern of the speech and noise, differences in the spatial relationship of the speech and noise sources, and re-verboration effects.
2. *Nonacoustic factors*, such as size of message set, a priori probability of occurrence of each message or unit of speech, the listener’s motivation and familiarity with the speech material, the role of visual cues, and the talker’s speech habits.
3. *Random or quasi-random factors*, such as individual differences between talkers and listeners, day-to-day variations in a listener’s ability or a talker’s effectiveness, effects of randomization in the choice of test material, and random sampling errors.

It should be noted that the deleterious effect of noise on speech intelligibility may be greater for elderly listeners or listeners with sensory neural hearing impairments. The standard includes a familiar plot of talker-to-listener distances for normal, raised, very loud, and shout voice levels. The data show that SI for face-to-face conversation at a distance of 3 ft for normal voice is prevalent at 60 dBA. The standard does not indicate, but references do indicate that this is for a steady noise. Intermittent noise such as an aircraft flyover event is not addressed in the standard.

**Federal Interagency Committee on Noise, “Federal Agency Review of Selected Airport Noise Analysis Issues,” *Noise Analysis Report*, Vol. 1, Aug. 1992, 119 pp.**

FICON was formed in 1990 to review federal policies that govern the assessment of airport noise impacts. Although the FICON report has policy and technical sections, this review is limited to the technical section. The review focused on a number of issues including SI. With respect to SI, the review includes a version of the talker-to-distance SI curve described in the previous reference (ANSI). The review concludes that “No quantitative relationship has been established between SI and learning in school classrooms, and therefore no additional criteria have been developed for quantifying SI effects on learning by students. However, it is clear that if speech communication is degraded in a classroom, the learning process can be assumed to be degraded.” With respect to SI in general, FICON states that

From a technical perspective, whenever intrusive noise exceeds approximately 60 dB indoors, there will be interference with speech communication . . . Increasing the indoor level of intrusive noise to 80 dB reduces intelligibility to near zero, even if a loud voice is used. . . . some degree of indoor speech interference would be expected whenever exterior noise levels exceed 75 dB to 85 dB (windows open and closed, respectively).

For purposes of assessing SI, FICON suggests

If speech interference is a particularly critical issue requiring detailed analysis, the supplemental metric, Time Above (TA) (the total time that the noise level exceeds a “threshold” level during a specified interval), provides a useful “single number” indicator of the potential for speech interference. . . . For specific locations at which speech interference is a critical concern, tabulation of the individual aircraft operations affecting the location, including the number of each type of operation by aircraft type, the noise levels (SEL and possibly  $L_{max}$ ) associated with each type of event, and the timing of the events may provide the most useful information.

FICON further points out that these analyses are within the capabilities of INM.

***Guidelines for Community Noise, World Health Organization, Presented at the WHO–Expert Task Force Meeting, London, U.K., 2000.***

The WHO guidelines cover a broad range of noise impacts including SI. This is a very comprehensive document that represents the state of the research as of April 1999. The WHO guidelines do not discuss aircraft noise, or for that matter intermittent noise, specifically. The discussion provided relates primarily to a steady-state noise. In that regard, WHO states,

Noise interference with speech comprehension results in a large number of personal disabilities, handicaps, and behavioral changes. Problems with concentration, fatigue, uncertainty, and lack of self-confidence, irritation, misunderstandings, decreased working capacity, problems in human relations, and a number of stress reactions have all been identified. Particularly vulnerable to these types of effects are the hearing impaired, the elderly, children in the process of language and reading acquisition, and individuals who are not familiar with the spoken language).

Additionally, “For complete sentence intelligibility in listeners with normal hearing, the signal-to-noise ratio (i.e., the difference between the speech level and the sound pressure level of the interfering noise) should be 15–18 dBA.” The WHO guidelines go on to suggest, “For speech to be intelligible when listening to complicated messages (at school, listening to foreign languages, telephone conversation), it is recommended that the signal-to-noise ratio should be at least 15 dBA. Thus, with a speech level of 50 dBA (at 1 m distance this level corresponds to a casual speech level of both women and men), the sound pressure level of interfering noise should not exceed 35 dBA.” The WHO guidelines conclude,

It is usually possible to express the relationship between noise levels and speech intelligibility in a single diagram, based on the following assumptions and empirical observations, and for speaker-to-listener distance of about 1 m: a. Speech in relaxed conversation is 100% intelligible in background noise levels of about 35 dBA, and can be understood fairly well in background levels of 45 dBA. b. Speech with more vocal effort can be understood when the background sound pressure level is about 65 dBA.

Intermittent noise such as an aircraft flyover event is not addressed in the guidelines.

**Lee, C.S.Y. and G.G. Fleming, *General Health Effects of Transportation Noise*, U.S. Department of Transportation, Washington, D.C., June 2002, 44 pp.**

The FRA sponsored this report to support a rulemaking process about the use of locomotive horns and the accompanying environmental impact statement. This document reviews select current and past research on the effect of transportation noise on physiological and psychological health for both people and wildlife. With respect to SI, the report notes that “The effects of noise are compounded by other factors also influencing speech intelligibility, including speech pronunciation, distance between speaker and listener, hearing acuity, level of attention, reverberation characteristics of the listening environment, and sound characteristics of the interfering noise.” In addition, the familiar talker-to-listener distance curve for various levels of speech is provided. The report does not address the issue of steady-state versus an intermittent noise.

**CHAPTER SIX: EFFECTS OF AVIATION NOISE ON SCHOOLS**

The effect of aviation noise on a children’s learning ability and retention of information in schools is of critical concern worldwide, with several new and potentially conclusive studies completed in the last few years. Most of the new research and related results took place either in Munich, where many studies were done using the old and new Munich airports before and after the closing of one and opening of the other, or in the United States through FICAN. Most types of school-effect studies utilize a binary definition; that is, describing two subject environments of noise exposure, a high-noise setting and low-noise setting, which makes it difficult to define a dose-response curve. However, it is usually clear that noise levels above a certain  $L_{eq}$  affect a child’s learning experiences. Note that in nearly all the studies, the noise metric used does not define a demarcation point for impact; that is, the data presented are not sufficient to define a threshold noise level at which effects on school children are significant.

In 1995, Evans et al. demonstrated that for chronic noise exposure associated with elevated hormone and cardiovascular measures, there were reduced cardiovascular responses to tasks presented under acute noise, reduced test scores in a standardized reading test under quiet conditions, poorer long-term memory, and diminished quality of life on a standardized index. Children within high-noise areas showed evidence of poor persistence on challenging tasks, and reported considerable annoyance with community noise levels, adjusted for individual differences in rating criteria for annoyance judgments. The data, collected around Munich International Airport and in a quiet urban Munich neighborhood, showed the dynamic range of noise exposures of approximately 9 dBA (24-h  $L_{eq}$  of 68 dBA near the airport and 59 dBA not near the airport).

In 1998, Evans et al., again studied children living around the new Munich International Airport and children “outside the noise impact zone.” This study included 217 children. Again, a binary classification of noise and quiet groups was used, which does not lend itself to determining a dose-response relationship. The difference between the noisy and quiet group was only 7 dBA. However, it is interesting to note that data collected before and after the inauguration of a major new airport in noise-impacted and comparison communities show that noise significantly elevates stress among children at ambient noise levels, often somewhere in the range of 55 to 62 dBA  $L_{eq}$ , far below those necessary to produce hearing damage.

Other studies of aviation noise effects on children in the area around the old and new Munich airports were completed by Hygge et al. (2002). Children near the old and new airport locations, as well as children near other sites with no aviation noise who were used as a control group, were closely matched for socioeconomic status. They evaluated a total of 326 children in three data collection waves, pre- and post-switching of the airports. After the switch, long-term memory and reading were impaired in the noise group at the new airport, and improved in the formerly noise-exposed group at the old airport. Short-term memory also improved in the latter group after the airport was closed, whereas speech perception was impaired in the newly noise-exposed group.

Interesting differences in the effects of aviation noise on classroom learning experiences come from Hygge’s 2003 study where 1,358 children aged 12 to 14 years participated in 10 noise experiments in their ordinary classrooms and were tested for recall and recognition of a text exactly one week later. Overall, there was a strong noise effect on recall, and a smaller but significant effect on recognition. From a sound source located in the classroom, the single-source studies, aircraft, and road traffic impaired recall at both noise levels, yet train noise and verbal noise did not affect recognition or recall. Given that road noise and verbal noise were relatively constant sources and the aircraft and train noise were event-type sources, these observed differences are not expected.

FICAN published a position paper in 2000 regarding effects of aircraft noise on classroom learning. It summarized research on its effects and indicated that aircraft noise can interfere with learning in the areas of reading, motivation, language and speech acquisition, and memory. The strongest findings are in the area of reading, where more than 20 studies have shown that children in noise-impact zones are negatively affected by aircraft. Research has confirmed conclusions from studies completed in the 1970s that show a decrement of reading when outdoor noise levels equal or exceed  $L_{eq}$  of 65 dBA.

FICAN (“Findings of the FICAN Pilot Study . . .” 2007) released an initial study involving 35 public schools in Texas

and Illinois situated near three airports. Results of the study indicate that

Student failure rate may be due to impaired learning in the classroom, perhaps caused in part by noise stress. To the extent that noise stress contributes to student failure, then failing students are the ones most likely to benefit from noise reduction. In contrast, top-score students are less likely to benefit. Such a rationale is consistent with the results of this study.

Although the study proclaims that a link exists between the reduction of aircraft noise in classrooms and improvements in the academic performance of students in public schools, it also states that additional research examining more schools for longer periods of time is needed to make more detailed conclusions that could apply broadly. “The airports and schools in this study are not guaranteed to be representative. For that reason, results of this study should not be used nationally without subsequent studies of many additional airports and schools. In addition, this study’s analysis is not yet fully reviewed.”

Regarding indoor classroom acoustical performance criteria, two main works stand out that additionally complement each other. The Acoustical Society of America’s 2002 publication, “Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools,” provides performance criteria, design requirements, and design guidelines for new school classrooms and other learning spaces. These criteria are keyed to the acoustical qualities needed to achieve a high degree of speech intelligibility in learning spaces, and the standard is a very good guideline for best practice in the acoustical design of the classroom. The standard recommends that the noise standard be 5 dBA higher than the steady-state noise standard, resulting in an interior noise level of 40 or 45 dBA (depending on room size), and shall not be exceeded for more than 10% of the noisiest hour. The second publication, Bistafa and Bradley (2000), is a very technical comparison of speech intelligibility metrics in the classroom based on various background noise. Speech intelligibility metrics that take into account sound reflections in the room and the background noise were compared, presuming diffuse sound field. For quiet classrooms, the reverberation time that maximizes speech intelligibility metrics is between 0.1 and 0.3 s; speech intelligibility of 100% is possible with reverberation times up to 0.4 to 0.5 s, making this the recommended range. The study, consistent with the ANSI standard recommendation for steady-state noise, recommends ideal and acceptable background noise level of classrooms of 20 and 25 dB, respectively, below the voice level at 1 m in front of the talker. For example, for a talking voice level of 60 dBA, the maximum background noise level should not exceed 35 to 45 dBA in the classroom. The Bistafa and Bradley report considers only steady-state noise and does not address intermittent noise such as noise from aircraft flyovers.

## Summary

The research on the effects of aviation noise on schools has focused on identifying noise as an important issue in the



classroom. However, there has been little work on establishing a dose-response relationship between aviation noise and classroom effects. This lack of a reliable dose-response relationship between aircraft noise and classroom effects makes the evaluation of aircraft noise on schools and setting policy very difficult. Although it is clear that at high enough noise levels speech communication is virtually impossible, there is no clear threshold for when aircraft noise begins to effect schools. Much of the research has focused on the use of standardized test scores and stress hormone measurement in cross-sectional studies. These studies tend to be weak in describing the noise exposure at the subject schools. One German study of significance (Evans et al. 1995) involved a longitudinal study that has well-described noise exposure and avoids the pitfalls of cross-sectional studies. In that study, noise levels of 68 dBA  $L_{eq}$  had a pronounced effect, whereas at 59 dBA  $L_{eq}$  the effects were small. In other cross-sectional studies effects were identified for outdoor noise exposures as low as 35 dBA  $L_{eq}$ . It is not plausible that a school in a typical neighborhood could have an ambient noise level this low. In one study, where aircraft, road, rail, and speech noises were reproduced in the classroom, it was shown that aircraft noise had a greater effect on learning tasks than did the other noise sources when played at equivalent noise levels. That study suggests that SI alone is not the operative mechanism, but that distraction may play an important role, particularly at lower noise levels. No studies were identified where observations of student activity were compared with aircraft noise levels during aircraft flyovers. There is a clear need for additional research on the effects of aviation noise on schools with classroom studies, including noise measurements and observations of student responses to aircraft activity.

#### **Annotated Bibliography—Effects of Aviation Noise on Schools**

**Acoustical Society of America, “Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools,” American National Standard, June 2002, 51 pp.**

The standard provides acoustical performance criteria, design requirements, and design guidelines for new school classrooms and other learning spaces. The standard may be applied when practicable to the major renovation of existing classrooms. These criteria, requirements, and guidelines are keyed to the acoustical qualities needed to achieve a high degree of speech intelligibility in learning spaces. This standard provides a very good guideline for the acoustical design of the classroom. As such, the document emphasizes room reverberation time; sound isolation between rooms; and noise from heating, ventilating, and air-conditioning systems. The standard devotes a small section on recommendations for interior noise levels from outside sources, but this is clearly not a focus of the standard. With respect to “unsteady background noise from transportation noise sources,” which presumably includes aircraft, rail, and road noise, the standard recommends that the

noise standard be 5 dBA higher than the steady-state noise standard, resulting in an interior standard of 40 or 45 dBA (depending on room size). This standard shall not be exceeded for more than 10% of the noisiest hour (6 min). Unfortunately, this standard devotes just two short paragraphs out of 51 pages to providing guidance on mitigating the effect of outdoor transportation noise levels in classrooms.

**Bistafa, S.R. and J.S. Bradley, “Reverberation Time and Maximum Background Noise Level for Classrooms from a Comparative Study of Speech Intelligibility Metrics,” *The Journal of the Acoustical Society of America*, Vol. 107, No. 2, Feb. 2000, pp. 861–875.**

This article is a very technical comparison of speech intelligibility metrics in the classroom based on various background noises. Speech intelligibility metrics that accounted for sound reflections in the room and background noise were compared, assuming a diffuse sound field. Under this assumption, sound decays exponentially with a decay constant inversely proportional to reverberation time. Analysis was done for three sizes of rectangular classrooms. The sound source was the human voice without amplification, and background noise was taken into account by noise-to-signal ratio. Correlation between the metrics and speech intelligibility were presented and applied to the classrooms under study. Relationships between some speech intelligibility metrics were also established. For each noise-to-signal ratio, the value of each speech intelligibility metric was maximized for a specific reverberation time. For quiet classrooms, the reverberation time that maximized the speech intelligibility metrics was between 0.1 and 0.3 s. Speech intelligibility of 100% was possible with reverberation times up to 0.4 to 0.5 s, which is the recommended range. The study suggests ideal and acceptable background noise levels of classrooms of 20 and 25 dB, respectively, below the voice level at 1 m in front of the talker. For a talking voice level of 60 dBA, this results in maximum background levels of 35 to 45 dBA in the classroom. This is the recommended level for a steady-state noise and is consistent with the ANSI standard recommendation for a steady-state noise. This report does not address an intermittent noise such as aircraft noise or noise from any outdoor transportation noise sources.

**Clark, C., R. Martin, E. van Kempen, T. Alfred, J. Head, and H.W. Davies, “Exposure-Effect Relations Between Aircraft and Road Traffic Noise Exposure at School and Reading Comprehension,” *American Journal of Epidemiology*, Vol. 163, No. 1, Nov. 2005, pp. 27–37.**

This paper reports on the 2001 to 2003 RANCH project (Road Traffic and Aircraft Noise Exposure and Children’s Cognition and Health), the first cross-national epidemiological study known to examine exposure-effect relations between aircraft and road traffic noise exposure and reading comprehension. Participants were 2,010 children aged 9 to 10 years from 89 schools around Amsterdam Schiphol,

Madrid Bajas, and London Heathrow airports. Data from the Netherlands, Spain, and the United Kingdom were pooled and analyzed using multi-level modeling. Aircraft noise exposure at schools was linearly associated with impaired reading comprehension; the association was maintained after adjustment for socioeconomic variables. Findings were consistent across the three countries, which varied with respect to a range of socioeconomic and environmental variables, thus offering robust evidence of a direct exposure-effect relation between aircraft noise and reading comprehension. The data reported here are from the same study described previously (Stansfeld et al. 2005). Again, the authors reported outdoor  $L_{eq}$  for all schools mentioned in the study at 30 dBA to 70 dBA (data were reported in 5 dB bands centered in this range). The authors do not identify how the schools with outdoor levels in the 30 to 45 dBA  $L_{eq}$  were determined. It is not supported by known noise levels in urban and suburban neighborhoods; a school located in a region with sufficient population to support a school could not have an outdoor ambient noise level as low as 30 dBA  $L_{eq}$ .

**Evans, G.W., M. Bullinger, and S. Hygge, “Chronic Noise Exposure and Physiological Response: A Prospective Study of Children Living Under Environmental Stress,” *Psychological Science*, Vol. 9, No. 1, Jan. 1998, pp. 75–77.**

This is another study that examined children living near the new Munich International Airport and children “outside the noise impact zone.” The study used 217 children. The results were classified in terms of two groups labeled as “noisy” and “quiet.” Again, this is a binary classification that does not lend itself to determining a dose-response relationship. The noise exposure after the opening of the airport was a 24-h  $L_{eq}$  of 62 dBA, whereas the noise level before opening was 52 dBA  $L_{eq}$ ; the quiet community used for comparison had a  $L_{eq}$  of 55 dBA, with the difference between the noisy and quiet groups only 7 dBA. Chronic exposure to aircraft noise elevated psychophysiological stress (resting blood pressure, overnight epinephrine, and nonepinephrine) and depressed quality-of-life indicators over a two-year period among 9- to 11-year-old children. Data collected before and after the inauguration of a major new international airport in noise-impacted and comparison communities show that noise significantly elevates stress among children at ambient levels far below those necessary to produce hearing damage. It is interesting to note that this impact occurred somewhere in the range between 55 and 62 dBA  $L_{eq}$ .

**Evans, G.W., S. Hygge, and M. Bullinger, “Chronic Noise and Psychological Stress,” *Psychological Science*, Vol. 6, No. 6, Nov. 1995, pp. 333–338.**

The authors demonstrate that chronic noise exposure is associated with elevated neuroendocrine and cardiovascular measures, muted cardiovascular reactivity to a task presented under acute noise, deficits in a standardized reading test administered under quiet conditions, poorer long-term memory,

and diminished quality of life on a standardized index. Children within high-noise areas also showed evidence of poor persistence on challenging tasks and habituation to auditory distraction on a signal-to-noise task. They reported considerable annoyance with community noise levels, as measured utilizing a calibration procedure that adjusts for individual differences in rating criteria for annoyance judgments. The data were collected around Munich International Airport and in a quiet urban Munich neighborhood. The dynamic range of the noise exposures between the “noisy” community and the “quiet” community was approximately 9 dBA (24-h  $L_{eq}$  of 68 dBA near the airport and 59 dBA not near the airport). This type of noise reporting is typical of the school effects studies; that is, describing the two subject environments as a high-noise setting and a low-noise setting. This binary definition of noise exposure makes the task of defining a dose-response curve difficult. However, one can see that at noise levels below 60 dBA  $L_{eq}$  the effect on school children is small, whereas at noise levels above 65 dBA  $L_{eq}$  the effects are well-identified. Note that this does not define 65  $L_{eq}$  as the demarcation point for impact; indeed the data as presented in this and similar studies are not sufficient to define a threshold noise level at which effects on school children are significant.

**Federal Interagency Committee on Aviation Noise, “Findings of the FICAN Pilot Study and the Relationship Between Aircraft Noise Reduction and Changes in Standardized Test Scores” [Online]. Available: [http://www.fican.org/pdf/FICAN\\_Findings\\_on\\_school\\_study.pdf](http://www.fican.org/pdf/FICAN_Findings_on_school_study.pdf), July 2007.**

Recent FICAN findings report that research on the effects of aircraft noise on children’s learning suggests that aircraft noise can interfere with learning in the following areas: reading, motivation, language and speech acquisition, and memory. The FICAN pilot study demonstrated a very strong relationship between reduced noise levels and better test scores. The strongest findings to date are in the area of reading, where more than 20 studies have shown that children in noise-impact zones are negatively affected by aircraft. In September 2000, FICAN undertook a pilot study to evaluate the effectiveness of school sound insulation programs. This finding reports on the results of that study. The study was designed to address two key questions: (1) is abrupt aircraft noise reduction within classrooms related to mandatory, standardized test-score improvement, after controlling for demographics, and (2) does this relationship vary by age group, by student group, and/or by test type? The study included 35 public schools close to three airports in the United States. Abrupt noise reduction at these schools resulted from either airport closure or newly implemented sound insulation. In the analysis, the noise-reduction group was compared with the control group (same school, but four years before noise reduction). Analysis consisted of multi-level regression with “change in test scores” regressed against a range of variables such as “change in cumulative noise exposure.” “After controlling for demographics, the study found (1) a

substantial association between noise reduction and decreased failure (worst-score) rates for high school students, and (2) significant association between noise reduction and increased average test scores for student/test subgroups” FICAN goes on to recommend that additional studies be conducted that expand the scope of this work in several ways by incorporating a larger number of airports and schools, following individual students from year to year, determining which tests were actually given in “teaching” classrooms and which were given elsewhere, obtaining airport data directly from airports, and incorporating actual outdoor-to-indoor measurements at each school. This pilot study provides minimal information about the net exposure to noise at any of the schools, but reports results solely in terms of the reduction in noise level. For example, the 20% decrease in failure rate in high school students was correlated to a 5% reduction in the time that the classroom noise exceeded 40 dBA. Although this is a very significant result, the report does not describe the before and after times that the classroom noise exceeded 40 dBA. Therefore, these results, although lending important credence to the value of classroom noise reduction, are not helpful in determining a threshold for school sound insulation. For example, would a 50% reduction in time above 40 dBA at a school where the time above 40 dBA is currently 1 min benefit from a sound insulation program? Although this pilot study showed some significant improvements, the results were in fact mixed. The failure rate in elementary and middle school students did not correlate to changes in noise level. When the  $L_{max}$  level for aircraft events greater than 40 dBA was reduced by 20 events, middle and elementary students demonstrated improved test scores, whereas high school students demonstrated poorer average test scores. The top scores for all groups showed a reduction of 5 points when a 5% decrease in percent time above 40 dBA was achieved. This demonstrates the complexity of correlating student performance with noise level and the need for further research. This type of study, before and after a step change in school noise levels, is very promising because it involves the same students and would appear to offer better opportunities for correlating noise to student performance than typical cross-sectional studies.

**Federal Interagency Committee on Aviation Noise, “Position Paper on Research into the Effects of Aircraft Noise on Classroom Learning,” Sep. 2000 [Online]. Available: [www.fican.org/pdf/Effects\\_aircraft.pdf](http://www.fican.org/pdf/Effects_aircraft.pdf).**

In 2000, FICAN published a position paper summarizing the research of the effects of aircraft noise on children’s classroom learning and indicated that aircraft noise can interfere with learning in the following areas: reading, motivation, language and speech acquisition, and memory. The strongest finding to date is in the area of reading, where more than 20 studies have shown that children in noise impact zones are negatively affected by aircraft. Recent research confirms conclusions from studies in the 1970s showing a decrement

of reading when outdoor noise levels equal or exceed a  $L_{eq}$  of 65 dBA. It is also possible that, for a given  $L_{eq}$ , the effects of aircraft noise on classroom learning may be greater than the effects of road and railroad traffic. Members of FICAN agreed that:

(1) Further work should be done to establish whether school day  $L_{eq}$  is the appropriate measure for determining the effect of aircraft noise on classroom learning, (2) In the absence of appropriations for specific research, FICAN encourages before and after evaluations of the effectiveness of noise mitigation in schools, (3) FICAN will undertake a pilot study to evaluate the effectiveness of school sound insulation programs, and (4) FICAN supports the work of the American National Standards Institute (ANSI) in its efforts to develop a standard for classroom noise.

With respect to point (1), FICAN posed the question regarding the use of  $L_{eq}$  that has not been addressed in any of the more recent research. That question being whether “a teacher pausing for the flyover of an aircraft at x dB every 20 min has the same effect on classroom learning as pausing for an aircraft at x minus 10 dB every 2 min.” Although the two cases would have the same  $L_{eq}$ , the interruption pattern would be different, and the effects on the classroom learning could be different.

**Haines, M.M., S.A. Stansfeld, R.F.S. Job, B. Berglund, and J. Head, “A Follow-Up Study of Effects of Chronic Aircraft Noise Exposure on Child Stress Responses and Cognition,” *International Journal of Epidemiology*, Vol. 30, 2001, pp. 839–845.**

This study is a follow-up to the FICAN study described previously. One purpose of the follow-up study was to determine if habituation affects child stress response and cognition. The results of this repeated measures study were not conclusive. Nevertheless, they provide stronger evidence than previous studies that noise exposure affects child cognition and stress responses and that these effects do not habituate over a one-year period. The authors’ conclusion that the main reading effect remained constant between baseline and follow-up, despite marked variation in the acute noise interference at testing, provides further evidence that the cognitive impairments are the result of chronic exposure rather than acute interference at the time of testing. These results do not support the sustained attention hypothesis previously used to account for the effects of noise on cognition in children. The within-subjects analyses indicate that children’s development in reading comprehension may be adversely affected by chronic aircraft noise exposure. Noise annoyance remains constant over a year with no strong evidence of habituation. Further research should look at the long-term implications of these effects and examine further underlying mechanisms. The noise exposure identified in this report is a  $L_{eq}$  66 dBA for the school with aircraft noise and 57 dBA  $L_{eq}$  for the school without aircraft noise. The 66 dBA  $L_{eq}$  conflicts with the stated 63 dBA  $L_{eq}$  in the previous study for the same school one year earlier. A 3 dBA change in  $L_{eq}$  over one year

is not likely. This highlights a general problem with some of the studies of effects on school children, which is a weakness in defining the noise environments at the test schools.

**Haines, M.M., S.A. Stansfeld, S. Brentnall, J. Head, B. Berry, and M. Jiggins, "The West London Schools Study: The Effects of Chronic Aircraft Noise Exposure on Child Health," *Psychological Medicine*, Vol. 31, 2001, pp. 1385–1396.**

The authors refer to previous studies that have shown that the cognitive performance of children is impaired by chronic aircraft noise, but comment that these studies have not been of sufficient size to account adequately for the role of confounding factors. The objective of this study was to test whether cognitive impairments and stress responses (catecholamines, cortisol, and perceived stress) are attributable to aircraft noise exposure after adjustment for school and individual level confounding factors and to examine whether children exposed to high levels of social disadvantage are at greater risk of noise effects. The cognitive performance and health of 451 children aged 8 to 11 years, attending 10 schools in high aircraft-noise areas (16-h outdoor  $L_{eq}$  greater than 63 dBA) were compared with children attending 10 matched control schools exposed to lower levels of aircraft noise (16-h outdoor  $L_{eq}$  less than 57 dBA). Noise exposure was associated with impaired reading on difficult items and raised annoyance after adjustment for age, main language spoken, and household deprivation. There was no variation in the size of the noise effects in vulnerable subgroups of children. High levels of noise exposure were not associated with impairments in mean reading score, memory, attention, or stress responses. Aircraft noise was weakly associated with hyperactivity and psychological morbidity. The authors concluded that chronic noise exposure is associated with raised noise annoyance in children. The results indicated that chronic aircraft noise exposure does not always lead to generalized cognitive effects but, rather, more selective cognitive impairments on difficult tests in children. Note that the outdoor noise exposures for the school with aircraft noise and the school without aircraft noise is a rather small dynamic range, 57 to 63 dBA  $L_{eq}$  or 6 dBA, and that the observed effects were not evident at 57 dBA  $L_{eq}$ .

**Hiramatsu, K., T. Tokuyama, T. Matsui, T. Miyakita, Y. Osada, and T. Yamamoto, "The Okinawa Study: Effect of Chronic Aircraft Noise Exposure on Memory of School Children," 2003, 2 pp.**

The impact of chronic aircraft noise exposure on school-aged children's memory was investigated in the vicinity of two military airfields in Okinawa, Japan. The noise exposure for the exposed groups was divided into three groups, 70 to 75 DNL, 60 to 65 DNL, and 60 to 75 DNL. This rough classification of the noise levels makes interpreting the results difficult and no dose-response relationship is reported or derivable from the data. The authors concluded that

... no significant increase of odds ratio was found against  $L_{dn}$  concerning the short-term memory score and the long-term memory score of 15 questions presented in the 1st day and the 2nd day tests. Significant trend of increase of odds ratio was found against  $L_{dn}$  concerning the 5 questions presented in the 2nd day long-term memory test.

The authors reported that the result obtained in the present study is in line with previous studies and suggest that chronic aircraft noise exposure lowers the ability of long-term memory of school children and, as a result, they run the risk of lower learning ability.

**Hygge, S., "Classroom Experiments on the Effects of Different Noise Sources and Sound Levels on Long-Term Recall and Recognition in Children," *Applied Cognitive Psychology*, Vol. 17, Oct. 2003, pp. 895–914.**

A total of 1,358 children aged 12 to 14 years participated in 10 noise experiments in their ordinary classrooms and were tested for recall and recognition of a text exactly one week later. Single and combined noise sources were presented for 15 min at 66 dBA  $L_{eq}$ . Data were analyzed between subjects because the first within-subjects analysis revealed a noise after-effect or an asymmetric transfer effect. Overall, there was a strong noise effect on recall, and a smaller, but significant effect on recognition. In the single-source studies, aircraft and road traffic noise impaired recall at both noise levels. Train noise and verbal noise did not affect recognition or recall. Some of the paired combinations of aircraft noise with train or road traffic, with one or the other as the dominant source, interfered with recall and recognition. This study was done using a sound source located in the classroom replaying recorded noise. Interestingly, noise from traffic and aircraft showed strong effects on recall and learning, whereas train noise and verbal noise (spoken word in a language not familiar to students) did not show the effect even though noise levels for each source were identical. The author states that given that road noise and verbal noise were relatively constant sources and the aircraft and train noise were event-type sources, these observed differences are interesting and not expected.

**Hygge, S., G.W. Evans, and M. Bullinger, "A Prospective Study of Some Effects of Aircraft Noise on Cognitive Performance in School Children," *Psychological Science*, Vol. 13, No. 5, Sep. 2002, pp. 469–474.**

This is one of many studies that were done using the area around the old and new Munich airports. Before the opening of the new Munich International Airport and the termination of the old airport, children near both sites were recruited into aircraft-noise groups (aircraft noise at present or pending) and control groups with no aircraft noise (closely matched by socioeconomic status). A total of 326 children (mean age = 10.4 years) took part in three data-collection waves, one before and two after the switch-over of the airports. After the switch, long-term memory and reading were impaired in

the noise group at the new airport, and improved in the formerly noise-exposed group at the old airport. Short-term memory also improved in the latter group after the old airport was closed. At the new airport, speech perception was impaired in the newly noise-exposed group. Mediation analyses suggest that poorer reading was not mediated by speech perception, and that impaired recall was in part mediated by reading. The report provided the 24-h  $L_{eq}$  data that showed that the old airport had noise exposures as high as 68 dBA  $L_{eq}$  with aircraft noise and as low as 55 dBA  $L_{eq}$  without aircraft noise. At the new airport, the noise levels were as low as 53 dBA  $L_{eq}$  before opening and 62 dBA  $L_{eq}$  after opening.

**Stansfeld, S.A., B. Berglund, C. Clark, I. Lopez-Barrio, P. Fischer, and E. Ohrstrom, "Aircraft and Road Traffic Noise and Children's Cognition and Health: A Cross-National Study," *Lancet*, Vol. 365, June 2005, pp. 1942–1949.**

The authors did a cross-national, cross-sectional study in which they assessed 2,844 of 3,207 children aged 9 to 10 years who were attending 89 schools in the Netherlands, Spain, and the United Kingdom located in areas around three major airports. They selected children by extent of exposure to external aircraft and road traffic noise at schools as predicted from noise contour maps, modeling, and on-site measurements, and matched schools within countries for socioeconomic status. They measured cognitive and health outcomes with standardized tests and questionnaires administered in the classroom. They also used a questionnaire to obtain information from parents about socioeconomic status, education, and ethnic origin. The results identified linear exposure-effect associations between exposure to chronic aircraft noise and impairment of reading comprehension and recognition memory, and a non-linear association with annoyance maintained after adjustment for mother's education, socioeconomic status, longstanding illness, and extent of classroom insulation against noise. Exposure to road traffic noise was linearly associated with increases in episodic memory (conceptual recall and information recall), but also with annoyance. Neither aircraft noise nor traffic noise affected sustained attention, self-reported health, or overall mental health. The findings indicated that a chronic environmental stressor—aircraft noise—could impair cognitive development in children, specifically reading comprehension. The authors concluded that schools exposed to high levels of aircraft noise are not healthy educational environments. The study sample was large, multi-country, and of apparent high quality. However, the noise exposure data reported for the study schools is highly questionable. The range of outdoor  $L_{eq}$  for all schools reported in the study is from 30 dBA to 70 dBA (data were reported in 5 dB bands centered in this range). The authors do not identify how the schools with outdoor levels in the 30 to 45 dBA  $L_{eq}$  were determined. It is not supported by known noise levels in urban and suburban neighborhoods, because schools located in a region with sufficient population to support a school are not known to have an outdoor noise level as low as 30 dBA  $L_{eq}$ . The primary author was contacted and

he confirmed that these were indeed outdoor noise levels. However, the presence of school buses, local roadway transportation, or even the students themselves on the campus would preclude having an outdoor level as low as 30 dBA. The reported results for schools from 50 to 70 dBA  $L_{eq}$  tend to still support the study findings; however, the data for schools reported with outdoor  $L_{eq}$  exposures less than 50 dBA should be regarded with caution. It is interesting to note that the results show effects on reading scores at schools with an outdoor  $L_{eq}$  of 35 to 40 dBA are not plausible. The effects identified at the higher noise levels are more credible, although the lowest reading scores occurred at schools with noise in the 55 to 60 dBA range, whereas schools with noise greater than 60 dBA  $L_{eq}$  had better reading scores. Although the authors have presented very plausible conclusions, the noise exposure data are of questionable use in attempting to define any kind of dose-response relationship.

#### **CHAPTER SEVEN: EFFECTS OF AVIATION NOISE ON PARKS, OPEN SPACE, AND WILDERNESS**

Most of the standards and research related to the effects of aviation noise on parks are directed toward efforts to identify, define, measure, quantify, and address compliance with the natural soundscape of the wilderness park environment, such as Native American lands and U.S. national parks. There are different kinds of parks and open space ranging from urban "pocket parks" to remote wilderness areas. Although research has focused mostly on wilderness parks, two studies on urban parks are discussed in this synthesis.

With the passage of the National Parks Overflight Act of 1987, the FAA and the National Park Service (NPS) were tasked to join forces and begin the process of restoring "natural quiet" to the nation's parks. In 2000, the National Parks Air Tour Management Act (NPATMA) required the development of air tour management plans (ATMP) for commercial air tour operators who currently conduct or propose to conduct flights for sightseeing purposes over national parks or tribal lands. According to NPATMA, the objective for ATMPs is to develop acceptable and effective measures to mitigate or prevent significant adverse impacts, if any, of commercial air tour operations on the natural and cultural resources and visitor experiences in national park units as well as tribal lands (those included in or abutting a national park). NPATMA also designates the FAA as the lead agency in assessing environmental impacts of commercial air tour operations under NEPA, and the NPS as the cooperating agency. Any ATMP for a national park may prohibit commercial air tour operations and may establish conditions or restrictions of operations, including noise restrictions, visual restrictions, or other impacts. The Act does not provide specific noise limits to be considered as part of the ATMP. Additionally, the 2000–2004 NPS "Soundscape Preservation and Noise Management" Director's Order #47 articulated National Park Service operational policies that require, to the fullest extent practicable, the protection, maintenance, or

restoration of the natural soundscape resource in a condition unimpaired by inappropriate or excessive noise sources. In Order #47, an outline of the park director's responsibilities includes natural soundscape preservation as part of the operating policies of the park. Although the order provides a broad structure for consideration of soundscape preservation in the park facilities planning process, it does not address specific noise level goals or specific programs.

In 1994, the NPS provided a report to Congress with an extensive review of aircraft overflights of the national parks (National Park Service 1994). Compiled by a team of experts in a number of fields, it covers effects of overflights on natural quiet, wildlife, visitors, culture and historical resources, and safety. The report includes a dose-response curve for visitor annoyance in terms of time that aircraft are audible and hourly  $L_{eq}$ . The report concludes that aircraft overflights can and do produce impacts on both visitor and park resources; however, the impacts do not occur evenly throughout the park system and are considerably greater at some than at others. Additionally,

wild animals respond to low-altitude aircraft overflights, although the manner in which they do so depends on life-history characteristics of the species, characteristics of the aircraft, flight activities, and a variety of factors such as habitat type and previous exposure to aircraft. . . . The primary concern . . . is that the flights may cause physiological and/or behavioral responses that in turn reduce the wildlife's fitness or ability to survive (National Park Service 1994).

Lastly, the report concluded that back-country visitors consistently show greater sensitivity to the sounds of overflights than do front-country visitors, including visitors at easily accessible overlooks.

In 2005, the FAA published a report that summarizes the findings of all known aircraft noise (dose) and visitor annoyance (response) data previously collected in the national parks (Rapoza et al. 2005). The accumulated data consist of almost 2,500 visitor interviews and simultaneous acoustical measurements collected at four different national parks between 1992 and 1999, including two major FAA dose-response measurement programs in 1997 (short-hike) and 1998 (overlook).

The dose-response data obtained from these studies can be used to determine the relationships between aircraft noise and visitor response for purposes of assessing aircraft noise in the national parks. Important results from the 2005 FAA report included the finding that the vast majority of visitors (92% to 94%) rate annoyance equal to or higher than interference with enjoyment. Visitors appear to be less sensitive to high-altitude jet overflight noise as compared with noise from tour aircraft. However, the data do not show this with statistical certainty and no definitive conclusions can be drawn. Visitor response to tour overflight noise differs between overlooks and short hikes. In addition, it appears that

a respondent's familiarity with the site can influence visitor response to aircraft noise; that is, repeat visitors generally are more annoyed. The descriptors that showed the best overall performance were A-weighted %TAA and aircraft equivalent sound levels:  $L_{Aeq,1h}$ ,  $\Delta L_{Aeq,Tac}$ , and  $\Delta L_{Aeq,Tresp}$ . The report also presents some preliminary concepts of combining %TAA and  $\Delta L_{Aeq,Tac}$  for the development of meaningful noise criteria that can be applied to national park assessments in the future.

Some of the most provocative recent research has been done by Horonjeff (2005) who provides a good summary background of the efforts to define methods to quantify the natural soundscape of the wilderness park environment. The author defines the soundscape in terms of duration of quiet time and time a visitor has to wait until he or she experiences quiet times of certain durations. This "wait time" provides a valuable means for evaluating the impact of human-made sources on areas where the ambient environment is largely devoid of human-made sounds. It provides two basic pieces of information that may be used for comparisons across sites or for comparisons against established criteria for regulatory or planning purposes. In terms of defining periods of natural quiet for purposes of analyzing transportation projects near parks, the author states

For forecasting purposes, the use of computer models is the only efficient means by which these effects may be evaluated over large land areas, such as an entire Park or Native American lands. This is especially true when evaluating roadway routings, alternative air traffic routes, changes in aircraft or vehicular fleet mix, and potential beneficial effects of "quiet aircraft" technologies (and similar issues regarding all-terrain vehicles, motorcycles, personal watercraft, snowmobiles, and snow coaches) (Horonjeff 2005).

Very little recent research has been completed that discusses noise in urban parks. Brambilla and Maffei (2006) identify the importance of characterizing the soundscapes of urban park environments properly, taking into account the multi-dimensionality of the individual perception, which includes the effect of non-acoustic factors such as visual impression, and matching the personal expectation of the environment with the actual experience. Through noise surveys and laboratory listening tests, results showed that the subject's expectation to hear a sound in a specific environment influences the corresponding annoyance. Furthermore, the acceptability of the non-natural sound increases with decreasing levels and detectability. These findings are significant as they point out that loudness of a noise source is not the only aspect of its acceptance. Natural sounds expected in a park setting are deemed acceptable no matter their sound level, whereas unexpected sounds such as aircraft and road noise are judged as more annoying than unexpected sounds.

Zannin et al. (2006) provided an evaluation of noise pollution in six urban parks in the city of Curitiba, Brazil.

Measured levels were compared with limits permitted by local legislation and were thus classified as “acoustically polluted or unpolluted.” Measured values were also evaluated according to international legislation from Rome, Germany, WHO, and the EPA. Noise levels in the urban parks of downtown Curitiba do not satisfy any of the standards used. The study provides useful comparison of various international noise limits that may be applied to parks.

### Summary

National parks have been a focus of park and open space noise research in the United States. Preserving the natural quiet is a controversial topic and subject to congressional mandate. The FAA has developed specific analytical tools included as part of the most recent version of the INM for use in analyzing aviation noise impacts in national parks. Very little research has been done on the effect of aviation, or any other kinds of noise, on the more common urban and suburban parks. The research on urban parks that has been done in Europe indicates that users consider noise a very important factor in park enjoyment, but that park users judge sounds differently based on whether the noise is an expected or unexpected part of the park environment.

### Annotated Bibliography—Effects of Aviation Noise on Parks, Open Space, and Wilderness

**Brambilla, G. and L. Maffei, “Responses to Noise in Urban Parks and in Rural Quiet Areas,”** *ACTA Acustica United with Acustica*, Vol. 92, 2006, pp. 881–886.

This article is one of the very few papers that deals specifically with noise in urban parks rather than wilderness parks. The authors identify the importance of characterizing the soundscape of these environments properly, taking into account the multi-dimensionality of the individual perception, which includes the effect of non-acoustic factors on subjective evaluation, such as visual impression, and matching the personal expectation of the environment with the actual experience. This paper describes two experimental investigations carried out recently in Italy. The first deals with noise surveys and collection of subjective appraisals of three urban parks in Naples, whereas the second consists of laboratory listening tests in which sounds recorded binaurally in countryside parks have been mixed with sounds from various sources at different signal-to-noise ratios and played back by headphones to a group of subjects. The results obtained show that the subject’s expectation to hear a sound in a specific environment (its congruence with the environment in which it occurs) influences the corresponding annoyance. In particular, the more the sound is congruent with the expectation of the park, the less is the evoked annoyance and, conversely, the more is its acceptability. Furthermore, the acceptability of the sound increases with its decreasing levels and detectability. The authors’ survey of urban park users showed that the most frequent reasons to

visit the park are to accompany children (41% of subjects) and to look for quiet (26%). The aspects reported by the subjects as the most important for the acceptability of the park were clean air, cleanliness, landscape, safety, vegetation, and silence. Silence was rated very important by 57% of subjects on average; however, for all parks it was ranked the lowest important criterion among the considered aspects (cleanliness and clean air ranked highest with 100% respondents identifying). The authors identified that

natural sounds are widely expected to be heard in the parks and the most expected is bird twittering (96%). However, noise from aircraft flyovers and road traffic are also mentioned by 21% and 6% of the subjects, respectively (average across the parks). These two transport noises are rated very annoying by a large percentage of subjects (46% for road traffic and 41% for aircraft flyover) most likely because they are the least expected to be heard in the park. Indeed, the subject’s expectation to hear a sound in a specific environment, that is its congruence with the environment where it is heard, influences the corresponding annoyance.

The significance of the findings of this study is that loudness of a noise source is not the most important aspect of its acceptance. Natural sounds that are expected in a park setting are deemed acceptable no matter their sound level, whereas unexpected sounds such as aircraft and road noise are judged as annoying.

**Fleming, G.G., C.J. Roof, A.S. Rapoza, D.R. Read, J.C. Webster, and P.C. Liebman, *Development of Noise Dose/Visitor Response Relationships for the National Parks’ Overflight Rule: Bryce Canyon National Park Study*, U. S. Department of Transportation, Washington, D.C., July 1998, 256 pp.**

The FAA’s Office of Environment and Energy, with the assistance of the Acoustics Facility at the Department of Transportation’s John A. Volpe National Transportation Systems Center, conducted research in support of the National Parks Overflight Rule (National Rule). The foundation of the research program for the National Rule is the performance of noise dose/visitor response (dose-response) studies in several national parks. This document summarizes the results of a dose-response study conducted along two separate segments of a front-country, short-hike trail at Bryce Canyon National Park during the period August 19 to August 27, 1997. More than 900 visitor interviews and simultaneous acoustical and meteorological measurements were collected during the period. These data and results constitute the largest single aircraft noise dose-response data set collected in the national parks’ environment. Respondents were subjected to doses from helicopters, propeller, and jet aircraft, including a wide range of actual sound levels and durations (i.e., time during which aircraft were audible). The findings of this study indicated that approximately one-quarter of the survey respondents expressed annoyance as a result of overflight noise, which included contributions from high-altitude jets, general aviation, and air tour operations at the park. The level

of visitor annoyance is mediated by the phenomenon of base level of annoyance, indicating an apparent predisposition by a certain percentage of visitors who expressed annoyance, yet in effect experienced no noise from overflights. It is also interesting to note that visitors as a whole reported a number of other factors besides overflight noise as their primary concern (e.g., the crowds/other people, trail conditions, weather, seeing footprints or people off the trail, and a lack of restroom facilities). The relationship between visitor annoyance resulting from aircraft overflights and a total of 14 time-, level-, and event-based descriptors was investigated through statistical analyses for this study. In particular, three descriptors appear to model park visitor annoyance better than others; in order of performance they are change in sound exposure level ( $L_{AE,Tadj}$ ), aircraft percent time audible (%TA), and aircraft percent time audible without the inclusion of high-altitude jet aircraft (%TAw/ojet). The predicted models developed with the equivalent sound level family of descriptors also performed quite well. In relation to this, a far greater percentage of respondents identified the “level” of aircraft noise as being the most annoying factor (25.6%), followed by “time” aircraft were heard (9.0%), and the “number” of events (6.9%). The results of this and other dose-response studies can be used to develop a set of dose-response relationships (curves) that can provide guidance in important policy decisions with respect to park overflights.

**Horonjeff, R.D., “Queuing for Quiet—The Natural Soundscape from a Visitor Perspective,” Presented at the ASA (Acoustical Society of America)/Noise-Con 2005 Meeting, Minneapolis, Minn., Oct. 19, 2005.**

This paper provides the reader with a good summary background of the efforts to define methods quantifying the natural soundscape of the wilderness park environment. With passage of the National Parks Overflight Act of 1987 (PL 100-91), the FAA and NPS were tasked to join forces and begin the process of restoring “natural quiet” to the nation’s parks. The issues were the growth of air tour activity and its impact on ground visitor enjoyment and cultural resources at mainland U.S. and Hawaiian parks. The author defines the soundscape in terms of duration of quiet time and the time a visitor has to wait until he or she experiences quiet times of certain durations. This “wait time” provides a valuable means for evaluating the impact of human-made sources on areas whose ambient environment is largely devoid of human-made sounds. It provides two basic pieces of information that may be used for comparisons across sites, or for comparisons against established criteria for regulatory or planning purposes. Upon arrival at a specific location, the descriptor provides information on (1) the expected (average) wait time for a desired noise-free interval duration, and (2) whether lengthy durations are even attainable at the site. Examples for various parks including the Grand Canyon (affected by air tour operations) and White Sands National Monument (military overflights) are given. The author concludes,

Perhaps the major observation to be reached from this investigation is that sound sources relatively low in level, by urban and suburban standards, are distinctly audible in low-ambient environments. And their presence is readily obvious at long distances. During low wind conditions, it was not unusual for the ambient-sound level to drop near or below the human threshold of hearing. Under such conditions, motorized sources can be audible for long periods of time. Under favorable propagation conditions, both tour and jet aircraft can be heard at distances of ten miles or more.

In terms of defining the periods of natural quiet for purposes of analyzing transportation projects near parks, the author states,

For forecasting purposes, the use of computer models is the only efficient means by which these effects may be evaluated over large land areas, such as an entire Park or Native American lands. This is especially true when evaluating roadway routings, alternative air traffic routes, changes in aircraft or vehicular fleet mix, and potential beneficial effects of “quiet aircraft” technologies (and similar issues regarding all-terrain vehicles, motorcycles, personal watercraft, snowmobiles, and snow coaches).

The author then describes aircraft noise models, such as the FAA’s INM, that can be used for this purpose.

#### **National Parks Air Tour Management Act of 2000, 11 pp.**

This act requires the development of ATMP for national parks. Before commencing commercial air tour operations over a national park or tribal lands, a commercial air tour operator must apply to the FAA for authority to conduct the operations over the park or tribal lands. Whenever an ATMP limits the number of commercial air tour operations over a national park during a specified time frame, the FAA must issue operation specifications to commercial air tour operators that conduct the operations. ATMPs for a national park:

- May prohibit commercial air tour operations;
- May establish conditions for the conduct of commercial air tour operations, including commercial air tour routes, maximum or minimum altitudes, time-of-day restrictions, restrictions for particular events, maximum number of flights per unit of time, intrusions on privacy of tribal lands, and mitigation of noise, visual, or other impacts;
- Must apply to all commercial air tour operations within one-half mile outside the boundary of a national park;
- Shall include incentives (such as preferred commercial air tour routes and altitudes, relief from caps and curfews) for the adoption of quiet aircraft technology by commercial air tour operators conducting commercial air tour operations at the park;
- Shall provide for the initial allocation of opportunities to conduct commercial air tour operations if the plan includes a limitation on the number of commercial air tour operations for any time period; and
- Shall justify and document the need for measures taken pursuant to implementation of this law.



The Act does not provide specific noise limits to consider as part of the ATMP.

**National Park Service, *Report on Effects of Aircraft Overflights on the National Park System, Prepared Pursuant to Public Law 100-91, The National Parks Overflights Act of 1987, Sep. 1994, 222 pp.***

This report to Congress is an extensive review of aircraft overflights of the national parks. It covers effects of overflights on natural quiet, cultural, and historical resources, wildlife, visitors, and safety. The report was compiled by a team of experts from various fields and is a very comprehensive and readable reference document. Summaries of the number of overflights and time of aircraft audibility are provided for a large number of park sites. The report includes dose-response curves for visitor annoyance for the time that aircraft are audible and hourly  $L_{eq}$ . The report concludes, "Aircraft overflights can and do produce impacts both on visitors and on park resources. These impacts, however, do not occur evenly throughout the park system, but occur at some parks to a considerably greater extent than at others." The report identifies commercial and sightseeing operations as more common than other types of overflights (military and park administrative overflights). Helicopters and low-level jets are more likely to be of concern to park managers than other types of aircraft.

The indigenous sound levels in national parks are often considerably lower than sound levels commonly experienced in most residential areas. In such park areas of low ambient sound levels, even distant aircraft can be easily heard. Complete preservation of natural quiet under these circumstances can mean that aircraft must fly several miles from the area to be protected. Natural quiet is an increasingly scarce resource in America. The NPS needs to protect some of these uniquely quiet places.

With respect to the effects of overflights the report concludes that,

wild animals respond to low-altitude aircraft overflights, although the manner in which they do so depends on life-history characteristics of the species, characteristics of the aircraft, flight activities, and a variety of factors such as habitat type and previous exposure to aircraft. Of most concern related to wildlife in parks are (1) low-altitude overflights by military aircraft, and (2) light, fixed wing aircraft and helicopter activities related to tourism. The primary concern stemming from these low-level overflights related to wildlife is that the flights may cause physiological and/or behavioral responses that in turn reduce the wildlife's fitness or ability to survive.

Visitors report impacts (interference with enjoyment, annoyance, and interference with appreciation of natural quiet) depending on the levels of overflight sound that the visitors may have experienced. However, reported impacts are highly variable from location to location, and the results of the dose-response work and the survey of Grand Canyon visitors suggest that visitor sensitivity to overflight-produced sound is greater for activities where visitors remove themselves

from automotive transportation and, possibly, from other visitors. Back-country visitors, people on oar-powered river trips, and visitors who take short hikes away from their cars, consistently show greater sensitivity to the sound of overflights than do front-country visitors, including visitors at easily accessible overlooks.

***National Parks Air Tour Management Act: More Flexibility and Better Enforcement Needed, U.S. Government Accountability Office, Washington, D.C., Jan. 2006, 69 pp.***

The Government Accountability Office (GAO) conducted this study primarily because of concerns that noise from air tours over national parks could impair visitors' experiences and park resources. The report deals mostly with compliance and implementation issues and does not include guidelines on park noise levels or methods to measure the effects of overflight noise on parks. Congress passed the National Parks Air Tour Management Act of 2000 to regulate air tours. The act requires the FAA and the NPS to develop air tour management plans for all parks where air tour operators apply to conduct tours. A plan may establish controls over tours, such as routes, altitudes, time-of-day restrictions, and/or a maximum number of flights for a given period; or ban all air tours. The GAO reports that the

FAA and the Park Service have taken some steps to implement the National Parks Air Tour Management Act, but almost 6 years after its passage, the required air tour management plans have not been completed. FAA issued regulations implementing the act and the agencies began developing plans at nine parks. But implementation has been slow, in part, because FAA needed to address airline security after the September 11, 2001, attacks and because the two agencies disagreed over how to comply with environmental laws.

Most of the parks responded that they had not experienced any positive or negative effects of the implementation of the act or that they were uncertain or did not know the extent of the effect. Nonetheless, 47% responded that their park could benefit by having a plan to mitigate or prevent potential adverse effects on park resources, visitor experiences, and air safety. The GAO identified four key issues that needed to be addressed to improve implementation of the act:

1. Lack of flexibility for determining which parks should develop plans. Not all parks required to develop a plan may need one because they have few air tours or are more affected by other types of flights. However, the act does not provide the agencies with any flexibility to exclude some parks.
2. Absence of Park Service funding for its share of plan development costs. The Park Service has not requested nor received funding for its share of the costs of developing plans.
3. Limited ability to verify and enforce the number of air tours. Air tour operators are not required to report the number of tours they conduct. As a result, the agencies are limited in their ability to enforce the act. Based on

information provided by operators, GAO found some operators had inappropriately exceeded their number of authorized tours.

4. FAA's inadequate guidance concerning the act's safety requirements. FAA has not instructed its district offices or air tour operators on how to interpret the act's requirement that operators meet a specified level of safety certification.

To allow more cost-effective implementation of the National Parks Air Tour Management Act, the GAO suggests that Congress may wish to consider amending the act to authorize the FAA and Park Service to determine which park units should develop ATMPs. In addition, the GAO recommends that FAA take a number of actions to improve compliance, enforcement, and implementation of the act.

**Rapoza, A.S., G.G. Fleming, C.S.Y. Lee, and C.J. Roof, *Study of Visitor Response to Air Tour and Other Aircraft Noise in National Parks*, U.S. Department of Transportation, Federal Aviation Authority, Washington, D.C., Jan. 2005, 103 pp.**

This document summarizes the findings of a study that considers all known aircraft noise-dose and visitor-response data previously collected in national parks. These data consist of almost 2,500 visitor interviews and simultaneous acoustical measurements collected at four different national parks between 1992 and 1999. These data are used to develop relationships that relate the noise (dose) data to visitor response for assessing aircraft noise in national parks. In addition to the development of dose-response relationships, the study focused on several key issues. The vast majority of visitors (92% to 94%) rated annoyance equal to or higher than interference with enjoyment. Visitors appear to be less sensitive to high-altitude jet overflight noise as compared with noise from tour aircraft. However, the data do not show this with statistical certainty and no definitive conclusions can be drawn. Visitor response to tour aircraft overflight noise differs between overlooks and short hikes. It appears that a respondent's familiarity with the site can influence visitor response to aircraft noise; that is, repeat visitors generally are more annoyed. The acoustic descriptors are combined by determining their respective values on the dose-response relationship curves at equal levels of percent annoyance/interference with enjoyment. Graphics are presented that show the %TAA and the change in aircraft sound exposure level ( $\Delta L_{AE,Tac}$ ) values for equal annoyance levels in 5% increments. They show that it is possible to reduce annoyance by reducing either %TAA or  $\Delta L_{AE,Tac}$ .

**“Soundscape Preservation and Noise Management,” Director's Order #47, Dec. 1, 2000–Dec. 1, 2004, National Park Service, Washington, D.C., 6 pp.**

The purpose of this Director's Order was to articulate NPS operational policies that would require, to the fullest extent

practicable, the protection, maintenance, or restoration of the natural soundscape resource in a condition unimpaired by inappropriate or excessive noise sources. This order included an outline of the responsibilities of a park director to incorporate natural soundscape preservation as part of the operating policies of the park. Public Law 106-181 and implementing FAA regulations provide for a cooperative FAA/NPS public planning process to develop an ATMP when and where a commercial air tour operator seeks to provide tours over units of the national park system (the legislation exempts Grand Canyon National Park, Rocky Mountain National Park, and parks in Alaska from the process). The Service will assist the FAA in this localized process and determine the nature and extent of impacts on natural and cultural resources and visitor experience opportunities. This order provided a broad structure for consideration of soundscape preservation in the park facilities' planning process, but did not address specific noise level goals or specific programs.

**Zannin, P.H.T., A.M.C. Ferreira, and B. Szeremetta, “Evaluation of Noise Pollution in Urban Parks,” *Environmental Monitoring and Assessment*, Vol. 118, 2006, pp. 423–433.**

The study provides an evaluation of noise pollution in six urban parks located in the city of Curitiba, Brazil. Equivalent noise levels ( $L_{eq}$ ) were measured at 303 points (each point measured during 3 min) spread throughout the parks. Measured values were compared with limits allowed by local legislation, and the parks were thus classified as “acoustically polluted or unpolluted.” Measured values were also evaluated according to international legislation: Decree no. 12 of the City Council of Rome, DIN 18005 for German cities, the WHO, and EPA. Urban parks in the downtown area of Curitiba, surrounded by roads with heavy traffic and in the midst of intense commercial activities, do not satisfy any of the standards used. The most noise-polluted parks in Curitiba were the Public Walk Park and the Botanical Garden Park, with measured  $L_{eq}$  of 64.8 dBA and 67 dBA. The study provides a useful comparison of various international noise limits that may be applied to parks. However, the study is primarily a measurement exercise that provides some interesting descriptions of Brazilian driving habits and age and condition of the local motor vehicles. The study does not survey park users or include any specific information concerning the impacts that the high noise levels have on park use.

## **CHAPTER EIGHT: AVIATION LOW-FREQUENCY NOISE AND VIBRATION**

Low-frequency noise represents a special issue warranting a separate section in this synthesis on the effects of aviation noise. The issue is that outdoor A-weighted noise measurements may not appropriately reflect LFN levels that can induce potentially annoying secondary emissions inside residences near runways. The A-weighted decibel applies an adjustment to measured sound levels to account for the

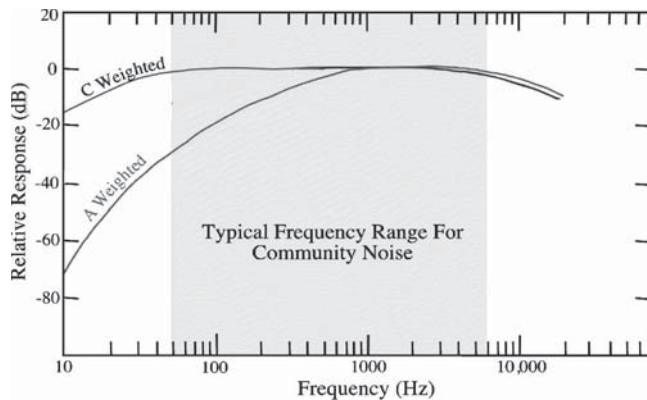


FIGURE A12 A- and C-weighting curves.

human judgment of loudness. Figure A12 shows the A-weighting and C-weighting curves commonly used in community and occupational noise settings, respectively. People do not hear low frequencies as well as higher frequencies. For example, a sound at 200 Hz would have to be approximately 11 dB louder than a sound at 1,000 Hz for people to judge them as the same loudness. At 50 Hz the sound would have to be 30 dB louder to be judged as the same loudness. Although in most cases this frequency weighting reflects a person's perception of loudness, there are special cases where the A-weighted decibel may not adequately describe the impact of LFN.

The special cases in aviation are for observers located near airport runways where the jet noise at the start of take-off roll and/or the jet noise from thrust reversers may result in LFN levels that are not typical of other areas in the airport environs. LFN is not absorbed by the atmosphere, nor blocked by terrain and buildings, as well as higher frequencies. Therefore, LFN can sometimes be audible at greater distances than higher frequency noise.

LFN has been studied at a small number of airports where community concern about LFN has been acute. The general conclusion from these studies is that LFN can induce structural building response that may cause the rattle of windows, fixtures, pictures, and the like. The LFN-induced rattle has been identified as causing annoyance well beyond the annoyance expected based on noise level alone. An Expert Panel convened by the communities around Minneapolis–St. Paul International Airport (MSP) (*Findings of the Low-Frequency Noise Expert Panel* 2000) produced a controversial report that described a new noise metric and dose-response relationship for LFN. Although FICAN concurred with some of the MSP findings, it was largely critical of the MSP study. It did not agree that vibration impact (rattle) should be predicted using sound level as a surrogate for vibration level, and noted that the MSP study did not include vibration measurements. FICAN concluded that “it is premature to consider adopting LFSL [low-frequency sound level] and the impact criteria without further research” (Federal Interagency Committee on Aviation Noise 2002).

At the present time there is no universally accepted method of describing LFN and its impact on communities around airports. Some efforts to use the C-weighting for this purpose have been noted. The C-weighting, although more sensitive to LFN, is equally sensitive to higher frequencies, as are A-weighted noise levels. Therefore, the only way to deduce the low-frequency content of a sound using the C-weighting is to compare the A- and C-weighted noise measurements. As seen in Figure A12, this approach represents a poor surrogate for making octave or one-third octave measurements at the lower frequencies, because the C-weighting will include sounds in frequencies above those that induce rattle. The MSP studies suggested that low-frequency-induced rattle can be described by measuring the sum of the maximum noise levels in the one-third octave bands between 25 Hz and 80 Hz.

The recently completed low-frequency study done under the PARTNER/COE Transport Canada programs (Hodgdon et al. 2007), under sponsorship of the FAA and NASA, examined many of these issues. The PARTNER Low Frequency Noise Study provides a comprehensive effort on describing LFN effects, but the subject remains controversial (Fidell and Harris 2007) and work remains to be done. Because the PARTNER study field measurements were limited to one airport with two less-common house construction types, additional measurements of interior LFN effects are needed.

Note that the previous discussion of LFN is applicable to aircraft noise, which includes many frequencies of sound (broadband). If the low-frequency sound consists of a pure tone, other interesting phenomena may occur; however, these are not relevant to aviation LFN.

### Summary

LFN is an issue for observers located near an airport runway where jet noise at the start of take-off roll and/or the thrust reversers may cause LFN impacts not common to other parts of the airport environs. It is unique in that it may not be adequately described by the A-weighted decibel, and may cause structural vibration that may lead to increased annoyance resulting from rattling of windows, bric-a-brac on shelves, or hangings on walls. LFN studies, such as the one done for MSP, have proven to be controversial and ongoing research is attempting to address the LFN issues. Among the outstanding issues are which metrics to use to describe LFN and what noise levels are compatible with residential land uses.

### Annotated Bibliography—Aviation Low-Frequency Noise and Vibration

**Atchley, A., “Low Frequency Noise Study,” Penn State, Purdue, Partnerships for AiR Transportation Noise and Emissions Reduction, Power Point Presentation, University**

**of California Berkeley Airport Noise Symposium, 2005, 35 pp.**

This report documents a study to investigate human response to the low-frequency content of aviation noise, or LFN. The study was conducted on behalf of the FAA by the Partnership for Air Transportation Noise and Emissions Reduction (PARTNER), an FAA/NASA/Transport Canada-sponsored Center of Excellence. The investigation was designed to address FICAN's comments on a previous LFN study conducted by a panel of experts at MSP and included both field measurements and laboratory studies. The major findings were

1. Start of take-off roll, acceleration down the runway, and thrust reversal generate high levels of LFN (below 200 Hz) at critical distances from runways (around 3,000 ft in the study), which can be annoying to people living in the vicinity of airports.
2. The Hubbard exterior sound pressure level threshold criteria should be used as a first assessment of the potential for LFN impact.
3. Assessment of impact should include both single and multiple events in areas where noise from multiple runways can affect a neighborhood simultaneously.
4. A-weighted sound pressure level ( $L_{Amax}$ ) and C-weighted sound pressure level ( $L_{Cmax}$ ) metrics correlate well with laboratory-based subjective response to indoor aircraft noise when LFN levels are low to moderate. Because these metrics are simple to implement, they should be used to predict subjective response to indoor aircraft noise when the levels are appropriate for A- and C-weightings and there are no high LFN levels.
5. When high LFN levels are present, Tokita and Nakamura thresholds can be used as indicators of the potential for annoyance owing to LFN. C-weighted sound exposure level ( $L_{CE}$ ) metric should be used as a single-number metric for assessing the potential for annoyance. Data lower than 50 Hz are needed to assess vibration/rattle annoyance. Loudness algorithms should include frequency content below 50 Hz to optimally correlate with the perception of LFN.
6. Overall the findings suggest that people are responding to the broad spectral content and any predictive metric should quantify the full broadband noise.
7. The risk of window rattle is lowered with preload and avoiding resonance response in the design. Outdoor-indoor transmission class is a better rating for rattle-prone applications than sound transmission class commonly used in rating windows for transmission loss.

**Berglund, B. and P. Hassmén "Sources and Effects of Low-Frequency Noise," *The Journal of the Acoustical Society of America*, Vol. 99, No. 5, May 1996, pp. 2985–3002.**

This article presents an exhaustive review of the effects of LFN from many types of sources, including aircraft. LFN is common as background noise in urban environments and as

an emission from many artificial sources: road vehicles, aircraft, industrial machinery, artillery and mining explosions, and air movement machinery including wind turbines, compressors, and ventilation or air-conditioning units. The effects of LFN are of particular concern because of its pervasiveness owing to numerous sources, efficient propagation, and reduced efficacy of many structures (dwellings, walls, and hearing protection) in attenuating LFN compared with other noise. The authors state that intense (~150 dB) LFN appears to produce clear symptoms including respiratory impairment and aural pain. The authors concluded that

although the effects of lower intensities of low-frequency noise are difficult to establish for methodological reasons, evidence suggests that a number of adverse effects of noise in general arise from exposure to low-frequency noise: Loudness judgments and annoyance reactions are sometimes reported to be greater for low-frequency noise than other noises for equal sound-pressure level; annoyance is exacerbated by rattle or vibration induced by low-frequency noise; speech intelligibility may be reduced more by low-frequency noise than other noises except those in the frequency range of speech itself, because of the upward spread of masking.

Shortcomings in current research are identified and recommendations for further research are made.

***Findings of the Low-Frequency Noise Expert Panel, Volumes I, II, and III, City of Richfield and Metropolitan Airports Commission (MAC), Minn., Apr. 2000, 219 pp.***

This report documents the findings of an Expert Panel selected to review LFN. These findings were controversial and subject to critical review by FICAN (Federal Interagency Committee on Aviation Noise 2002) followed by response from the authors. The history of the study is that the city of Richfield, Minnesota, and the Metropolitan Airports Commission (MAC) agreed in December 1998 to undertake detailed studies of existing and potential impacts of low-frequency aircraft noise in communities around MSP. The agreement established a Low-Frequency Noise Expert Panel (the Expert Panel) and a Low-Frequency Noise Policy Committee (the Policy Committee). This three-volume document reflects the views of the majority of the Expert Panel. Volume I contains an Executive Summary; Volumes II and III contain supporting technical detail and appendices, respectively. The primary effect of current and anticipated low-frequency aircraft noise on the residents of neighborhoods near MSP is rattle-related annoyance. Low-frequency aircraft noise (apart from that of low-altitude, high-speed military aircraft) poses no known risk of adverse public health consequences, nor a risk of structural damage. Under the expected circumstances of residential exposure, low-frequency aircraft noise will not interfere with indoor speech, nor is this LFN itself likely to awaken people. The Expert Panel recommended that the Policy Committee adopt the sum of the maximum sound levels in the 25 Hz to 80 Hz one-third octave bands LFSL during individual aircraft noise

events as the preferred descriptor of low-frequency aircraft noise in the vicinity of MSP. The Expert Panel further recommended “that the Policy Committee adopt the arithmetic average of the greatest low-frequency sound levels of aircraft noise events in excess of LFSL = 60 dB as the measure of effective low-frequency aircraft noise dose” (this value is intended to represent the maximum low-frequency sound level that occurs a few times each day in neighborhoods near runways, because that was the most common response to questioning about the frequency of annoyance produced by rattle and vibration). A social survey of the annoyance of low-frequency aircraft noise and noise-induced rattle was conducted in a Minneapolis neighborhood. Annoyance resulting from low-frequency aircraft noise was strongly related to LFSL values. Windows were the most cited sources of rattling noises. In terms of mitigating LFN, the report states that the LFN reduction provided by residences can be increased by approximately 5 dB by adding a heavy layer to the outside or inside (e.g., the equivalent of a 1-in. heavy-weight plaster/stucco skin resiliently supported from the standard construction). The upper limit of improvement is approximately 10 dB. “Such an improvement would require use of a complex structure (e.g., a brick wall with minimal openings toward the noise source, and/or an insulated cavity wall with separately supported interior and exterior cladding and multi-pane windows of limited size).”

**Federal Interagency Committee on Aviation Noise, *FICAN on the Findings of the Minneapolis–St. Paul International Airport (MSP) Low-Frequency Noise (LFN) Expert Panel*, Apr. 2002, 7 pp.**

FICAN developed extensive comments on the MSP low-frequency study, concurring with some findings, but disagreeing with others. FICAN concurred with the findings that LFN from civil aircraft will not pose a public health risk, risk of structural damage, or an increase in indoor SI. FICAN disagreed with the panel’s findings that LFN-induced rattle increased annoyance, citing NASA studies of helicopter noise. It was critical of a vibration impact (rattle) being predicted or measured by sound level in lieu of an actual vibration measurement. The MSP study did not include vibration measurements. In terms of the LFSL metric proposed by the MSP Expert Panel,

FICAN is not comfortable with the proposed measure on several grounds. First, LFSL, an artificially constructed single event noise metric that is the average of the maximum sound levels in the one-third octave bands from 25 to 80 Hz during a given event. In other words, the metric will often be made up of one-third octave band frequency data measured at different times during a particular event. No other noise metric use in airport analysis is artificially constructed in such a manner. FICAN finds little scientific justification for this artificial construction.”

FICAN considers the 60 dB LFSL “very nebulous.” Among the criticisms is again that it is a sound-level base

surrogate for vibration. FICAN further criticizes the questionnaire used in the social survey as well as the consideration of survey data from the two airports considered (El Segundo data near Los Angeles International Airport was also used in the Expert Panel work). Finally, FICAN concluded that “it is premature to consider adopting LFSL and the impact criteria without further research.”

**Fidell, S., A. Harris, and L. Southerland, *Response to FICAN Comments on Low-Frequency Noise Expert Panel Report, Letter to Mr. Alan Zusman, Chair, FICAN, June 2003, 18 pp.***

The three authors of the MSP Expert Panel prepared detailed responses to the FICAN comments and disagreements. The response criticizes the “generally dismissive” tenor of the FICAN comments and responds in detail to each comment. For example, in responding to the FICAN criticism of the rattle-induced increase in annoyance by citing a NASA study, the Expert Panel points out the NASA study was based on the A-weighted decibel and not comparable to the MSP study while further pointing to studies that support the rattle-induced annoyance theory. The Expert Panel further points out that it is not necessary to conduct vibration measurements to identify rattle and that such vibration measurements would be subject to much variation based on how and where such measurements were made. With respect to the claim that LFSL is “artificial,” the Expert Panel argues that such a finding is misleading and inconsistent with virtually all metrics constructed to predict community response to aircraft noise. “In short, there is no technical basis for FICAN’s rejection of LFSL as artificial and unscientific that does not apply in equal or greater measure to other noise metrics that FICAN endorses to describe aircraft noise.” The Expert Panel provides a detailed argument supporting LFSL 60 dB as a dose threshold and responds in detail to each of the FICAN criticisms. It is clear that the Expert Panel has demonstrated a benefit to using a sound level measurement as a surrogate for vibration measurements for purposes of identifying rattle resulting from aircraft noise. Finally, the three authors concluded that “the understandings documented in the report of the Low Frequency Noise Expert Panel are adequate to support at least interim criteria for assessments of low-frequency aircraft noise impacts. Although further research can document additional findings of the same sort as those of the Expert Panel report, it is unlikely that further studies will yield a marked improvement in the technical basis for regulatory policy concerning effects of low-frequency aircraft noise in residential areas near airports.”

**Fidell, S. and A. Harris, “Critique: PARTNER LFN Study Fails to Provide Useful Information, Harris, Fidell Say,” *Airport Noise Report*, Vol. 19, No. 42, Dec. 7, 2007, pp. 191–193.**

Two of the authors of the MSP Low-Frequency Noise Study provided a critique of the PARTNER Low-Frequency Noise

Study in the weekly industry newsletter *Airport Noise Report*. Some of the more significant comments in the authors' critique are that

The PARTNER study did not produce information that would permit airports to contour or otherwise accurately predict low-frequency aircraft noise doses in one-third octave bands within communities at particular distances and orientations from runways; nor did it shed any new light on the prevalence of annoyance with low-frequency aircraft noise in airport communities; nor did it identify any practical methods for predicting the occurrence of noise-induced rattle in common wood frame residential construction.

In addition the authors state that the study "fail[s] to emphasize the limited range of rattle signals tested in the PARTNER study and the inconsistency of the finding with those of other laboratory studies," and "the finding that C-weighted noise levels correlated better with laboratory judgments of the annoyance (of sounds that contained limited amounts of rattle) than "metrics specifically designed to quantify low-frequency noise impact" implies little about the ability of C-weighted noise levels to usefully predict the prevalence of annoyance among residents of neighborhoods near runway thresholds and sidelines."

**Fidell, S., L. Silvati, K. Pearsons, and R. Howe, "Field Study of the Annoyance of Low-Frequency Runway Sideline Noise," *The Journal of the Acoustical Society of America*, Vol. 106, No. 3, Sep. 1999, pp. 1408–1415.**

This article includes the measurement of LFN near the sideline to the runways at Los Angeles International Airport, as well as surveys of residents' response to the LFN. A LFN to annoyance dose-response curve is presented. The authors explain that "outdoor A-weighted noise measurements may not appropriately reflect LFN levels that can induce potentially annoying secondary emissions inside residences near runways." Contours of LFN levels were estimated in a residential area adjacent to a busy runway from the multi-site measurements of runway sideline noise in the one-third octave bands between 25 Hz and 80 Hz, inclusive. Neighborhood residents were interviewed to determine the prevalence of annoyance attributable to runway low-frequency sideline noise (frequencies below 100 Hz), and of its audible manifestations inside homes (such as rattles). "Survey respondents highly annoyed by rattle and vibration were concentrated in areas with low-frequency sound levels resulting from aircraft operations in excess of 75 to 80 dB."

**Hodgdon, K., A. Atchley, and R. Bernhard, "Low Frequency Noise Study," Partnerships for AiR Transportation Noise and Emissions Reduction Am FAA/NASA/Transport Canada sponsored Center of Excellence, Report No. Partner-COE-2007-001, Apr. 2007 (public release date Nov. 26, 2007), 105 pp.**

This report documents a study to investigate human response to the low-frequency content of aviation noise, or LFN. The

investigation was designed to address FICAN's comments on a previous LFN study conducted by a panel of experts at MSP and included both field measurements and laboratory studies. The major findings were:

1. Start-of-takeoff-roll, acceleration down the runway, and thrust reversal generate high levels of LFN (below 200 Hz) at critical distances from runways (around 3,000 ft in the study), which can be annoying to people living around airports.
2. Hubbard exterior sound level criteria works well as a first level assessment tool for vibration/rattle due to LFN.
3. A-weighted Sound Pressure Level ( $L_{Amax}$ ) and C-weighted Sound Pressure Level ( $L_{Cmax}$ ) metrics correlate well with laboratory based subjective response to indoor aircraft noise when LFN levels are low to moderate. The same holds for rattle annoyance (again for low to moderate level LFN). Also, multiple low level LFN events may cause rattle (i.e., simultaneous multiple runway operations).
4. When high levels of LFN are present, Tokita & Nakamura thresholds with C-Weighted Sound Exposure Level (LCE) metric should be used as an indicator of potential for LFN annoyance. The low-frequency noise based metrics did not perform as well as LCE. Data lower than 50 Hz is needed to assess vibration/rattle annoyance.
5. The risk of window rattle is lowered with preload and avoiding resonance response in the design. Outdoor-Indoor Transmission Class (OITC) is a better rating for rattle prone applications than Sound Transmission Class (STC) commonly used in rating windows for transmission loss.

The report further recommended that the methods used in the noise models, such as the INM, be investigated to determine if the levels and directivity of thrust reverser noise are adequately accounted for in the models. With respect to ranking tests, the study concluded that audible rattle was not ranked as the most annoying probably owing to the louder overall noise content of the signal. The report also concluded that the A-weighted decibel correlated well with the subjective rankings. Two homes were used in the study, a brick home and stone home located on the Dulles International Airport property.

That the A-weighted decibel did so well is curious and unexpected. This may suggest that the Dulles studies included more noise in the higher frequency bands than is expected in a home where more of the high-frequency noise has been attenuated by the atmosphere or the structure.

The study found that for purposes of evaluating the performance of home mitigation strategies, sound transmission class is not an adequate measure of transmission loss of building elements such as windows, and that outdoor-indoor transmission class is a better measure where LFN is a concern.

The study is a comprehensive review of measurement data, survey rankings, and comparison of noise metrics. The validation of the Tokita and Nakamura thresholds for assessing LFN is particularly useful. However, the results are still quite controversial, as can be seen in the critique of this study made by two of the MSP low-frequency study authors.

## CHAPTER NINE: AVIATION NOISE EFFECTS ON WILDLIFE AND DOMESTIC ANIMALS

It is difficult to study the effects of aviation noise on wild animals in their own environment and under natural conditions. However, as urban areas of the United States continue to grow, protecting natural habitats and their inhabitants becomes a greater concern. Although noise is often defined as unwanted sound for humans, it has been suggested that it is also the case for animals (Bowles and Yack 2004). “Noise” is best defined as any sound that (1) causes hearing loss; (2) masks signals needed for communication, navigation, prey detection, predator avoidance, and environmental monitoring; (3) effects non-auditory health; (4) effects biologically significant changes in behavior; and (5) alters population, including declines in abundance, changes in distribution, or reproductive failures.

The effects of aviation noise on animals have been studied extensively over the past 20 years, with much of the work being conducted by U.S. Air Force-sponsored researchers. The studies have revealed that the effects are highly species-dependent and that the degree of the effect may vary widely. Responses of animals to aircraft noise vary from almost no reaction to virtually no tolerance of the sound. The question of how adaptable animals are remains largely unanswered. Both wild and domesticated animals have been studied, although more research has centered on domesticated or laboratory animals (such as rats and mice). Most research is observation-based, and tends to be high quality.

A high-quality study of helicopter overflights over a Mexican Spotted Owl habitat in New Mexico (Delaney et al. 1999) identified noise levels that caused the owls to exhibit alert behavior or flush. To evaluate nesting and non-nesting spotted owl responses to helicopter noise, the authors measured flush frequency, flush distance, alert behavior, response duration, prey delivery rates, female trips from the nest, and nest attentiveness during manipulated and non-manipulated periods. The owls’ responses were more correlated to distance from the noise source rather than the noise levels themselves. Observations showed that noise sources on the ground were of greater concern than noise sources in the air.

Fish have been reported to respond to noise within their environment, such as underwater explosions and the sound of fishing vessels; however, aircraft noise is very rarely a part of that environment. Most airborne sound is reflected off the water’s surface, with only a small fraction actually penetrating the air–water boundary.

Although it is not possible to generalize a dose-response relationship for all wildlife and farm animals, a summary of the findings of effects of noise and sonic booms is provided in Tables A1 through A4. Although these are not definitive

dose-response relations, the tables are indicative of the species studied and of some of the effects observed (Manci et al. 1988). This work was done in 1988 and although there has been a significant body of work done since, there are no concise summaries that cover such a broad range of species. There are no generalized dose-response curves that cover all or most species.

### **Annotated Bibliography—Aviation Noise Effects on Wildlife and Domestic Animals**

**“Annotated Bibliography, Impacts of Noise and Overflights on Wildlife,” National Park Service, Natural Sounds Program, Washington, D.C., 2005, 32 pp.**

This is a very comprehensive annotated bibliography with the results presented in a three-column format. Included are title, citation, and abstract. It includes 76 documents divided into the following categories: literature reviews, physiological effects of noise, effects of non-aviation noise sources, overflights and aircraft noise, ecological and population impacts from noise, and habituation. In the section on overflights and aircraft noise, 31 titles are reviewed covering a broad range of species and aircraft types. It is impossible to generalize or summarize the results of such a broad range of studies in this synthesis; however, it is clear that some reports disclosed dramatic effects (“Mountain Sheep and Helicopter Surveys: Ramifications for the Conservation of Large Mammals”), although others reported that other factors overwhelm the noise effects (“Effects of Fixed-Wing Military Aircraft Noise on California Gnatcatcher Reproduction”).

**Bowles, A.E. and T. Yack, *Noise Impacts on Wildlife in the Tahoe Basin: Review of TRPA Noise Criteria Applied to Animals*, Hubbs–SeaWorld Research Institute, Orlando, Fla., Nov. 2004, 90 pp.**

This report is a comprehensive review of the noise criteria established to protect wildlife in the Tahoe Basin. The Tahoe Regional Planning Agency (TRPA) is tasked to maintain significant scenic, recreational, educational, scientific, natural, and public health values in the Lake Tahoe Basin and environs. TRPA initiated the present review to determine whether current regulations adequately protect Special Interest Species from exposure to noise from human-made sources such as aircraft, off-highway vehicles, and road traffic. The human voice and amplified sources such as radios and “boomboxes” were considered as well. This report summarizes animal responses to each of these noise types and the potential for biologically important consequences. It includes a detailed literature review of current research on noise impacts on a wide variety of species. The report addresses hearing loss, as well as

indirect effects caused by noise as a signal that can occur even at low exposure levels. Signals are sounds that animals can use to detect and track potentially dangerous sources over long ranges

TABLE A1  
SOME POSSIBLE NEGATIVE EFFECTS OF NOISE AND SONIC BOOMS ON ANIMALS

Species	Type of Noise	Effect
Domestic Livestock		
Various species	Sonic boom (80–370 mN/m <sup>2</sup> ); low-level subsonic flights (50–200 m) (Nixon et al. 1968; Bond et al. 1974; Espmark et al. 1974)	Startle reaction
Dairy cow	Exploding paper bags (Ely and Petersen 1941) General noise (105 dB) (Kovalcik and Sottnik 1971) Tractor engine sound (97 dB) (Broucek et al. 1983) General noise (1 kHz, 110 dB) (Broucek et al. 1983)	Cessation of milk ejection Reduces feed consumption, milk yield, and rate of milk release Increased glucose concentration and leukocyte counts in the blood; reduced level of hemoglobin Increase in glycemia, nonesterified fatty acids, creatin; decrease in hemoglobin and thyroxin concentration
Goat	Jet noise (Sugawara et al. 1979)	Reduced milk yield
Swine	General noise (108–120 dB) (Borg 1981)  General noise (93 dB) (Dufour 1980)  Recorded aircraft noise (120–135 dB) (Bond et al. 1963)	Influence on hormonal system: increase of plasma 11-OH-corticosterone and catecholamines; decreased corticosteroid level Aldosteronism (excess secretion of aldosterone from the adrenals) Increased heart rate
Sheep	White noise (100 dB) (Ames and Arehart 1972) White noise (90 dB) (Ames 1978) General noise (4 kHz, 100 dB) (Ames 1978)	Higher heart rate and respiration rate; lower feeding efficiency Decreased thyroid activity Increased number of corpora lutea; more lambs/ewe
Wild Ungulates		
Reindeer	Sonic booms (35–702 Pa) (Espmark 1972)	Slight startle responses: raising of head, pricking the ears, scenting the air
Caribou	Low-altitude aircraft (<200 ft): fixed-wing, helicopter (Klein 1973) Low-altitude aircraft (<500 ft): fixed-wing, helicopter (Calef et al. 1976) General noise (Calef 1974)	Running and panic behavior  Escape or strong panic reactions  Increased incidence of miscarriages; lower birth rates
Pronghorn	Low-altitude helicopters (150 ft, slant range of 500 ft; 77 dBA) (Luz and Smith 1976)	Running
Laboratory Rodents and Rabbits		
Various species	General noise (150 Hz–40 kHz, 132–140 dB) (Anthony and Ackerman 1957)	Anxiety-like " behavior
Guinea pig	General noise (128 dB SPL) (Beagley 1965); simulated sonic booms (130 dB) (Hajeau-Chargois et al. 1970)	Anatomical hearing damage; hearing loss
Mouse	Simulated sonic booms (Reinis 1976) Intermittent noise (110 dB) (Anthony and Ackerman 1955) Recorded subway noise (105 dB SPL) (Busnel and Holin 1978)  Continuous, high-intensity jet engine noise (127 dB); random onset noise (103–110 dB); high-frequency noise (113 dB) (Nawrot et al. 1980) General noise (106 dB) (Ishii and Yokobori 1960)	Auditory damage; inner ear bleeding Decrease in circulating eosinophils; adrenal activation Longer time interval between litters; lower weight gain of young; increased incidence of miscarriage, resorption, and malformations Decreased pregnancy rate (all groups); decrease in number of implantation sites per litter and fetolethal effects (high-intensity jet noise) Teratogenic effects
Rat	General noise (105 dB SPL) (Moller 1978; Borg 1979, 1981) General noise (80 dB SPL) (Borg 1978a,b,c) General intermittent sound (Buckley and Smokler 1970) Recorded thunderclaps (98–100 dB SPL, 50–200 Hz) (Ogle and Lockett 1966) Electric buzzer (110 dB) (Sackler et al. 1959)  General noise (1 kHz, 95 dB) (Fell et al. 1976) General noise (120 Hz, 95–105 dB) (Jurtschuk et al. 1959)	Hearing loss; damage to inner ear structure  Vasoconstriction Rise in blood pressure; hypertension  Increased urinary excretion of sodium and potassium; excretion of oxytocin and vasopressin Decreased adrenal, body, thymus, spleen, liver, pituitary, ovary, and uterine weights; slight gain in thyroid weight; increased production of ACTH; inhibition of gonadotrophin, ovarian hormones, and possible inhibition of the thyrotrophic and thyroid hormones Suppressed thyroid activity Reduced glutathione levels in blood, increased adrenal weights and ascorbic acid; decrease in total adrenal cholesterol

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TABLE A1  
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Species	Type of Noise	Effect
Domestic rabbit	Intermittent noise (95 dB) (Hrubes and Benes 1965)	Increased secretion of catecholamines in the urine; increased free fatty acids in the blood plasma; increased weight of the adrenals; inhibition of growth
	General noise (92 dB) (Gamble 1982)	Persistent vaginal estrus prolonged vaginal cornification; higher preweaning mortality of young
	White noise (102–114 dB) (Friedman et al. 1967)	Change in the hypothalamus
	Electric bell (95–100 dB) (Zondek and Isacher 1964)	Enlarged ovaries; persistent estrus; follicular hematomas
	General noise (Zondek 1964)	Decreased fertility
	White noise (107–112 dB) (Nayfield and Besch 1981)	Increased adrenal weights; decreased spleen and thymus weights
Chinchilla	White noise (102–114 dB) (Friedman et al. 1967)	Change in the hypothalamus; higher plasma cholesterol and plasma triglycerides; fat deposits in the irises of the eyes; more aortic atherosclerosis and higher cholesterol content in the aortas
	Electric bell (95–100 dB) (Zondek and Isacher 1964)	Enlarged ovaries; persistent estrus; follicular hematomas
Wild Rodents		
Desert kangaroo rat	ORV noise (78–110 dB SPL) (Brattstrom and Bondello 1983)	Temporary threshold shift in hearing
House mouse (feral)	Aircraft (110–120 dB) (Chesser et al. 1975)	Increased adrenal weights
Cotton rat	Recorded aircraft noise (110 dB SPL) (Pritchett et al. 1978)	Increased body weights; increased secretion of ACTH
	High-pitched whistles (Hepworth 1966)	Enlarged ovaries; persistent estrus; follicular hematomas
Carnivores		
Domestic cat	Noisy laboratory (Liberman and Beil 1979)	Hearing threshold shifts; loss or damage to hair cells of inner ear
	General noise (100–1,000 Hz) (Miller et al. 1963)	Hearing threshold shifts
Domestic dog	Sudden loud noises (Stephens 1980)	Increase in plasma corticosteroid concentrations
Farm-raised mink	Simulated sonic booms (167–294 mN/m <sup>2</sup> ) (Travis et al. 1974)	Brief startle reaction
Wolf/grizzly bear	Low-altitude fixed-wing aircraft and helicopters (Klein 1973)	Startle reaction; running
Aquatic Mammals		
Beluga whale	Boat traffic (Acoustical Society of America 1980)	Easily displaced
Pinnepeds	Sonic booms (80–89 dBA SPL) (Jehl and Cooper 1980)	Startle reactions
Elephant seal	Impulse noise created by a carbide pest control cannon (115.6–145.5 dBA) (Stewart 1982)	Alert behavior
Sea lion	Simulated boom (Stewart 1982)	Left beach during non-breeding season and went into surf
Other Mammal Groups		
Rhesus monkey	General noise [ $L_{eq}$ (24): 85 dB] (Peterson et al. 1981)	Increased blood pressure

Source: Manci et al. 1988.

and animals respond in the way they would to other types of stimuli (visual or olfactory cues). When noise is a signal, animals often respond as soon as the sound becomes readily audible, within 10 dB or so of the noise floor. In such cases, approach distance is as important at sound level as a measure of the potential for impact.

For this reason data on both noise and approach distances are considered in this review. Although noise is often

defined as unwanted sound for humans, the authors suggest that

for animals “noise” is best defined as any sound that (1) causes hearing loss; (2) masks signals needed for communication, navigation, prey detection, predator avoidance, and environmental monitoring; (3) effects non-auditory health; (4) effects biologically significant changes in behavior; and (5) alters population including declines in abundance, changes in distribution, or reproductive failures.

TABLE A2  
SOME POSSIBLE NEGATIVE EFFECTS OF NOISE AND SONIC BOOMS ON BIRDS

Species	Type of noise	Effect
Poultry		
Domestic chicken	Simulated sonic booms (156.3 dB) (Jehl and Cooper 1980)	Decrease in weight of 19-day-old chicks
	General noise (100 dB) (Borg 1981)	Increase in 11-hydrocorticosteroid in blood plasma
	Recordings of aircraft flyovers (115 dB) (Stadelman 1958b)	Interruption of brooding
Japanese quail	Aircraft noise (3 or more days) (Hamm 1967)	Reduced egg production by keeping hens from feed and water due to noise stress
	General noise (100–8,000 Hz, 80 dB) (Woolf et al. 1976)	Accelerated hatching
Laboratory Birds		
Canary	White noise (95–100 dB SPL) (Marler et al. 1973)	Hearing loss (20–60 dB)
Waterbirds		
Brant/geese	Low-altitude aircraft (helicopter, jet, propeller) and other human disturbances (Ward et al. 1986)	Flight response
	Snow goose	Cessna 185 (300–10,000 ft AGL) (Gunn and Livingston 1974)
Waterfowl/seabirds	Low-altitude aircraft (float-plane, fixed-wing, helicopter; 100–750 ft AGL) (Gunn and Livingston 1974)	Flight response
Seabirds	Sonic booms (72–89 dBA SPL) (Jehl and Cooper 1980)	Startle responses; flushed off nest
	Simulated sonic booms (155.6–145.5 dBA) (Stewart 1982)	Flushed and circled; returned to roost within 2–10 min
Sooty tern	Frequent sonic booms (Austin et al. 1970)	98% reduction in reproduction of the colony
Herring gull	Low-altitude supersonic transports (Burger 1981)	More fighting; lower clutch size due to broken eggs during fighting bouts
Hérons	Helicopter flyovers; fixed-wing (60–120 m) (Kushlan 1979)	Alert reaction
Lapland longspur	Low-altitude helicopters (Gunn and Livingston 1974)	Lower hatching and fledging success; higher nest abandonment; premature disappearance of nestlings
Raptors		
Bald eagle	Aircraft (jet, propeller) (Fleischner and Weisberg 1986)	“Turning of the head to at the jet” (5% of the observations), flying from a perch site (5%)

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TABLE A2  
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Species	Type of noise	Effect
Eagles/hawks/ falcons	Low-altitude jets and sonic booms (82–114 dBA) (Ellis 1981)	“Noticeably alarmed” responses
	Helicopter (White and Sherrod 1973)	Panic, frantic escape behavior when helicopter appeared from over the top of a cliff
California condor	Blasting, drilling, sonic boom, low-altitude aircraft (Shaw 1970; Wilbur 1978)	Adults flush from nest; some nests abandoned
Songbirds		
Unspecified	Sonic boom (1.15 mean psf) created by F-111 jets (Higgins 1974)	Continuous songs of birds were completely silenced 4–8 s before arrival of the audible sonic boom; “raucous discordant cries” for a few seconds when boom was audible, returned to “normal songs” within 10 s after the audible boom
Raven	Sonic boom (Davis 1967)	Raucous calling, flapping, soaring, and chasing by groups of ravens

Source: Mancini et al. 1988.

The authors go on to state that whereas hearing damage and masking are important potential effects, few studies on wildlife have focused on them.

Instead, a great many studies have documented disturbance-induced defensive behaviors such as alerting, defensive crouching, avoidance, and flight. The effect of inducing these behavioral responses must be estimated with caution. Often, these behaviors are simply an indication that animals have detected an unfamiliar or unexpected sound. In such cases, habituation with no significant effect can be expected.

The authors provide some important guidance on measurement techniques when considering noise impacts on wildlife including:

- Long-term average metrics such as CNEL that include penalties for noise emitted at night should not be applied to animals without justification.
- If animals hear well outside the range of human hearing and are exposed to sound sources with energy in that part of their range, A-weighting should not be used.
- Criteria to prevent noise masking should not be based on average measures ( $L_{eq}$ , average SPL), especially if noise consists of periods of relative quiet punctuated by infrequent loud noises (e.g., flights from an airport). Median sound level ( $L_{50}$ ) is a better measure.
- SEL is preferable to  $L_{max}$  as a metric for describing event-related exposure in animals because it allows an

TABLE A3  
SOME POSSIBLE NEGATIVE EFFECTS OF NOISE AND SONIC BOOMS ON FISH

Species	Type of noise	Effect
Rainbow Trout	Sonic boom (max. 4,16 psf) (Rucker 1973)	Slight behavioral reaction
Herring	Taped sounds from a fishing fleet (Schwarz and Greer 1984)	Avoidance, alarm, and startle responses
	Sound pressures (2–18 Pa) on wall of tank (Blaxter and Hoss 1981)	Startle responses
Sheepshead Minnow/Longnose Killifish	Tanks exposed to high noise levels (up to +30 dB/ub) (Banner and Hyatt 1973)	Reduced growth rates; reduced viability of minnow eggs
Guppy	Simulated sonic booms (Dancer et al. 1973)	Short duration reactions
Asian Aya	Underwater sound (200–600 Hz, 72–80 dB) (Konagaya 1980a)	Jumping response
Unspecified	Underwater dredging sound (38–75 dB) (Konagaya 1980b)	Negative responses; avoidance of the acoustical field of the worksite

Source: Mancini et al. 1988.

TABLE A4  
SOME POSSIBLE NEGATIVE EFFECTS OF NOISE ON AMPHIBIANS, REPTILES, AND INVERTEBRATES

Species	Type of Noise	Effect
Amphibians		
Spadefoot toad	Recorded motorcycle sounds (95 dBA) (Brattstrom and Bondello 1983)	Elicited emergence from burrows, a potentially detrimental impact on the population if occurs outside the normal breeding season
Reptiles		
India browntree snake	Airplane passing overhead (Yahya 1978)	Alert behavior
Desert iguana	ORV noise (114 dB for 1 and 10 h) (Bondello 1976)	Shift in hearing threshold; permanent hearing sensitivity loss
Mojave fringed-toed lizard	Taped dune buggy sounds (95 dB) (Bondello et al. 1979)	Hearing loss after less than 9-min exposure
Invertebrates		
Brown shrimp	Aquarium noise (25–400 Hz, 30 dB) (Lagardere 1982)	Decreased food uptake, growth, and reproduction; increased cannibalism and mortality
Indian-meal moth	General noise (120–2,000 Hz) (Kirkpatrick and Harein 1965)	75% reduction in emerging adults when larval stage was exposed
Corn earworm/flour moth	General noise (2–40 kHz) (Tsao 1969) Pulsed sound (50 kHz, 65 dB SPL) (Cutkomp 1969)	Cessation of movement 50% reduction in longevity; 59% reduction in the number of eggs per female
Honey bee	General noise (200–2,000 Hz, 107–119 dB SPL) (Frings and Little 1957; Little 1959)	Cessation of movement
Locusts	General noise (4 kHz, 80 dB SPL) (Shulov 1969)	Flying response
Midges	General noise (125 Hz, 13–18 dB above ambient noise) (Frings and Frings 1959)	Swarming of males around source

Source: Manci et al. 1988.

apples-to-apples comparison of high-amplitude sources with different durations.

**Delaney, D.K., T.G. Grubb, P. Beier, L.L. Pater, and M.H. Reiser, "Effects of Helicopter Noise on Mexican Spotted Owls," *The Journal of Wildlife Management*, Vol. 63, No. 1, 1999, pp. 60–76.**

This article presents the results of a very high-quality development of a dose-response relationship for helicopter and chain saw noise on Mexican Spotted Owls. Military helicopter training over the Lincoln National Forest in south-central New Mexico has been severely limited to protect nesting Mexican Spotted Owls. To evaluate nesting and non-nesting spotted owl responses to helicopter noise, the authors measured flush frequency, flush distance, alert behavior, response duration, prey delivery rates, female trips from the nest, and nest attentiveness during manipulated and non-manipulated periods.

Chain saws were included in our manipulations to increase experimental options and to facilitate comparative results. The authors analyzed stimulus events by measuring noise levels as un-weighted one-third-octave band levels, applying frequency weighting to the resultant spectra, and calculating the SEL for total sound energy and the 0.5-s equivalent maximum energy level ( $L_{eq}$  max 0.5-s) for helicopters, and the 10-s equivalent average energy level ( $L_{eq}$  avg. 10-s) for chain saws. An owl-weighting (dBO) curve was estimated to emphasize the middle frequency range where strigiform owls have the highest hearing sensitivity. Manipulated and non-manipulated nest sites did not differ in reproductive success or the number of young fledged. As stimulus distance decreased, spotted owl flush frequency increased, regardless of stimulus type or season. No spotted owl flushes were recorded when noise stimuli were greater than 105 m away. Spotted owls returned to pre-disturbance behavior within 10 to 15 min after a stimulus event. All adult flushes during the nesting

season occurred after juveniles had left the nest. Spotted owl flush rates in response to helicopters did not differ between non-nesting and nesting seasons. Spotted owls did not flush when the SEL noise level for helicopters was less than or equal to 102 dBO (92 dBA) and the  $L_{eq}$  level for chain saws was less than or equal to 59 dBO (46 dBA). Chain saws were more disturbing to spotted owls than helicopter flights at comparable distances, consistent with previous studies that showed that ground-borne human activity is considered more threatening than airborne activity. The data indicated that a 105-m buffer zone for helicopter overflights on the Lincoln National Forest would minimize spotted owl flush response and any potential effects on nesting activity.

**Kasello, P.A., "Synthesis of Noise Effects on Wildlife Populations," Presented at the 2005 International Conference on Ecology and Transportation, North Carolina State University, Raleigh, N.C., 2006, pp. 33–35.**

This report contains a partial summary of a literature review dealing with the effect of noise on wildlife, emphasizing the effects on birds. The review focuses on roadway noise and does not address aircraft noise. Beginning in the Netherlands and, later, in the United States, a series of studies has indicated that road noise has a negative effect on bird populations (particularly during breeding) in a variety of species. These effects can be significant with "effect distances" (i.e., those within which the density of birds is reduced) of 2,000 m to 3,000 m from the road. In these reports, the effect distances increase with the density of traffic on the road, being greatest near large, multi-lane highways with high densities. A similar effect has been reported for both grassland and woodland species. The author points out that it is important to note that (1) not all species have shown this effect and (2) some species show the opposite response, increasing in numbers near roads or utilizing rights-of-way. It is important to determine the cause of this effect and to utilize additional or alternative methods beyond population densities as the sole measure of effect distance, because the latter is susceptible to variation resulting from changes in overall population density.

**Larkin, R.P., *Effects of Military Noise on Wildlife: A Literature Review*, Center for Wildlife Ecology, Champaign, Ill., 1995, 87 pp.**

This literature review was sponsored by the U.S. Army Civil Engineering Research Laboratory and addresses the effects on wildlife of noise associated with military training activities, especially vehicle noise, artillery, small-arms and other blast noise, and helicopter noise. It does not address effects on aquatic animals and effects of fixed-wing aircraft engine noise and sonic booms. Physical (acoustic) and biological principles are briefly reviewed and traumatic, physiological, and behavioral effects are discussed in relation to population-level effects. Noise affects wildlife differently from humans and the effects of noise on wildlife vary from serious to nonexistent in

different species and situations. "Risk of hearing damage in wildlife is probably greater from exposure to nearby blast noise from bombs and large weapons than from long-lasting exposure to continuous noise or from muzzle blast of small arms fire." The author points out that the direct physiological effects of noise on wildlife, if present, are difficult to measure in the field; telemetric measurement of physiological variables such as heart rate has met with more success technically than as an indicator of health and survival.

Behavioral effects that might decrease chances of surviving and reproducing include retreat from favorable habitat near noise sources and reduction of time spent feeding with resulting energy depletion. Serious effects such as decreased reproductive success have been documented in some studies and documented to be lacking in other studies on other species. Decreased responsiveness after repeated noises is frequently observed and usually attributed to habituation. Vehicle noise can interfere with animal communication essential for reproduction. On the other hand, people afoot may cause stronger behavioral reactions than people in vehicles.

Responses to helicopters from several kilometers distant are documented; however, both the response to helicopters and the degree to which such a response may habituate with time vary greatly. Vehicles and helicopters pose difficulty for researchers trying to separate acoustic from visual or other indications of their presence. This exemplifies the concern that animal noise effects research is hampered by a preponderance of small, disconnected, anecdotal, or correlational studies as opposed to coherent programs of controlled experiments.

Comparability among studies is complicated by terms lacking generally accepted definitions (e.g., "disturbance") and by species differences. Future research should stress quantification of exposure of subjects to noise, experimental approaches such as broadcasting accurate recordings of sounds, and observer effects.

**Manci, K.M., D.N. Gladwin, R. Villela, and M.G. Cavendish, "Effects of Aircraft Noise and Sonic Boom on Domestic Animals and Wildlife: A Literature Synthesis," U.S. Air Force, Engineering and Services Center, U.S. Department of the Interior, Fish and Wildlife Service, June 1988, 87 pp.**

This report prepared by the U.S. Air Force and U.S. Department of the Interior provides a review of research on aircraft noise and sonic booms on wildlife. The authors point out that whereas much research has been done, many gaps still exist on the overall effects of aircraft noise on wildlife. The report has a brief discussion of the physics of sound and sources of aircraft noise. The main emphasis of the report is the extensive review of literature on noise and sonic boom effects on domestic animals and wildlife. A very useful portion of this review are the summary tables that illuminate the possible effects of noise and sonic booms for animals, birds, fish, and amphibians, reptiles, and invertebrates. The tables list the species, type of noise, and the potential effects. Discussions of various effects are also presented.

## CHAPTER TEN: AVIATION NOISE EFFECTS ON PROPERTY VALUE

Aviation noise has an indirect effect on property value. The effects of aviation noise on the buyer/seller determine the value of properties within proximity to aircraft operations. Extensive research describes the health, hearing, sleep disturbance, and annoyance effects of aviation noise on humans. From these studies, one can infer that humans naturally prefer quiet versus noise. The buyer includes the preference for less noise as part of the decision-making process when buying a home. The noise level at a given property location becomes one of many property features and amenities (e.g., number of rooms, crime rate, and proximity to schools) that make up the total value of that property.

The research conducted on the effects of aviation noise on property value used several different methodologies resulting in outcomes ranging from effects of substantial negative impact to effects of no impact. As expected, no research concluded that noise had positive effects on property value. Most studies attempted to control for and measure the noise variable alone. However, some studies coupled aviation noise with airport proximity, and therefore measured the positive and negative impacts of two variables that essentially could not be present without the other (or that were dependent on each other). Recent studies used GIS to not only analyze large amounts of data, but also integrate spatial autocorrelation to analyze the relationships among residential properties and other features in proximity; that is, other homes, airports, schools, roads, etc. Looking ahead at future research, one can expect that the powerful GIS tool will facilitate a better understanding of this topic.

Newman and Beattie (1985) summarized that “while an effect is observed it is considered an influence which is often offset by the advantages associated with ready access to the airport and employment opportunities.” Still, “studies indicate that a one decibel change in cumulative airport noise exposure (in DNL) usually results in a 0.5% to 2% decrease in real estate value.” Furthermore, “there seems to be a decline in the noise depreciation index over time. . . . This could be due either to noise sensitive people being replaced by those less bothered by noise, or to the enhanced commercial value of land near airports” (Newman and Beattie 1985). In contrast, when “comparing 1995–1999 with 2000–2002, we find that the noise discount is relatively larger during the latter period” (Cohen and Coughlin 2006). The FAA concluded that “because there are many other factors that affect the price and desirability of a residence, the annoyance of aircraft noise remains just one of the considerations that affect the market value of a home” (Newman and Beattie 1985).

A common technique included the use of hedonic price models (methods of estimating demand or pricing), which assigned values to numerous amenities of a residential property. The Nelson study (Nelson 2004) used a common coefficient

referred to as the Noise Depreciation Index (NDI) or noise discount, which is a decrease in property value per 1 dB DNL increase in noise level. Nelson cites *Noise and Prices* as the source for the NDI metric. NDI is commonly used to measure the effect of noise on property values. A meta-regression analysis of 33 NDI estimates conducted at 23 airports in the United States and Canada concluded that, “the cumulative noise discount in the U.S. is about 0.5% to 0.6% per decibel at noise exposure levels of noise 75 dB or less, while in Canada the discount is 0.8% to 0.9%” (Nelson 2004).

Since 1985, studies continue to show that aviation noise has negative effects on property value. A few studies, including a report conducted for the FAA, found that the NDI values increased as property values increased (Desai and Chen 1994), meaning that a low-priced home had a lower NDI when compared with a high-priced home. The report attempted to create a methodology that could be used nationwide to assess noise impacts on property value, but concluded, “the magnitude of this impact cannot be estimated at the national level, given the wide variation in the study results and the fact that only four airports were considered” (Desai and Chen 1994).

In contrast to most results, a study conducted in the city of College Park, Georgia, concluded that noise did not significantly affect the values of residential properties (Lipscomb 2003). Unique community demographics and characteristics attributed to this finding, whereas many community residents were employed in airport-related occupations. Therefore, distance from the airport (short work commute) was given greater importance during the home purchasing process.

Results from a survey of 200 realtors and 70 appraisers in 35 suburban communities near Chicago O’Hare International Airport found that “. . . a significant segment of buyers lack adequate information about the noise environment. Accordingly, their bid prices for properties will tend to be too high, and their expectations for the amenity levels of their dwellings will tend to be disappointed after the purchase” (Frankel 1991).

Although the survey showed that residential property turnover was not affected by aircraft noise, “over 75% of realtors indicated that the market required more time to move a noisy property than a quiet one, and 22% of them thought an appreciably greater amount of time was needed” (Frankel 1991). Frankel continued by classifying noise-affected property owners into two groups.

First, there are those who came to their locations when those locations were quiet, either because no airport yet existed or because the scope of its operations was limited, and who later became subject to aircraft noise. Second, there are those who purchased properties after the establishment of the airport and its current level of operations, acquiring those properties from previous owners or from the developers of new residential areas. It is the members of the first group who bear the true burden of airport noise (Frankel 1991).

If noise exposure decreased property value, one could have reasonably presumed that the second group was compensated for the existing noise exposure once they willingly purchased properties that sold at a market-discounted price. This has led to the description of aircraft noise as a one-time effect on property value. Prospective homebuyers that lacked information about the noise characteristics of noise-impacted properties “handicaps the operations of the real estate market, results in disappointment for some buyers, and serves to exacerbate conflict between homeowners and the airport authority” (Frankel 1991).

A study conducted around Manchester Airport, England, showed that when using the Noise and Number Index measure (previous official index of aircraft noise in England; the Noise and Number Index is similar to the DNL metric but uses perceived noisiness curves, not perceived loudness curves) results revealed no significant negative relationship between noise and property value (Tomkins et al. 1998).

However, a significant negative relationship between noise and dwelling price is detected when the  $L_{eq}$  measure is substituted . . . A possible conclusion might therefore be that, although it defines a smaller core of properties affected by noise,  $L_{eq}$  nevertheless displays greater accuracy in identifying those which are truly noise-blighted.

Proximity to the airport also had significant impacts, but at a decreasing rate. Hence, “noise nuisance and distance have quite distinct and opposite effects upon property prices” (Tomkins et al. 1998). The net impact was that property location in close proximity to the airport was a more important factor of property value than noise. The study interestingly concluded:

that not all property prices are higher than they would otherwise be in the absence of the airport. Much depends upon the particular configuration of noise and proximity characteristics and thus some households are net gainers whilst others are net losers in terms of property values. Households which benefit the most are those living near to the airport, but whose location in relation to the flight path places them on a relatively low-level noise contour. Households which suffer the most are those at some distance from the airport but which nevertheless are exposed to higher noise levels.

Lastly, studies showed buyer demand was an important component in the real estate market. A buyer’s demand or willingness to pay guided the seller’s asking price. Unfortunately for researchers, determining a buyer’s demand was highly complex owing to extensive decision-making variables, not the least of which was the buyer’s perception of noise. On one hand, some buyers “will not purchase a property at any cost that is by a detrimental condition. [On the other hand] a portion of the population seems more or less imperturbable” by the effects of noise (Bell 2001).

## Summary

The studies of the effects of aviation noise on property values are highly complex owing to the differences in methodologies,

airport/community environments, market conditions, and demand variables involved. Although most studies concluded that aviation noise effects on property value range from some negative impacts to significant negative impacts, some studies combined airport noise and proximity and concluded that the net effect on property value was positive. Prospective homebuyers were at times not well-informed about the noise levels of aircraft operations near the property of interest. Lacking information often led to high bid prices and possible disappointment after purchase. Homeowners that experienced an increase in noise levels bear the burden of aviation noise. However, once noise levels stabilized, the next homeowner was compensated once the property value adjusted owing to the effects of noise. Lastly, the technology available to analyze data has improved throughout the years. The spatial nature of aircraft operations, noise contours, and property location will continue to prompt studies founded in GIS analysis that will improve our understanding of the effects of aviation noise on property value.

## Annotated Bibliography—Aviation Noise Effects on Property Values

**Bell, R., “The Impact of Airport Noise on Residential Real Estate,”** *The Appraisal Journal*, Vol. 69, No. 3, July 2001, pp. 312–321.

The author’s discussion on this topic was very succinct and informative. From the perspective of a real estate professional, noise was classified as a Detrimental Condition that was imposed on homeowners on a permanent basis. The document presented no further original research, but referenced several well-known sources and study results. Additionally, the author outlined the measurement of noise, presented some of the health effects of airport noise, and concluded that as population and airports expand, defining property valuation will challenge the real estate analyst. This document did not include an original Noise Depreciation Index per decibel.

**Cohen, J.P. and C.C. Coughlin, *Spatial Hedonic Models of Airport Noise, Proximity, and Housing Prices*, Federal Reserve Bank of St. Louis, Sep. 2006, 27 pp.**

Despite the refrain that housing prices are determined by “location, location, and location,” no prior studies of airport noise and housing prices have incorporated spatial econometric techniques. The authors compare various spatial econometric models and hedonic models (methods of estimating demand or pricing) to examine the impact of noise on 2003 housing values near Hartsfield–Jackson Atlanta International Airport. Spatial effects are best captured by a model including both spatial autocorrelation and autoregressive parameters estimated by a generalized-moments approach. The inclusion of spatial effects magnifies the negative price impacts of airport noise. Finally, after controlling for noise, houses farther from the airport tend to sell for less, implying that airport proximity is an amenity. This paper included highly technical descriptions of

the spatial models and techniques used and included very useful references from several, at times, contrasting references. This document did not include an NDI per decibel, but did include a noise discount in the 65 dB and 70 dB DNL contours for the log, semi-log, and linear specification.

**Desai, V. and J. Chen, “The Impact of Airport Noise on Housing Values: A Summary Report,” FAA, Office of Environment and Energy, Washington, D.C., Sep. 1994.**

This report presents a summary of an analytical approach designed to estimate the effect of airport noise on housing values. The report describes a procedure that consists of three steps: (1) identification (by a local realtor) of two neighborhoods that have similar characteristics except for noise levels, (2) selection of a sample of houses from each neighborhood with reasonably similar individual housing characteristics, and (3) use of a modified appraisal process (by a local appraiser) and statistical modeling to compare the housing values in the two neighborhoods. The results of the studies indicate that the neighborhood pair model is viable and helps establish the boundaries of the effect that airport noise has on housing values at a given airport. The report concludes that “the magnitude of this impact cannot be estimated at the national level at this time, since the results varied across a wide range for the airports studied, and only a small sample of airports was considered.” The primary objective of these studies was not to examine the issue of airport noise impact in detail at the local level, but to assess the feasibility of a method to examine the effect of airport noise on property values. The studies indicate that the methodology is viable and reasonably economical, and there are several approaches that may be used to implement this technique for a nationwide examination.

**FAA Airport Benefit-Cost Analysis Guidance, Federal Aviation Administration, Washington, D.C., Dec. 15, 1999.**

The document includes guidance to use the INM to identify a noise benefit in terms of a reduction in the non-compatible land-use area, and costs in terms of an increase in the noise non-compatible land-use area. However, there was no further guidance to quantify noise benefits and costs. This document did not include an NDI.

**Frankel, M., “Aircraft Noise and Residential Property Values: Results of a Survey Study,” *The Appraisal Journal*, Jan. 1991, pp. 96–108.**

This study included the results of two surveys of realtors and appraisers in 35 suburban communities near Chicago’s O’Hare International Airport who were knowledgeable about real estate markets and property transactions. The author addressed the home-buying process from the perspective of the real estate professional and compared the survey results with a previous hedonic study done by Nelson (2004). The survey noise discount results were fairly similar until the 68 dB DNL.

At higher noise levels, the survey results were much higher than the hedonic study. The author concluded that a buyer was compensated for the purchase of a home within areas affected by airport noise once market-discounting forces reduced the price of the home. This document did not include an NDI per decibel, but reported property discounts at four different noise levels ranging from 62.5 dB to 77.5 db DNL.

**Gillen, D., *The Role of Noise Valuation in Assessing Infrastructure Investment and Management: A Case Study of Pearson International Airport*, IV Ibero-American Congress on Environmental Acoustics, Sep. 14–17, 2004, 33 pp.**

This paper examined the modeling that was undertaken to establish both a value for noise or quiet as well as a measure of the economic costs of a runway expansion project at Pearson International Airport. The valuation was based on the use of the hedonic model. The valuations were a key input in the benefit-cost analysis of the runway expansion, which was one component of the environmental assessment of the project. The author described in detail the quantification of changes to noise exposure by measuring the existing homeowners’ enjoyment levels, transaction costs of moving, cost of lost utility by those who move, and increased nuisance noise and reduction in services from the homes of those who choose not to move. “The magnitude will depend on a number of factors including sensitivity to noise and activities that are perceived affected by noise such as sleep, reaction, or solitude.” The paper also examined the difference in noise depreciation between condominiums and single or semi-detached homes. Results showed that the NDI for condominiums was less than half that for single or semi-detached homes. Therefore, the author concluded that condominiums were less affected by airport noise.

**Judd, G.D. and D.T. Winkler, “The Impact of an Air Cargo Hub on Property Values,” Presented at the American Real Estate Society 2000 Conference, Santa Barbara, Calif., Mar. 29–Apr. 1, 2000, 7 pp.**

This paper examined the impact on property values after a public announcement regarding the start of hub operations by a major U.S. cargo airline at the Piedmont–Triad Airport. Airport expansion and associated growth bring about increased income and employment, and proximity to the Piedmont–Triad Airport is an amenity associated with location. For residential properties, however, airport proximity may have negative effects on home prices because of increases in noise, traffic congestion, and perceived crash potential. By the use of a hedonic model, the authors attempted to measure the impact of an announcement of an increase in noise. Because there was no change in actual aircraft operations at the time of this study, the impacts of a change in noise levels was not calculated. Although the announcement brought on much debate, “results of the research reveal that residential property values and associated volumes of sales in



close proximity to the airport were unaffected by the hub announcement, while housing more distant from the airport experienced an increase in value." This document did not include an NDI.

**Lipscomb, C., "Small Cities Matter, Too: The Impacts of an Airport and Local Infrastructure on Housing Prices in a Small Urban City," *Review of Urban and Regional Development Studies*, Vol. 15, No. 3, Nov. 2003, pp. 255–273.**

According to the author, small cities with a relatively smaller number of amenities and features tend to have fewer numbers of variables that operate to determine house prices. Therefore, hedonic prices could be estimated adequately for a single neighborhood in a small city with publicly available data, particularly for local officials who do not have the time or financial resources to complete detailed studies of their cities. In this study, a general model was estimated that uncovered the impacts of airport-related noise, local recreational amenities, public transportation services, and schools on housing prices in the city of College Park, Georgia. A unique condition that may have biased the results whereas "[the city] houses a high percentage of Hartsfield International Airport employees . . . Higher [property] sales prices due to being closer to the airport suggests that the benefits of being near a large air transportation hub outweigh the liabilities." The study showed that neighborhood amenities affected property value as well. The author concludes,

For planners and economic developers in other small urban cities interested in revitalizing neighborhoods and increasing property values, these results suggest that playgrounds, parks, and other recreational infrastructure (tennis court, basketball courts, etc.) can be used as economic development tools to revitalize neighborhoods with low property values.

This document did not include an NDI, but listed price fluctuation for airport proximity and for local amenities.

**Nelson, J.P., "Meta-Analysis of Airport Noise and Hedonic Property Values: Problems and Prospects," *Journal of Transportation Economics and Policy*, Vol. 38, No. 1, Jan. 2004, 27 pp.**

Twenty hedonic property value studies were analyzed, covering 33 estimates of the noise discount for 23 airports in Canada and the United States. Meta-analysis was applied to the negative relationship between airport noise exposure and residential property values. About one-third of the estimates have not been previously reported in the literature or were not included in previous meta-analysis. The weighted-mean NDI or noise discount is 0.58% per decibel. A meta-regression analysis examined the variability in the noise discounts that might be the result of country, year, sample size, model specification, mean property value, data aggregation, or accessibility to airport employment and travel opportunities. The cumulative NDI in the United States was approximately 0.5% to 0.6% per decibel at

noise exposure levels of 75 dB or less, whereas in Canada the discount was 0.8% to 0.9% per decibel.

**Salvi, M., *Spatial Estimation of the Impact of Airport Noise on Residential Housing Prices, Zurcher Kantonalbank, Zurich, and École Polytechnique Federale, Lausanne, Switzerland, 2007, 20 pp.***

This paper applied spatial econometric techniques to measure the impact of airport noise on the price of single-family homes in the Zurich airport area. A hedonic model was specified with a spatial error component accounting for local spatial dependence. The estimation technique was based on the generalized moment estimator. The analysis concluded that there was a significant non-linear impact of airport noise on housing prices. For moderate noise levels of 55 dB  $L_{eq}$ , depreciations amount to 2.4% of the transaction price, increasing non-linearly to 27.2% for noise levels around 68 dB  $L_{eq}$ .

**Tomkins, J., N. Topham, J. Twomey, and R. Ward, "Noise Versus Access: The Impact of an Airport in an Urban Property Market," *Urban Studies*, Vol. 35, No. 2, 1998, pp. 243–258.**

This paper addressed the general question of whether the costs to those within airport proximity outweigh the benefits of access, employment, and improved infrastructure. Noise impact areas were based in the Noise and Number Index. Based on data relating to Manchester airport and its surrounding areas, the approach by the authors involved an investigation of the extent to which such proximity effects were capitalized into residential property prices. The results provided some evidence to suggest that circumstances may exist where positive attributes, such as improved access and employment opportunities, may be more highly valued by local residents than the negative externality effects of airport proximity. The authors concluded that properties that are close to the airport, but within a low-noise level area, received the most benefits of proximity.

**Uyeno, D., S.W. Hamilton, and A.J.G. Biggs, "Density of Residential Land Use and the Impact of Airport Noise," *The Journal of Transport Economics and Policy*, Vol. 27, No. 1, Jan. 1993, pp. 3–18.**

The study estimated the impact of airport noise on property values for detached houses near Vancouver International Airport and, for the first time in the literature, for multiple-unit residential condominiums (buildings with many individually owned units, either owner-occupied or rented by that owner to another party) and for vacant land. The hedonic models used assigned different amenity variables to single-family homes, condominiums, and vacant land that resulted in NDI values of 0.65%, 0.90%, and 1.7%, respectively. Contrary to other studies, this study showed that condominiums had a higher NDI than single-family homes.

## CHAPTER ELEVEN: EFFECT OF METEOROLOGY ON AVIATION NOISE

Meteorology plays a very important role in the propagation of sound. Temperature and/or wind gradients cause refraction (bending) of sound waves. Air absorbs sound; therefore, as sound travels through the atmosphere it is attenuated by this absorption. Complicating matters is that air absorption varies with temperature and humidity and the frequency of the sound. For example, sound is absorbed much better in hot, dry conditions than cold, dry conditions. Figure A13 plots sound absorption as a function of temperature and humidity. The absorption effect is a smaller effect than refraction effects. In the real atmosphere the temperature, humidity, and wind speed and direction are not homogeneous, but are changing constantly.

If the atmosphere were homogeneous, the task of describing sound propagation would be relatively simple. Under normal atmospheric conditions, temperature decreases with altitude (adiabatic lapse rate). The resulting effect on sound waves is that sound waves are bent upward. When temperature increases with altitude, it is called a temperature inversion, and temperature inversions are common at night. Temperature inversions cause sound waves to bend downward. It was keenly observed during the Civil War and World War I that cannon fire and bomb blasts were sometimes heard at very great distances from the battlefield, although not audible at much nearer distances. This phenomenon could not be explained by air absorption leading to refraction or bending of sound waves. Wind gradients can produce a similar effect at low wind speeds. A wind gradient results when wind speeds near the ground are slower than wind speeds at increasing altitudes. This gradient causes refraction of sound waves in the same way that temperature gradients do. At high wind speeds turbulence creates a very complex mixing effect.

A schematic diagram of the effects of weather on sound propagation is shown in Figure A14. The INM includes the effect of meteorology in two ways: First, temperature is used to calculate aircraft performance; that is, an aircraft climbs much better in cool weather than hot weather. The option to match atmospheric sound propagation to aircraft performance was added to INM Version 6.0. The INM uses noise data in the form of NPD curves. These data come from aircraft certification data that are corrected to a standard temperature and humidity. The NPD curves in the INM are at the standard temperature and humidity. INM Version 7 includes options to adjust the NPD curves to the user-selected average temperature and humidity (*INM Users Guide 2007*). For temperatures near standard conditions or at distances near the airport, this adjustment is small; however, at large propagation distances or non-standard conditions the effects are non-trivial. Even this correction is somewhat simplistic, in that it is based on a homogeneous atmosphere; that is, constant temperature and humidity. It does not attempt to correct for temperature gradients.

One of the consequences of the complex way weather affects sound propagation is that noise models are limited to estimating noise levels for average conditions. For any given flyover the noise experienced at an observer location is the product of the aircraft noise level and the effect of the atmosphere on sound propagation. Comparing noise model predictions with short-term noise measurements is meaningless, because atmospheric effects are not adequately accounted for in the model. However, long-term measurements will produce an average noise level in which atmospheric effects will tend to average out and comparison with noise model results will be much more meaningful. This caution should be noted for any short-term measurement program.

### Summary

As evidenced by even a generalized discussion of aviation noise effects by meteorology, this field of study is incredibly technically detailed and complex. Most new research published discussing these effects are not for the average reader. However, a very brief and minimally complex summary is provided here.

Gabrielson's (2006) "Refraction of Sound in the Atmosphere," is an excellent history of sound propagation through atmosphere from the 1700s to date. It should be mandatory reading for anyone seeking to understand the propagation of sound through the atmosphere, and how weather affects that propagation. For example, he notes a school of thought during the Civil War and World War I that provided evidence of refraction through the observation of battle cannons or bomb blast sound at long distances that were not heard at short distances. Recorded observations proved beyond a doubt that refraction of sound in the atmosphere caused sound to be inaudible in some areas and clearly audible in others, completely independent of the effects of distance. Gabrielson's publication is a fabulous history of atmospheric influences on sound.

Several publications are extraordinarily complex, such as Hallberg et al.'s (1985) report describing the problem's complexity and some of the physics of the problem. Results indicate that sound level increases as the curvature goes from negative to positive values. Comparisons with other investigations agreed. However, calculations of acoustic theory results showed large discrepancies with those measured. Five years later, in 1990, NASA's Fourth International Symposium on Long-Range Sound Propagation included 22 technical papers that, while scientific in nature, are presented in three broad sections: ground effects on propagation, infrasound (very low frequency) propagation, and meteorological effects on sound propagation.

In 1994, Wilson and Thomson's report discussed the effects of atmospheric wind and temperature fluctuations on acoustic signal variability, with emphasis on large-scale turbulence.

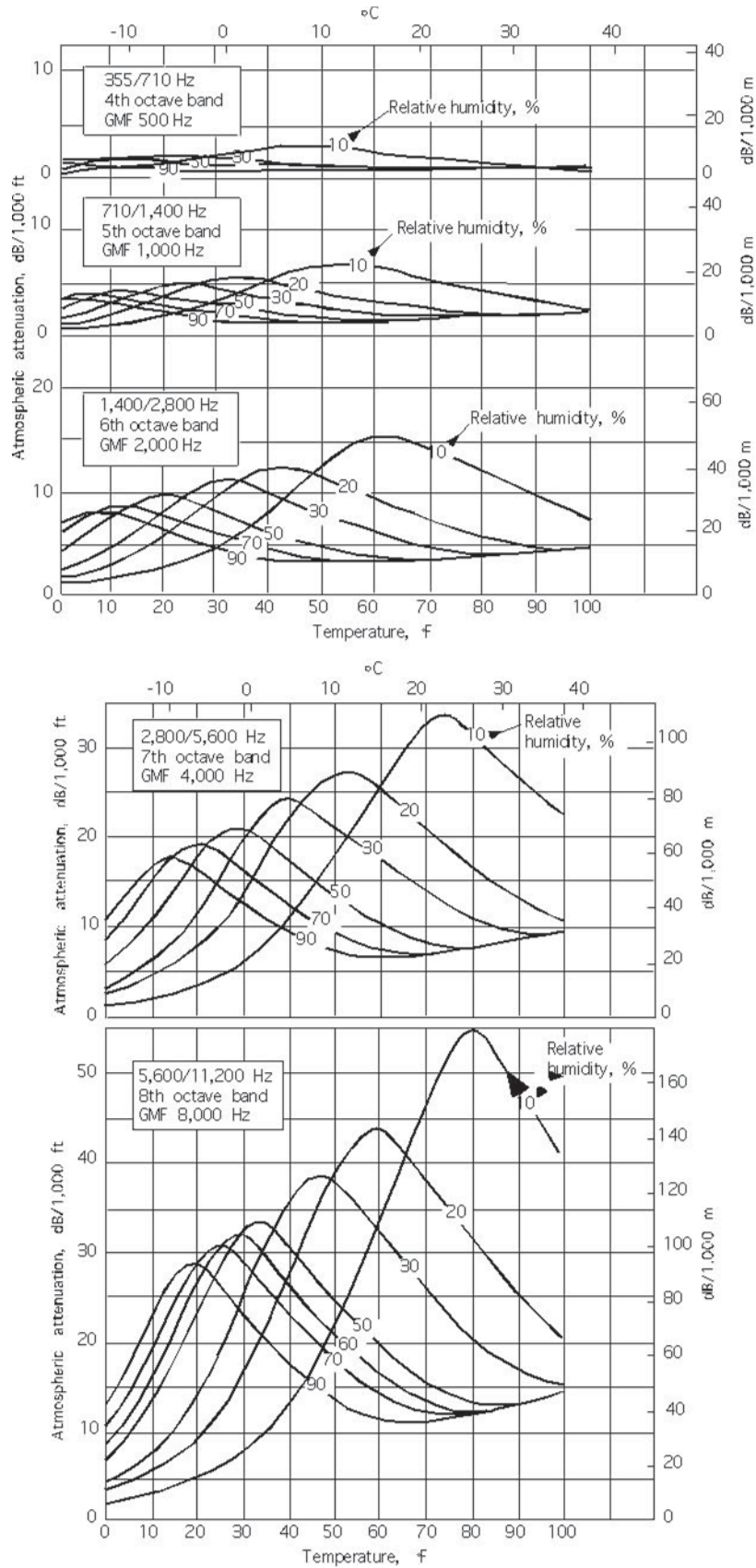


FIGURE A13 Atmospheric sound absorption as a function of temperature and humidity (Beranek, *Noise and Vibration*, McGraw-Hill 1981).

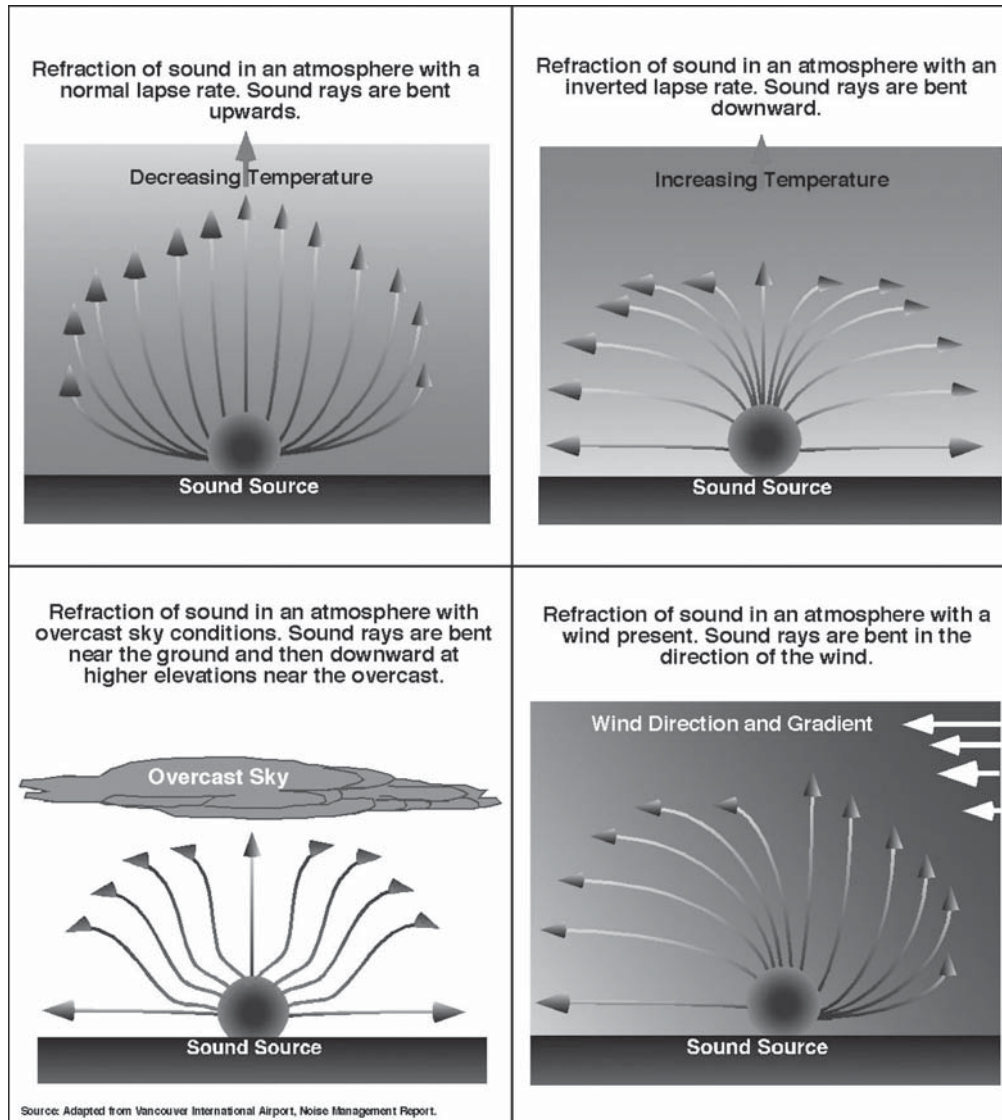


FIGURE A14 Effects of weather on sound propagation (Mestre Greve Associates 2007).

Although very technically complex, the article shows how simplistic assumptions of atmospheric homogeneity may result in significant differences to real-world conditions.

The *Report on Standard Method of Computing Noise Contours Around Civil Airports* (2005), commonly referred to as Doc. 29, is analogous to SEA AIR 1845, which is the technical basis for computations contained in the INM. Appendix D of Doc. 29 outlines temperature and humidity corrections that may be needed in the acoustic model portion of a noise model such as INM, which use noise data in the form of NPD curves. In the INM, the NPD are at standard temperature and humidity. Doc. 29 provides technical routines to adjust the NPD to actual standard conditions of temperature and humidity. It does not attempt to correct for temperature gradients, however.

Another technical article describing atmospheric experiments of sound propagation is Swearingen and White's

(2007) description of how sound propagation through a forest is affected by the microclimate of the canopy, scattering by trunks and stems, and ground reflection. Each of these effects is such a strong contributor to the attenuation of sound that mutual interactions between the phenomena could become important. Results indicate high frequency attenuation owing to the forest that increases with distance. The article captures the complexity of the problem and identifies model techniques for this particular application, but does not provide a general solution useable in today's aircraft noise models.

#### Annotated Bibliography—Effect of Meteorology on Aviation Noise

Embleton, T., "Tutorial on Sound Propagation Outdoors," *The Journal of the Acoustical Society of America*, Vol. 100, No. 1, July 1996, pp. 31–48.

This tutorial is a comprehensive guide to the propagation of sound outdoors, and provides a history of propagation theories and description of the physical properties involved. In addition to the narrative description of the physics involved, technical details are provided. The tutorial emphasizes field measurements and physical interpretations.

**European Civil Aviation Conference, *Report on Standard Method of Computing Noise Contours Around Civil Airports*, Doc. 29, Ed. 3, Vol. 2, 2005, 126 pp.**

This document, commonly referred to as Doc. 29, is analogous to SAE AIR 1845, which is the technical basis for the computations contained in the INM. Doc. 29 includes Appendix D, which outlines the temperature and humidity corrections that may be needed in the acoustic model portion of a noise model such as INM. INM has historically used temperature to account for the change in aircraft performance that results from a change in air density. As the temperature increases the air gets thinner, and an aircraft does not perform as well as it does at lower temperatures. The noise models use noise data in the form of NPD curves. These are curves of noise level versus distance, with separate curves for each power setting. These curves are derived from aircraft certification data. Aircraft certification data are collected within a specified range of temperature, humidity, and wind conditions and corrected to a standard temperature and humidity. The NPD curves in the INM are at the standard temperature and humidity. Doc. 29 provides technical routines to adjust the NPD curves to the actual temperature and humidity from standard conditions. For temperatures near standard conditions or at distances near the airport, this adjustment is small. However, at large propagation distances the effects are non-trivial. INM Version 7 contains the ability to provide this temperature and humidity correction to the acoustic model. Even this correction is somewhat simplistic, in that it is based on a homogeneous atmosphere; that is, constant temperature and humidity. It does not attempt to correct for refractions.

**Gabrielson, T.B., “Refraction of Sound in the Atmosphere,” *Acoustics Today*, Apr. 2006, pp. 7–16.**

This article presents an excellent history of the evolution of thinking about sound propagation through the atmosphere. The author begins by pointing out how natural it is to think that sound travels more or less in a straight line. For the most part, when you hear a sound you know where to look. As the science of sound developed in the 18th and 19th centuries there was great misunderstanding about sound propagation. Early theories on sound propagation focused solely on absorption of sound by air and that absorption varied with temperature, humidity, and the frequency of the sound. The need for understanding sound propagation was acute, with hundreds of ships being wrecked in thick coastal fogs. Because lighthouses were of little use in this weather, more powerful sound signals able to give warning and guidance at

great distance were needed. Interestingly, the prevailing belief was that sound traveled poorly through fog (and rain and snow). However, sound does penetrate fog, “but the contrary belief had become the ‘expert opinion’ from the early 17th well into the 19th century.” Curious observations confounded the best expert opinions. Sound traveled better with the wind than against the wind; houses and hills did not always block sound, and distant sound appeared clearer and louder at night. Another curious observation that ultimately led to experiments proving the refraction, or bending, of sound waves was the observation that during battle cannon blasts were often heard from very long distances away, although not heard at closer locations. Such observations were common during the Civil War. The history of the development of this science by such pioneers as Stokes, Reynolds, and Schrodinger, and the use of kites to measure temperature gradients in the atmosphere are included in this interesting and well laid out paper. World War I provided more evidence of refraction through observation of bomb blast sound at long distances that were not heard at short distances. Remember that observation of bomb blast noise was a key early warning signal. After the war a series of experiments were set up in which bomb blasts were witnessed by observers located throughout Europe. The recorded observations proved beyond a doubt that refraction of sound in the atmosphere, the bending of the sound waves with temperature and wind gradients, caused sound to be inaudible in some areas and clearly audible in others, completely independent of the effects of distance. This article is mandatory reading for anyone seeking to understand the propagation of sound through the atmosphere and how weather affects that propagation.

**Hallberg, B., C. Larsson, and S. Israelsson, “Measurements of Meteorological Effects of Long-Range Sound Propagation Using *m*-sequence Correlation,” *The Journal of the Acoustical Society of America*, Vol. 78, No. 3, Sep. 1985, pp. 1038–1044.**

This is a very technical article that is not for every reader. However, the introduction and first section do a good job of outlining the complexity and some of the physics of the problem. A correlation method was used for measuring sound levels 1 km away from a point source 1.25 m above the ground, a crop field and a snow-covered ground, respectively. Meteorological parameters were monitored simultaneously. Wind speed and temperature were measured at several elevations, together with wind direction, relative humidity, and atmospheric pressure at a single height. The effect of refraction on the sound level variation is interpreted in terms of the curvature for near-horizontal sound rays. It is found that the sound level increases as the curvature goes from negative to positive values. Comparisons with other investigations were made, and qualitative agreement is found. Calculations with acoustic theory were made, the results of which show large discrepancies with those measured.

**National Aeronautics and Space Administration, “Fourth International Symposium on Long-Range Sound Propagation,” Proceedings of a Symposium Sponsored by NASA, the University of Mississippi, and the Open University of England, Langley Research Center, May 1990, 282 pp.**

This symposium included 22 technical papers by scientists studying long-range propagation of sound. The papers are very technical and presented in three broad sections: ground effects on propagation, infrasound (very-low frequency) propagation, and meteorological effects on sound propagation. A reader seeking technical and mathematical descriptions of long-range sound propagation will find the symposium proceedings useful. It is not for the lay non-technical reader.

**Swearingen, M.E. and M.J. White, “Influence of Scattering, Atmospheric Refraction, and Ground Effect on Sound Propagation Through a Pine Forest,” *The Journal of the Acoustical Society of America*, Vol. 122, No. 1, July 2007, pp. 113–119.**

This is a very technical article that describes experiments of sound propagation through a forest, which is affected by the microclimate in the canopy, scattering by trunks and stems, and ground reflection. Each of these effects is such a strong contributor to the attenuation of sound that mutual interactions between the phenomena could become important. A sound propagation model for use in a forest has been developed that incorporates scattering from trunks and branches and atmospheric refraction. Comparisons with experimental data are made. Cumulative influences of the separate phenomena are examined. The method developed in this paper is compared with previously published methods. The overall comparison with spectral transmission data is good, suggesting that the model captures the necessary details. The results show high frequency attenuation owing to the forest that increases with distance. The paper captures the complexity of the problem and identifies model techniques for this particular application, but does not provide a general solution useable in today’s aircraft noise models.

**Wilson, D.K. and D.W. Thomson, “Acoustic Propagation Through Anisotropic, Surface-Layer Turbulence,” *The Journal of the Acoustical Society of America*, Vol. 96, No. 2, Aug. 1994, pp. 1080–1095.**

The effects of atmospheric wind and temperature fluctuations on acoustic signal variability are discussed, with emphasis on the effects of large-scale turbulence. This is a very technical journal article, but it is useful to show that simplistic assumptions of atmospheric homogeneity may result in significant differences to real-world conditions. Such large-scale turbulence is anisotropic (different properties at different locations), is generated by both shear and buoyancy instabilities, and has structure that depends strongly on the meteorological conditions as well as the distance from the ground. Previous

research in the atmospheric sciences literature regarding length scales and anisotropy is reviewed and incorporated into an acoustic propagation model. An important conclusion is that large-scale turbulence is a significant cause of acoustic signal fluctuations, particularly in the signal phase. This is important to realize when comparing noise measurement results with noise model results. Noise models produce an estimate of an average over time, although noise measurement results may differ significantly for a given single event.

## **CHAPTER TWELVE: EFFECT OF TOPOGRAPHY AND GROUND ABSORPTION ON AVIATION NOISE**

Aircraft sound heard by an observer can be influenced by a number of factors. In the previous chapter, the effect of meteorology was one such factor. In this chapter, the propagation of sound over the ground and how sound is affected by terrain is discussed. This is a highly complex and technical topic and only a simplified description of shielding and ground effects is presented in this synthesis. When an aircraft is directly overhead, the sound experienced by an observer is only affected by meteorology. However, when the aircraft is at lower elevation angles the sound experienced by an observer is the sum of the sound that travels in a straight line from the aircraft and the sound reflected off of the ground. The interaction of sound traveling over the ground is complex. It is often simplified into “soft” and “hard” ground propagation. Sound propagation over water is an example of hard ground propagation. Water does not absorb sound well, making it a good reflector of sound. The acoustics of sound’s interaction with ground are very complex; however, good empirical methods are available and incorporated into sound propagation models. The effect of ground absorption on a sound traveling near the ground is addressed by lateral attenuation algorithms used in models like the INM and are defined by industry standards. In this case the standard is published by the SAE in AIR 5662 (*Method for Predicting Lateral Attenuation of Airplane Noise* 2006).

Terrain may have two effects on sound propagation. An observer on a hill is higher and closer to an aircraft than if on flat terrain. Terrain can also act as a sound barrier. These examples are shown schematically in Figure A15. INM includes both effects in computing aircraft noise levels.

The amount of noise reduction that terrain shielding provides is critically dependent on the geometry of the barrier. Figure A16 shows a schematic diagram of an earthen berm shielding an aircraft during a ground runup. For the barrier to be effective it must break the line of sight (solid line) between the observer and the aircraft engines. The amount of noise reduction is dependent on how much the line of sight is broken and the frequency of the sound. The difference in path length between the line of sight and the path over the top of the barrier (broken line) is an important factor in determining the barrier noise reduction; the higher the

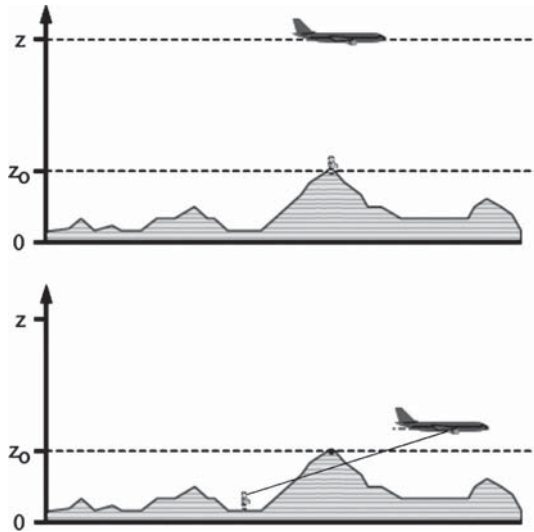


FIGURE A15 Schematic of terrain effects (Mestre Greve Associates 2007).

barrier, the greater the noise reduction. The barrier will attenuate high-frequency sound much better than low-frequency sound.

### Summary

Although most research related to topography and ground absorption is highly technical in nature, generalized conclusions may be made. Recent research has validated and recalibrated various noise prediction models that have increased the understanding of sound wave influences.

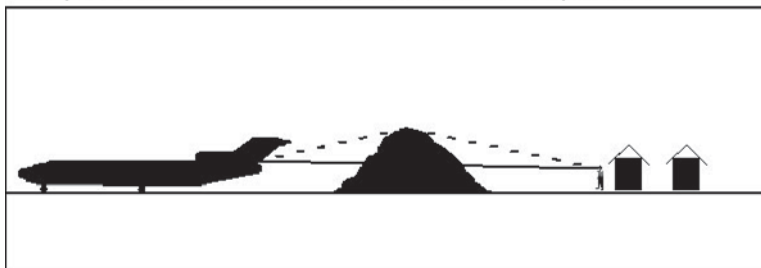
The FHWA's Traffic Noise Model (1998) was prepared for traffic noise analysis, but includes one of the best descriptions of how noise barrier effects on transportation noise can be modeled. It includes detailed methodologies to compute noise barrier effects created by either natural topography or man-made structures. Although this information has enabled the increased sophistication of barrier noise reduction, it remains fundamental in all topographical analyses.

NOISEMAP is a noise contour prediction model used by the Air Force and other organizations to compute environmental noise around airbases and airports. Within NOISEMAP, the world is presumed flat and ideal in temperature/humidity—flat terrain, no barriers or obstructions to the line of sight between source and receiver, and ideal standardized temperature and humidity. In 1992, Plotkin et al. extended NOISEMAP to account for three-dimensional terrain effects and for the effect of varying ground properties. The report presents detailed descriptions of how the NOISEMAP model would have to be modified to account for topography. Another noise prediction model is the FAA's INM, currently updated in 2007 by means of INM Version 7. INM Versions 6.2 and later had the ability to correct for local topography, slant range distance, and shielding effect for terrain that blocks line of sight between the aircraft and observer. Terrain data may now be imported into INM from standard digital terrain sources, or input by the user, which is fully described in the *INM User's Guide* (2007). The inclusion of shielding calculations in the INM allows it to work better at new airports that have hills or steep valleys nearby. The shielding calculations in INM Version 7 are based on the methodology implemented in FHWA's Traffic Noise Model.

In 1994, NATO/CCMS issued a final report from the working groups identifying various modeling techniques used in different countries and describing issues associated with modeling topographic effects on aviation noise (NATO/CCMS 1994). Included are the effects of slant range distance and the effects of shielding. The report presents recommendations for including topographic effects in aviation modeling.

Some of the most provocative new research has been prepared by the Volpe Center at the Massachusetts Institute of Technology. In their May 2000 report, Senzig et al. examined the applicability of currently available mathematical models of lateral attenuation. Analysis of the data revealed that lateral attenuation is a function of aircraft geometry;

Example of Earth Berm Noise Barrier for Ground Runup Noise :



- The higher the barrier, the greater the noise reduction
- Barrier must break 'line of sight' between source and receiver
- Barriers are good for high frequency noise, very poor for low frequency noise
- Barriers are most effective close to the source or close to the receiver
- Barriers are typically used for maintenance runup noise, not takeoff roll noise

FIGURE A16 Example of terrain shielding geometry (Mestre Greve Associates 2007).

lateral attenuation for aircraft with tail-mounted engines generally agreed with published literature, although lateral attenuation for aircraft with wing-mounted engines were found to be less than documented in the literature. This lower lateral attenuation calculation results in an underprediction of sideline noise in the existing noise prediction models. SAE's AIR 5662 (2006) represents a major reformulation of a 1981 AIR (AIR 1751), and provides detailed calculation methods to calculate lateral attenuation. It includes the effects of engine mount position (fuselage versus wing mount). INM Version 7 (referenced earlier) includes the methodology specified in AIR 5662 for calculating lateral attenuation.

In summary, both noise prediction models, INM Version 7 and NOISEMAP, are the most commonly used in the United States and much of the world and have been updated to include algorithms for adjusting lateral attenuation and local terrain specifications where needed.

#### **Annotated Bibliography—Effect of Topography and Ground Absorption on Aviation Noise**

***INM User's Guide, Version 7.0, FAA-AEE-07-04, Office of Environment and Energy, Federal Aviation Administration, Washington, D.C., Apr. 2007, 446 pp.***

INM includes the ability to correct for local topography. This includes the effect of topography on slant range distance (the distance between the observer and aircraft) when the observer is on higher terrain and thus closer to the aircraft. INM Version 6.2 and later also includes the ability to calculate shielding effects for terrain that blocks line of sight between the aircraft and the observer. Terrain data may be imported into INM from standard digital terrain sources or input by the user. The *User's Guide* provides detailed instructions on how to implement this and all the other features of the INM. The inclusion of shielding calculations in the INM allows the INM to work better near airports that have hills or steep valleys nearby.

***Method for Predicting Lateral Attenuation of Airplane Noise, SAE AIR 5662, Society of Automotive Engineers (SAE), Washington, D.C., 2006.***

SAE published this Aerospace Information Report (AIR) in 2006. It represents a major reformulation of a 1981 AIR (AIR 1751). Lateral attenuation is very important when an aircraft is at a low-elevation angle relative to the observer. Lateral attenuation accounts for the interaction of the sound wave with the ground as the sound propagates near the ground. Even as the elevation angle increases, the ground has a significant effect on the sound level at the receiver. At high-elevation angles the effect of the ground attenuation disappears. AIR 5662 provides detailed calculation methods to compute lateral attenuation. It includes the effects of engine mount position (fuselage versus wing mount) on lateral attenuation. INM Version 7 includes the methodology specified in AIR 5662 for calculating lateral attenuation.

***NATO/CCMS Working Group Study, Effects of Topography on Propagation of Noise in the Vicinity of Airfields, No. 200, June 1994, 44 pp.***

This volume constitutes the final report of the working group that was established as a subgroup to the Pilot Study on Aircraft Noise under the auspices of NATO's Committee on the Challenges of Modern Society. The report identifies the various modeling techniques used in different countries and describes the issues associated with modeling topographic effects on aviation noise. Sample calculations and contours are presented. The report discusses the effect of topography on slant range distance (an observer is closer to an aircraft when that observer is on a hill) and the effects of shielding resulting from topography. Shielding is not important when aircraft are directly overhead of an observer, but may be very important when an aircraft is at low elevation angles and a hill is between the observer and the aircraft. The report presents recommendations for including topographic effects in aviation modeling.

***Plotkin, K.J., C.L. Moulton, and E. Stusnick, Feasibility of Incorporation of Terrain Effects into NOISEMAP, Dayton, Ohio, Oct. 1992, 42 pp.***

NOISEMAP is used by the Air Force and other organizations to compute environmental noise around airbases and airports. Within NOISEMAP, ground is assumed to be flat and level, at the same altitude as the airbase and runways. The only effect of ground on sound propagation is incorporated in a single algorithm representing average attenuation of sound at small angles of incidence. In most situations, the "flat earth" and "average ground absorption" assumptions are entirely reasonable. There are, however, situations where ground is particularly "hard" or "soft," or where the ground has significant departures from flat and level. A study has therefore been conducted of the feasibility of extending NOISEMAP to account for three-dimensional terrain effects and for the effect of varying ground properties. The report presents detailed descriptions of how the NOISEMAP model would have to be modified to account for topography.

***Senzig, D.A., G.G. Fleming, and J.P. Clarke, Lateral Attenuation of Aircraft Sound Levels over an Acoustically Hard Water Surface—Logan Airport Study, Langley Research Center, National Aeronautics and Space Administration, Hampton, Va., May 2000, 101 pp.***

NASA's Langley Research Center sponsored the Acoustics Facility at the U.S.DOT's John A. Volpe National Transportation Systems Center and the Massachusetts Institute of Technology to conduct a noise measurement study at Logan International Airport in Boston, Massachusetts, during the summer of 1999 to examine the applicability of currently available mathematical models of lateral attenuation. Analysis of the data collected revealed that lateral attenuation is a function of aircraft geometry. Lateral attenuation for aircraft



with tail-mounted engines was found to agree with the published literature, as well as that included in existing aircraft noise models. Lateral attenuation for aircraft with wing-mounted engines was found to be less than documented in the literature. This lower lateral attenuation for aircraft with wing-mounted engines results in a general under-prediction of sideline noise in the existing noise models. Measurement sites included effects of over-water sound propagation. Mathematical details of the model of sound propagation over “hard” and “soft” surfaces are provided.

***Traffic Noise Model (FHWA TNM®), Version 1.0—Technical Manual, FHWA-PD-96-010, DOT-VNTSC-FHWA-98-2, Final Report, Federal Highway Administration, Washington, D.C., Feb. 1998.***

This technical manual describes the FHWA *Traffic Noise Model*. Although it does not address aircraft noise specifically, the principals and equations for estimating the shielding effects of a barrier, such as that formed by topographic shielding, are described in detail. It is a useful resource for understanding noise barrier effects.

## CHAPTER THIRTEEN: CONCLUSIONS

Nearly every aspect of aviation, and related technology, has changed since the 1985 publication of FAA’s “Aviation Noise Effects.” Although much has been learned, both technically and socially, the process of identifying, quantifying, and alleviating noise effects of aviation remains an art. We now know that because aviation noise does not approximate those of occupational health criteria, hearing loss is unlikely; aviation noise effects do not influence newborn birth weight, and annoyance may be largely influenced by non-acoustic factors. Sleep interference, with great variability between laboratory and in-home studies, occurs much less than previously thought. We have also learned that cross-sectional studies are notoriously difficult to interpret, often report conflicting results, and do not result in dose-response relationships.

Investigations that report a distinct percentage of the population who are “highly annoyed” at any given day-night average noise level may be incorrectly interpreted as having

a more precise meaning than should be taken from the data. Areas of annoyance that remain to be investigated include the relationship between single-event noise levels and annoyance. Use of data not previously available, including airport noise monitoring systems, flight tracking systems, and geographic information systems, may prove to be a rich source of data in understanding annoyance and meteorological and topographical effects.

Aviation noise effects on schools and school children have been well-researched and documented. Recent studies indicate a potential link between aviation noise and both reading comprehension and learning motivation, particularly for those children who are already scholastically challenged. Other studies indicate increased stress levels for children in high-noise environments. New best practices designs for interior classroom acoustics and speech intelligibility have been completed, but do not address intermittent noise such as aviation noise. Some research has indicated that effects of aviation noise may differ from the effects of other transportation noises. Speech interference, although quite important, has not had the benefit of research as related to intermittent noise sources.

New definitions and criteria for natural soundscape in national parks and Native American tribe lands are being established, and new dose-response relationships may be used to guide important policy decisions. Low frequency noise with its related vibration, meteorological, and topological data continue to drive modeling improvements, and correct some limited under-predictions of sideline-noise levels. Home property values may have limited relationship to noise levels, and future research linked with powerful geographic information system tools may provide new insights. Although long-term averages are typically used in conjunction with land use planning and residential property location, new research indicates that the use of  $L_{eq}$  (equivalent sound level) may display a greater accuracy in identifying areas most affected by aviation noise.

In conclusion, despite decades of research and new, well-documented information, aviation noise effects continue to be an enigma waiting to be solved.

Abbreviations used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI-NA	Airports Council International-North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation