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A Critical Review of Time-of-Day Weighting Factors for Cumulative Measures of Community Noise Exposure

S. Fidell and T. J. Schultz

April 1980

Submitted to:
Office of Noise Abatement and Control
Environmental Protection Agency
Washington, D.C.

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ABSTRACT

This report was prepared at the request of the Office of Noise Abatement and Control of the Environmental Protection Agency to review the rationale and evidence for time of day weighting factors applied to cumulative measures of community noise exposure such as the Day-Night Sound Level (L_{dn}). The nature of the controversy over "nighttime penalties" was examined, as was the evidence of differential human sensitivity to noise exposure at different times of day. It was determined that available information does not support rigorous arguments for or against time of day weighting factors, but that ample grounds exist for maintaining time of day weighting factors of some form.

ACKNOWLEDGEMENTS

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I. INTRODUCTION

A. The Issues in Dispute

Are noises heard at different times of day* equally disturbing to people? If not, how should an index of community noise exposure account for an actual or presumed difference in human sensitivity to noise exposure as a function of time of day? These two questions have been a focus of controversy since serious efforts to formalize community noise measurements began a quarter of a century ago. Although definitive answers to these questions are not yet at hand, indices purporting to reflect community reaction to overall noise exposure have proliferated.

A common strategy used to account for a greater presumed potential of nighttime noise exposure to create disturbance is to treat such exposure as of greater magnitude than actually measured. Examples of community noise rating procedures that make an adjustment of this sort (a "nighttime penalty") are the Noise Exposure Forecast (NEF), Community Noise Equivalent Level (CNEL), and the Day-Night Sound Level (L_{dn}).

The Day-Night Sound Level is of special interest for present purposes because the U. S. Environmental Protection Agency has adopted the measure as the preferred rating for noise from sources of all kinds, in the preparation of Environmental Impact Statements concerning noise. It is defined as follows:

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*It should be understood from the outset that human activities, rather than the time at which they occur, are the substantive issue in the ensuing discussion. Time of day is merely a convenient surrogate susceptible to regulation.

$$L_{dn} = 10 \log_{10} (1/24) [15 (10^{L_d/10}) + 9 (10^{(L_n + 10)/10})],$$

where L_d and L_n represent the daytime and nighttime energy-equivalent sound levels, respectively.

The "Levels Document" (EPA, 1974) states that the inclusion of a 10 dB nighttime weighting in the L_{dn} formula "was predicated on its extensive prior usage, together with an examination of the diurnal variation in environmental noise". Specifically, according to von Gierke (1975), "Justification for the 10 dB penalty on nighttime noises is derived from ... (consideration of data that indicate that) ... in quiet environments ($L_{dn}<55$), L_d is the controlling factor determining L_{dn}; whereas, in noisy environments ($L_{dn}>65$), L_n is only 3 to 4 dB below L_d. Therefore, the 10 dB nighttime penalty is effective in characterizing the need for day and nighttime noise reduction."

The thrust of von Gierke's argument seems to be that a 10 dB nighttime penalty has little or no effect on daily exposure levels experienced by people who already enjoy a relatively low ambient noise environment, and therefore does no harm in such cases. At the same time, however, a nighttime penalty forces attention to noise reduction at all times of day in areas in which people are exposed to higher ambient noise levels. Galloway (1977) characterizes the latter effect of a nighttime penalty as "increased pressure toward a general reduction in all noise levels if specified noise criteria are to be met".

B. The Nature of the Dispute

The controversy over time of day weighting factors, although carried out at several levels and from a variety of motivations, has become institutionalized. Among the most identifiable parties to the dispute are:

1) Transportation Industries (including trade association representing airlines and other operators of equipment that generate high noise levels);

2) Related Commercial Interests (including airport operators and businesses involved indirectly with transportation and other high noise level operations);

3) The Public (as individuals exposed to noise, civic action groups, plaintiffs in legal actions, and also as taxpayers underwriting the costs of noise abatement);

4) The Government (executive, legislative, and judicial branches at all levels from local to federal); and

5) The Research Community (both domestic and international).

The interests of these parties are not always apparent, even to the parties themselves! While some of the interests are zero-sum, others conflict less directly. For example, airlines purport to find energy summation indices that include a nighttime weighting factor unacceptably simple (Collier, 1980) and too restrictive

(Linn, 1980). Airport operators, on the other hand, welcome the weighting factor embodied in the Day-Night Sound Level (L_{dn}) as providing a clear limit to their liability (Connors, 1980).

Similarly, Federal regulatory agencies seek consistency and universality in noise measures that incorporate time of day weighting factors (Marrazzo, 1980; Wessler, 1980), but federal courts (cf. Santa Monica Airport Association et al. vs. City of Santa Monica, C.D. Cal. No. CV 77-2852-IH) have not felt encumbered by such restraints, and have chosen different noise measures for various purposes.

The positions of federal and state legislatures, responding at some times to constituents' noise complaints but at other times to special interest groups, can rarely be predicted. Likewise, state and municipal executive agencies have adopted a bewildering set of positions expressed in local noise ordinances and policies. The research community is sufficiently divided in its opinions that it can hardly be said to have a position at all.

As currently conducted in the United States, the debate over time of day weighting factors is self-perpetuating. There are strong economic and other reasons for prolonging the debate: industry sometimes profits in the short run from the paralysis of indecision; legislatures have repeated opportunities to placate different interests from time to time; the research community has the time to carry out more research; etc. Further, because no conceivable voluntary compromise can reconcile the strong conflicting interests to all parties' satisfaction, there is little danger that this pluralistic controversy will terminate of its own accord.

The persistent search for a compromise minimally painful to the greatest number of parties to the debate thus seems fruitless. Not all of the arguments raised address scientific or technical issues, nor are all of them raised in a dispassionate quest for truth. Indeed, arguments that some parties find compelling have less to do with effects of noise on people than with effects of regulation on industry (Janssen, 1980).

As the most visible manifestation of a noise measure including a time of day weighting factor, L_{dn} serves as something of a lightning rod, attracting constant criticism (as well as spirited defense). Much of the criticism is misdirected, in that it would almost certainly be directed at any other noise measure that might serve as a basis for regulatory action.

C. The Technical Basis for a Nighttime Penalty*

Nighttime penalties imposed on noise exposure are inferred primarily from three types of studies: case studies, social surveys, and laboratory investigations of noise effects such as sleep interference, annoyance, and speech intelligibility. Although complaint studies and social surveys are widely felt to demonstrate higher sensitivity to nighttime noise, firm data to support an appropriate magnitude for a nighttime penalty are hard to find (Galloway, 1974).

It is not only the data that are hard to find: carefully reasoned and logically compelling arguments in favor of the

*Strictly speaking, a nighttime "penalty" could equally be considered a daytime license. The term "penalty" is in such common use to describe nighttime weightings, however, that the terms are used synonymously in this report.

existing procedures are also scarce. What formal argument can be found tends to be constructed of bits and pieces chosen from disparate studies of uneven reliability and generalizability. The persuasiveness of such argument depends in part upon the will to believe. It is important to understand, however, that there are a number of grounds favoring a nighttime penalty that have little or nothing to do with technical information gleaned from scientific studies.

This report brings the record up to date by reviewing the controversy about time of day weighting factors. It is important to do so, because, as Ollerhead (1978) puts it:

> "In theory, the implications of this penalty are far-reaching. For example, according to Ldn methodology, one aircraft departing at 11:05 PM is as bad for the airport neighbors as ten aircraft departing between 10:45 and 10:59 PM. In practice, noise exposure tends not to follow such a precise pattern in any regular way and, largely because nighttime noise exposure levels are usually fairly low anyway, the 10 dB penalty is never put to a severe test. However, this does not mean that it never will be; since very long term outcomes of planning decisions may well depend on the broad validity of composite noise indices, it is important that although built-in penalties cannot be based soundly on scientific principles, they at least represent the best possible guesses."

II. ARGUMENTS FOR AND AGAINST TIME OF DAY WEIGHTING FACTORS

Many arguments for and against time of day weighting factors have been offered. The principal arguments, ranging from the intuitive through the empirical and pragmatic to the deductive, are categorized below.

A. Arguments in Favor of a Time of Day Weighting Factor

1. Arguments Based on Intuition

A nighttime penalty has undeniable intuitive appeal. Who has not been disgruntled after having been awakened in the night by an intruding noise? Who could be churlish enough not to imagine that the neighbors were likewise bothered? What administrator or agency would risk public wrath by suggesting removal of an existing nighttime penalty sanctioned by custom?

Intuitions of this sort are based on personal experience rather than quantitative evidence. They do not give due consideration to countervailing influences of noise exposure on people at other times of day. Nonetheless, their appeal is so strong that they may render consideration of more rigorous arguments moot.

A number of tacit assumptions underlie these intuitive arguments. Not all of them are readily identified, partly because they are so fundamental that they form the framework within which people conceive of the need for a nighttime penalty. It may be helpful, however, to consider the implications of two of these tacit assumptions.

a. A Nighttime Penalty is Intended to Provide Relief From Noise Exposure to the Residential Population

The intuitive focus of attention of a nighttime penalty is clearly the residential setting. The residential population is virtually always larger at night than during the day, by a factor of perhaps two to four. All other things being equal*, greatest-good-for-the-greatest-number thinking (akin to the "equivalent fully impacted population" concept of the Noise Impact Index (von Gierke et al., 1979)) suggests the need to compensate a 24 hour measure of noise exposure for the increased size of the nighttime residential population.

The assumption that a nighttime penalty is intended to confer benefits primarily upon people in a residential setting seems to be entirely reasonable. One (arguably) receives compensation for occupational noise exposure, and can more or less control recreational noise exposure, but cannot escape involuntary residential noise exposure. Besides, why else would a nighttime penalty be useful if not to help support the sanctity of the home?

Since this assumption deals more with values than matters of objective fact, it is unprofitable to challenge in any event.

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*As usual, all other things are probably not equal in this instance, since differential sensitivity to noise exposure of human populations engaged in different activities at different times of day also warrants consideration.

b. Sleep is Highly Susceptible to Interference From Outdoor Community Noise Exposure

It is popularly assumed that sleep is a fragile activity, readily degraded in quality by nocturnal noise intrusions. As corollaries to this position, it is further assumed by many that occurrences of sleep interference are among the most annoying consequences of noise exposure; and that even small amounts of degradation of sleep quality can have potentially serious influences on health.

Assumptions of this sort are in principle amenable to scientific study, and are in fact readily challenged. They also misdirect attention away from other effects of nighttime noise exposure, notably speech interference and annoyance.

2. Arguments From Moral or Ethical Considerations

The home is commonly viewed as an "acoustic sanctuary" to which people may retreat at night to escape involuntary daytime noise exposure. In this view, people are thought to be entitled to an extra measure of peace and quiet in the home, irrespective of the at-home activities in which they may voluntarily choose to engage. This is the view of the home implicit in hearing damage risk criteria that posit a daily 16 hour recovery period following 8 hours of occupational exposure. More colloquially, if a man's home is his castle, ought it not be a castle in which he can peacefully repose and converse without undue vocal effort?

Knowledge of the existence of such an acoustic sanctuary may render more tolerable the annoyances of non-residential exposure. It might therefore be argued that if nighttime noise levels were permitted to rise unchecked, community reaction to daytime exposure might become more intense.

3. Arguments Based on Sleep Interference Effects

Perhaps the most common justification offered for a nighttime penalty is the potential of nocturnal noise to disturb sleep. Although it is widely believed that small amounts of chronic sleep interference may pose health hazards, reliable empirical information of the sort needed for systematic assessments of dosage-effect relationships for noise and sleep interference is almost totally lacking. Traditional means of studying the effects of noise exposure on sleep are, for reasons discussed below, not able to produce the amount and kind of information needed to establish sleep interference noise criteria upon which rigorously defensible decisions about nighttime noise penalties can be based.

The two major sources of information about the relationship between noise exposure and sleep disturbance are real-time laboratory data on individual sleep habits, and post hoc social survey data on the prevalence of disturbance. There is also a small body of information derived from field studies of sleep quality.

Laboratory study, although capable in principle of generating detailed dosage-effect relationships (because of the opportunity for precise control of exposure), is so expensive that large-scale studies are simply not economical. Typical laboratory studies involve only a handful of self selected volunteers, from whose behavior it requires a sizeable act of faith to generalize meaningfully to the American population (although this has, of course, been tried). Furthermore, in the absence of genuine theoretical understanding of human sleep habits, it is not clear that the elaborate assumptions and statistical treatment of electrophysiological data can be interpreted usefully for public health and welfare analyses.

In a deliberate attempt to combine the rigorous control of laboratory measurements and the naturalism of the home environment, several studies of sleep electrophysiology and behavioral awakening in the field have been conducted, some using telephone lines to connect laboratory equipment to people sleeping in their own homes. Even this hybrid technique has not yet, for reasons of cost, provided enough information to establish reliable dosage-effect relationships of the desired kind.

Social surveys, on the other hand, offer the opportunity for collection of information about large numbers of people in a representative manner, but cannot link noise exposure and the corresponding sleep effects very closely. Besides, most social surveys on noise effects have concentrated on factors other than sleep disturbance, assigning only one or two general questions to the assessment of sleep interference.

In summary, available information about the relationships between noise exposure and sleep quality are both scarce (for reasons of cost in the case of laboratory study and inattention in the case of social surveys) and incomplete (for reasons of difficulty of interpretation in the case of laboratory study and lack of specificity in the case of social surveys).

Fundamental questions about the relationships between noise exposure and sleep disturbance thus continue to go unanswered. These include such matters as whether cumulative measures of exposure (e.g., L_{dn}) are useful predictors of sleep quality in communities of varying lifestyle and population density; whether sleep quality is similar in communities with similar exposure but different numbers of intrusive events; and so forth.

Thus, there is room for argument about whether the scientific information about sleep interference from noise exposure under real world conditions justifies the need for a nighttime noise penalty. There is little prospect that manipulations of this literature can provide specific guidance for the size of a nighttime noise penalty, even if a decision is made on other grounds that such a penalty is indeed desirable.

Appendix A contains a review of the scientific literature in this area. No fully consistent interpretation of the findings reviewed in Appendix A can be made. Although sleep interference is a sacred cow (because of the likelihood that it may have adverse impacts on health), mean and median responses of noise surveys to questions about effects of nighttime noise intrusions are surprisingly mild. Many people, in fact, respond to the effect "I don't know, I was asleep at the time" when asked about their experiences with nighttime noise.

On the other hand, there is some reason to believe that there are large individual differences in susceptibility to sleep interference, and it can be argued that environmental noise ratings should be structured to confer protection on the noise sensitive portion of the population, rather than a fictional "average" person.

As Bryan (1973) notes,

> "Until recently it was thought that everyone reacted in much the same way to noise. Indeed, our noise laws assume this by saying, effectively, that there is a noise level when the average and reasonable person is annoyed and this is the level at which the public must be protected. However, there is evidence from both laboratory and field studies that this first order approximation is inadequate."

The existence of extreme groups was mentioned as long ago as 1963 in a Central Office of Information survey of attitudes of people living near London Heathrow Airport to the noise of the aircraft. This survey (Noise-Final Report, 1963) found that even at the lowest noise levels, 10 percent of the sample interviewed was intensely annoyed. (It is also true that thirty percent of the sample was unconcerned whatever the noise levels were.)

Thus, even though the percentage of noise survey respondents who report that noise disturbs their sleep is relatively small, there may be reason to argue against abandonment of a night-time noise penalty in order to protect noise sensitive people.

4) A non-negligible proportion of the population may be of such susceptibility to sleep interference and annoyance due to nighttime noise exposure that it enjoys little benefit from regulations intended to confer protection on a hypothetical average person.

The following list of arguments provides a guide to reasoning that supports the need for modification of existing time of day weighting factors:

1) Community noise ratings that currently impose time of day weighting factors lack face validity because they are simplistic and in large measure arbitrary. They are not supported by a systematic rationale or a consistent data base to justify their necessity or magnitude.

2) The mode of implementation of existing time of day weighting factors is awkward and inflexible. They do not directly accomplish the goal of lowering nighttime exposure levels, do not faithfully reflect continuous changes in human sensitivity to exposure, and may produce undesirable side effects.

3) More reasonable bases for time of day weighting factors can probably be constructed to accomplish useful goals of reducing nighttime exposure in a more direct fashion:

   a. More people are home at night than at other times of day, so that opportunities for annoyance and speech communication interference are commensurately greater at night.

b. The well established trend toward lower nighttime background noise levels renders intruding noises more detectable, and hence, more annoying at night.

III. EXPERIENCE WITH TIME OF DAY WEIGHTING FACTORS

A. Some Examples of Extant Time of Day Weighting Factors*

The first formal proposal of a nighttime penalty (Rosenblith et al., 1953) was accompanied by this explanation: "Time of Day. Most residents agree that the intruding noise is more tolerable in the daytime than during the evening. During the night, the background noise levels from traffic and other sources are usually lower than the corresponding daytime levels and hence an intruding noise is subject to less masking. Therefore, the noise is more noticeable. We estimate that a correction number of -1 should be applied to the level rank if the intruding noise occurs only in the daytime. No correction is applied for round-the-clock operation or for operation after, say, ten o'clock at night." This entirely ad hoc correction of -1 in level rank permits "daytime only" noises 5 dB higher in level than round-the-clock or nighttime noises.

The nighttime weighting factor of 10 dB used in the current CNR and civil NEF methods of rating *aircraft* noise is based on annoyance ratings derived from one social survey. It was estimated in the 1961 London social survey (Noise-Final Report, 1963) that a reduction of 17 NNI units was required to achieve the same acceptability for nighttime aircraft operations as for day operations. (For a fixed noise level, this is equivalent to 11 units in CNR or NEF.)

Ollerhead (1978) comments as follows on this reasoning:

*This section draws heavily on Galloway (1977).

> "In fact, this (17 NNI) increment was the estimated difference between typical daytime (0800-2300) and nighttime (2300-0800) values of Noise and Number Index (NNI) then in existence. Since 28% of the respondents said that they were most bothered by aircraft noise at night and 24% were most bothered during the day (the remainder either were not bothered at all or did not directly discriminate between these two periods), it was assumed that daytime and nighttime noise exposures made roughly equal contributions to evoked annoyance. Superficially, this seems logical enough. However, one might wonder what conclusion would have been reached if the survey had been performed at an airport where the noise exposure difference was not 17 NNI and/or where the day-night percentages were very different. Certainly, it is not possible to infer from these results what percentage of people would be most bothered at night if, for example, the day and night percentages were very different. Certainly, it is not possible to infer from these results what percentage of people would be most bothered at night if, for example, the day and night NNI values were equal.
>
> It must also be pointed out that of the 24% bothered during the daytime, 19% were referring specifically to the evening period between 6:00 and 11:00 PM (that is, only 5% were most bothered during the day between 8:00 AM and 6:00 PM)."

The other existing aircraft noise rating methods that make adjustments for day/night noise levels have significantly different computational approaches. Both CNR and NEF assess nighttime exposure, on an energy basis, to be 12 dB more disturbing than daytime. The French, however, have developed a complex adjustment applied to a three-period day, in which daytime (0600-2200), early nighttime (2200-0200), and late nighttime (0200-0600) are weighted according to the expression:

$$10 \log_{10} N_D + 6 \log_{10} [(3N_1 + N_2) -1],$$

where N_D, N_1, and N_2 are the numbers of operations in the three time periods (Galloway, 1974).

The ICAO index, WECPNL, permits either two-period or three-period days. Using the two-period day, 0700-2200 and 2200-0700, the nighttime noise levels are adjusted by 10 dB.

The International Standards Organization also allows either a two-period or a three-period division of the day in assessing noise with respect to community response (ISO R-1996, 1971). The corrections to the criterion level, against which the noise in question is to be compared, are zero for daytime, -5 dB for evening, and -10 to -15 dB for nighttime; for the two-period version, the corrections would be zero and -10 to -15 dB. The international standard does not specify the hours defining the various periods, but leaves it up to the individual country to set its own limits in accordance with its idiosyncratic life-style.

The CNEL measure adopted for rating airport noise environments in California adopts the ICAO specification for three periods in the day, 0700-1900, 1900-2200, 2200-0700. The evening and nighttime periods, respectively, are given 5 dB and 10 dB adjustments on noise level, not noise exposure. Day-night average sound level uses the same two-period day and 10 dB adjustment as the WECPNL measure.

There is clearly little detailed agreement about the time period of application or the appropriate magnitude for a time of day weighting factor among the various community noise rating procedures in current use.

B. Does a 10 dB Nighttime Penalty Lower Nighttime Noise Levels 10 dB?

In the heat of argument about the necessity and appropriate size for time of day weighting factors, their actual effects are sometimes overlooked. They can be surprisingly small. This section examines some of the influences of nighttime penalties on general urban noise and aircraft noise exposure.

One way to examine the effects of time of day weighting factors on a cumulative measure of noise exposure is to consider the increase in weighted noise exposure they provide relative to a straight energy summation. For the case of general urban noise, a relationship between L_{eq} and L_{dn} derived from 24 hour noise measurements at 100 sites around the United States (Galloway et al., 1973) is:

$$L_{dn} - L_{eq} = 3.38 \text{ dB}; \sigma = 1.32 \text{ dB}.$$

In other words, the real world distribution of noise sources over times of day is such that a 10 dB nighttime penalty produces only a 3 dB difference in levels vis à vis an unweighted energy summation. Thus, if the goal of a nighttime penalty is to reduce nighttime urban exposure levels, incorporation of a time of day weighting factor into an energy summation is among the less direct ways to accomplish this goal.

Table I presents two similar analyses for the case of aircraft noise exposure. The first case assumes a uniform distribution

Two examples of field experimental procedures are worth comment in passing. The first, Galanter's (1980) "clock rating" procedure, requires people exposed to aircraft noise in their homes to mark time periods of noise exposure during which they are annoyed in varying degrees by inking in hours on a clock face with colored pens. The technique is an interesting variant of Titchener's (1905) stimulus error ("confusing sensations with their stimuli"), since it requires test participants to rank order time periods of exposure (dosage) rather than indicate annoyance at the time of occurrence (response). Responses may also reflect conventional social wisdom rather than attitudes.

But for the immediacy of collecting such information at a particular time of day in the home, the same rating procedure could equally well be undertaken in the laboratory.

The second procedure provides an operationally definable behavioral response at the time of annoyance. Most recently employed by Horonjeff and Teffeteller (1979), the procedure instructs test participants to press a button on a personal annoyance counter whenever they hear a sound they would rather not have heard. Response rates per unit time may be calculated for whatever intervals totals are recorded and noise exposure measurements are available. The same index of annoyance (the overt act of pressing a button) may be used for comparing reactions at all times of day. Although fuller development of this technique requires more sophisticated hardware than is currently in use, meaningful data have already been collected by this technique in several studies.

B. Meaningfulness of Exposure Conditions

Regardless of what form of design is adopted for field experimentation, it is necessary that test participants from whose behavior one wishes to infer time of day weighting factors actually be exposed to noise in the environment of interest at all times of day. This is necessary both for face validity and for logical consistency in inferences. One cannot logically put together the reactions of people exposed only to nighttime noise with the reactions of people exposed only to daytime noise and then claim to derive a meaningful set of time of day weighting factors. There are no convincing a priori reasons to ignore the very real possibility that reactions to nighttime exposure, for example, interact with memory of daytime exposure conditions. By the same token, one cannot credibly claim to stitch together a consistent set of time of day weighting factors from the reactions of people who do not have any experience with exposure at some times of day.

It does not suffice, for example, to draw inferences about nighttime sensitivity to noise exposure from a sample composed of some people who hear a log of nighttime noise but little or no daytime noise, other people who hear a lot of daytime noise but little nighttime noise, or other sets of people with peculiar exposure circumstances. In such a procedure one never has an opportunity to learn how the opinions of people who do not experience noise exposure at some time of day would be affected if they did hear noises at such times. The problem with such a research design is not that different individuals are exposed to different noise environments, but that no individuals are exposed to a realistic 24 hour cycle of noise.

C. What May be Gained from Additional Research

Kryter (1980) asserts that additional social survey research in the area of differential sensitivity to noise exposure at different times of day is unlikely to reveal radically different findings from those currently available, and that the most that can be expected from additional research is a strengthening of existing information about time of day weighting factors. He also makes the point that some degree of uncertainty in quantification of human response is inevitable, thus (by extension) not worth a major effort to reduce.

Van Os (1980) reinforces this view by noting that additional research can be expected to be afflicted by additional nuisance variables, and that there is something to be said for quitting while ahead. According to Van Os, the solution to the problem of divining time of day weighting factors in Holland has been "to stop worrying about the problem".

Many of the same points may be made with greater force in the case of field studies of physiological effects of noise exposure at different times of day. Does the heart beat slightly faster when airplanes fly overhead in the morning than in the afternoon? Would it matter if it did? Are different hormones released into the bloodstream while sleeping and waking people are exposed to aircraft noise? Can potential differences of this nature be said to have health consequences?

Effects of this sort are enormously expensive to study even with caged infra-human primates. The cost of conducting a meaningful study on a respectable sample of unrestrained humans exceeds all reasonable bounds. Physiological time of day effects attributable to noise exposure are so subtle and uninterpretable that they could not serve as the basis for systemtic arguments about time of day weighting factors in any event.

As noted by Fields (1980), the greatest payoff for continued research is likely to come from field experimentation in which as much control (or at least observation) as is economically feasible is exercised over the temporal linkage between exposure and response.

It should not be expected, however, that even this new type of research will be able to satisfy the essentially insatiable demands of some parties to the controversy over time of day weighting factors for "more information".

V. SUMMARY AND RECOMMENDATIONS

As with many issues of social policy, the case in favor of some form of time of day weighting factor for measures of community noise exposure is untidy, but strong enough to persuade most people of the reasonableness of the position. It does not follow that the present implementation of time of day weighting factors in a measure such as L_{dn} is optimal. Unfortunately, the search for an optimal scheme, like the quest for the Holy Grail, is predestined to failure. No scheme complex enough to incorporate weighting factors that reflect alleged differences in human sensitivities to noise exposure at various times of day is likely to gain acceptance.

Consider, for example, the likelihood of acceptance of a scheme that penalized weekday noise exposure 1) rather heavily during the dinner hour to minimize interference with family conversation; 2) somewhat less so in the remaining evening hours to permit unimpaired television viewing; 3) quite severely around 11 PM so that people could fall asleep quickly without intruding noises; 4) relatively lightly again during the early AM hours when people tend to be in deep sleep, and 5) fairly heavily again around 5-6 AM to prevent premature awakenings from light sleep. On weekends, of course, ...

Much of the controversy about time of day weighting factors concerns their magnitude and manner of implementation rather than their necessity. Another large portion of the controversy deals with quibblings over the chain of reasoning leading from noise effects research to any specific weighting factor. The controversy is fueled by conflicting interpretations of the research findings summarized in Appendices A and B, and by other extra-scientific motivations as well.

Much of the controversy can be avoided if an effort is made to infer an appropriate magnitude for a time of day weighting factor from first principles, rather than from arguments drawn from a data base that will contain gross uncertainties for the foreseeable future.

The following reasoning modifies the "equivalent fully impacted population" concept of the Noise Impact Index to suggest deductive arguments in favor of a time of day weighting factor. The goal of the suggested time of day weighting factor is to maintain a constant "equivalent fully impacted residential population" throughout the day. Compensation is thus necessary for any objectively definable factors that would tend to produce a change in the equivalent fully impacted residential population at any time.

Note that this line of reasoning does not even address the question of differential human sensitivity to noise exposure as a function of ongoing activity at different times of day, and hence is not challengeable on grounds of inconclusive or conflicting evidence about such sensitivities.

Two dominant factors can be identified that, unless compensated, would tend to produce larger evening and nighttime equivalent fully impacted residential populations. First, since the residential population swells by a factor of at least two to four during evening and nighttime hours, a weighting factor of about three to six decibels during these hours is justifiable to maintain a constant equivalent fully impacted residential population throughout the day.

Second, since noise from most human activities diminishes at night, nighttime background noise levels tend to drop in most communities. If it is assumed that the detectability of intruding noises governs both their direct annoyance and their ability to delay the onset of sleep, yet another weighting factor is justifiable to preclude a greater nighttime equivalent fully impacted residential population.

Time of day weighting factors necessitated by these two effects should be additive, and preferably expressed in terms of stricter levels of tolerable exposure to a non-weighted 24 hour cumulative measure (i.e., a straight energy summation). If necessary for the sake of a conservative margin of safety, a nominal early morning weighting factor may be added to acknowledge the potentially adverse health effects of noise exposure on sleep. Ideally, time of day weighting factors composed as suggested here should reflect local residential patterns and changes in background noise levels. Furthermore, the weighting factors should be gradually, rather than abruptly, applied.

This level of complexity will doubtless raise objections of administrative inconvenience. For the sake of simplicity, compromises may be worked out from careful studies of nationwide residential patterns and noise exposure circumstances. These compromises would be based on estimates of average differences in residential population sizes at varying times of day, and average differences in background noise levels at varying times of day.

VI. CONCLUSIONS

A. The following answers are suggested to the two questions posed at the beginning of this document:

1) Are noises heard at different times of day equally disturbing to people?

There is good reason to believe that noises occurring during daytime hours may be less disturbing than noises occurring at other times of day. This belief has no necessary basis in differential human sensitivity to noise exposure at different times of day, but is related to the greater detectability of intruding noises in the presence of generally lower nighttime background noise levels, and the greater numbers of people at home to be disturbed at night.

2) How should an index of community noise exposure account for an actual or presumed difference in human sensitivity to noise exposure as a function of time of day?

An index of community noise exposure should incorporate time of day weighting factors that maintain a constant equivalent fully impacted residential population at all times of day. This goal may be accomplished without reference to the noise effects literature by simple compensations for demographic and exposure patterns.

B. The debate over time of day weighting factors is pluralistic and self-sustaining. The two most effective resolutions of the debate are 1) to stop worrying about it, and 2) to wield a sword capable of cutting through the Gordian Knot of the controversy.

C. There are good and sufficient reasons for including time of day weighting factors in metrics of community noise exposure that have nothing to do with differential human sensitivity to noise exposure at different times of day.

D. A 10 dB nighttime penalty, while undoubtedly not exactly correct, may well be tolerably close to the truth for most purposes.

E. The struggle necessary to establish widespread acceptance for an alternative time of day weighting factor may jeopardize the credibility of measures (such as L_{dn}) that currently incorporate a 10 dB nighttime penalty, while gaining only a small increment in precision of quantification of human response to community noise exposure.

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APPENDIX A

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APPENDIX A

REVIEW OF THE LITERATURE ON SLEEP INTERFERENCE DUE TO NOISE EXPOSURE

A. Laboratory Studies of Sleep

Precisely because laboratory studies of effects of noise on sleep are conducted in the laboratory rather than in the world at large, attempts to apply inferences drawn from them to real world criteria for sleep interference lack a certain face validity. Such studies are also expensive and tend to use non-representative and small samples of test subjects. Laboratory studies should not be overlooked, however, if only because they provide a background for understanding field studies of noise effects on sleep. This section of Appendix A draws heavily from Miller (1971), to which the reader is referred for procedural detail of electrophysiological measurements of sleep quality. It is assumed in the following discussion that the reader is familiar with classifications of EEG records of sleep into the customary stages.

1. Effects of Brief Noises on Sleep

Effects of relatively brief noises (about 3 minutes' duration or less) on a person sleeping in a quiet environment have been studied most thoroughly. Typically, presentations of the sounds are widely spaced throughout a sleep period of 5-7 hours.

A summary of some of these observations is presented in Figure A-1. The dashed lines are hypothetical curves which represent

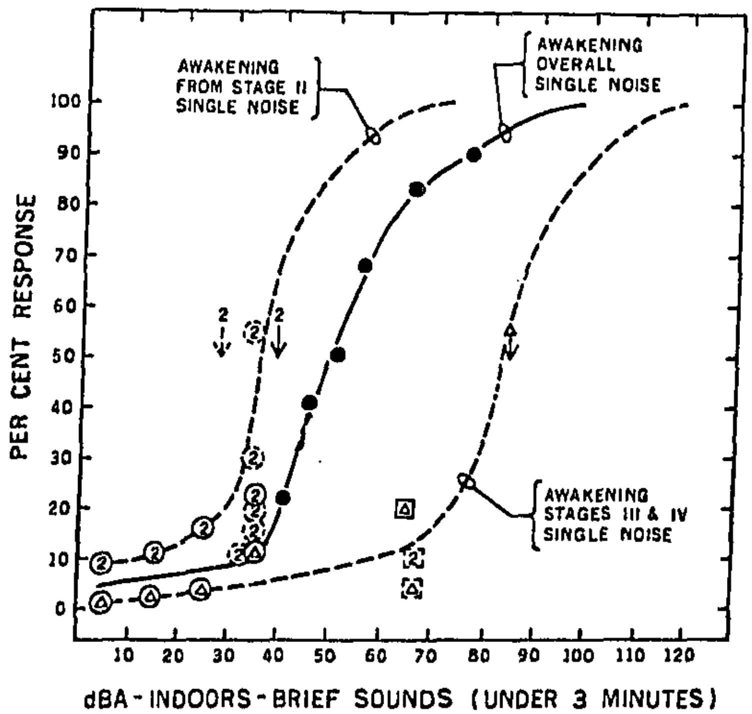

Figure A-1. Awakenings to sound from various laboratory studies are shown. The horizontal axis gives the approximate A-weighted sound level (dBA) of the noise. The curves labelled "awakening" are from normally rested young adults who were sleeping in a laboratory and were moderately motivated to awake in response to sound. The percentage of awakening responses will depend not only on the intensity of the sound but also on the definition of "awakening", the motivation of the subject to awake in response to sound, and the sleep stage (I, II, III, IV or I-REM) when the stimulus is presented. The filled circles were gathered throughout the night without regard to sleep stage. Data from sleep stage II are represented by 2's; those from sleep stages III and IV by deltas, Δ's.

the percentages of awakenings under conditions in which the subject: 1) is a normally rested young male adult who has been adapted for several nights to the procedures of a quiet sleep laboratory, 2) has been instructed to press an easily reached button to indicate that he has awakened, and 3) has been moderately motivated to awake and respond to noise (such motivation can be established by instructions which imply that somehow the subject's ability is being tested). A datum for sleep Stage II is indicated by an Arabic two, 2. A datum for sleep Stages III and IV is indicated by a Greek delta, Δ.

While in Stage II, subjects may be awakened by signals on the order of 30-40 decibels above the level at which they can be detected when people are conscious, alert, and attentive. While in Stages III or IV, signals may have to be as much as 50-80 decibels above the level at which they can be detected by conscious, alert, attentive people, to awaken sleepers. There is also at least strong anecdotal evidence that the meaning of an acoustic signal affects its likelihood of awakening.

The filled circles represent the percentage of sleepers that awake to a 3-minute sound at each A-weighted sound level (dBA) or lower; this curve is based on data from 350 persons, each tested in his own bedroom. The measurements were made between 2:00 and 7:00 AM, so it is reasonable to assume that most of the subjects were roused from Stages II or I-REM.

There is clear evidence that motivation to awake can influence the probability of awakening to noise. The effects of motivation, however, depend on the stage of sleep and the intensity level of noise. Motivation may have a strong influence on arousal to weak acoustic signals only during light sleep. For moderately strong signals, motivation to awake may have a powerful effect on the probability of an upward shift in sleep stage (probably also awakening) from all depths of sleep. Motivation has little influence on awakening due to strong acoustic stimulation; for example, brief noises with A-weighted sound levels of about 120 decibels will probably awaken nearly everyone from any stage of sleep.

2. Fluctuating Noise Levels

An extensive French study (Muzet, 1973) of the effects of noise on sleep contrasted the effects on sleep of different kinds of noise. Several measures of the quality of sleep were used, including the amount of time in each sleep stage, numbers of brief awakenings (as evidenced by the appearance of alpha waves in the electroencephalogram), numbers of bodily movements, degree of muscular tension, occurrence of perturbations in heart rate, presence of eye movements, and occurrence of various components of the electroencephalogram.

Artificial sounds (crescendoes of white noise that rose to about 80 decibels in 10 seconds and were terminated abruptly), sounds of aircraft flyovers with peak values of 72 and 89 decibels (either 16 or 33 per night), and traffic noise were presented to sleepers in various experiments.

The time required to fall asleep was longer for the noise conditions than the control conditions. Under control conditions, about 26 minutes elapsed between going to bed and the first occurrence of Stage IV. With traffic noise, the delay between going to bed and the first occurrence of Stage IV was 33 or 52 minutes depending on the type of noise. When noises were presented, there was a tendency for sleep to be much lighter than normal for the first half of the night, and slightly deeper than normal for the second half of the night. Thus, there was a tendency to compensate for the loss of deep sleep in the early part of the night. Nonetheless, almost all measures of sleep disturbance indicated that sleep was disturbed overall and throughout the sleep period.

The results with traffic noise were of particular interest. These sounds were actually recorded in a bedroom near a busy street. One set of recordings was made between 10:00 PM and midnight. Another was made between midnight and 4:00 AM. The 10:00 PM to midnight sample represented about 4.3 vehicles passing per minute while the midnight to 4:00 AM sample had only about 1.8 vehicles per minute. The peaks in both samples reached A-weighted sound levels of nearly 80 dBA, but the long-term averages were 70 dBA for the high-density traffic and only 61 dBA for the low-density traffic. The control night had steady ventilation noise with a median A-weighted sound level of 48 dBA.

Interestingly, light traffic caused the greatest sleep disturbance, approximately doubling both the time required to get to sleep (11.9 to 29.1 min.) and the time before the onset of deep sleep (32.6 to 52.0 min.), despite the fact that the median level of this noise exposure was 9 dB less than for the heavy traffic

7- and 8-year-old children are slightly less sensitive to noise during sleep than are middle-aged adults. However, since general sleep disturbance in children (enuresis, somnambulism, night terrors, and nightmares) seems to peak between 4 and 6 years of age, sleep disturbance by noise may have a special impact on children in this age range. It is well known, for instance, that thunderstorms can waken and frighten children.

5. Sleep Stage and Accumulated Sleep

In terms of either behavioral awakening, or an upward shift in sleep stage as indicated by the electroencephalogram, sleep can be influenced most easily in Stages I and II and least easily in Stages III and IV. Sometimes I-REM seems to be more like III and IV in this regard; at other times it is more like Stages I and II. A person can be aroused from sleep more easily the longer he has slept, regardless of current sleep stage.

6. Stimulus Meaning and Familiarity

The effects of stimulus meaning and familiarity are closely bound to those of motivation and stimulus intensity. There is considerable evidence that sleepers can discriminate among stimuli if the differences were learned and the discrimination was established while they were awake. In a classic experiment, it was demonstrated that sleeping subjects will respond when their own names are spoken, but show few responses to other names. Generally, when auditory stimuli are faint and similar, discriminations are probably performed better in light sleep (I, II, and I-REM) than during deep sleep (III and IV).

The effect of stimulus familiarity on arousal from sleep has not been studied extensively. In one experiment, small but consistent differences were found between familiar and unfamiliar sounds: "familiar" sounds shifted sleep stages less frequently than "unfamiliar" sounds.

7. Adaptation to Sleep Disturbance by Noise

Whether adaptation to a noisy environment takes place is the subject of considerable debate. Consequently, laboratory studies during the last decade have tended to concentrate on adaptation and habituation to noise. According to Miller, 1971, the stronger the stimulus, the less likely it is that total adaptation will take place. Behavioral awakening and the duration of awakening will probably show the most adaptation. Upward shifts in sleep stage are likely to show some adaptation, but less than behavioral awakening. Brief responses in the electroencephalogram and automonic responses such as changes in heart rate, blood flow, skin resistance, and so on appear to show very little adaptation. The most significant and surprising finding has been that adaptation, even in behavioral awakening, has been absent or slight.

8. Canadian Study on Response to Truck Noise

Thiessen has recently reported a Canadian laboratory study of habituation to truck noise (1978). Sixteen subjects slept 12 to 24 nights in succession in the laboratory, while seven truck noises, at an A-weighted level of 65 dB, were played back in unequal intervals during the first six hours of the night. Besides obtaining their behavioral awakening response by requiring that they press a button if they awake for nay reason whatsoever, their sleep was also monitored by means of an EEG to measure the other changes in sleep stages. Frontal electrodes were used, one being located at the center of the forehead while the other was located to one side near the hairline.

The results are shown in Figure A-2, which plots the probability of sleep disturbance versus the number of nights of exposure. The open circles represent the probability of waking; the solid circles represent the probability of any shift in sleep level. The latter show no significant habituation in 24 nights while the waking response is clearly adapting and drops to half value in about two weeks.

A further experiment with 12 subjects involved alternating nights with noise and nights without noise, increasing the number of noises to 18 to 20 presented during the whole night. The results were very similar. The total number of shifts had a fairly constant probability while the behavioral awakening dropped to half the original value by the end of the 24 night session or on the 12th noise night.

9. French Study of Habituation of Heart Rate and Finger Pulse

Another recent study from France investigated the habituation of heart rate and finger pulse responses to road traffic noises (Muzet et al., 1978). Six healthy subjects, aged 19-24, slept in the laboraotry for 1 adaptation and 2 baseline nights, followed by 15 disturbed and 2 recovery nights. Air temperature and relative humidity were kept constant at respectively 20° C and

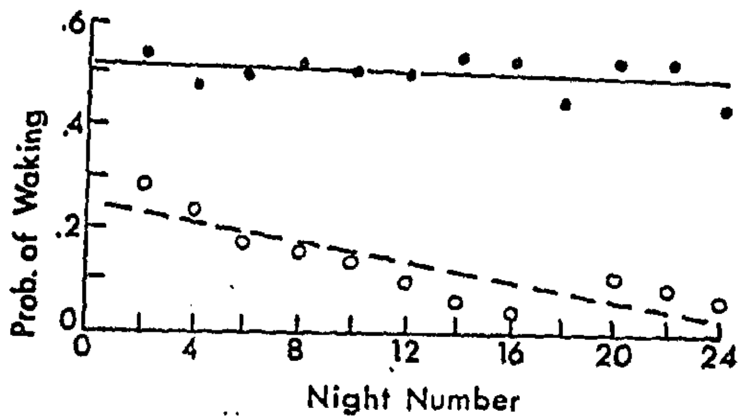

Figure A-2. The probability of shift in sleep level due to a truck noise of 65 dB (A-weighted) is shown by the solid circles. The open circles give the probability of waking. The solid and dashed lines give the respective linear regression lines.

60%, while the background noise was 35 dBA. During the disturbed nights, traffic noises with peak intensity of 45, 55 and 65 dBA were semi-randomly presented through loudspeakers between 2300 and 0700 hours at a rate of 30 noises of each peak intensity per hour (a total of 90 events per hour, 720 noises per night). Each morning after awakening, the subjects had to fill in a sleep questionnaire. Cardiovascular measures (heart rate, finger pulse amplitude, and pulse wave velocity) were recorded every night by a computer.

The heart rate response was obtained by averaging heart rates observed at the time of each noise; an average was made for each noise intensity, both over two-hour periods and for the entire night. Finger pulse response was obtained similarly, but was expressed in relative and not absolute value.

The magnitude of heart rate as well as finger pulse responses did not decrease from the beginning to the end of the disturbed night; it even increased slightly for the 65 dBA peak intensity noise as time went on. While the subjects stopped mentioning noise as a disturbing event of their sleep after two to seven disturbed nights, there was no habituation in the all-night average heart rate or the finger pulse responses to the loudest noise. Even with the lower noise levels (45 to 55 dBA), there was no habituation of the responses.

10. Dutch Study on Habituation to Traffic Noise

Habituation to general traffic noise was also investigated in a recent Dutch laboratory study (Jurriëns, 1978), carried out over a period of thirty nights. In order to study habituation to a noisy condition, a pilot study was carried out in which 6 young male subjects slept during more than 30 consecutive nights in a specially designed bedroom in the laboratory.

The first 10 nights were relatively quiet, the air-conditioning determining a continuous level less than 35 dBA. In the next 20 nights, traffic noise was played back, which had been recorded during a whole night along a highway and which was attenuated and frequency-corrected to stimulate the sound insulation of an average facade. The equivalent sound level over a short period varied from about 40 dBA in the middle of the night to 60 dBA in the early evening and in the morning.

The EEG, EOG and ECG of the subjects were recorded. In the evening they completed a questionnaire about the past day, and in the morning they did a simple varying interval reaction test and completed questionnaires about sleep quality and mood.

Of the possible physiological variables, as a first approach, the delta intensity was obtained by filtering out the EEG-activity between .5 and 2.5 Hz. Expressed as a level in dB, its grpahical variation during a night gave an overall picture of the rhythmic activity and a fair approximation of the amount of sleep in Stages III and IV (deep sleep).

The average delta intensity level over the first 10 nights was higher for all 6 subjects than the average over the second 20 nights, 4 of these differences being significant. That is, continued noise exposure lessened the amount of deep sleep. Measures for reaction time, sleep quality, the mood states "vigor" and "well-being by day" also clearly tend to decrease in the second period of 20 nights, some of the differences being significant.

11. German Study of Habituation to Various Mixes of Noise

A recent series of five German laboratory experiments on habituation used as a stimulus, traffic noise intermixed with other kinds of quite intense noise (Ehrenstein, 1978). The sleep stage patterns of 52 subjects (19-69 years) were studied.

Continuous or intermittent noise from street traffic, traffic noise with intermittent bursts of noise from air hammers or pile drivers, and noise from jet aircraft flyovers served as acoustic stimuli. The equivalent sound levels measured near the head of the sleeper varied between 54 and 76 dBA; maximal peak levels of the jet flyover noise reached 100 dBA.

The overall sleep length was not affected by the noise. Continuous traffic noise led to changes in the total amount of the various sleep stages during the first night: slow wave sleep (Stages III and IV) significantly decreased; the mean increase of intermittent wakefulness and the mean decrease of sleep State REM were significant only in some of the experiments. Most of these changes disappeared after several consecutive noise-disturbed nights.

The arousing effects of single noise events (passing motor car or jet flyover) were evaluated by calculating the percentage of noise-induced sleep-stage changes. (Spontaneous sleep-stage changes were taken into account by use of the pseudostimulus-technique.)

The arousing effects were strongest in slow wave (Stages III and IV) sleep. No adaptation was observed during 3 nights disturbed by the noise of jet flyovers and 5 nights disturbed by the noise of passing motorcars. This result agrees with that of Thiessen (Figure A-2, above).

The sleep stage patterns completely adapted during 8 consecutive nights when a continuous noise with super imposed bursts of noise from air hammers or pile drivers (L_{eq} = 76 dBA) was presented, although daytime self-estimations of mood and vigilance showed a progressive deterioration. These last results call in question the significance of sleep stage patterns as a sufficient and valid measure of noise effects on sleep.

12. Summary: Habituation and Adaptation to Noise

The general conclusion from the studies reported above is that some aspects of sleep (awakening) may tend to adapt to noise intrusions of certain kinds, but that others (changes in sleep state) may not.

Griefahn (1977) has calculated an habituation function demonstrating an increase of 0-reactions (all reactions less than a change of one sleep stage) and a decrease of awakening-reactions caused by noise. The ascent of the curve of habituation gradually becomes flatter and is about 0 by the ninth test night.

The increase of 0-reactions, as well as the decrease of awakening reactions, depends on the information content of the noise, and decreases with the number of stimuli (Griefahn, 1977).

The adaptation that seems apparent from everyday experience may be the result of 1) changes in the motivation to awake; and 2) amnesia for awakening. The last point is partially supported by the observation that subjects in sleep laboratories sometimes cannot remember the number of times that they awaken. Pearsons et al. (1973), however, report good agreement between electrophysiological numbers of awakenings and subjective reports of awakenings.

There is clear evidence for adaptation to the total sleeping environment, noise exposure aside. Normal sleep is rarely if ever observed during the first night in the laboratory. It is likely that some of the disturbance reported by the rural person trying to sleep in an urban area and the urban person trying to sleep in a rural area is but the "first night" effect. It is commonplace, however, that people who have difficulty sleeping for whatever reason, "hear" many sounds.

13. Other Factors

There are, of course, many other factors that affect sleep and arousal. These include mental and physical disease, drug use, general stress, and so on. Most of these have not been studied in relation to the problem of sleep disturbance by noise. Generally, persons with disorders that result in light, restless sleep or frequent awakenings appear to be more frequently aroused by sounds than will normal persons or persons with disorders that produce unusually deep and prolonged sleep.

14. Noise, Sleep Disturbance, Health, and the Quality of Life

Laboratory studies have shown that brief sounds of sufficient intensity, as well as fluctuating noise levels, can change the normal sleep pattern in the direction of lighter sleep. The effects of noise are to produce sleep patterns that are more like those of "poor sleepers" than "good sleepers".

According to Miller (1971), it is debatable whether such sleep disturbance constitutes a meaningful health hazard. While normal sleep is necessary for physical and mental health, most persons who lose sleep compensate by spending more time in deep sleep, by becoming less responsive to external stimuli, and by napping. Thus, it may be very difficult to deprive a normal person of sufficient sleep to produce adverse health effects.

On the other hand, laboratory data clearly support the notion that people exposed to sufficient noise will complain of sleep loss. Everyday experience strongly supports the notion that a "good" sleep is important to feelings of well-being.

All factors considered, one must tentatively assume that sleep disturbance by excessive noise will reduce one's feelings of well-being. When noise conditions are so severe as to disturb sleep on a chronic, unrelenting basis, then such sleep disturbance may constitute a hazard to one's physical and mental health (Miller, 1971).

15. The Relevance of Laboratory Studies of Sleep Disturbance by Noise to the Nighttime Penalty

The relevance of the laboratory studies of sleep disturbance by noise of various kinds is best found in the results summarized in Figure A-1. It shows that indoor noise levels greater than 35 dBA are required to awaken subjects from Stage II (light) sleep, while levels greater than 80 dBA are needed for arousal from deep sleep. With open windows, the corresponding outdoor levels would be about 15 dB higher and with windows closed, about 25 dB higher (Environmental Protection Agency, 1974), in each case. Thus, outdoor noise levels exceeding 50 to 60 dBA will tend to arouse people from light sleep; such levels occur frequently in urban areas. On the other hand, levels over 95 to 105 dBA outdoors would be required to awaken most people from deep sleep. Such levels, lasting as long as three minutes (corresponding to the laboratory stimuli studied) are relatively rare, even in noisy city downtown areas.

The maximum benefit from sleep appears to come from the deep sleep periods; if deprived of deep sleep for a certain time, the person compensates later by spending more time in deep sleep. The function of light sleep is not well understood, but it appears to be less critical to people's well-being.

The combination of a strong probability of finding noise levels in urban areas high enough to disturb relatively unimportant light sleep, and the slight probability of finding noise levels high enough to interrupt the necessary deep sleep, together, offer only a rather ambiguous justification for the nighttime penalty in a rating for urban noise in general.

B. Field Studies of Sleep Quality

1. Studies at Los Angeles International Airport

Two related electrophysiological studies of sleep quality have been conducted in the homes of long term residents in the landing paths at Los Angeles International Airport. In both studies, compact EEG telemetry equipment was used in conjunction with automatic noise monitoring equipment in an attempt to establish direct relationships between individual flyovers and occurrences of sleep disturbance.

The first study (Pearsons et al., 1973) found small but reliable differences (accounting for at most 16% of the variance between groups) in amounts of "light" and "deep" sleep of test participants at the airport and a control group of people living nearby (but beyond the influence of landing noise). Individual aircraft noise intrusions were indeed found to shift sleep stages in the group living near the airport. An average of four awakenings per night was observed for these test participants.

A second study by the same researchers (Pearsons et al., 1974) was conducted in conjunction with the start of a night curfew on airport operations in the vicinity of the homes of a small group of test participants at Los Angeles International Airport. Although noise measurements confirmed a large reduction in noise levels following the curfew, sleep measures indicated no statistically significant changes in sleep patterns either immediately after the change in operations or approximately a month thereafter. Furthermore, no strong relationship was observed between noise level and sleep disturbance over the range of 60 to 90 dBA.

2. A Computer Controlled Behavioral Awakening Study

A more recent field study of sleep quality was conducted by Horonjeff et al. (1979). Horonjeff et al. developed a sophisticated technique for exposing test participants to calibrated noise exposure conditions in their own homes, and recording their behavioral awakening responses in an adaptive experimental design. A laboratory computer connected by telephone lines to the test participants' homes was able to generate sequences of noise exposure, observe the test participants' response or lack of response to the exposure, and decide in real time how to adjust the course of experimentation throughout the remainder of the night to collect as much information as possible about the likelihood of awakening due to transient and continuous (15 minute) exposure to four different signals heard at many different levels.

By measuring typical background noise levels in the sleeping environment, Horonjeff et al. were able to relate probabilities of awakening not only to absolute signal level, but also to signal to noise ratio. Furthermore, they demonstrated that susceptability to awakening is an energy-like process: the longer the signal duration, the higher the probability of awakening. An integrated measure (d'-seconds) that reflects both signal duration and its signal to noise ratio provided the best predictability of probability of awakening.

3. On-Going Studies of Sleep Disturbance by Noise

A joint research project is underway, in Denmark, France, The Netherlands, and the United Kingdom, concerning the effects of noise on sleep and psychological performance. The studies are being carried out by four national laboratories, according to a common procedure, taking the usual laboratory measurement equipment into the homes of the subjects, for measurements under normal living conditions, to minimize the interference of the unfamiliar laboratory environment on the test results. The teams will make measurements of a variety of physiological parameter and tests of psychological performance of persons living in noisy environments near highways for one or more years. The outside noise levels will be chosen to correspond to L_{eq} greater than 60 dBA (or L_1 above 70 dBA).

The data from the first phase (1977-78) is being analyzed; it will guide the conduct of the second phase (1979-80).

It is hoped that the results of this large-scale effort will help clarify the question of variability of community response to noise at different times of the day.

C. Sleep Interference Effects Inferred From Social Surveys on Noise Annoyance

Before considering findings of social surveys, it is useful to recall some of the limitations on surveys as a means of discovering the relationship between noise and sleep disturbance.

First, most surveys have treated sleep disturbance as only one aspect of overall annoyance; therefore, with few exceptions, the questions concerned with sleep were scarce, and were embedded in a context of general annoyance with the transportation noise source under study. As a result, only a small part of the interview dealt explicitly with sleep, and only a limited amount of sleep information was gained. Perhaps worse, the context of annoyance established by the other interview questions may have biased the subjects' responses to the sleep questions.

Although social surveys offer the opportunity to gather information from large numbers (sometimes thousands) of people in a representative manner, they cannot establish reliable, detailed relationships between noise and sleep, for two reasons.

a. It is not possible to measure directly the noise to which the subjects were exposed; noise levels must be inferred from measurements made at "typical" locations in the interview neighborhood, and at particular times; or, they must be calculated from data on distance-to-source, source sound power, sound propagation losses, etc. In either case, the transportation noise exposure attributed to each subject is an approximation, and no reckoning at all is made of the noise generated (and heard) inside the home.

b. When a subject expresses annoyance or describes sleep disturbance, it is not clear at what time the disturbance occurred; does the respondent have in mind a general reaction over a period of time (how long?); or does he remember and respond to a specific annoying event?

In the laboratory, both the magnitude and the time-of-occurrence of the noise stimulus can be precisely known. In a social survey, the stimulus and response are known only via rather remote inferences.

Nevertheless, it is in a real-life context (that is, the home) that meaningful relationships must be sought between real-life noise intrusions and real-life responses to them.

1. Aircraft Noise and Sleep Disturbance

In this section, sleep disturbance results from a number of aircraft noise surveys are described. These survey results lend themselves better than laboratory studies to distinguishing between disturbance at different times of day.

a. First Heathrow Study

In the first survey of aircraft noise annoyance around Heathrow Airport, London, only one question concerned sleep disturbance (Does the noise of aircraft ever wake you up?); it is not clear from "Noise-Final Report", 1963, whether that question was asked separately or in a question that included interference with radio/ television listening or conversation, or house vibration. In any case, the early suggestions for a nighttime noise penalty rested on the showing, from this survey, that the noise exposure from nighttime aircraft operations needs to be 17 dB lower than daytime levels to elicit a comparable community response. Ollerhead's skepticism concerning that conclusion has already been noted.

b. Second Heathrow (1967) and Gatwick (1971) Airport Surveys

Special attention was given to nighttime disturbance when the Heathrow survey was repeated in 1967 (Her Majesty's Stationery Office, 1971). The results on annoyance due to aircraft flying at night were summarized as follows: "Over half the people in the fifteen mile area around Heathrow are still up at 11:00 PM but almost all are in bed by midnight. Most are up by 8:00 AM on weekdays.

"Because of the severe restrictions on the use of Heathrow at night, nighttime exposure in terms of loudness and number of aircraft heard was very much lower than during the daytime.

A special scale was constructed to measure annoyance due to aircraft flying at night. Analysis of this scale in relation to the general annoyance scale indicated that there is a separable element of annoyance due to aircraft flying at night but there is a very large general factor of annoyance which is measured by both the nighttime and the general annoyance scale.

A notable point about nighttime annoyance is that almost half the sample claimed to suffer no disturbance at all from aircraft at night. Those who claimed to have difficulty in sleeping were more annoyed by aircraft noise at night, suggesting a large psychological component in vulnerability to nighttime noise.

The association between level of nighttime exposure to aircraft noise and nighttime annoyance was lower than that between daytime exposure and general annoyance. A further interesting point is that in fact the general annoyance scale is more highly correlated with nighttime exposure than is the specific night annoyance scale. This may be because daytime exposure is more important in determining general annoyance reactions and what is reflected here in the correlation between night and day exposure patterns." (Her Majesty's Stationery Office, 1971).

Thus, according to the Second Heathrow report, no clear results were obtained on the relation between aircraft noise and nighttime disturbance. Under closer scrutiny, however, this negative conclusion is explained by the fact that nighttime noise exposure is substantially reduced in London by nighttime limits on both the number of flights permitted and use of noisier aircraft. The daytime noise exposure substantially outweighs the nighttime exposure and thus governs the overall subjective response.

Ollerhead supplements these qualitative results from the Second Heathrow survey, adding some unpublished survey results of his own, from London (Gatwick) Airport (1971) (Ollerhead, 1978). Respondents were shown a card representing an annoyance scale. It displayed the integers between end points 1 and 7; the end points were designated "not at all bothered" and "very much bothered", respectively; the other scale steps were not named.

In order to separate annoyance components corresponding to different times of the day, they were then asked: "Look at this scale and pick out the number which indicates how bothered or annoyed you feel during the morning ... and during the afternoon/evening/night.

The mean responses and standard deviations listed in Table I show that both surveys gave similar results. The differences between morning and afternoon means and between evening and night means are statistically indistinguishable; however, the differences between the means for morning or afternoon and evening or night are highly significant (at the 0.05% level). These results appear to confirm that people are more annoyed by aircraft noise at night than during the day, but that the noise is equally bothersome during the evening and night.

Unfortunately, it is not clear whether respondents were describing the cumulative effects of noise during each of the time periods or the response evoked by individual aircraft sounds as and when they intrude. Although it seems more likely that they would be expressing some general or continuing level of agitation (corresponding to the second response), they were given no instructions concerning this important distinction.

TABLE I

ANNOYANCE SCORES FOR DIFFERENT TIMES OF THE DAY

	Morning	Afternoon	Evening	Night
Heathrow (4699 respondents)				
Mean	2.53	2.47	3.31	3.14
Standard Deviation	2.22	2.17	2.33	2.39
Gatwick (1030 respondents)				
Mean	1.75	1.74	2.45	2.48
Standard Deviation	1.30	1.31	1.76	1.86

No traffic dtails were reported, but it may be assumed that hourly aircraft movements were distributed roughly in the typical ratio 5:4:1 for the three periods of day, evening and night. Thus, if the second response is true such that annoyance is dependent upon the number of flights per hour, then in terms of their capacity to evoke annoyance, aircraft are over four times more effective at night than during the daytime or evening. If, on the other hand, the cumulative effects are more relevant, the total number of flights per period (morning, afternoon, evening, or night) may be the controlling factor and these are distributed in the approximate ratio 4:4:2:1. This would imply that one nighttime aircraft is only as annoying as two evening aircraft but more annoying than four daytime aircraft."

c. Los Angeles (LAX) Airport (Ollerhead, 1978 and Fidell et al., 1975)

"An alternative approach was demonstrated by Fidell and Jones (1975), who studied the effects upon community annoyance of a dramatic reduction in nighttime aircraft noise. This was an experiment in which night approaches to Los Angeles International Airport were diverted from a westerly to an easterly direction - a measure which between 11:00 PM and 6:00 AM reduced equivalent continuous noise levels by 25 to 30 dBA in residential areas to the east of the airport. Surveys of responses were made during the week prior to the change, immediately after the change, and four to six weeks after the change. In each survey the following question was asked: "Does aircraft noise annoy you more when you are trying to sleep at night or does it annoy you more at times during the day?"

The percengates of respondents who reported more annoyance during the daytime were (for the three surveys) 68%, 66% and 72%. No significance can be attached to the differences between these three results but they appear to reveal a total lack of public sensitivity to the nighttime noise (which was removed). This is supported by the responses, in the third survey, to the question, "Have you noticed any increase or decrease in number of flights near your home in the last month?"

These responses were distributed as follows: none noticed (or don't know) - 60%; decrease - 20%; and increase - 20%."

This indifference of the LAX neighbors to a complete cessation of nighttime flights is astonishing because the airport noise has been a hotly disputed issue there. One possible explanation is that the number of daytime operations at the airport is so great (687) that complete elimination of the 50 nighttime flights lowered the day-night average sound level by less than 3 dB, so no substantial change in community response occurred.

No appreciable effects were observed in terms of reduction in annoyance, or reduced speech or sleep interference. But large, consistent and statistically significant differences in response patterns as a function of noise exposure were observed both before and after cessation of the late-night flights. Details with respect to sleep disturbance are as follows.

Specifically, in the high noise exposure area before cessation of the night flights (L_{dn} = 90-85 dBA), 92% of the 328 respondents reported annoyance due to aircraft noise. The average intensity of annoyance was 2.4 on a scale of 0 to 4. But, in contrast to the rather large group who reported speech interference (68% to 90%), only 20% said that aircraft noise interfered with their sleep; those whose sleep was disturbed reported a somewhat higher average annoyance (2.9).

One-fourth of the high noise exposure area respondents reported trouble getting to sleep at night; three-fifths of these (16% of the total) because of aircraft noise. The average affected respondent experienced this difficulty about four or five nights in a typical week. About half the respondents reported awakening at night, about half of these by aircraft noise, between three or four times a week on the average.

Less than 15% of the high noise area respondents reported greater annoyance from aircraft noise when they were trying to sleep at night than at other times during the day!

In the moderate exposure area before night flight cessation (L_{dn} = 60-65 dBA), only 82% of the 378 respondents reported annoyance; the average annoyance was also less (1.73). Interference with speech (telephone) was reported by 33%, sleep disturbance by only 16%.

As was the case in the high noise exposure group, daytime annoyance was reported to be greater than nighttime annoyance, although the percentage of respondents for whom this was true was somewhat smaller (79% vs. 85%).

One hundred and twelve respondents in the high noise exposure area were re-interviewed during the week immediately after late-night flights were discontinued.

Overall, the reactions of these respondents did not change with the cessation of late-night flights. If anything, there was an increase in the extent and intensity of overall annoyance, but the increases were so small that they were likely to have been the product of chance variation. There were increases as well as decreases in both the proportions of respondents who said aircraft noise interfered with listening activities and in the average intensity of the reported annoyance of those whose listening was disturbed.

In the area of sleep interference, a drop was observed in the average number of nights in a week that people reported trouble getting to sleep because of aircraft noise (from 4-5 nights to 3.3 nights), but this difference was not paralleled by other reactions. The proportion of respondents who said aircraft noise interfered with their sleep actually increased (from 20% to 32%) while the proportion of people who reported trouble getting to sleep or sleep interruption remained almost constant. There was, in other words, no consistent pattern of change in reported sleep interference. Similarly, there was no change in the proportion of respondents who reported greater annoyance when trying to sleep than at other times (and vice versa).

One-hundred and forty-seven respondents in the moderate noise exposure areas were re-interviewed during the week immediately after late-night flights were discontinued. While there was some tendency for reactions to aircraft noise at this time to be weaker than they were before the flights were discontinued, the differences were slight and inconsistent.

The proportions of those who said their sleep was interfered with and of those who said they had trouble getting to sleep or were awakened once they got to sleep because of aircraft noise decreased by from 2% to 4%. The intensity of their annoyance decreased by a fourth of a scale category; the number of times they reported awakening in the past week decreased by 0.13 of a time.

The average number of nights they reported trouble getting to sleep, however, increased by 0.27 of a night. There was also a decrease from 21% to 17% in the percentage of those who reported greater annoyance when trying to sleep than at other times during the day.

The responses in both the high noise exposure and moderate noise exposure areas in an interview following the resumption of late night flights were so small that none was statistically significant.

One of the most unexpected findings was obtained in response to Question 21: "Does aircraft noise annoy you more when you are trying to sleep at night or does it annoy you more at other times during the day?" The percentage of all respondents who indicated greater daytime annoyance was 68% in the first round interviews, 66% in the second round interviews, and 72% in the third round interviews.

1. Implications of LAX Survey Data for Nighttime Penalty

If the explanation for the lack of significant reaction to discontinuing late night flights is that degraded sleep patterns had not recovered during the survey period, the comparative costs of nighttime and daytime noise to the community remain unknown.

On the other hand, if the correct explanation of these data is that the numbers of overflights were insufficient to make a significant difference to people, then, although the data of this study do not challenge the 10 dB penalty for community noise in general, there is a possibility that 10 dB is too large a penalty for aircraft noise.

Whatever the explanation for the nighttime insensitivity in Los Angeles, these results are at odds with the Second Heathrow and Gatwick Airport results, which do indicate some increase in annoyance at night.

However, results from Borsky's survey of residents living near New York's John F. Kennedy Airport lie somewhere between the two.

d. J. F. Kennedy Airport, New York (Ollerhead, 1978 and Borsky, 1975)

As in the London study, respondents to this survey were asked to quantify separately their feelings of annoyance during day (0700 to 1900), evening (1900 to 2300), and nighttime (2300 to 0700) periods. The average responses, in relation to average aircraft movements, are listed in Table II.

TABLE II

VARIATIONS IN ANNOYANCE AT NEW YORK (JFK) AIRPORT

	Average Hourly Aircraft Movements	Average Annoyance Score	Annoyance/ Movement
Day	6.12	2.24	0.37
Evening	8.30	2.83	0.34
Night	2.92	1.93	0.66

The average annoyance was less at nighttime than in the daytime or evening; but the annoyance per aircraft movement is higher at night. The average annoyance is greatest in the evening, 26% greater than in the daytime; but the annoyance per movement is virtually the same in the evening as in the daytime.

On the basis of the figures for annoyance/movement, Borsky suggested that "each nighttime flight has the equivalent annoyance effect of two day or evening flights" and that the widely used 10 dB penalty, which implies a 10:1 ratio, is therefore "much too high".

e. TRACOR Study

A large scale social survey on aircraft noise has been conducted in the United by Tracor, Inc. under NASA sponsorship; seven U.S. cities were surveyed. In a preliminary report of the TRACOR work, Hazard (1968) indicated that average annoyance scores were more than doubled if aircraft were heard between midnight and 6 AM. However, in the final TRACOR report (1971) nothing whatever was said on the subject, and no explanation was given for the omission.

f. Swiss Airport Noise Studies

In studies of community response to aircraft noise in the neighborhoods of the airports in Zürich, Geneva and Basel, special attention was given to the relative annoyance during daytime, evening and nighttime periods (Anon., 1974).

The increase in correlation between directly-expressed annoyance and various expressions for the noise exposure was investigated as additional terms were added to the basic noise rating (PNdB) to account for the number of flights in the evening (6 PM to 10 PM) and nighttime (10 PM to 6 AM). The sample population was 3940. The results are shown in Table III.

TABLE III. MULTIPLE CORRELATION COEFFICIENTS BETWEEN AIRCRAFT NOISE ANNOYANCE AND NOISE EXPOSURE RATINGS

Correlation Coefficient	Variance	Increase in Variance	Independent Variables in the Noise Rating
0.5639	0.3180	0.3180	L_{NP}
0.5907	0.3489	0.0309	L_{NP}, log N
0.5953	0.3544	0.0055	L_{NP}, log N, evening flights
0.5955	0.3547	0.0003	L_{NP}, log N, evening flights and nighttime flights

Accounting for the number of evening flights contributes more to correlation than accounting for the number of nighttime flights.

Otherwise stated, the partial correlation coefficients with respect to evening and nighttime flights are:

$$r_{xy.uv} = 0.0539 \text{ and } r_{x'y.uv} = 0.0920,$$

where x = percent nighttime flights.

x' = percent evening flights

$u = L_{NP}$

$v = \log N$

Table IV shows the relationship between people especially disturbed at night and the number of nighttime flights. Table V shows a similar comparison for the evening.

TABLE IV. PERCENTAGE OF PEOPLE WHOSE SLEEP IS DISTURBED AT NIGHT, AS A FUNCTION OF THE PERCENTAGE OF DAILY FLIGHTS OCCURRING AT NIGHT (10 PM to 6 AM)

	PERCENT NIGHTTIME MOVEMENTS			
	0 - 4.9%	5 - 9.9%	25 - 30%	
Percent People Disturbed at Night	10.8 (1497)	26.5 (2405)	35.9 (39)	$\chi^2 = 144.9$ $p < 0.001$ $\sigma = 0.49$

TABLE V. PERCENTAGE OF PEOPLE ESPECIALLY DISTURBED IN THE EVENING AS A FUNCTION OF THE PERCENT OF DAILY FLIGHTS OCCURRING IN THE EVENING (6 PM TO 10 PM)

	PERCENT EVENING MOVEMENTS			
	14 - 19.9%	20 - 24.9%	25 - 30%	
Percent People Disturbed in the Evening	22.0 (2577)	38.7 (108)	28.6 (1250)	$\chi^2 = 32.0$ $p < 0.001$ $\sigma = 0.17$

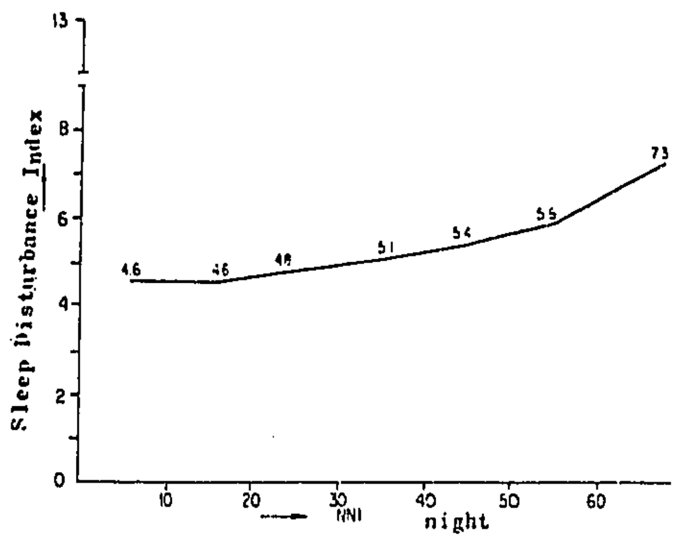

Figure A-3. Average Sleep Disturbance Index as a Function of Nighttime NNI (Sample Population = 3931)

2. Railroad Noise and Sleep Disturbance

Only a few surveys have been designed to study the relation between the noise of railroads and human reactions. Those that have been conducted are recent, and the data are still under analysis. Thus, there is much less reliable information on the effects of rail noise than noise of aircraft and road and street traffic.

Note also that the railroad surveys have dealt with true railroad operations (passenger and freight) but not rapid transit systems. These two types of operation are so different in type of equipment, frequency of operation and duration of train passages, that one must be very cautious and skeptical about applying conclusions from the railroad noise surveys to rapid transit noise.

a. French Railroad Noise Survey (Aubrée, 1973)

A study of people's reactions to the noise of railroad trains was carried out in a region near Paris in the 1970's. Very weak dependence was found between the noise exposure and its effects on sleep. There was, however, significant correlation ($r = 0.15$ to 0.21) between poor quality of sleep and age. Considering the orrelation between quality of sleep and nighttime noise exposure for different age categories, one finds a distinct threshold. The correlation between train noise and sleep disturbance, which is almost null for the population under 40 years ($r = 0.16$, $N = 153$), becomes significant at the 5% level ($r = 0.27$) for the population over 50 ($N = 68$).

The noise under study was only in exceptional cases the primary cause of sleep disturbance for people under forty. But among the more aged, however, general poor quality of sleep permitted respondents to hear nighttime noise more frequently, and thus to be annoyed and to mention the noise as disturbing sleep.

b. Second French Railroad Study

Another French study (Vernet, 1978) dealt specifically with the effect of a railway train noise on sleep compared to road traffic noise. This was a field study, in which the physiological responses of sleeping subjects (EEG, EOG, EMG, EKG, and plethysmograph data) were recorded for subsequent comparison with recordings of the train noise, and analyzed to determine L_{eq}. Comparisons were also made of the sleep disturbance caused by road traffic noise with the same values of L_{eq}.

The fact that there was the same percentage of disturbances for both road and rail noise suggests that people do not become more conditioned to rail than to road noise. However, the total number of sleep disturbances was three times greater for road traffic than for rail noise at the same value of L_{eq}. It should be noted, however, that it required about three times as many road vehicle passages as train passages to generate the same value of L_{eq} because the peak noise level during a train passage is so high.

The percentage of awakenings increased with increases in the peak noise level for peak levels exceeding 52 dBA indoors, corresponding to 64 dBA outdoors, with windows open. Awakenings did not occur for noise levels lower than 52 dBA and no sleep disturbance of any kind occurred for levels below 45 dBA indoors.

APPENDIX B

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APPENDIX B

REVIEW OF LITERATURE ON TIME OF DAY EFFECTS OF NOISE EXPOSURE ON ANNOYANCE AND COMMUNICATION INTERFERENCE

This appendix reviews information about annoyance and communication interference due to noise exposure at different times of day. The two major sources of information on this topic are social surveys of community reaction to aircraft and surface traffic noise.

A. Aircraft Noise Studies

1. Burbank and Atlanta Airports (Horonjeff et al., 1979)

A recent comparison of community responses to aircraft noise at the airports in Burbank, California, and Atlanta, Georgia, was intended to develop operational definitions for the relative acceptability of noise intrusions at different times of day, to apply them to a real-time survey of aircraft noise intrusions in people's homes, and to estimate weighting factors for the four periods of the day.

The basic approach of this investigation was a field study in which people rated their annoyance to individual aircraft flyovers in their own homes for periods of two to four weeks. Simultaneous monitoring of aircraft sound levels permitted correlation between judged annoyance and aircraft sound level. Sound levels observed to produce the same level of annoyance for different periods of the day were determined for each test participant. Differences in these equally annoying sound levels were averaged across participants. The mean difference was considered a time-of-day weighting factor.

The "interview" procedure that was adopted was intended to take advantage of a real-life situation in the natural environment of the home and the specificity gained by an immediate report of annoyance by the test subjects.

Previous experience by Fidell et al. (1973) indicated that people who had been instructed to "push the button on your wrist whenever you hear a sound you would rather not have heard" did indeed respond at all times of day, including nighttime hours. Clearly people did not push this button while asleep, but they did push whenever awakened by aircraft overflights. In a more recent behavioral awakening experiment (Horonjeff et al., 1978) participants reliably pressed a button beneath their pillow when instructed to press any time they were awakened, regardless of the reason. Again, people did not respond while asleep; they did, however, occasionally respond moments after a sound had occurred without any recollection of having been awakened by noise!

It was therefore decided that a simple button push would suffice for twenty-four hour data collection as an index of the annoyance of aircraft noise intrusions in the Burbank/Atlanta study. A single centrally located aircraft noise monitoring station provided noise exposure information.

The major findings of this study, relevant to the noise penalty question, were:

a) Most test participants reported that they were never awakened by aircraft noise at night.

b) Most participants found it difficult to assign numbers reflecting their relative annoyance with aircraft noise exposure at different times of day. When asked how many times they would have to push a button to express their relative annoyance with overflight noise at various times of day, the following average values were reported. At Burbank, the equivalent number of responses during morning, afternoon, evening, and night, averaged over individuals, were 5.1, 4.2, 14.6, and 10.2, respectively. (However there was little or no nighttime aircraft activity at Burbank.) In Atlanta, the corresponding figures were 2.4, 2.0, 3.4, and 2.9 responses.

c) Three different analyses of over 1200 person-days of data produced by the current technique in two airport communities revealed no major differences in sensitivity to aircraft noise exposure as a function of time of day. Differences between morning and afternoon periods were statistically insignificant. Differences between evening and nighttime periods and other times of day (morning, afternoon, and combined daytime hours), although unlikely to have arisen by chance alone, were small (less than two decibels) and are of little practical significance.

d) These observed differences in sensitivity do not support the current 10 dB nighttime penalty for aircraft noise exposure. Indeed, these small differences in sensitivity would suggest that people have a slightly <u>greater</u> tolerance for nighttime noise exposure!

2. Third Survey at London (Heathrow) Airport (Ollerhead et al., 1977)

Further evidence concerning the time-of-day question was sought in a pilot survey performed in the environs of London (Heathrow) Airport in 1972, during which a questionnaire was administered to 600 residents.

The main purpose of the survey was to test the questionnaire, and no attempt was made to obtain a population sample which was fully representative of any segment of the community. Instead, an adequate range of aircraft noise exposures (in terms of Noise and Number Index), road traffic noise level, and socioeconomic status was provided.

To estimate the most relevant aircraft noise characteristics at each residence, respondents were asked to confine their attention to conditions during the four weeks immediately preceding the interview.

Aircraft noise variables estimated at the exterior of each residence on the basis of known aircraft movements during that period included Noise and Number Index, the number and average duration of aircraft sounds as a function of the level exceeded, and equivalent continuous level. These were calculated separately for the three periods of interest: day (0700 to 1900), evening (1900 to 2300), and night (2300 to 0700). Relative to some of these variables, the survey samples were distributed as shown in Tables B-II and B-III.

TABLE B-II. DISTRIBUTION OF 600 SURVEY RESPONDENTS WITH RESPECT TO NNI, FROM THE 1972 HEATHROW STUDY

NNI	Day	Evening	Night
Under 20	158	234	278
20 to 30	14	127	160
30 to 40	174	173	121
40 to 50	164	62	41
50 to 60	73	4	
60 to 70	17	0	

TABLE B-III. DISTRIBUTION OF 600 SURVEY RESPONDENTS WITH RESPECT TO NUMBER OF AIRCRAFT SOUNDS N IN EXCESS OF 80 PNdB FROM THE 1972 HEATHROW STUDY

N	Day	Evening	Night
Under 3	151	163	247
3 to 5	1	60	58
6 to 16	11	132	123
17 to 40	0	128	172
41 to 100	245	117	0
Over 100	192	0	0

The mean relationship between the daytime, evening, and night-time NNI variables were

$$\text{NNI (evening)} \approx \text{NNI (day)} - 13$$
$$(\text{rank correlation } R = 0.99),$$

$$\text{NNI (night)} \approx \text{NNI (day)} - 17$$

Since the evening and nighttime values of NNI are relatively small, the daytime L_{eq} value is practically identical to the day-night sound level L_{dn}, and an approximate transformation was found to be

$$L_{dn} \approx L_{eq}\ (\text{day}) \approx 0.61\ \text{NNI (day)} + 43,\ \text{dBA}$$

$$(R = 0.95).$$

Figure B-1 compares group mean annoyance scores as functions of daytime NNI. A linear regression line is fitted and the product-moment correlation coefficient is 0.98. The collapse of the three sets of data indicates that reactions to aircraft noise in the vicinity of London Airport have remained fairly uniform over a period of several years (the 1972 results for 20 to 30 NNI have been omitted due to small sample size).

The vertical lines in Figure B-1 indicate the scatter of individual annoyance scores about the mean values in terms of $\pm$ 1 standard deviation. That these are rather large is apparent from the fact that for the 1972 survey, the rank correlation coefficient relating daytime noise exposure (NNI) and individual annoyance scores is

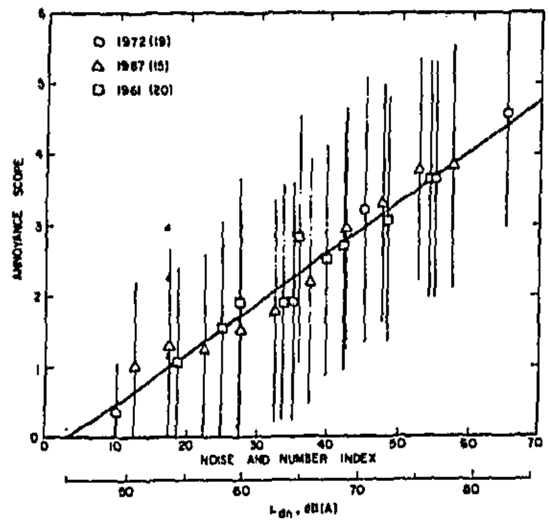

Figure B-1. Annoyance Reactions from Three Surveys at London (Heathrow) Airport. The symbols represent the mean values averaged for respondents grouped by noise intervals; vertical lines show ± 1 standard deviation. The regression line is fitted to the mean values.

B. Review of Surface Traffic Noise Survey Results

1. Vienna Street Traffic

In one of the earliest noise surveys, done in Vienna (Austria) in 1964 (Bruckmayer et al., 1967), in order to find neighborhoods with the same percentage of people highly disturbed at nighttime as in other neighborhoods in the daytime, the average sound level over 24 hours in the neighborhood had to be about 10 dB lower, as shown in Figure B-4 (windows open in both cases).

2. Paris Street Traffic Survey, 1969

In a survey dealing with street traffic noise in Paris (Aubrée, 1971), there was found to be almost complete independence between annoyance in nighttime activities and the noise exposure; the highest correlation coefficient was 0.05. This result was surprising because, in a pilot survey, the people interviewed had frequently mentioned nighttime noise as being the most annoying.

Upon closer study, however, it was determined that, in responding to questions about sleep disturbance, the subjects actually gave reasons other than the noise for the interruption of their sleep. Once awakened, they felt annoyed by the noise, but it wasn't the noise that had awakened them.

3. Swiss Surveys of the Effects of Aircraft and Street Traffic Noise

A number of Swiss surveys concerned with aircraft noise also

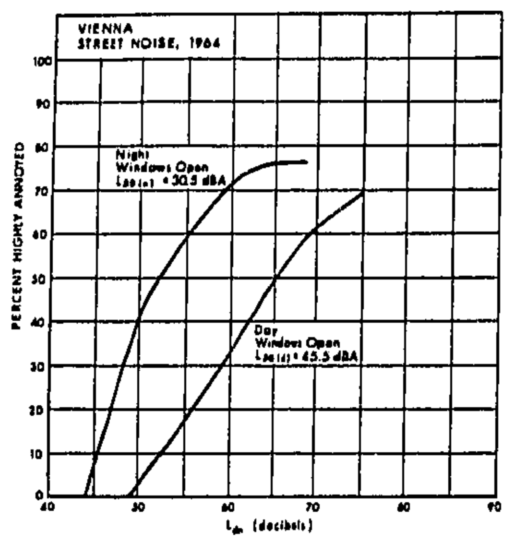

Figure B-4. Annoyance Due to Street Traffic Noise in Vienna, 1964. On average, the same amount of annoyance is caused at night by noise levels 10 dB lower than in the daytime.

investigated annoyance due to street traffic noise (1974). Comparing the multiple correlations between expressed annoyance due to traffic noise and noise exposure ratings with different independent variables, accounting for the nighttime noise did not yield a significant improvement, as shown in Table B-V.

TABLE B-V. MULTIPLE CORRELATIONS BETWEEN EXPRESSED ANNOYANCE AND VARIOUS COMBINATIONS OF VARIABLES

R	R^2	Increase in R^2	Independent Variables In The Noise Exposure Rating
0.4231	0.1790	0.1790	L_{50}
0.4637	0.2150	0.0360	L_{50}, log $M_{PWE/h}$*
0.4807	0.2311	0.0161	L_{50}, log $M_{PWE/h}$, L_1
0.4809	0.2313	0.0003	L_{50}, log $M_{PWE/h}$, L_1 $(L_{50(Day)}-L_{50(Evening)})$
0.4809	0.2313	0.0000	L_{50}, log $M_{PWE/h}$, L_1 $(L_{50(Day)}-L_{50(Night)})$

When asked what is the most disturbed time of day, the responses were distributed as in Table B-VI.

*$M_{PWE/h}$ is the number of trucks per hour.

TABLE B-VI. MOST DISTURBED TIME OF DAY

Question: At which time of the day are you disturbed most?

Time of Day h	Study I %	Study II %
06 - 09	35	15
09 - 19	20	30
19 - 22*	14	28
22*- 06	24	27
all the time	8	--

In Study II (the high noise exposure area) disturbances are regularly spread over day, evening and night; for Study I, the disturbances occur mostly early in the morning, which can be explained by the fact that the noise disturbs mostly recreative functions.

In Study II, in spite of the lower percentage of people naming night as the "most disturbed" period, the number of strongly disturbed persons increased by 10 to 20% as compared to the daytime. All this points to the fact that nocturnal noise - contrary to the results of the Viennese study (Lang, 1975) which was a comparable survey - has a special importance.

*Read 23 instead of 22 for Study I.

Another more recent Swiss report (Wehrli, 1979), reviewing the results of four different street traffic noise surveys, presents a comparison between daytime and nighttime annoyance according to one Zurich survey, as shown in Figure B-5.

The figure shows that, in the lower noise ranges, for the same noise level the generally experienced annoyance is greater at night than in the daytime. In the range between 45 and 50 dBA, the percentage of highly annoyed persons is already in the neighborhood of 10%; between 55 and 60 dBA, it comes to more than 20%. This difference between day and night decreases, however, as the noise exposure increases.

According to Wehrli, 1979, in the analysis of the data from the individual measurement locations, it appeared that, as a rule, people living in comparatively quiet streets were annoyed more seriously at night, whereas those living in very noisy streets (over 65 dBA) were annoyed more seriously in the daytime.

An evaluation of the most disturbed time of the day, on the basis of individual sections of the day, is possible with three of the surveys. The results are given in Table B-VII.

The results of two surveys (ZH 1978 and ZH 1976) show a large measure of agreement: serious annoyance in the early morning hours, more serious than that experienced in the daytime or in the evening; a quarter to a third of the persons questioned feel most annoyed during the night. If a distinction is made between the "acoustical day" and the "acoustical night", the great majority of the persons questioned (two-thirds) are annoyed most seriously during the acoustical day (from 6 AM to 10 PM).

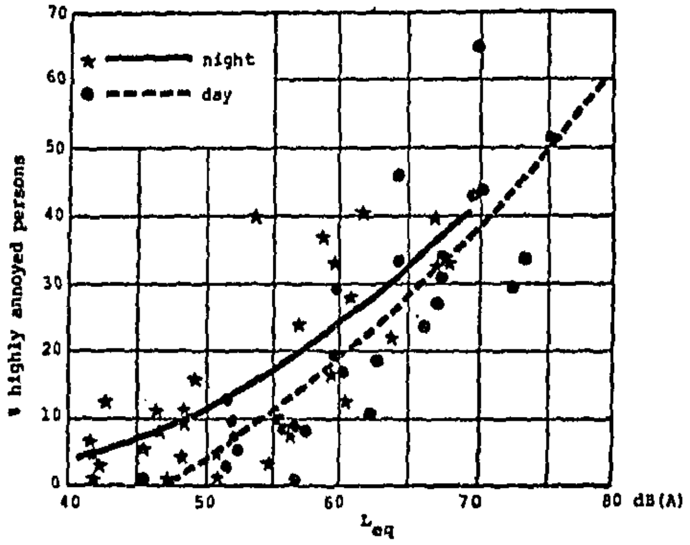

Figure B-5. Proportion of Highly Annoyed People vs. Daytime and Nighttime Noise Exposure, According to Survey ZH 1973.

TABLE B-VII. MOST DISTURBED TIME OF THE DAY

Time of the Day	Percentage of "most disturbed" mentions: Zürich, 1978 (N = 1600)	Zürich, 1977 (N = 1200)	Zürich, 1976 N = 700)
Early morning (6 to 8 or 9 AM)	26	11	34
During the day (8 or 9 AM to 7 PM)	21	23	20
Evening (7 to 10 or 11 PM)	14	26	14
Night (10 or 11 PM to 6 AM)	31	40	24
Always the same	8	--	8

The ZH 1977 survey differs from the other two in its results, mainly because of the larger proportion of people who are annoyed most during the night. This may well be due to the fact that the streets concerned carry very heavy urban traffic at night. Taking the average of the three surveys, however, the great majority of the persons questioned are particularly annoyed in various parts of the daytime (Wehrli, 1979).

This report also presents a comparison of individual annoyances and reactions in terms of the noise exposure during the day and at night.

Note that in Figure B-6 (nighttime disturbance), almost all of the annoyance and reactions show a marked increase, starting in

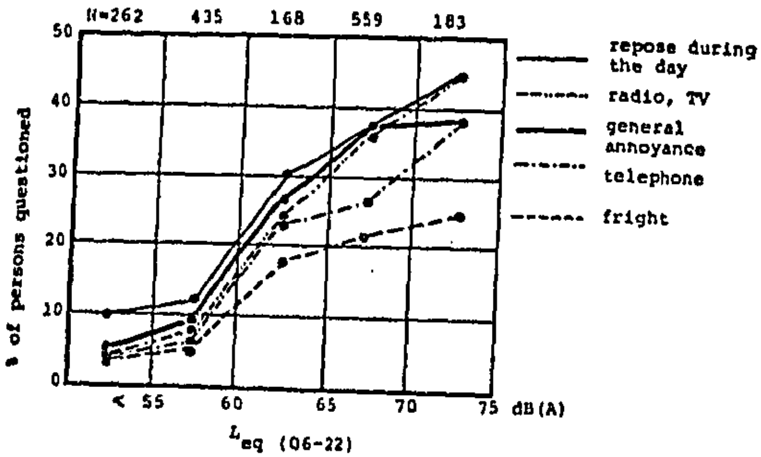

Figure B-6. Individual Annoyances and General Annoyance in Terms of Daytime Noise Exposure (Percentage of "highly" or "almost daily" annoyed persons).

the region of 55 dBA, compared to the daytime responses of Figure B-7.

Comparing the various annoyances with one another, early-morning sleeplessness ("waking up too early") is much more pronounced than sleeplessness in the early or middle hours of the night. This result agrees with the frequency mentions of the early morning hours as the most disturbed time of the day (cf. Table B-VII) (Wehrli,1979).

General annoyance is marked mainly by early-morning sleeplessness, and when general annoyance is serious, frequent closing of the windows is often accompanied by a strong tendency to move elsewhere. The symptoms of annoyance that have just been mentioned occur in the region of 65 to 70 dBA with more than a third of the persons questioned (Wehrli, 1979).

A comparison of these individual annoyances and reactions for all four surveys is shown in Table B-VIII, with reference to the critical noise range of 65 to 70 dBA.

TABLE B-VIII COMPARISON OF INDIVIDUAL ANNOYANCES AND REACTIONS FOR A NOISE EXPOSURE OF 65 TO 70 dBA, FOR ALL FOUR SURVEYS ("Amost daily" or "frequent" annoyances are counted)

Annoyance:	Basel 1974	Zürich 1976	Zürich 1977	Zürich 1978
Disturbed rest, relaxation	27	27	32	38
Interference with communication	19	17	27	32
	N = 944	N = 700	N = 1200	N = 1600

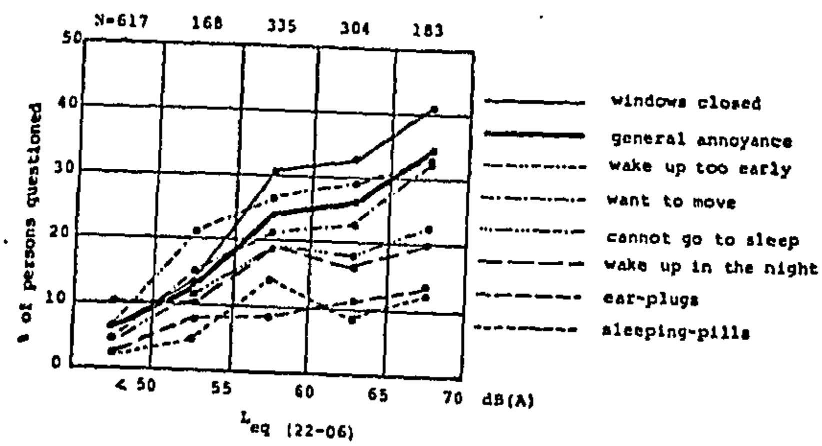

Figure B-7. Comparison of Individual Annoyances and Reactions in Terms of Noise Exposure at Night (percentage of "highly" or "almost daily" annoyed persons).

From these results, it may be concluded that with a daytime noise-exposure range of 65 to 70 dBA, about a third of the people are subject to almost daily disturbances of their needed rest. In the case of interference with communication, the differences between the four surveys are greater. On an average, a quarter of the persons questioned complain of almost daily interference with communication in this noise range.

On the basis of the Swiss results (with special reference to the later surveys, ZH 1977 and ZH 1978), we may derive the following threshold values: for general quality of living, the daytime noise exposure (between 6 AM and 10 PM) should not exceed an L_{eq} of 60 dBA; a noise exposure exceeding 70 dBA is to be regarded as unacceptable. At night, on the other hand, the threshold value should be in the region of 50 to 55 dBA. If, in addition, we take recent research on sleep into consideration, a threshold value of 50 dBA seems to be indicated (Wehrli, 1979).

4. Viennese Survey of Street Traffic Noise and Noise Annoyance

A social survey on traffic noise was carried out during 1973, involving interviews with 2624 subjects (Lang, 1975). Among the results of interest in the present context are the plots of percentage of people highly annoyed by the traffic noise by day and by night; they are of special interest because the plots are given both for dwellings facing the noisy street and again irrespective of the dwelling orientation.

Figure B-8 shows the percent highly annoyed versus L_{eq} for dwellings facing the street; Figure B-9 shows the same thing for all dwellings.

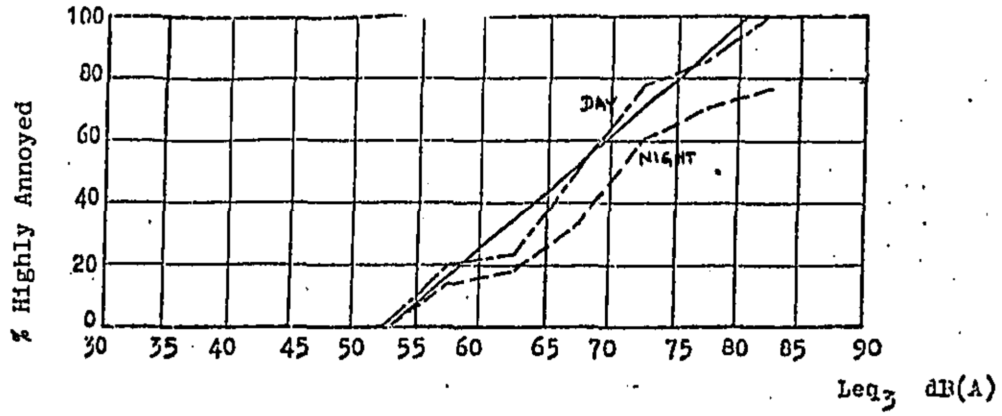

Figure B-8. Percent of People Highly Annoyed by Traffic Noise, by Day and by Night, Whose Dwellings Face Onto the Street.

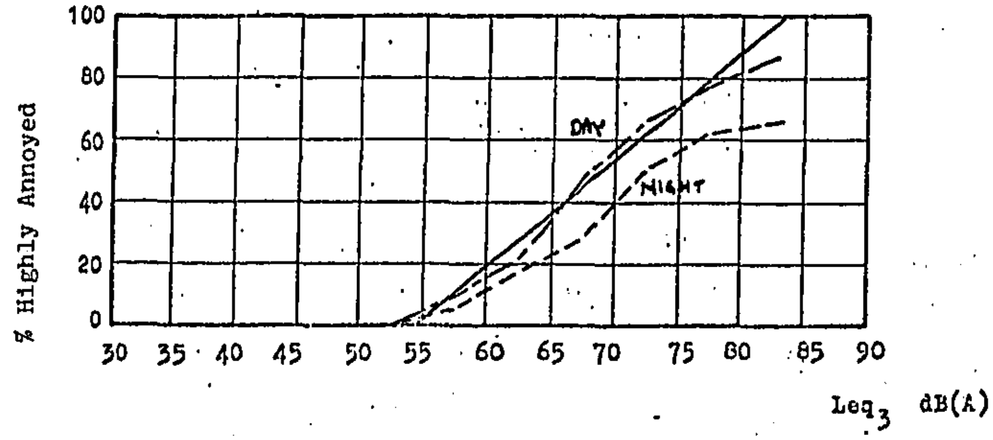

Figure B-9. Percent of People Highly Annoyed by Traffic Noise, by Day and by Night, Irrespective of Dwelling Orientation.

These results contradict those of a number of the Swiss surveys (Wanner, 1977; Wehrli, 1979; and Wanner, 1977) where traffic noise annoyance was greater at night.

5. Danish Social Survey of Street Traffic Noise Annoyance

In 1972-73 a social survey of noise annoyance due to street noise was conducted in 28 housing areas in Copenhagen (Relster, 1975).

The areas surveyed did not represent a continuum of noise exposure, as in many other surveys, but consisted of "high noise areas" (L_{eq} > 69 dBA) and "quiet areas" (L_{eq} = 51 to 63 dBA).

Several questions were asked of the 960 interviewed persons that concern sleep disturbance.

TABLE B-IX. INDISPOSITION TO FALL ASLEEP
Question: Do you find it hard to fall asleep at night?

	Noisy Areas		Quiet Areas	
Indisposition to fall asleep	Number of persons	Number of persons in percentages	Number of persons	Number of persons in percentages
Yes always, yes often, yes sometimes	184	38.6	143	29.5
No rarely, no never	293	61.4	340	70.5
Total	477	100.0	483	100.0

A significant difference was found in indisposition to fall asleep in noisy and quiet areas. In noisy areas, there are more persons having trouble falling asleep than in quiet areas.

Table B-X gives the responses to a question on quality of sleep. In this case, no significant difference was found as to <u>how well</u> the subject sleeps, once he is asleep.

TABLE B-X. QUALITY OF SLEEP

Question: Do you sleep well at night, once you have fallen asleep?

	Noisy Areas		Quiet Areas	
Do you sleep well at night, once you have fallen asleep?	Number of persons	Number of persons in percentages	Number of persons	Number of persons in percentages
Yes always, yes usually	401	84.0	437	90.5
No rarely, no never	44	9.3	33	6.8
Yes, but I wake up early in the morning	32	6.7	13	2.7
Total	477	100.0	483	100.0

6. Belgian Social Survey of Street Traffic Noise Annoyance

An extensive social survey was conducted in Antwerp and Brussels in 1975 and 1976 (Myncke, 1977). The questions that concern the present matter of a nighttime noise penalty led to some peculiar results on the correlation between noise and annoyance.

Table B-XI shows that the correlation between the disturbance of diurnal activities and the diurnal traffic noise is good and highly significant. The other variables (nocturnal disturbance, general statements on traffic noise, supposed physiological effects, and satisfaction with the environment), correlate rather poorly.

In comparing the results in Table B-XI with the results in Table B-XII, where the correlation between the different annoyance variables with the <u>nocturnal</u> traffic noise is given, it is surprising that there are no large differences. In fact, the disturbance of <u>diurnal</u> activities correlates as well with the measurements of <u>nocturnal</u> traffic noise as with the measurements of <u>diurnal</u> traffic noise, while the nocturnal disturbance correlates as <u>poorly</u> with the <u>nocturnal</u> traffic noise as with the <u>diurnal</u> traffic noise! In the investigation in Brussels the correlation between nocturnal disturbance and nocturnal traffic noise was better, but still not compelling.

There are several potential explanations for the poor nocturnal disturbance correlation:

1) The researchers observed that some inhabitants of quiet streets declared themselves highly disturbed by the few passing cars at night, while in noisy streets some inhabitants declared that they were never disturbed by the nocturnal traffic noise.

2) In both Antwerp and Brussels, the noise levels at night are <u>proportionally</u> lower than the diurnal noise levels. This means that noisy streets by day are also noisy at night, and quiet

TABLE XI Correlation between the mean factorscores and the noise indices (DAY)

		ANTWERP					BRUSSELS				
		FS1	FS2	FS3	FS4	FS5	FS1	FS2	FS3	FS4	FS5
L_1 Day	r =	,83	,15	-,04	,32	,11	,82	,55	-,35	-,15	,52
	p =	,001	,184	,415	,021	,241	,001	,003	,047	,236	,004
L_{10}Day	r =	,85	,11	,00	,32	-,20	,86	,36	-,40	-,18	,51
	p =	,001	,250	,496	,023	,115	,001	,043	,027	,195	,005
L_{50}Day	r =	,86	,13	-,04	,38	-,21	,83	,29	-,25	-,17	,51
	p =	,001	,220	,393	,007	,094	,001	,086	,117	,220	,005
L_{90}Day	r =	,78	,11	-,09	,42	-,14	,78	,27	-,14	-,13	,47
	p =	,001	,241	,292	,003	,189	,001	,101	,259	,266	,010
L_{eq}Day	r =	,86	,14	-,03	,33	-,18	,86	,41	-,32	-,15	,56
	p =	,001	,199	,419	,019	,139	,001	,023	,062	,239	,002
TNI Day	r =	,47	,04	,13	-,02	-,16	,51	,38	-,53	-,14	,20
	p =	,001	,405	,220	,450	,168	,005	,034	,004	,255	,121
NPL Day	r =	,70	,12	,05	,16	-,16	,76	,50	-,48	-,16	,43
	p =	,001	,239	,391	,163	,160	,001	,007	,009	,235	,019
$\log_{10}$V/h Day	r =	,83	,04	-,06	,31	-,18	,85	,18	-,24	-,19	,44
	p =	,001	,417	,365	,031	,146	,001	,209	,135	,200	,018

FS1 : DISTURBANCE OF DIURNAL ACTIVITIES BY TRAFFIC NOISE

FS2 : NOCTURNAL DISTURBANCE

FS3 : GENERAL STATEMENTS ON TRAFFIC NOISE

FS4 : SUPPOSED PHYSICAL (PHYSIOLOGICAL) EFFECTS OF TRAFFIC NOISE

FS5 : SATISFACTION WITH THE ENVIRONMENT

TABLE XII Correlation between the mean factorscores and the noise indices (NIGHT)

		ANTWERP					BRUSSELS				
		FS1	FS2	FS3	FS4	FS5	FS1	FS2	FS3	FS4	FS5
L_1 Night	r =	,82	,12	,05	,40	-,22	,50	,46	-,21	-,05	,54
	p =	,001	,229	,392	,007	,093	,069	,091	,284	,449	,055
L_{10}Night	r =	,80	,15	-,08	,41	-,23	,48	,54	-,01	,02	,61
	p =	,001	,187	,317	,005	,084	,079	,053	,485	,478	,029
L_{50}Night	r =	,68	,21	-,17	,29	-,13	,40	,39	,44	,21	,10
	p =	,001	,103	,160	,038	,226	,125	,132	,104	,277	,391
L_{90}Night	r =	,22	-,04	-,10	,16	,02	,50	,01	,41	,12	-,26
	p =	,089	,418	,278	,164	,446	,069	,492	,120	,370	,235
L_{eq}Night	r =	,82	,14	-,02	,41	-,18	,47	,52	-,16	-,01	,58
	p =	,001	,201	,456	,005	,142	,085	,062	,333	,490	,039
TNI Night	r =	,80	,17	-,06	,39	-,26	,25	,52	-,19	-,03	,71
	p =	,001	,147	,373	,007	,059	,240	,06	,300	,465	,011
NPL Night	r =	,81	,14	,00	,41	-,25	,35	,56	-,19	,01	,71
	p =	,001	,202	,497	,005	,064	,163	,047	,302	,487	,011
$\log_{10}$V/h	r =	,82	,07	-,09	,25	-,13	,66	,37	,35	,38	-,49
Night	p =	,001	,352	,316	,094	,251	,052	,206	,220	,202	,135

FS1 : DISTURBANCE OF DIURNAL ACTIVITIES BY TRAFFIC NOISE

FS2 : NOCTURNAL DISTURBANCE

FS3 : GENERAL STATEMENTS ON TRAFFIC NOISE

FS4 : SUPPOSED PHYSICAL (PHYSIOLOGICAL) EFFECTS OF TRAFFIC NOISE

FS5 : SATISFACTION WITH THE ENVIRONMENT

streets are also quiet during the night period. This is clear from the correlation between the diurnal noise measurements and the nocturnal noise measurements: The correlation between L_1 Day and L_1 Night is .93; between L_{10} Day and L_{10} Night: .86.

7. British Survey on Railroad Noise Annoyance

A nationwide social survey on the response to railroad noise has been carried out at 403 locations with 1453 respondents along the 11,288 miles of railroad routes in Great Britain. The data are still being analyzed at this time, though some preliminary results have already been reported (Walker et al., 1977; Fields et al., 1978; and Fields, 1978). Since the data are preliminary, the numerical results may be subject to modifications in the final reports of the study, though the general conclusions will probably not be changed.

The analysis of the social data has concentrated on the type of disturbance arising from railroad noise; the relationships between the different noise ratings and annoyance; the independent effect of the number of noisy events on annoyance; local neighborhood factors affecting annoyance; individual attitudes affecting annoyance; the relative annoyance caused by railroad and road traffic noise; and the number of people living in high noise levels from railroads.

The activity most greatly disturbed is talking in the garden. Also of concern is disturbance of conversation indoors with the windows open, and the startle effect.

An annoyance index was formed from the responses to five questions dealing with: (10b) whether the subject is at all bothered, disturbed, or annoyed; (11b) how the subject feels about the amount of noise from trains; (17b) how much the noise bohers or annoyes him on a four-stepped scale, all steps named, from "Not at all" to "very much"; (43b) the subject's rating of the amount of railroad noise at his house, on a ten-point scale with the end-points named "No noise at all" and "The worst imaginably amount of railway noise;" and (61) how the subject feels about the noise of all trains on a seven-step scale with the end-points named "Definitely Satisfactory" and "Definitely Unsatisfactory."

This index was correlated against the various noise ratings to see which gives best prediction of community response. None of the ratings gave better correlation than $L_{eq(24)}$.

In attempting a preliminary estimate for an acceptable level of railway noise, it developed that a great deal depends on the assumed shape of the curve relating noise exposure and annoyance, that is, whether it is linear or curvilinear. This choice also influences estimates of the effects of attitudinal factors on the subjective response. (That is, some of the variance that could not be explained by the noise exposure in pact surveys and that had to be attributed to attitudinal variables, may have resulted from the fact that a linear regression was fitted to data that require a curve.)

It is claimed that the annoyance results of this British survey agree closely with the data from the French railroad survey, based conducted in spring and summer, the open-window season. The conclusion that people are especially tolerant of railway noise is yet to be firmly established.