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Research on the Effect of Noise at Different Times of Day: Models, Methods, and Findings

James M. Fields

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RESEARCH ON THE EFFECT OF NOISE AT DIFFERENT TIMES OF DAY: METHODS AND A REVIEW OF FINDINGS

James M. Fields
April 1985

The "EVENING" and "DAY" labels in Figure 6 are reversed. The corrected figure appears below. The orginally published figure (Ollerhead, 1978; Fig. 4) was incorrectly labeled (personal communication with J. B. Ollerhead; April 12, 1985).

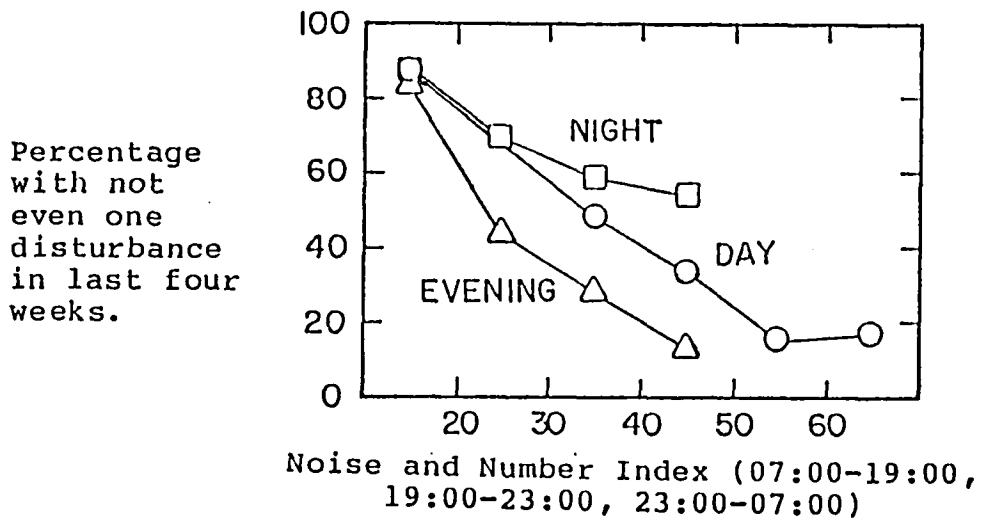

Figure 6: Reports of no disturbance by noise level in three time periods (1972 Heathrow survey).

(Source: Ollerhead, 1978; Fig. 4.
Question: This question about frequency of annoyance is reproduced in Appendix A).

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SUMMARY

It is often hypothesized that the impact of noise is affected by the time of day at which noise occurs. The differential impact of similar noise levels at different times of day is conventionally quantified in terms of weights which are applied to nighttime noise so as to numerically represent its greater annoyance potential.

Many studies have discussed the issue of nighttime weights. This report finds that methodological difficulties interfere with a simple comparison of the studies' estimates of the nighttime weights. Some of these difficulties have not been previously recognized. Some evidence suggests that analyses of direct rankings of daytime and nighttime noise lead to higher estimates of nighttime weights than do analyses of the relative impact of daytime and nighttime noise on total annoyance. Some of the differences in estimates of nighttime weights are reduced when the estimates of nighttime weights from 12 studies are normalized. Though the resulting estimates still disagree, the estimates do not support higher nighttime weights than those used in existing noise indices.

Common assumptions about annoyance during the nighttime are evaluated. Annoyance during the night is distinct from sleep interference. There is some limited evidence that nighttime annoyance may be affected by noise in other periods. Some evidence suggests that the relative importance of noise level and the number of noise events may be dependent on the time of day: the noise level of single events may be relatively more important at night.

The figures presented in the report include all previously published figures in which long-term, nighttime responses are related to nighttime noise levels.

Data collection techniques and analysis methods are recommended which would lead to better, more comparable, estimates of nighttime weights from different studies.

INTRODUCTION

The time of day at which noise occurs is recognized to be a factor which affects the impact of noise in communities. Many survey publications discuss residents' reactions to noise at different times of day. These discussions are most useful to policy makers when guidance is provided on two issues: the relative importance of noise events of the same noise level at different times of day and the definition of noise levels which protect the sleep of residents.

Laboratory studies of unconscious behavior and physiological processes have provided basic information about sleep and the mechanisms of noise interference with sleep (Lukas, 1975; Griefahn, 1978). Laboratory studies have also provided detailed information about one daytime activity, speech interference. The information from the laboratory studies is not, however, sufficient by itself to meet policy needs. The social surveys can validate laboratory findings with representative samples of people experiencing noise sources on a continuous basis within the context of their own individualized home noise environments. Social surveys also provide answers about the relative importance of the different types of interferences. Such information cannot be obtained from the specialized laboratory studies of either speech or sleep interference.

Several recent reviews have summarized the guidance available from existing social surveys (Fidell and Schultz, 1980; Shepherd, 1982). After providing guidance to policy makers the reviews conclude that the available social survey evidence on time-of-day effects does not lead to clear conclusions. In spite of a large amount of discussion there is not clear evidence on those issues which are of chief interest to policy makers.

The purposes of this report are to determine why the previous work has not led to firm conclusions and to establish a basis for developing better information in the future. The report focuses on field studies, especially social surveys.

The report begins with an "Overview" of five components of any time-of-day response model. The primary concern of the next sections is with one of these components, the time-of-day weights. These weights can be thought of as numerical penalities which are applied to nighttime noise levels. The sections discussing these time-of-day weights first consider four noise/response models, each with a different time-of-day adjustment.

The most widely accepted of these noise/response models (adjusted energy model) is examined in the remainder of the report. Alternative expressions for the weights in this model are described and four different methods for estimating the values of the weights

are described. Finally the research findings on the values of these weights are presented. After the research review, a critique is presented of the relative advantages and disadvantages of the alternative methods which are used to estimate the time-of-day weights.

The remainder of the report focuses on a second major concern, the nature of the response to noise during one time period, the nighttime period. The central issue is whether factors other than the time-of-day weighting must be considered in developing a model of nighttime response. Six questions about the nature of the nighttime response are explored by reviewing existing research. All of the available data on responses at specified nighttime noise levels are presented in the figures in this section. The concluding section of the report summarizes the findings and presents recommendations for methods to be used in future work.

SYMBOLS AND ABBREVIATIONS

More details for noise indices and scales for acoustical measurements can be found in general noise references (e.g., Bennett and Pearsons, 1981).

a,c,g,h,q	Constants used in time-of-day models
A_j	Annoyance for period j
A_T	Annoyance for the total 24-hour period
B	Partial regression coefficient for time period (j) or noise index (I)
CNEL	Community Noise Equivalent Level, dB
CNR	Composite Noise Rating
D_j	Regression coefficient for dummy variable for period j
E_k	Error term (The part of annoyance score for individual "k" which is not explained by variables in a model)
LDN	Day-night Average Sound Level
LEQ_j	Equivalent continuous sound level for period j, dB
L_I	Noise level for noise index I, dB
L_{ij}	Sound level of noise event i in period j. (Unless otherwise specified this is normalized to a 24-hour period. Thus it is the 24-hr. LEQ value for event i

in period j. The relative sound pressure squared is thus $10^{L_{ij}/10}$).

M	Dummy variable used in regression analysis (M=1 if the observation is in the category).
N	Number of noise events
NEF	Noise Exposure Forecast
$P_{A_j > A_d}$	Proportion of sample ranking period j as more annoying than period d
$R_{A_T \cdot L_I}$	Correlation coefficient from the regression of A_T on L_I
t_j	Number of hours in period j
WECPNL	Weighted Equivalent Continuous Perceived Noise Level, dB

Additional Subscripts

d	Daytime period
e	Evening period
i	A single noise event
I	Noise index I
j	A time period
k	A person
L	Noise level L
n	Nighttime period

Time-period Weight Symbols

ADJD	Additive adjustment in decibel difference model, dB
ADJN	Weight in the ratio of numbers model

ADJP	Additive adjustment in independent effect model, dB
D_{L_j}	Decibel value to be added to the single event sound level or a single hour LEQ for time j before being summed, (decibel weight), dB
$D_{L\&T_j}$	Decibel value to be added to a sound level (usually LEQ) for period j when no other method is used to adjust for period length, (decibel plus time weight), dB
w_j	Weight to be multiplied by number of events (N) or relative sound pressure squared ($10^{(L_i/10)}$) (number weight)

OVERVIEW

Components of Time-of-Day Response Models

Any attempt to model the reactions of people to noise events at different times of day must include theories about five components which are implicit in time-of-day models. Each of the components is briefly listed here. The second and third are briefly considered in the second half of this report. The last two receive extensive discussion in this report. A somewhat more detailed discussion of this general model can be found in an earlier publication (Fields, 1980).

1. Definition of time periods.- While there could theoretically be a large number of time periods, only two (day and night) or three (day, evening, night) are discussed in this report. Most noise indices and most of the data used in this report define the periods with the same boundaries: night, 22:00 to 07:00; evening, 19:00 to 22:00, and day, 07:00 to 19:00 (in two-period indices the day is 07:00 to 22:00).

2. Dose-response model for each time period.- The noise indices and the studies reviewed here assume that the noise level within any period can be represented with the equivalent energy model. Indices which ignore duration still combine number of events and noise levels according to the equivalent energy model. Evidence concerning use of the same noise model in all periods is reviewed in this report.

3. Mediating variable model for each time period.- Annoyance is known to be affected by a number of characteristics of individuals and neighborhoods. These need to be represented in a comprehensive time-of-day annoyance model only if the values of the variables change or if the relationship between the variables and annoyance changes from one time period to the next. The values of such variables as ambient noise level and type

of activity do change through the day. The relationship between most variables and annoyance might generally be assumed to not change. Several hypothesized exceptions are briefly examined later.

4. Model for combining period effects.- The most widely used model for combining period effects, found in such indices as LDN, NEF, and CNR, is labeled "adjusted energy model" in this report. Other models which are implied in analyses of past studies will also be described.

5. Weights for combining periods.- Once a model for combining period effects is accepted, the last requirement is to specify the values of the parameters in the model. In LDN for example a weight of 10 is applied to the nighttime period. The focus of most of the research and of this report is on the estimated values of these time-period weights.

Reports Reviewed in this Study

Reports from over 200 surveys of residents' reactions to noise were examined (Fields, 1981). Approximately thirty of these surveys provided information about the issues discussed in this report. Twelve of these thirty provided estimates of the weightings for reactions at different times of day. Table I describes these twelve aircraft, road traffic and railway noise studies. Although the noise estimation procedures are described in table I, no judgements are made about the relative accuracy of the noise data from the twelve surveys because such information is not available in published reports. The annoyance questions from the twelve studies are reproduced in Appendix A.

FINDINGS ABOUT TIME-OF-DAY WEIGHTS

Annoyance is generally assumed to be related to a noise index with a model of this general form:

$$A_{T_k} = a + B_I \cdot L_{I_k} + E_k$$

The effects of the unmeasured variables (E_k) are assumed to be additive with a mean of zero. The actual estimation equations presented later do not include this error term. The relationship is assumed to be linear in the notation used here, as in fact it is over the noise levels present in most studies, but the issues raised by the analyses presented here could also be applied to curvilinear models including quadratic or cubic models.

Some noise indices add all the noise events together on purely a physical basis. If, however, reactions to physically equivalent

noises at different times of day differ, the simple physical summation of the noise levels will not adequately represent the impact of the noise. In order to account for possible differences in reactions to different classifications of noise (e.g. noise at different times of day) some type of adjustment is made to the values of the physical noise index. These adjustments are commonly referred to as "time-of-day weights" in the acoustical literature. (The term "weight" is used throughout this paper for both multiplicative and additive adjustments even though in the statistical literature the term "weight" is normally used for only multiplicative adjustments). A common approach is to assume that the reactions to nighttime noise would be the same as those to daytime noise except that there is greater sensitivity to nighttime noise. The sensitivity to nighttime noise is then accounted for by using a time-of-day weight to increase the nighttime noise levels so that they are equal to the noise levels which would produce subjectively equivalent reactions in the daytime.

The twelve studies in table I calculated numerical adjustments which take into account differences in reactions to noise at different times of day. In most reports the adjustment has been compared to the value of 10 decibels associated with the nighttime period in widely accepted noise indices (LDN, WECPNL, NEF). Upon close examination, however, it is found that in spite of the common use of a decibel value, the type of parameter being estimated is not always the same. Differences in the parameters occur either because fundamentally different time-of-day reaction models are used (not all accept the conventional energy model) or because, even with the conventional energy model, the weight has been expressed in a different form (e.g. logarithmically transformed). In order to compare the results from the studies it is thus necessary to identify the type of time-of-day model and, for those studies sharing the same model, to calculate the same parameter within that model. Four different models are described under "Four Time-of-day Models". The succeeding sections only consider the first of the models, the conventional energy model. Three ways of expressing the weights in the conventional energy model are presented. Four methods for calculating these weights are next identified. The results from the studies are then compared after the same weight has been calculated for each study.

Four Time-of-Day Models

In reviewing the time-of-day research it was discovered that four time-of-day response models have been used. The first model is the conventional model found in noise indices. The second and third models are explicitly recognized alternatives to the conventional energy model. The fourth model has unwittingly been implied by the ratio analysis techniques used in several studies in which the objective was to estimate parameters in the conventional

energy model. Time-of-day publications do not offer a theoretical basis for any of the unconventional models or perform empirical analyses to determine which model best explains annoyance.

Model 1: Adjusted energy.- This is the conventional "energy model" accepted in such indices as LDN, NEF, and CNEL. In this model the noise level within each time period is adjusted before being combined with the noise levels from other time periods to make a 24-hour index (L_I). The noise level is adjusted with a numerical weight. In this report that weight is represented by the symbol "w_j" for the time period "j". This weight is multiplied by the number of noise events or the relative pressure squared of the value of the sound levels. (Transformations of this weight which are used in some other notations will be discussed in the next section.) With the multiplicative weight the model for three periods is written as:

$$L_I = q + c \bullet 10 \bullet \log_{10}\left(\sum_{i=1}^{N_d} 10^{L_{id}/10} + w_e \bullet \sum_{i=1}^{N_e} 10^{L_{ie}/10} + w_n \bullet \sum_{i=1}^{N_n} 10^{L_{in}/10}\right)$$

(The daytime weight is not explicitly represented because it is understood to always be $w_d=1$). In the first two columns of table II, values of the evening weights (w_e) in established noise indices range from 1 for LDN to 12.6 for WECPNL. For the nighttime weights (w_n), values range from 1 for LEQ to 16.7 for NEF. (The other expressions for the weights in table II will be discussed later).

The relationship between annoyance and the time-period noise levels is the following:

$$A_T = a + B_I \bullet 10 \bullet \log_{10}\left(\sum_{i=1}^{N_d} 10^{L_{id}/10} + w_e \bullet \sum_{i=1}^{N_e} 10^{L_{ie}/10} + w_n \bullet \sum_{i=1}^{N_n} 10^{L_{in}/10}\right)$$

The survey estimates of the nighttime weight (w_n) are presented in the last column of table III. They range from less than 1 to 25. (These weights will be discussed in more detail later).

Model 2: Independent effect.- This is the first of three models which differ from the conventional energy model. As such, it does not yield a weight which is strictly comparable to a weight in the conventional model. Annoyance is predicted with the following equation using this model:

$$A_T = g + B_{L_d} \bullet L_d + B_{L_e} \bullet L_e + B_{L_n} \bullet L_n$$

Annoyance is directly proportional to the noise level in each period, irrespective of the noise level in any other period. Thus

a change in the nighttime noise level from, for example, 50 to 55 dB(A) (LEQ) will be assumed to have the same impact on total annoyance whether the daytime noise level is 40 or 80 dB. In the the adjusted energy model, on the other hand, the change from 50 to 55 dB(A) (LEQ) would be expected to have an important impact if the daytime and nighttime noise levels were subjectively approximately equal (e.g., for w_n=10, when LEQ_d=60dB and LEQ_n=50dB) but would have no impact at all if the levels were quite different (e.g., LEQ_d=80dB and LEQ_n=50dB).

The differential impact of the two periods occurs because annoyance is assumed to increase more rapidly with noise level (steeper regression slope) during the day than during the night. A time-of-day adjustment can be expressed in terms of the number of decibels in the daytime which will bring about the same change in annoyance as a single decibel in the evening or the night:

$$ADJP_e = \frac{B_{L_e}}{B_{L_d}} \qquad \text{and} \qquad ADJP_n = \frac{B_{L_n}}{B_{L_d}}$$

In table IV, two of the studies implicitly accept this model. Though the reports from these studies do not contain arguments supporting this model, the model has been discussed in the context of summing annoyance from combined noise sources. The "independent effects" label was previously applied by Taylor (1982; p. 125) to an identical model used for a noise index which combined the noise from several sources.

Model 3: Decibel difference.- This model implies that annoyance is independently affected by the value of LEQ for the total 24-hour period and number of decibels which separate the noise levels of the two time periods. The model for two periods is the following:

$$A_T = h + B_{L_{24}} \bullet LEQ_{24} + B_{dn} (LEQ_d - LEQ_n)$$

An adjustment can then be defined as the difference between the daytime and nighttime noise levels which is equivalent to a one decibel effect of 24-hour LEQ.

$$ADJD = \frac{B_{dn}}{B_{L_{24}}}$$

(Only two time periods are represented in the equations here and later in the report in order to shorten the presentation). If the nighttime noise is more annoying then the adjustment would be negative; that is, the lower the nighttime noise, the more the value of the index should be reduced. This type of combined noise source

model is labeled the "energy difference" model by Taylor (1982; p. 125). It is represented by estimates from the Western Ontario traffic survey in table IV.

Model 4: Ratio of numbers.- Several studies which attempt to estimate the weight in the conventional adjusted energy model have unwittingly used a different annoyance model.

The model is implicit when the noise levels of the events are unknown and a ratio analysis is performed which relates the ratio of two time-period annoyance scores to the ratio of the numbers of events in the two periods:

$$\frac{\frac{A_n}{A_d}}{\frac{N_n}{N_d}} = ADJN$$

The ratio can be rewritten as:

$$\frac{A_n}{A_d} = \frac{N_n}{N_d} \bullet ADJN$$

It thus follows that the annoyance models for each of the two periods can have only multiplicative terms in them:

$$A_d = c \bullet N_d \qquad A_n = c \bullet (N_n \bullet ADJN)$$

This model departs from all other previously proposed annoyance models in at least two respects: annoyance is directly proportional to numbers of events (not $\log_{10}$ number) and the effects of all additional variables (such as noise level or attitudinal variables) are multiplicative not additive. The two studies which use this model in table IV are the U.S. Army impulse noise survey and the 1973 JFK airport survey. Since neither of these studies mentions these departures from standard models, it must be assumed that this ratio-of-numbers model is not actually proposed as an alternative to the conventional model. (A unique interpretation of the meaning of the U.S. Army interview question which would avoid the use of the model is discussed in Appendix C).

Given the radically different annoyance models it is not possible to derive the value of the conventional weight (w_j) from the value of ADJN. The direction of the difference is clear; because the additive effects of other disturbance variables have not been removed, the value of ADJN will be lower than the value of w_j which would have been estimated from the same data. In one simulation

based on data from the 1967 Heathrow survey, ADJN was about 30% below w_j (see Appendix C).

Alternative Expressions for Weights in Noise Indices

Number weights.- Throughout this report the weights in the adjusted energy model are multiplicative weights (w_j) which are multiplied by the number of noise events or the relative pressure squared values of the noise levels during the nighttime period. When the relative pressure squared value of the noise level is used, the results are summed over noise events (when each of the individual noise events are weighted) or are summed over the number of hours in the time period (when each of the noise levels is an hourly noise level). The weight of 10 and 3 in CNEL are multiplicative number weights.

Decibel transformation.- These adjustments to nighttime noise could of course be expressed in terms of decibels. Such a decibel weight (D_{L_j}) is simply a logarithmic transformation of the multiplicative weight:

$$D_{L_j} = 10 \bullet \log_{10}(w_j)$$

This simple decibel weight is added to a noise level. The term "weight" is used for this additive adjustment in conformity with conventions in the acoustical literature even though the term "weight" is reserved for multiplicative adjustments in the statistical literature. Once again the adjustment is made to either the individual noise events (before they are summed) or to each of the hourly noise levels (before they are summed).

The adjusted energy model as found in the noise indices can be written with either the multiplicative number weights or the decibel weights. If the individual noise events are summed with the multiplicative weights the equation is the following:

$$L_I = a + c \bullet 10 \bullet \log_{10}\left\{\left(\sum_{i=1}^{N_d} 10^{L_{id}/10} + w_n \bullet \sum_{i=1}^{N_n} 10^{L_{in}/10}\right)/24\right\}$$

If the individual noise events are summed after adding the decibel weight then the equation is the following:

$$L_I = a + c \bullet 10 \bullet \log_{10}\left\{\left(\sum_{i=1}^{N_d} 10^{L_{id}/10} + \sum_{i=1}^{N_n} 10^{(L_{in}+D_{L_n})/10}\right)/24\right\}$$

If, the averaged hourly noise levels are summed (mutiplied by the number of hours in each period) after adding the decibel weights

then the equation is the following:

$$L_I = a + c \bullet 10 \bullet \log_{10} \left\{ (t_d \bullet 10^{LEQ_d/10} + t_n \bullet 10^{(LEQ_n + D_{L_n})/10})/24 \right\}$$

Decibel-time transformation.- Three widely accepted indices (CNR, NEF, and WECPNL) use time-of-day adjustments which combine the standard additive decibel weight with an adjustment for the relative lengths of the time periods. This type of combined adjustment is represented by "$D_{L\&T_j}$" (i.e. "Level and Time" adjustment) and is referred to as a combined "decibel-time" weight in this report. The general form of an index with this adjustment is the following:

$$L_I = a + c \bullet 10 \bullet \log_{10} \left\{ t_d \bullet (10^{LEQ_d/10} + 10^{(LEQ_n + D_{L\&T_n})/10})/24 \right\}$$

The important difference between this equation and the previous equations follows from the absence of the summation signs and any indicators of the length of the period. The indicator of the relative length of the two time periods is included in the $D_{L\&T_j}$ adjustment. As a result, the relationship between this combined decibel-time adjustment and the standard decibel weight is the following:

$$D_{L\&T_j} = D_{L_j} + 10 \bullet \log_{10} (t_j/t_d)$$

This weight ($D_{L\&T_j}$) has the unfortunate property that its value changes with the relative length of the time periods. It is thus unsuitable as a weight for a general model of time-of-day effects. This combined decibel-time adjustment is often found in the literature because it can be added to period noise levels without any further summation when these noise levels are represented by a noise index (e.g. LEQ) which measures the average noise level per unit of time. Galloway has given this combined decibel-time adjustment the label "exposure" adjustment (1980, p. 9).

Confusion has sometimes arisen in describing noise indices and in analyses of studies because the type of numerical weight which has been calculated is not reported. The ten-unit weight in CNEL is a number (relative pressure squared) weight (w_j) while the combined decibel-time adjustment of 10 units in NEF is equivalent to a 16.67 number weight. The relationship between these various weightings is presented for selected values in table II.

The distinctions between the different transformations of the weights can be especially important for evening weights: an

evening combined decibel-time adjustment of $D_{L\&T_j}=5$ in WECPNL is equivalent to a $w_j=12.6$ number weight (table II). Unless otherwise stated the weighting described in this report is a number (relative pressure squared) weighting. This weighting is more directly transferable between different indices than are the other weightings since it can be applied to either numbers of events or the sum which is added in the indices $(\sum_{i=1}^{N_j} 10^{L_{ij}/10})$ and since its value does not depend on the length of the time period.

Four Methods for Estimating Time-of-Day Weights

Four methods have been identified which can be used to evaluate the time-of-day weights in the energy model. The first method seems to be theoretically attractive but has not yet been applied. The remaining three methods are all represented by studies in table III.

Method 1: Total Annoyance Regression.- Total annoyance is regressed on the noise levels in the form of a two-period or three-period noise index. For a three-period index:

$$A_T = a + B_I \bullet 10 \bullet \log_{10}(B_d \bullet \sum_{i=1}^{N_d} 10^{L_{id}/10} + B_e \bullet \sum_{i=1}^{N_e} 10^{L_{ie}/10} + B_n \bullet \sum_{i=1}^{N_n} 10^{L_{in}/10})$$

The values for the weights are ratios of the partial regression coefficients within the parentheses in the above equation:

$$w_e = \frac{B_e}{B_d} \qquad w_n = \frac{B_n}{B_d}$$

No studies have thus far used this method even though it would provide direct estimates of the time-of-day weights.

Method 2: Noise Index Correlation.- Two alternative noise indices (I_1 and I_2) are each correlated separately with total 24-hour annoyance. The values of the multiple correlation coefficients are compared. If $R_{A \cdot I_1} > R_{A \cdot I_2}$ then it is concluded that Index 1 is "better".

This method actually provides only a test of the relative value of two indices: it does not estimate a particular value of the weight. It is quite possible that the predetermined value of the weight in the "better" index might still be very different from the weight which is "best" for the data set. If one of two indices

is more highly correlated with annoyance, the only information obtained is that the value of w_j is greater or less that some value (usually unspecified) which lies between the values of w_j used in the two indices. In the comparison of LEQ and LDN, a finding that LDN is "better" simply indicates that the weight is $w_j=4$ or more. (The basis for this estimate is explained under "Inherent limitations" of the method in the "CRITIQUE OF METHODS" section of this report).

Table III contains the results from six of these comparisons of pairs of indices. Most compare LEQ with LDN. The Australian five airport study uses this method to narrow the range of estimated values by comparing the correlations for indices in which the $D_{L\&T_j}$ weightings are incremented in three-decibel steps.

Method 3: Period Response Comparison.- The annoyance measures used in this method are directly parallel questions about the annoyance with noise during each period. Each time-period annoyance measure can be regressed on the appropriate noise level for that period. If the noise referred to in each period is the noise during an average hour (e.g. LEQ), the regression equation for period "j" is:

$$A_j = a_j + B_j \bullet 10 \bullet \log_{10}\left\{\left(\sum_{i=1}^{N_j} 10^{L_{ij}/10}\right)/t_j\right\}$$

If the slopes from the regression analyses in each of the periods are found to be equal ($B_d=B_e=B_n=B_L$) then a dummy variable regression analysis may be used to directly estimate the weights (the dummy variables are scored either zero or $M_j=1$ for the appropriate time period).

$$A_j = a + B_L \bullet 10 \bullet \log_{10}\left\{\left(\sum_{i=1}^{N} 10^{L_i/10}\right)/24\right\} + D_e \bullet M_e + D_n \bullet M_n$$

The values of the weights are then ratios of the parameters:

$$D_{L_e} = \frac{D_e}{B_L} \qquad\qquad D_{L_n} = \frac{D_n}{B_L}$$

The decibel weight is represented graphically in Figure 1. It is simply the number of decibels which separate the daytime annoyance curve from the annoyance curve for the evening or night period.

Slight modifications in the above procedures are required if the noise is rated in other units of time or if the noise levels used in the regression equations are defined differently. If the

noise asked about in the survey question is the noise from an average noise event (not an average hour of exposure) then exactly the same procedures are used to estimate the same decibel weight. In this case, of course, the sum of the noise levels in relative pressure squared units is divided by the number of noise events, not by the number of hours in the period.

If the noise asked about in the survey question is the sum total of the noise during each period, the respondents are being asked to consider the relative lengths of the periods. In this case the sum of the noise levels in relative pressure squared units should not be divided by either the number of events or the number of hours. The logarithm of this sum is not a recognized acoustical descriptor, but if annoyance is regressed on it, the ratio of the regression coefficients is again the time-of-day weight expressed in decibels. An error can arise if the respondent is asked about this sum total of the noise during the period, but the physical noise measure entered into the regression is the value of LEQ for the time period (an average hourly measure) rather than a quantity representing the sum of all the noise over all the hours. In this case the ratio of the regression coefficients produces the combined decibel-time weight ($D_{L\&T_j}$). The decibel weight must then be obtained by subtracting the time-period length adjustment.

Table III includes four studies in which the weighting has been calculated using this period response comparison method. The studies differ in the type of variable which is used as the period noise level indicator. Number of noise events is used in the 1972 Heathrow survey (Ollerhead, 1978). Time-period LEQ is used in both the Western Ontario Traffic Noise Survey (Bradley and Jonah, 1979) and in the USA Army impulse noise survey analysis of the reactions to impulse noise (Schomer, 1983, p. 554). As was explained earlier, the Army survey uses a different noise model for evaluating all other sources.

Method 4: Respondent Ranking.- Respondents directly rank the periods by answering a direct question about whether the noise is more annoying during an average hour in the daytime or in the nighttime. If it is found that night is most annoying but that the noise is less at night then it can be concluded that the weight (D_{L_n}) for nighttime noise should be greater than for daytime noise. When an attempt is made to estimate numerical weights for this difference the implicit model is:

$$P_{A_j > A_d} = f\left((L_j + D_{L_j}) - L_d\right)$$

The proportion of respondents rating period j as more annoying than

the daytime period ($P_{A_j>A_d}$) is a function of the actual difference in noise levels as well as a nighttime decibel weight. This relationship is presented graphically in figure 2. The decibel weight (D_{L_j}) is the number of decibels which separate a curve based on a time-of-day weight and one which would require no weight. There is only one point at which this difference can be easily estimated, the 50% point (i.e. $P_{A_j>A_d}=0.50$). This is the point at which the two periods appear to be equally annoying because equal numbers of people choose each period as the most annoying. At this one point it is not necessary to specify the forms of the curves in figure 2 because it can be assumed that the curve for $D_n=0$ would have a value of $P_{A_j>A_d}=0.50$ at the point where L_n-L_d equals zero. In order to estimate the value of the nighttime weight for any other point it would be necessary to specify the shapes of the two curves in figure 2.

For the annoyance questions which have been used in existing surveys there seems to be little basis for specifying the shapes of the curves. Two assumptions about the shapes are implicit in figure 2: (1) the two curves have the same form but are displaced along the abscissa by a constant difference, and (2) the curve is symetrical about the 50% point and approaches the abscissa with a steadily decreasing slope. The cumulative distribution for the logistic distribution is one of several curves which has this later property. This distribution is described by the following function:

$$P_{A_j>A_d} = f\left\{\frac{1}{1+10^{B_I\ (L_n+D_{L_n}\ -\ L_d)/10}}\right\}$$

The value of D_{L_n} describes the displacement along the abscissa and the term B_I describes the steepness of the slope of the curve. The slope could be expected to be determined by such factors as the ability of the population to distinguish between different noise levels and the extent to which the population agrees on a nighttime weighting. A shallow slope around the 50% point has one important consequence: even a small standard error for the estimate of the annoyance response will result in a large amount of imprecision in estimating the nighttime weighting.

It is again important to ensure that there is a congruence between the definition of the noise used in the annoyance question and the definition of the noise for the physical measurement.

Just as in the case of the period response comparison method, if respondents are asked to judge the relative annoyance from the total noise exposure then they should include the length of the period in their judgement. If the values of LEQ (an average hourly exposure measure) for each period are used, the differences in noise levels in figure 2, are decibel-time weights which combine both the nighttime decibel adjustment and the time-period length adjustment ($D_{L\&T_j}$).

In table III, five of the studies use the respondent ranking method. Only the analysis of the 1971 Heathrow survey (Wilson, 1963) attempts to provide a narrow numerical estimate of the weighting.

The period response comparison method and the respondent ranking method both are based on the comparison of the annoyance responses in the two periods. The difference is that in the first instance the comparison is made by the analyst, while in the second case the comparison is made directly by the respondent. The relationship between the two ratings is indicated in figure 3. When the comparison is made at two points where there is equal annoyance for each time period (i.e. points a and b in figure 3), then it is to be expected that the sample will divide equally in their direct judgement as to which time period is worse (i.e. $P_{A_n>A_d}=0.50$). When, however, points a and c are compared, it is clear that the percentage should be greater than 50%. It is not however clear just what this percentage should be. This is the basis for the difficulty in specifying the shape of the curve in figure 2.

Existing Estimates of Time-of-Day Weights

Eleven studies provide the fifteen estimates of the number relative pressure squared weight (w_j) in table III. The table is broken down into three parts on the basis of the type of estimation method which is used.

The total annoyance regression method has not been used, thus the first set of estimates in table III comes from Method 2: Noise index correlation. All of the annoyance scales used for this method are assumed in the publications to measure the annoyance for the entire 24-hour period (second column of the table). Three of the studies attempt to do this in a simple, straight-forward manner with questions about overall annoyance with the particular noise source: the Manchester traffic survey uses a "numeric scale" in which only the end points are labeled, the Canada railway yard survey uses a "verbal scale" which is subsequently numerically scored,and the British railway survey uses a mixture of these two

types. For the remaining three studies the respondent does not directly rate the total response. Instead the respondent's rating is only of annoyance during particular time periods (W. Ontario traffic) or of annoyance during activities which imply different time periods (combinations of sleep interference, speech interference and other activity interference questions for the Australian and USA surveys). Thus the researcher's judgement, not the respondent's feeling, is used to determine what combination of these time-period related questions will be used to form an overall annoyance index. As a result it is not possible to determine whether the annoyance index correctly represents the respondent's judgement of the relative importance of activity interferences at different times of day.

In the "Findings reported" column of table III the findings are reported in the same form as was found in the study publications. These findings have been converted to number weights in the next column. The method of making this conversion for each study is described in Appendix B. The first five estimates of the weights are all based on comparisons of the correlations between annoyance and a noise index with no nighttime weighting (LEQ_{24}) and a noise index with either a w_n=10 weighting (LDN) or a w_n=16.7 weighting (CNR). Such comparisons do not provide an estimate of the weight other than the weak statement that the value should be greater (or less than) a certain number: w_n<5.0 for the first two studies, w_n >5.0 for the USA airport survey, w_n >3.0 for the Canada railway and Western Ontario traffic surveys. (The method for deriving this boundary from the correlation analysis is described in the "CRITIQUE OF METHODS" section). The Australian airport survey provides a narrower description of the "best" estimate (0 <w_n <2) as well as confidence intervals for the upper values of the estimates. The upper 95% confidence interval for the night weighting is described in the publication as being close to the upper value of w_n <4, but the interval for the evening weighting is quite large and extends from below w_e=0 to almost w_e=16. Findings from other community response surveys suggest that the actual confidence intervals are probably even larger because simple random sampling assumptions cannot be met (Fields, 1984: p. 462).

The next method in table III, period response comparison, is represented by four studies, all of which use some type of time-period annoyance question. The information in the "Comments" column indicates that none of the surveys has a simple, direct measure of annoyance in the two periods beng compared: the 1972 Heathrow survey question refers to how frequently (not how much) people are annoyed, while the U.S. Army impulse noise survey and Western Ontario traffic survy require assumptions about how several period annoyance measures should be combined to represent annoyance during the daytime. The estimates range from nighttime noise having no effect in the 1972 Heathrow survey to a weight of w_n=13

for the U.S. Army impulse noise and the Western Ontario traffic surveys.

The last method in table III, respondent ranking, is used in five surveys. Problems which occur in the annoyance ratings in three of the surveys are noted in the "Comments" column: the 1961 Heathrow survey requires the researcher to combine annoyance measures from different time periods and the 1972 Heathrow survey and 1980 Australian airport survey suffer from difficulties in knowing how the annoyance questions were interpreted by respondents. The estimates range from a weighting of less than $w_n=1$ in the 1972 Heathrow survey to a weighting of $w_n=25$ for the 1961 Heathrow survey and to some value greater than $w_n=11$ for the Australian survey.

Since the findings in the next table, table IV, refer to other types of annoyance models, they do not provide direct estimates of the weights in the adjusted energy model. The three studies which use the first two models in table IV have already provided more direct estimates of the weights in table III. These British railway and USA airport study findings do, however, raise the issue of the accuracy of the estimates. In table IV the British railway coefficients for the three time-of-day periods are not statistically significant when they are included in the same equation. The unexplained negative sign for the daytime noise level in the next survey (USA airport) may also be due to large standard errors for the parameters. The results from the Western Ontario traffic survey for the decibel difference model are consistent with the finding reported earlier for this survey in table III: nighttime noise levels have more affect on annoyance than do daytime levels.

The findings for the next model in table IV, ratio of numbers model, show that nighttime noise events have more effect than daytime events. The value of conventional weights (w_j) for these studies would be greater than the ADJN values for the corresponding time periods. This may partly explain why the U.S. Army impulse noise survey provides an estimate of $w_j=13.2$ for the conventional model (table III) but that ADJN is only 2.5 (table IV).

Discussion

The data in table III do not provide a firm basis for selecting a nighttime weighting: the estimates from the different surveys differ, many estimates are not stated precisely, and methodological difficulties could affect many estimates. In spite of these difficulties several observations can still be made from the data.

Part of the difference in the estimates in the nighttime weight could of course be due to differences in the populations

surveyed or to deficiencies in the conventional time-of-day model. It is clear, however, that at least part of the difference is due to methodological considerations because alternative estimates from the same survey do not agree. In table III the first estimate of the nighttime weight from the 1980 Australian airport survey is $0 < w_n < 3$ but the second estimate from the same survey is that the weight is greater than $w_n=11$. The first estimate for the evening weight for the 1972 Heathrow survey is $w_e=4$, but a later estimate, using a respondent ranking method, indicates that daytime noise is more annoying (i.e., $w_e<1$). The time-of-day study methods obviously deserve careful attention.

There is some evidence that the different estimation methods used in table III may give systematically different estimates of the time-of-day weighting. The noise index correlation method seems to yield lower values of the weight than the other two methods. The average of the weights from the correlation analyses is lower than for the other methods. The same pattern is observed for the three surveys which used both the correlation method and one of the other two methods in the same survey (Western Ontario traffic survey, 1975 British railway survey, Australian airport survey).

The evidence in table III does not consistently support either a high or a low nighttime weighting. Of the 14 nighttime estimates in table III, four support a weighting of at least $w_n=10$ (Method 3; Army and W. Ontario traffic: Method 4; 1961 Heathrow and 1981 Australian). For a total of eight estimates a nighttime weighting of $w_n=10$ was better than no nighttime weighting (the additional four estimates are: Method 2; USA airport, Canada railway, W. Ontario traffic and Method 3; 1978 Zurich). On the other hand, for five estimates an unweighted index is better than a weight of $w_n=10$.

The evidence on an evening weighting is equally diverse. Of the five estimates of evening weights, three support weights of less than $w_e=5$ and two support weights of more than $w_e=6$.

Most of the discussion in the regulatory context about the values of nighttime weights for noise indices has centered around weights of less than $w_n=20$. The fact that there are estimates of less than $w_n=5$ for the nighttime weight but only one estimate greater than $w_n=14$, suggests that the range of values mentioned in such discussions (i.e., less than 20) is probably correct.

CRITIQUE OF METHODS FOR ESTIMATING WEIGHTS FOR THE ADJUSTED ENERGY MODEL

The validity of most of the estimates in table III can be questioned. In this section the reasons for the weaknesses of these estimates are explored by examining the studies in table III and by

analyzing the assumptions underlying the use of the different methods. Each of the four time-of-day estimation methods is examined in turn. In each case the evaluation considers three topics:

1. Prevalent problems in existing analysis. These problems could be expected to be solved in reanalyses of the existing data or in improved data collection designs.

2. Inherent weaknesses. These are characteristics which are not clearly soluable.

3. Relative strengths. These are the strong points for this method relative to the other methods.

Method 1: Total Annoyance Regression

With this method the total 24-hour annoyance is regressed on the noise levels in the different periods simultaneously. The time-of-day weights are directly estimated by ratios of regression coefficients.

Problems affecting current usage.- The reason this technique has not yet been used is probably because the nonlinear relationship between annoyance scores and the physical parameters requires more complex analysis techniques than have commonly been used in noise studies. Non-linear regression techniques could however be applied. Although these would take a small amount of development work, they should be readily usable in future analyses. Other potential problems concerning the selection of a 24-hour annoyance index are described below in the discussion of Method 2, the index correlation method.

One other factor may be responsible for the neglect of the annoyance regression method. The method makes explicit a problem which is easier to mistakenly ignore when other methods are used: the period noise levels are highly correlated. In a multiple regression analysis this is immediately apparent from the standard errors of the regression coefficients. The fault does not, however, lie with the regression procedure. If weak study design leads to high correlations between noise levels then the high correlations affect the validity of all analyses even if the particular analyses (e.g., analysis of period annoyance responses) do not explicitly quantify the problem. Evidence concerning this problem will be discussed later (Q.5 Does annoyance in other periods affect responses in the night period?).

Inherent weaknesses.- The validity of the method requires that the respondent integrate annoyance over the entire 24-hour period. Though the respondent is clearly the only person who is in a position to do this, it may be a difficult task. If people normally compartmentalize their day and night reactions then it

is essential that the survey question lead the respondent to integrate the two reactions. A conventional question which simply asks about "aircraft noise when you are here at home..." in the context of normal events in a neighborhood may be biased toward the recall of normal daytime events. Until there is research evidence to the contrary it would seem to be important to explicitly ask the respondent to integrate both day and night experiences into a single reaction.

Relative strength.- The overwhelming virtue of this method is that it provides a direct estimate of the time-of-day weight and of the standard error or the 95% confidence interval of that estimate.

Method 2: Noise Index Correlation

With this method the total 24-hour annoyance indicator (same annoyance measure as was required for the previous method) is correlated with noise indices which contain different time-of-day weights. The method aids in the choice of alternative indices even though it does not provide direct estimates of the optimum values.

Problems affecting current usage.- The chief requirement, as with the first method, is that the annoyance indicator be an unbiased measure of the entire 24-hour day. Three of the six analyses using this index correlation method in TABLE III clearly violate this requirement. These three analyses use annoyance indices which contain a mixture of questions which refer to different times of day or to activities which only occur at certain times of day. Since it is the researcher who determines the mix of daytime and nighttime annoyance items, the researcher is affecting the relative importance of day and night events in the index. Thus, there is the danger that the methodology is biasing the outcome.

Inherent weaknesses.- The technique does not provide a direct estimate of the value of the time-of-day weights or of the standard errors of the estimates of those weights. With these time-period weights it is only known that for this sample one combination of weights reduced the variation in annoyance more than another combination. It is not possible to know, for example, whether one index has the correct nighttime weight while the other index has the correct evening weight. Even in the case of a comparison of LEQ and LDN, if it is found that LDN is more highly correlated with annoyance, it does not show that the weight should be $w_n=10$.

In order to determine just what values of w_j are consistent with differences in correlations, LEQ and LDN were correlated with noise indices utilizing weights ranging from $w_n=2$ to $w_n=9$. First a set of values of daytime LEQ values and nighttime LEQ values were assembled. Ten noise indices were then created with weights rang-

ing from w_n=1(LEQ_{24}) to w_n=10(LDN). The correlations of each of the eight intermediate weighted indices (w_n=2 to w_n=9) with LEQ and LDN were compared. In an examination of three artificial sets of noise data and two sets of noise data taken from social surveys, it was found that in four of the five cases a value of w_n=4 was sufficient to create a higher correlation for LDN. For one of the artificial data sets a value of at least w_n=5 was required. Thus a finding that LDN is more highly correlated than LEQ only suggests that the value of w_n is greater than 3.0, a not very precise indicator. Such a finding also does not provide direct information about the confidence interval for the estimated value.

Relative strength.- The correlations are easily computed given the values of two noise indices.

Method 3: Period Response Comparison

With this method the period annoyance measures are related to each of the period noise levels and then the number of decibels which separate equivalent annoyance reactions are estimated.

Problems affecting current usage.- The most serious problem is ensuring that respondents are rating the noise in the same units of time (annoyance per event, annoyance per hour, or total annoyance per period). As is indicated in the "Comments" column of table III, two of the authors dismiss their own estimates on the basis that people responded on a total annoyance basis when they were asked for a per event basis (1972 Heathrow survey) or that they responded on the basis of hypothetically equal exposures rather than on the basis of existing exposures (Australian airport survey). Even the researchers do not seem to agree on the interpretation of the question. Very similiar time-period questions are interpreted differently in two studies; in the 1972 JFK Survey it is assumed that the answers are interpreted on a per hour basis (a doubling of annoyance is related to a doubling of number of events per hour) while the 1961 Heathrow survey assumes that answers can be interpreted on a per period basis (annoyance is related to differences in the total numbers of events during the periods).

A separate problem is faced in fitting the respondent's time-of-day time-period boundaries to the measured boundaries. Some studies ask about annoyance "...when you are trying to sleep" but then use the same nighttime period for the noise data irrespective of the time when people are sleeping.

Inherent weakness.- This method must make two critical assumptions, neither of which can be tested with the time-period data. The first assumption is that even though the respondent is only asked to make independent ratings of the two periods, the absolute

differences between these two ratings can be used to infer how the respondent would compare the two periods. It could at least be argued that the respondents may have different frames of reference when they rate the two periods so that the absolute scores can not be directly compared.

It is also necessary to accept a time-of-day model without testing it. While it is possible to test alternative time-of-day models with total annoyance response methods, no such test can be carried out with either this period comparison method or the respondent ranking method.

The method also assumes that people actually can provide a meaningful response to either an average hour during a period or to the sum of the noise during a period. Thus it is assumed that people understand the distinction between the types of ratings. This distinction is especially important for calculations of weights for the short evening period (See table II).

Relative strengths.- Separate annoyance responses for each time period can be directly analyzed to determine whether the same type of noise index is appropriate for each period. While this issue might be explored with the total regression method, this period comparison method would seem to be able to provide a much more sensitive analysis technique.

Method 4: Respondent Ranking

With this method the respondent's own explicit ranking of the relative annoyance of two periods is used to estimate the difference in decibels which would lead to the judgement that two periods are equally annoying.

Problems affecting current usage.- It would, of course, be possible to analyze the data from a study by relating each individual's (or each neighborhood's) ranking of day and night annoyance to the difference between daytime and nighttime noise levels. This would generate the type of informative annoyance curve found in figure 2. The present studies, however, present only a single data point for the entire study. For four of the five studies in table III, this provides only an estimate for the lower bound for the weight w_j. In the other case, the 1961 Heathrow study, the estimate of w_n=25 was offered on the assumption that if 24% are more annoyed during one period and 28% more annoyed during the other, then the periods are about equal (The remainder are never annoyed or are equally annoyed during the periods). Without any information about the form of the curve relating differences in time period noise levels to differences in time-period judgements, it is not possible to know whether or not the 4% gap in annoyance responses has any implications for the gap in noise level. In

short, a current problem is that the relationship betwen differences in noise levels and differences in annoyance has remained unanalyzed.

Current comparisons are also based on single questions about "worst periods" which normally allow for mention of at least three periods, instead of being based on questions which ask for explicit pairwise comparisons of all periods which will be compared in the final analysis. In the absence of such pairwise comparisons, the 1961 Heathrow study could only make a nighttime versus daytime comparison by adding together the day and evening responses. Other studies are left with quite weak statements because, for example, a rating that nighttime is worst does not provide a relative ranking of evening and daytime.

This respondent ranking method shares two of the period response comparison method problems. At least two of the studies do not clearly define periods for annoyance responses which match the noise data. In addition, it is again seen that respondents may be unclear as to whether they are to provide a per event, per hour or per total period annoyance ranking. This later problem would seem to be more amenable in the annoyance ranking format than in the former period rating format. New types of questions which would ask respondents to choose between alternatives such as a noise-free day or a noise-free evening would make it clear that a total period annoyance judgement was required.

Inherent weaknesses.- As with the period response comparison method, this method must accept a time-of-day model without any possibility of testing it. Unless new techniques are developed, the method also faces a problem in the fact that large numbers of respondents (18% of the respondents in the 1972 Heathrow survey; 44% in the British railway survey, Fields and Walker, 1982; p. 195) rate the periods equally. It is not immediately obvious how these large numbers of ties should be treated in the analysis. They can not simply be aggregated with one of the other groups as would be implied by the logical statement concerning the "percentage of the population which would rate time-period "j" as equally or more annoying". This treatment would give quite different estimates for the two ways of grouping the ties with the responses which are not tied. Ignoring all the tied responses, as was done in the studies here, however, also suffers from at least one deficiency; when two periods are equally annoying, then all of the respondents who give the most rational response ("the periods are equally annoying") are excluded from the analysis.

Relative strengths.- This method avoids some of the ambiguities noted for other methods concerning the possibility that comparable attention is not being directed to the annoyance experienced in each period. One other potential strength might be realized

if a type of question were used in which the respondent must allocate noise reduction resources between periods or decide which periods should be quiet. In this case it would be clear that the total period was being rated.

RESPONSES TO NOISE AT NIGHT

Introduction

The discussions of time-of-day weights in the previous sections of this paper have focused on only two of the five components in the general time-of-day model: the model for combining period effects and the values of the weights for combining the periods. The remainder of this report focuses on two other components in the general time-of-day model: the dose-response model for the nighttime and the effect of mediating variables in the nighttime. Three types of information about nighttime responses are presented in this section: figures which relate the extent of nighttime annoyance to nighttime noise levels, information about the relationship between sleep disturbance and nighttime annoyance, and findings concerning six questions about nighttime responses. The survey data which are used to provide this information are described first.

Available survey data.- Although reports often contain discussions of sleep disturbance and of the importance of nighttime noise, a close examination shows that many analyses do not have separate noise data for each time period. Such noise data are required to develop either a sleep disturbance or a nighttime annoyance model. (Most publications show both sleep disturbance and speech disturbance on the same figure as a function of a 24-hour, not a time-period, noise measure).

The only findings discussed in this report are those from studies where information is available about the nighttime noise levels. Other literature reviews have included a broader range of studies because they were considering any type of evidence which might help in constructing nighttime noise regulations (Fidell and Schultz, 1980; Rice and Morgan, 1982). The present report is more restrictive since the goal is to identify data which could provide a basis for further research work.

Relationship between Nighttime Annoyance and Nighttime Noise Levels

Publications from 200 surveys of human response to noise were examined. These publications contained 16 figures in which nighttime response was presented as a function of nighttime noise level. These figures are reproduced in Figures 4 to 19 this report. As was noted above, this excludes the many published figures in which

nighttime response is graphed as a function of 24-hour noise level. The figures are the best data available for predicting specific long-term survey responses from measured noise levels. The best definition of the meaning of the responses is provided by the survey question which accompanies each figure. The questions differ considerably between surveys. As a result, no attempt has been made to combine the data from the different surveys into a single dose-response relationship. The figures are discussed individually as they relate to one of the other issues addressed in this report.

Distinctions Between Sleep Disturbance and Nighttime Annoyance

The distinction between sleep disturbance by noise and annoyance from night noise has implications for both research and policy makers. Policy makers who set nighttime regulations are most concerned about minimizing sleep disturbance, thus some type of a threshold or single-event criteria is likely to be considered. On the other hand, policy makers who set overall 24-hour criteria (e.g., land use planners) are most concerned about minimizing total annoyance, thus some type of weighted 24-hour index is most likely to be considered. Time-of-day researchers are similarily divided between those studying sleep disturbance and those studying nighttime annoyance. Both researchers and administrators tend to assume that sleep disturbance is the basis for understanding or reducing nighttime annoyance. Careful thought about the subject, and the available research findings, however, suggest that the following three phenomena may be only loosely linked in the real world: interruption of continuous sleep, disturbance to sleep due to noise and annoyance with noise at night. Some possible reasons for a low correlation between the phenomena are explored here before turning to the research findings.

Sleep Interruptions in the Absence of Noise.- It is conventional to think of the nighttime period as consisting of a continuous uninterrupted sleep period. However, the evidence from an English survey around three airports (Figure 4) shows that about half of the population awakens at least once a night in the absence of any particular environmental noise problems. The average number of awakenings per night is almost 100 per 100 people (Figure 5). It should be noted that the 50% interruption in continuous sleep relates to sleep on a single night, the percentage who report chronic "problems" with sleep is lower (many people do not apparently consider some of the awakenings at night to be a problem). People also report a lower "average" rate of awakening for a long-term question than is consistent with reports of the previous night's awakenings (Aircraft..., 1980a, p. 20). Major reasons given for these breaks in the continuous sleep period are going to the bathroom, illness, tension, disturbance by children and habitual unexplained insomnia (Aircraft..., 1980b: tabulations to Q.15b and

15d; Langdon and Buller, 1977: p. 20). Thus interrupted sleep is not an unusual pattern. Difficulty in getting to sleep and waking up early also occur in the absence of noise.

Sleep Disturbance Due to Noise.- Pre-existing disturbances in a discontinuous sleep period thus provide a base upon which disturbances to sleep due to noise are overlayed. Some, perhaps most, of the genuine disturbances due to noise fit the popular conception that people who would otherwise remain in uninterrupted sleep for an extended period are brought to consciousness or change sleep stages because of the presence of loud, or at least distinct, noise events. In such cases there is a clear reduction in the amount of sleep time or an increase in the number of awakenings. However, there must be another large number of cases in which people who would awaken anyway are awakened at an earlier time than would have otherwise have occurred (either during the sleep period or at the end of the sleep period). In some such instances there may be no change in the total number of awakenings and only a very small change in the length of the sleep period.

Noise Annoyance at Night.- Noise annoyance at night concerns perceived experiences with noise during a defined number of nighttime hours. This annoyance could well be a function of factors other than the ones which disturb sleep. In fact it could be expected that nighttime annoyance would differ from sleep disturbance in at least the following six ways:

1. A single definition of the "night-period" (e.g. 23:00 to 07:00) will include some times when a large proportion of the population is normally awake and engaging in normal late evening or early morning activities. It should be expected that the experience during these relatively short periods of consciousness will have a large impact on the perception of the nighttime environment.

2. Noise may cause annoyance while a person is falling to sleep, laying awake or awakening in the morning, even if the noise does not disturb sleep at the time.

3. A person may actually be awakened by something other than noise, but then notice a noise event and thus assume that the noise event was responsible for the awakening. This increases nighttime annoyance without disturbing sleep.

4. Sleep may be disturbed by noise but a person may be unaware that noise is responsible. Thus there is sleep disturbance but no noise annoyance.

5. Some people may not have a distinct concept of nighttime annoyance, so that the so-called "nighttime noise annoyance" is no more than a respondent's general feeling toward the noise source.

6. "Nighttime" annoyance may be as strongly determined by the belief that nighttime noise must be worse, as it is by actual experiences with nighttime noise.

The findings in several surveys support the hypothesis that sleep interference and nighttime noise annoyance are related to noise level in different ways. In these surveys the slope relating noise level to the amount of total reported sleep interruption is less steep than that relating noise level to the amount of noise-source attributed sleep interruption. A set of social surveys around Heathrow, Gatwick and Manchester airports in England relates sleep disturbances on a single night to the noise level on that night (Brooker and Nurse, 1983). The slope relating noise level to interference attributed to aircraft is steeper than the slope relating noise level to interference attributed to "all" sources. This difference is found for awakening on a single night (fig. 4, fig. 5), awakening over the last three months (fig. 8, fig. 9), getting to sleep on a single night (fig. 10) and getting to sleep over the last three months (fig. 11). A similar finding emerged in the 1972 London road traffic survey in figure 12: the number of mentions of sleep disturbance (irrespective of reason) is only weakly, but not significantly, related to noise level, but the numbers of sleep disturbances which were attributed to traffic noise are significantly related to noise level (Langdon and Buller, 1977). If the effect of noise were simply to add to the number of other sleep disturbances then the slopes of the two types of lines should be equal. Since the slopes of the lines are not equal, serious questions are raised about the amount of additional sleep disturbance which can be attributed to noise. Similiar types of questions have been raised before in laboratory studies in which it is found that actual sleep disturbance and respondents' reports of sleep disturbance are weakly related (Wilkinson and Campbell, 1984). The empirical data reviewed here thus suggest that the distinctions between nighttime annoyance and sleep disturbance are important.

Questions about the Nighttime Model

The conventional adjusted energy model and all of the analyses up to this point are based on the assumption that nighttime noise can be represented by the same noise metric as daytime noise: any differences between the periods are assumed to be adequately represented by a simple weight. These assumptions are open to question. Reactions during the night could be fundamentally different from those during the day because the predominant activities are fundamentally different: people sleep during much of the night, but people attempt to communicate or concentrate during the day or the evening. (Evening and daytime processes are still assumed to be similiar). Given these fundamental differences, it is important to determine whether the same type of reaction model applies for daytime and nighttime noise.

While it is possible to question all aspects of day and night noise models (frequency weighting, tone corrections, duration effects), the present discussion considers six issues. Each of these issues is presented in the form of a question about an assumption in the conventional energy model. The three questions concern the slope of the nighttime noise response curve, the relative importance of noise level and number of events in the day and night periods, and the possible presence of nighttime noise level response thresholds. A small amount of attention will also be focused on three secondary questions about the time-of-day model: the definition of the boundaries for the nighttime noise model, the effect of annoyance in other periods on nighttime annoyance, and the effect of moderating variables.

The intent of the following discussion is to identify issues which require further attention. No attempt is made to systematically compare the numerical estimates from the different studies.

Q.1 Does nighttime annoyance increase as rapidly with noise level as does daytime annoyance? A critical assumption in the energy model is that the slopes of the noise-level/annoyance regression lines in each period are equal. Four studies which have compared the correlations of day and night reactions with appropriate noise and annoyance measures have reported that the correlations and thus probably the regression slopes of the noise/annoyance relationships are roughly equal in the different periods: 1971 Swiss three city survey (Graf, et.al, 1973; Tables 4.38, 4.39, 4.40), Western Ontario traffic survey, 1978 Zurich time-of-day survey, and the 1969 USA three airport survey.

There are, however, a number of additional surveys which have directly examined the slope itself and reported that the slope relating noise levels and annoyance is not as steep for nighttime as for daytime periods. The 1972 Heathrow survey provides evidence of this pattern in figure 6 in which the percentage of people who are not disturbed during the nighttime period changes more slowly with noise level than does the percentage during other periods. The French road traffic survey in 1979 (in figures 7a and 7b) found a less steep slope between nighttime annoyance and nighttime noise level than between daytime annoyance and daytime noise level. It must be noted that the nighttime noise measurement included only the five hours from 24:00 to 05:00 (Lambert, Simmonet, and Vallet, 1984). Lamure reports that the correlations were lower (thus probably also the regression slopes) for nighttime than for daytime relationships in three of the four studies which he reviewed (Lamure, 1981; Table 2).

The existing surveys do not consistently support the assumption (implied in the adjusted energy model) that the slope relating annoyance to noise level will be the same in all periods. The same issue is addressed with respect to the effects of numbers of night-

time noise events by the next question.

Q.2 How do numbers of nighttime noise events affect response? Though sleep disturbance studies consider the effects of number of noise events on sleep interruption, the issue for the energy model is whether the relative importance of noise level and numbers of events is the same for the nighttime and daytime periods.

Though the differences between daytime and nighttime models have not been rigorously tested, a number of surveys have reported findings which are consistent with weaker effects of number of events during the nighttime than the daytime. A before-after study at Los Angeles International Airport found that even though there was an almost complete elimination of nighttime flights, the nighttime annoyance did not change (Fidell and Jones, 1975). This lack of reaction to a change is especially important because more recent studies using the same methodology have found that similiar changes in daytime noise environments do lead to changes in reactions (Fidell et al., 1981). In the 1972 Heathrow survey (table III) it was found that people's perceptions of numbers of flights are sensitive to the numbers of daytime flights but totally insensitive to the numbers of nighttime flights. (It is not clear whether the same relationship would hold for reports of annoyance during the period). The 1975 British railway survey could find no relationship between the number of nighttime train passbys and the amount of nighttime annoyance even though overall annoyance is related to numbers of passbys (Fields and Walker, 1982; p. 196). The 1977 Zurich road traffic survey found no evidence for a change in nighttime response as the number of vehicles increased from 100 to 600 an hour, but did find a change in daytime response when numbers of vehicles increased from 100 to 600 an hour (Wanner et. al., 1977; Fig. 4).

A possible explanation for this phenomenon might be inferred from the findings in the 1978 Zurich time-of-day survey. It was found that it was in the quieter streets where the tendency was strongest to rate nighttime traffic as worse than daytime traffic. In addition the night sounds reported to be most annoying were the distinct, infrequent sounds such as car door closings and mopeds. On this basis it was concluded that people might be more likely to be awakened by those individual, clearly discernable but infrequent peak levels in the noise environments (Nemecek, et. al., 1981; p. 224). If this is the case then the numbers of ordinarily occuring noise events might have little effect on annoyance. The 1976 Heathrow survey (Second Heathrow Survey) found that the average number of nighttime noise events have no effect on nighttime annoyance, but that the numbers of night noise events under the noisiest operation conditions are strongly related to annoyance (Second..., 1971, p. 180).

None of the research here provides a definitive answer concerning the effect of the numbers of events on nighttime disturbance.

The simple assumption that number has the same effect during the day and night requires more testing. The studies also raise questions about the effect of ambient noise levels (or the detectability of sounds) and of familiarity with noise sources (see Q.6 below).

Q.3 Is there a sharp noise level threshold for nighttime response? Laboratory and in-home physiological studies often characterize reactions to individual noise events during the sleeping period in terms of noise level thresholds at which sleep disturbance begins. The data from social surveys are not exactly comparable because no social surveys have related particular reported sleep disturbances to particular single noise events. Instead the social surveys relate sleep disturbance to a description of the entire nighttime noise environment. The question to be considered here is whether there are sharp discontinuities or thresholds in the nighttime noise-annoyance relationship.

The 1972 London road traffic survey shows such a discontinuity for noise-attributed sleep difficulty in relation to nighttime L_{10} in figure 12, but does not provide comparable information about daytime activity interference. In the other studies where a long-term nighttime noise response is related to a long-term average noise level, there is either a basically continuous relationship or the relationship is no more curvilinear at night than during the day. In the 1978 Zurich time-of-day study (figure 13) a threshold is no more evident for nighttime than daytime. A distinct threshold is also not apparent for that survey in figure 14 where six indicators of nighttime disturbance are related to noise level. In the 1972 Heathrow Survey annoyance (measured as the percentage not bothered) in all three time periods appears to have a roughly linear relationship with noise level (NNI) in figure 6 (Ollerhead, 1978, p. 76). In figures 7a and 7b from the 1979 French road traffic survey there, in fact, appears to be less of a threshold, if any, for nighttime than for daytime annoyance, at least with noise levels measured in LEQ (Lambert et. al., 1984). The 1965 French four airport survey does not provide evidence for a threshold for either falling asleep (fig. 15) or awakening (fig. 16).

There is not support for a threshold from the Heathrow, Gatwick, Manchester nighttime survey for awakening (fig. 4, fig. 5, fig. 8, fig. 9), getting to sleep (fig. 10, fig. 11), or reports of keeping windows closed at night (fig. 17, fig. 18). The first report (based on the Heathrow and Gatwick data) concluded that there was support for a threshold at 60 to 70 LEQ on the basis of figure 19 (Airport..., 1980a; p. 21). However the weak pattern could not be reproduced in the Manchester survey in figure 19 and was not mentioned in the later report (Brooker and Nurse, 1983).

In general the social surveys do not support the concept of a sharper threshold for nighttime than daytime annoyance.

Q.4 Is the dose-response relationship the same for the entire nighttime period? Most existing noise indices have a single undifferentiated nighttime period. It has been observed in laboratory sleep studies, however, that people are more sensitive when they are trying to fall asleep and at the end of their sleep period than in the middle of the period. Ollerhead (1980) suggests that the same might be true for the field situation.

Some social surveys report the hours during the night when people are most disturbed, but do not control for the noise levels during those hours. Three surveys in the Zurich area found that nighttime annoyance was reported to be greater in either the early night period (22:00 to 24:00) or the early morning period (06:00 to 08:00) than during the central night period (24:00 to 06:00). These findings do not show whether people are more sensitive to noise during these periods, since, as the authors point out, the noise levels may also be higher in the early morning and early night periods. (Nemeck, et. al., 1981; p. 228). Thus, these studies leave unanswered the question as to whether the dose-response relationship is different at different periods within the night. Other analyses found a higher correlation of overall nighttime annoyance with the early night period noise level than with other night period noise levels. (1978 Zurich night survey). This finding thus suggested that the falling asleep period was the most critical one for nighttime annoyance (Wehrli et. al., 1978; p. 143).

Two studies which have made at least some attempt to control for differences in exposure levels at different times of night have not found an effect. Francois found that the early morning disturbance (06:00 to 08:00) around Orly and Charles de Gaulle airports is roughly what would be expected from the relationship between nighttime annoyance and nighttime noise levels (1977; p. 10). The 1972 London road traffic survey found that reported difficulty in getting to sleep due to road traffic noise is no more highly correlated with the 22:00 to 01:00 noise levels (the time when most people go to sleep) than with 01:00 to 05:00 or 22:00 to 06:00) noise levels (Langdon and Buller, 1977; p. 17). This may indicate that early night periods are not critical or, more likely, it indicates that the noise levels are so highly correlated that even quite a strong effect could not be detected.

While the possibility of a different average noise dose/response relationship at different hours of night can not be dismissed at this point, the existing evidence does not support it. Reasons for the lack of a strong pattern are easy to suggest. The laboratory finding of a lower awakening threshold at early and late sleep periods is only a very general pattern with a great deal of indi-individual variation. This wide variation must be added to the variation in the times at which people go to bed. Langdon and Buller, for example, suggest that about two hours elapse from the

time that 10% of the population is normally in bed until the time that 90% is in bed (1977, p. 16). The result is that at the time of any particular noise event there may be too much variation in the individuals' sleep stages and awakening sensitivity to create strong differences in the average of the awakening sensitivities.

Q.5 Does annoyance (or noise level) in other periods affect responses in the night period? It is known that daytime and nighttime noise levels are often highly correlated. There is thus an acoustical basis for expecting day and night annoyance levels to be highly correlated. The question here is whether the judgements of nighttime noise are made independently of daytime noise levels. This question is not often addressed since most studies of period annoyance measures do not report the association between annoyance in one period and the noise level in some other period.

The findings from several surveys which do report this relationship raise important questions about the independence of the judgements. The 1965 French four airport survey found that nighttime disturbances (interference with going to sleep, waking up) are more closely related to 24-hour noise levels than to nighttime noise levels (La Gene..., 1968; p. 62). The French railway survey also found a smaller correlation between nighttime annoyance and numbers of trains at night, than was found between nighttime annoyance and numbers of trains for the 24-hour period (Aubree, 1975; p. 31: Aubree, 1973).

Some of the previously mentioned findings are also consistent with a lack of independence between nighttime annoyance and daytime noise levels. This is one possible explanation for the lack of effect of the reduction in nighttime flights at Los Angeles International Airport (Fidell and Jones, 1975). It is consistent with some of the weak relationships between nighttime annoyance under "Q.1" in this section. Of course, the lack of independence could also operate in the opposite direction: daytime annoyance could conceivably be affected by nighttime experiences. The 1967 Heathrow survey found a closer correlation between the general, basically daytime oriented, activity index and nighttime noise than between a pure nighttime activity disturbance index and nighttime noise (Second..., 1971; p. 48).

It is not possible to draw conclusions about the independence of the various time-period judgements at this time. The existing research does raise enough questions to suggest that it is important that time-of-day studies control for noise levels at other times of day.

Q.6 What variables mediate the effect of nighttime noise on nighttime reactions? Many of the variables which affect daytime annoyance probably also affect nighttime reactions. The question, however, is whether there are variables which are only important,

or much more important, for nighttime reactions. Variables which have been proposed in the literature include the age and sex of the respondent, the location of the sleeping room in a house, the ambient noise level and familiarity with the noise. It is again important to remember the distinction between nighttime annoyance and sleep disturbance.

The usual observation that the sleep of women and older people is more likely to be discontinuous has also been observed in noise surveys (Langdon and Buller: 1977; p. 21; Second..., 1971: p. 44). There is also some weaker evidence from the field surveys that women and older people may be more likely to have their sleep disturbed by noise (as opposed to other factors). The correlation between noise level and annoyance was found to be stronger for the older (over 50) age groups in the 1979 French Road Traffic survey (Lambert, et. al., 1984, p. 165) and the French railway survey (Aubree, 1975; p. 32). Only quite weak tendencies for nighttime annoyance to increase with age were found in studies of road traffic in Zurich and aircraft noise around Orly and Charles de Gualle (Wehrli et. al., 1978; p. 145; Francois, 1977; p. 18). There is thus some mixed evidence that age and sex are related to nighttime annoyance. This contrasts with lack of an effect of age or sex on daytime or 24-hour annoyance measures.

Several studies provide evidence that nighttime reactions are affected by window closing patterns and the location of the bedroom in the house. The 1978 Zurich nighttime noise survey explored the effect of the position of the sleeping room. It was found that after controlling for the noise level at only the front facade of the building, the nighttime annoyance was higher for people sleeping in rooms on the noisier front of the house than on the quieter back of the house. This annoyance difference did not translate into comparable differences in the sleep disturbance which was reported to be due to traffic noise, however, because the people on the noisier sides reduced the noise levels in their bedrooms by closing their windows (Wehrli et. al., 1978; p. 145). The 1972 London Road Traffic survey also found that whether or not people slept in a room away from the road or closed their windows at night during the summer affected the levels of reported sleep disturbance (Langdon and Buller, 1977; p. 27).

Nighttime disturbances are often thought to be a function of the residents' familiarity with the sounds and with the relationship between ambient noise levels and levels of distinct noise events. Horonjeff et al. (1982) found that the "detectability" of sounds used in an in-home sleep experiment is a good predictor of individual sleep disturbance. The evidence from social surveys is mainly suggestive on this point. Nighttime annoyance was found to be a relatively more serious annoyance problem at equal NEF levels around a general aviation airport, with a few night flights in a low ambient noise situation, than it was in an urban, large

airport situation (Taylor, Hall and Birnie, 1981; p. 243). The importance of ambient noise or perhaps detectability is also suggested by the previously noted finding that the distinct traffic noises of car doors and mopeds are especially disturbing at night (Wehrli et al., 1978; p. 144). The 1978 Zurich road traffic survey found that annoyance was not any greater at the same noise level in village or suburban areas than it was in the city center. However, it is not clear if this was examined separately for nighttime noise (Nemecek et al., 1981; p. 230). Though the effect of ambient noise has not been adequately explored, it appears to be a potentially important explanation for variations in reports of nighttime disturbances.

SUMMARY OF FINDINGS AND RECOMMENDATIONS

The well-known inconsistencies in the estimates of time-of-day weightings from social surveys have been found to be parallelled by widespread, unrecognized inconsistencies in time-of-day annoyance models, study methods and analysis techniques. Many of these inconsistencies could be removed by fairly simple changes in analysis techniques. Thus, reasonably small changes in methodology may yield more consistency than has thus far been apparent. Although differences in types of annoyance models and time-of-day weights were controlled in the analyses presented in this report, the remaining differences in methodologies mean that final conclusions can not be drawn about either the degree of consistency in time-of-day models in different populations or the suitability of present time-of-day models.

The examination of past studies presented in this report has led to classifications of time-of-day models, weightings and study methods. Examination of the experiences with different methods also provides some suggested guidelines for continuing work on the development of time-of-day weightings.

Summary: Types of Models, Weights, and Methods

Four time-of-day models have been implied by the analyses in past studies. The first one is incorporated in accepted noise indices.

1. The <u>adjusted energy model</u> makes the conventional assumption found in LDN and NEF that noise levels in each period should be adjusted before being added logarithmically.

2. The <u>independent effect model</u> does not logarithmically sum the noise levels from different periods, it assumes that annoyance is directly proportional to the noise level, expressed in decibels, for each period irregardless of the noise levels in other periods.

3. The decibel difference model implies that annoyance is the result of the independent effect of the unweighted, logarithmically summed 24-hour noise level and the difference between the decibel values of the noise levels in two periods.

4. The ratio of numbers model implies that annoyance is directly proportional to the number of events (not the logarithmic transformation of number) and that the effects of numbers and levels of noise events are multiplicative not additive.

The weighting which is applied to noise at night can be expressed in three different forms. The preferred expression in this paper is the weight (w_n) which is the multiplier for either the number of noise events or the relative pressure squared value for the noise events (e.g. w_n=16.7 in NEF). This weight can be transformed logarithmically into a decibel weight ($D_{L_n}=10 \bullet \log_{10} w_n$). This decibel weight can then be added to the noise level (measured in dB) of each noise event (e.g. D_{L_n}=12.2 in NEF). If this simple decibel weight is added to an indicator of the relative length of the specified daytime and nighttime periods, the result is a combined "decibel-time" weight which is added to the average nighttime noise level (LEQ or average peak noise level) in an equation which does not otherwise include a term for the relative length of the periods (e.g. adjustment of 10 in NEF and WECPNL).

Four methods have been used to evaluate the weights in the adjusted energy model:

1. The total annoyance regression method derives weights from ratios of regression coefficients which are calculated from a regression of a 24-hour annoyance measure on the set of period noise levels.

2. The noise index correlation method compares the correlations of alternative noise indices with a 24-hour annoyance measure.

3. The period response comparison method derives weights from ratios of regression coefficients which are calculated from separate regressions of each period annoyance measure on that period's noise level.

4. The respondent ranking method derives the weights from the relation between differences in noise levels at different times of day and the percentages of people who rank one period as being worse than another.

Recommendations: Methods for Estimating Time-of-Day Weights

Three methods have thus been identified which can estimate the time-of-day weighting. (The fourth method for evaluating weights, the noise index correlation method, does not directly provide estimates of weights and thus is not discussed further here). Though each of the three methods provides an estimate of the same parameter and none can be totally dismissed at this point, they would appear to have different degrees of validity and different roles to play in a thorough analysis of the time-of-day weightings.

The total annoyance regression method would appear to give the most valid estimate on theoretical grounds. It requires the fewest assumptions. It directly addresses the central issue: How do combinations of noise levels at different times of day affect total annoyance? Each of the other two methods can provide additional supplementary information. The period comparison method can be used to explore the within period noise models and thus to check on the validity of assumptions in the energy model which are not easily explored with total annoyance regressions. The annoyance ranking method also has a role. Though it is weakened by several inherent assumptions, it does have one strength which complements a weakness in the total annoyance regression method: the annoyance ranking method forces the respondent to consciously focus on each of the periods and choose between them.

Recommendation: Analysis and Reporting of Time-of-Day Weights

Analyses of previous data and of new studies would yield estimates which are more valid, comparable and useful if the following practices were followed.

1. Time-of-day differences should be presented in the context of at least the adjusted energy model. This model provides a common comparison point even if better models are developed.

2. Actual "best fit" estimates of the numerical values of parameters should be calculated. The practice of only reporting LEQ and LDN comparisons presents much less information than can be drawn from a set of data.

3. The precision of numerical estimates (standard errors or 95% confidence intervals) should be reported in order to evaluate the reliability of an estimate or to compare the results from different surveys.

4. The form in which the weight in the energy model is being expressed should be explicitly specified (i.e., number weight, decibel transformation, or decibel-time transformation).

5. The annoyance index used in total annoyance regression or noise index correlation methods should only consist of items which individually require the respondent to give total 24-hour judgements. The use of activity indices which consist of investigator-determined mixes of day and night items are open to criticism.

6. Identical annoyance questions should be used for each time period if period comparison methods are to be used.

7. If respondent ranking techniques are used then the relative rankings for <u>each</u> person or noise environment (not only for the study as a whole) should be presented as a function of the number of decibels which separate daytime and nighttime noise levels for that person or noise environment.

8. Whenever possible, the assumptions underlying the energy model should be directly tested.

9. Period annoyance analyses should explicitly include noise levels from other periods in at least part of the analyses to determine whether it is possible to evaluate the independent contribution of noise during the period under consideration.

Summary: Nighttime Response Model

Several of the adjusted energy model assumptions about reactions in the nighttime period were examined. Some evidence suggests that the impact of changes in numbers of noise events may be less at night than in the day. It also appears to be important to determine whether noise levels at other times of day affect nighttime annoyance. No evidence was found for a sharper threshold for nighttime than daytime annoyance. Existing evidence is too weak to reject the assumption that the noise level/response relationship is uniform during the entire nighttime period. There is evidence that nighttime reactions are affected by acoustical characteristics of the sleeping room, by signal to noise ratios and by the age and sex of the residents. All existing social survey results in which average nighttime response is plotted by nighttime noise level are reproduced in this report. There is not enough uniformity in the measurements of nighttime disturbances to combine the results from the different surveys into a single estimate.

Recommendation: Time-of-Day Survey Designs

The type of design which is to be recommended depends very much on which of the nighttime variables is to be studied: nighttime annoyance with noise or sleep disturbance which can be attributed to noise.

Annoyance.- When the interest is in nighttime annoyance, (i.e., not only sleep disturbance) then some type of social survey design is useful. Such surveys could be more valuable if the following improvements were made:

1. Total annoyance measures should clearly specify that respondents are to consider both nighttime and daytime events in their judgements. The typical simple questions about "noise around here when you usually are at home" are open to the criticism that they are interpreted in a normal, usual daytime context.

2. Period annoyance questions should clearly specify the base for the annoyance judgement (per noise event, per hour, or per total period) which is being evaluated. Past researchers' experiences suggest that this is a critical problem.

3. Combinations of daytime and nighttime noise need to be included in the noise exposure design matrix so as to give as much independence as possible between daytime and nighttime noise levels. Such a design would make it possible to evaluate the independent contribution of noise at different periods of the day.

Sleep disturbance studies.- Conventional social surveys cannot be expected to provide much new information about sleep disturbance. The review of the nighttime noise model revealed considerable discrepancies between reports of all sleep interruptions and reports of sleep interruptions due to noise. If sleep disturbance studies are to be made in natural settings it would seem that at least the following characteristics are important:

1. The study design should link individual noise events to particular sleep interruptions.

2. Individual noise events should be measured, preferrably together with information about the ambient noise during the event.

3. Sleep interruptions should be measured in a way that does not require respondents to recall the event the following morning.

APPENDIX A
ANNOYANCE MEASURES USED IN 12 STUDIES

1. 1961 Heathrow Study

Period ranking question
Q. "Do you find the aircraft bother you most during the morning, the afternoon, the evening or the night?"

2. 1972 Heathrow Study

Period number-of-event perception
Q. "On the occasions when you have been here during the past four weeks, and when the aircraft noise has been at its worst, how many times would you say that you have actually been disturbed by aircraft noise during the daytime hours between 7:00 AM and 7:00 PM?" (A card was shown with the following alternatives on it: "None, Once or twice altogether, Once or twice a week, Once or twice a day, 3 to 5 times a day, 6 to 10 times a day, 11 to 20 times a day, 21 to 50 times a day, More than 50 times a day")

Period ranking question
Q. "When do you find the noise of an aircraft most disturbing around here: during the night when you are trying to sleep, during the evening, or during the daytime?"

3. Manchester Traffic Survey

Total annoyance rating
Q. "Could you show me on this card how satisfactory or unsatisfactory you feel the level of traffic noise to be." (The card uses the following format:

DEFINITELY								DEFINITELY
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	
SATISFACTORY								UNSATISFACTORY)

4. 1965 British Railway Survey

Summed annoyance index
This index is based on the average of a respondent's ratings on two verbal category scales and three numerical rating scales. All refer to annoyance with railway noise generally. (Fields and Walker, 1982, pg. 254)

Relative ranking question
Q.A "Do you find the train noise is more annoying at certain times of the day or is it always the same?

IF MORE ANNOYING AT CERTAIN TIMES

Q.B At what time do you find the train noise most annoying? (Morning 8-12 am, Afternoon 12-6, Evening 6-11 pm, Night 11-8, All equally, Evening and night)

5. 1969 USA Three Airport Survey

Activity interference index
This activity index is based on the sum of the annoyance expressed on nine activity items. Each item is scored from 0-4 depending on how much the person is annoyed by the particular interference. The end points are labeled "Extremely" and "Not at all." The nine items are the following: relaxing or resting inside, relaxing outside, sleeping, conversation, telephone converstaion, listening to records or tapes, listening to radio or TV, reading or concentration, and eating.

6. 1972 John F. Kennedy Airport (New York) Study

Period annoyance rating question
Q.A "During weekdays are you usually at home during most of the day from 7:00 Am to 7:00 PM?

IF YES ASK:
Q.B Using the Degree Scale, could you tell me how much the noise from the airplanes bothers or annoys you during the day?" (The question was then repeated for evening, 7 to 11 PM, and nights. The degree scale has 5 points the end points are labeled: Very much = 4, Not at all = 0)

7. US Army Impulse Noise Survey

Period annoyance question
Q.A "During the week Monday through Friday, are you usually home from around seven in the morning to six at night?

(If Yes)

Q.B Do any of the noises we've been talking about bother or annoy you during the day from around seven in the morning to six at night?

(If Yes)

Q.C What noises do that?

Artillery	Street traffic	Air-planes	Heli-copters	Children and dogs	Other

Q.D How often does the noise from (source) bother or annoy you during the day?" (Card #5). (The questions are repeated for evening and nighttime periods)

8. 1980 Australian Five Airport Survey

General annoyance scale
The noise index is based on the answers to 22 items concerning annoyance, disposition to complain, activity disturbance, and fear of aircraft crashing. The scale was dichotomized at a point which the authors felt represented "high annoyance" (Hede and Bullen, 1982, pgs. 64-68)

Period ranking question
Q. "Suppose you were able to have aircraft stopped from flying over in one of these 3-hour periods (Show Card E), which one would you most like to have free from aircraft noise?"

9. Western Ontario Traffic Survey

Total annoyance index
This index is based on a large number of both daytime and nighttime items. The selection of items was based on a factor analysis of 80 questionnaire items (Bradley and Jonah, 1977, pg. 35 and Appendix II).

Period annoyance question
Q. "Around this time of year, how annoyed are you by traffic noise during the folowing time periods in the week (Mon - Fri) when you are home? (Card C)"
(Card C has a format similiar to the following:

Not at all Annoyed			Moderately Annoyed			Very Annoyed
1	2	3	4	5	6	7

This question was repeated for six time periods. The method for combining responses into only two period scores is not described.)

10. Canada Railway Yard Survey

Total annoyance question
The respondents chose one of the following words to describe their annoyance: TREMENDOUSLY ANNOYED, GREATLY ANNOYED, CONSIDERABLY ANNOYED, MODERATELY ANNOYED, PARTIALLY ANNOYED, A LITTLE ANNOYED, NOT AT ALL ANNOYED.

11. 1978 Zurich Time-of-Day Survey and 1977 Swiss Road Traffic Survey

Period annoyance question - English translation

Q. "Let us assume that these are thermometers with which the degree of disturbance can be measured. The number 10 means that you are almost unbearably disturbed, the number 0 that you are not disturbed at all.

We would now like to find the disturbance experienced by you. Please mark on the first thermometer the disturbance experienced by you during the day, on the second the one experienced during the night. (Please simply mark the corresponding number)." (10 = extremely annoying, 0 = not at all disturbing)

[Q. Nehmen wir an, dies waren Therometer, mit denen man messen kann, wie stark man sich durch den Verkehrslarm gestort fuhlt. Die marke 10 bedeutet, dass man fast unertraglich gestort ist, die Marke 0, dass man uberhaupt nicht gestort ist.

Wir mochten nun die von Ihnen zuhause empfundene Storung erfassen. Wurden Sie bitte auf dem ersten Thermometer die von Ihnen tagsuber empfundene Storung eintragen, auf dem zweiten Thermometer diejenige Storung, die Sie in der Nacht empfinden. (Bitte einfach bei der entsprechenden Zahl ankreuzen).
(10 = stort unertraglich, 0 = stoert kein bisschen)]

APPENDIX B:
CALCULATION OF WEIGHTS IN TABLE III

Calculations are discussed in the order in which they appear in table III. The formula used to convert between types of weight parameters are given in the section "Alternative Expressions for Weights in Noise Indices".

Method 2: Noise index correlation

1975 British Railway, 1978-79 Canada Railway Yards, Western Ontario traffic and Manchester traffic.

The method of estimating the weight for LEQ/LDN comparisons is given in the CRITIQUE OF METHODS section of this paper.

1969 USA three airport survey

CNR has a decibel-time weight of $D_{L\&T_n} = 10$. For a nine hour nighttime period this gives a number weight of $w_n = \frac{15}{9} \bullet 10^{10/10} = 16.7$. Using the same three data sets as before (see CRITIQUE OF METHODS) the lowest value of a weight which would give a higher correlation for CNR than LEQ is $w_n > 5$.

1980 Australian Five airport survey

The single-hour decibel weights given in the article are simply converted to number (relative pressure squared) weights: e.g., the weight of $D_{L_e} = 6$ is equivalent to $w_e = 10^{6/10} = 4.0$.

Method 3: Period response estimation method

1972 Heathrow survey

The day and evening regression equations differ by a value of 6 dB measured in average peak noise level.

This provides a number weighting of $w_e = 10^{6/10} = 4.0$.

U.S. Army impulse noise survey

For a 15-hour day and a 9-hour night, the 9 dB difference in LEQ is equivalent to a number relative pressure squared weight of $w_n = \frac{15}{9} \bullet 10^{9/10} = 13.2$.

Western Ontario traffic survey

Given the assumption that period annoyance is affected by the length of the period, then the 9 dB(A)LEQ separation between daytime and nighttime dose-response curves for a nine hour day is equivalent to a 13.2 number/relative pressure squared weighting: $w_n = \frac{15}{9} \circ 10^{9/10} = 13.2.$

1978 Zurich time-of-day survey

The 5 dB LEQ finding of the difference between the daytime and nighttime annoyance thresholds refers to 8-hour night and 16-hour day periods. The 5 dB period weights is equal to a number (relative pressure squared) weight of $w_n = \frac{16}{8} \circ 10^{5/10} = 6.3.$

Method 4: Respondent ranking

1961 Heathrow survey

The 8-hour night period is assumed to be ranked the same as the 16-hour day period even though the peak levels were reported to be 8 PNdB lower and the number of aircraft is one-fourth as many. There are thus both a number weight of 4 and a noise level decibel weight of 8. This gives a total number/relative pressure squared weight of $w_n = 4 \circ 10^{8/10} = 25.2.$

1977 Zurich traffic survey

There was more annoyance during the 8-hour night period than during the 16 hour day period even though the daytime level is 8 dB LEQ higher. This 8 decibel decibel-time weight is equivalent to a number (relative pressure squared) weight of

$$w_n = \frac{16}{8} \circ 10^{8/10} = 12.6.$$

1980 Australian five airport survey

Respondents identified the period from which they would want to have aircraft noise excluded. If it is assumed that they took into account the present exposure during the rated periods, then the weights can be regarded as single period weights (all periods are of equal, three hour lengths). Annoyance was worse during the evening and night even though night levels were 10.6 dB less and evening levels were 7.8 dB less than daytime levels.

Thus $w_n = 10^{10.6/10} = 11.5$; $w_e = 10^{7.8/10} = 6.0.$

APPENDIX C:
EXAMPLE OF WEIGHTING IN THE RATIO OF NUMBERS MODEL

The algebra in the text shows that the the adjustments in this model are not directly comparable to the weights in the conventional energy model. An illustration based on data from the 1967 Heathrow survey shows that the divergence from the estimate of the conventional weight can be important.

Annoyance in the 1967 Heathrow survey was predicted by the following equation in which noise level (L) is the logarithmic average of the peak noise level measured in PNdB (Second, 1971: p. 174):

$$A = -9.073 + 0.1168 \bullet L + 0.3674 \bullet \log_{10}(N)$$

Nighttime weights were not studied in this survey. If a hypothetical nighttime weight of $w_n = 10$ is introduced then the nighttime equation would be:

$$A = -9.073 + 0.1168 \bullet L + 0.3674 \bullet \log_{10}(N \bullet 10)$$

If there are 6 times more daytime than nighttime events (the approximate artillery ratio in the U.S. Army study (Schomer, 1983)), a simple application of the independent adjusted number model used in the Army and JFK studies gives estimates of the time-of-day weighting in the independent adjusted number model (ADJN). The estimate of ADJN for L = 80 PNdB with 12 nighttime noise events and 72 daytime events is:

$$\text{ADJN} = \frac{\text{ratio of annoyance}}{\text{ratio of number}} = \frac{\frac{A_n}{A_d}}{\frac{N_n}{N_d}} =$$

$$\frac{\dfrac{-9.073 + 0.1168 \bullet (80) + 0.3674 \bullet \log_{10}(12 \bullet 10)}{-9.073 + 0.1168 \bullet (80) + 0.3674 \bullet \log_{10}(72)}}{\frac{12}{72}} = 6.5$$

For the Army study, which takes the logarithm of this ratio, the weight would be estimated to be $8.1 = \log_{10}(6.5)$.

For L = 100 PNdB with 12 nighttime noise events and 72 daytime events the estimate is:

$$ADJN = \frac{\dfrac{-9.073 + 0.1168 \bullet (100) + 0.3674 \bullet \log_{10}(12.10)}{-9.073 + 0.1168 \bullet (100) + 0.3674 \bullet \log_{10}(72)}}{\dfrac{12}{72}} = 6.1$$

The Army estimate is now $7.9 = \log_{10}(6.1)$.

This exercise shows that the estimate of the weight (ADJN) is different at different noise levels and thus is affected by noise level in a way which is not accounted for with a multiplicative model. The ADJN estimates are not the same as the number weight ($w_j = 10$) which is present in the equation.

One argument which states that the U.S. Army study has avoided the use of this model is based on a unique interpretation of the question used in the interview. The question first asked if the noise "bothers or annoys you" at the particular time of day. After asking about how often the noise "bothers of annoys you" the respondents were scored either zero or one depending upon whether they were bothered more often than "once every few months" (Appendix A). The author of the army report assumes that since the interview question mentions number of events, the answers will be unaffected by the noise levels of those events and the answers will follow the objective characteristics of the noise environment with respect to the form of the number relationship (direct relationship with number not $\log_{10}$ number) but not with respect to the counting of the number of events at different times of day (i.e., a time-of-day weighting will be needed). These assumptions are not shared with other researchers. In the 1972 Heathrow survey, judgements of numbers of events are related to noise level and $\log_{10}$ number (Ollerhead, 1978: p. 75). A review of the effects of noise level and numbers of events found that annoyance questions about frequency of annoyance are related to noise level as well as to number of events (Fields, 1984: p. 461).

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TABLE I: DESCRIPTION OF STUDIES USED IN COMPARISON OF WEIGHTS

Study title (references)	Number of interviews	Noise source	Definition of period e=evening n=night	Method to estimate noise levels
1961 Heathrow (Wilson, 1963)	1731	Aircraft	n = 23:00-7:00	Site measurements and interpolation
1972 Heathrow (Ollerhead, 1978)	600	Aircraft	e = 19:00-23:00 n = 23:00-7:00	Predictions from model
Manchester traffic (Yeowart, et al., 1977)	846	Road traffic	n = 22:00-7:00	Measurements at sites
1975 British railway (Fields and Walker, 1982)	1453	Railway	e = 19:00-21:00 n = 21:00-7:00	Measurements
1969 USA three airport (Edmiston and Connor, 1972)	2912	Aircraft	n = 22:00-7:00	Site measurement and interpolation
1972 JFK (New York) (Borsky, 1976)	1500	Aircraft	e = 19:00-23:00 n = 23:00-7:00	Levels not measured, numbers from airport records
1978 U.S. Army impulse (Schomer, 1983)	2147	Aircraft, road traffic, helicopters	e = 19:00-22:00 n = 22:00-7:00	Levels not measured, numbers from official records
		Artillery	n = 22:00-7:00	Impulse noise prediction model
1980 Australian five airport (Bullen and Hede, 1983)	3575	Aircraft	e = 19:00-22:00 n = 22:00-7:00	Prediction model corrected with measurements
W. Ontario traffic (Bradley and Jonah, 1979)	1150	Road traffic	n = 22:00-7:00	Measurements at sites

TABLE I (Cont.)

Study title (references)	Number of interviews	Noise source	Definition of period e=evening n=night	Method to estimate noise levels
1978-79 Canada railway yard (Dixit and Reburn, 1980)	544	Railway yard	n = 22:00-7:00	Measurements
1977 Zurich traffic (Wanner et al., 1977)	1297	Road traffic	n = 22:00-6:00	Measurements
1978 Zurich time-of-day (Wehrli et al., 1978)	1607	Road traffic	n = 22:00-6:00	Measurements

TABLE II: EXAMPLES OF RELATIONSHIPS BETWEEN THREE ALTERNATIVE EXPRESSIONS FOR TIME-OF-DAY WEIGHTS*

Hours in each Period	Number/relative pressure sq. weight (w_j)		Decibel weight (D_{L_j})		Combined decibel and time adjustment ($D_{L\&T_j}$)		Noise indices with these weights
	Evening (w_e)	Nighttime (w_n)	Evening (D_{L_e})	Nighttime (D_{L_n})	Evening ($D_{L\&T_e}$)	Nighttime ($D_{L\&T}$)	
	1	1.0	0	0	0	-2.2	LEQ (24 HR)
	1	5.0	0	7.0	0	4.8	
	1	5.3	0	7.2	0	5.0	
	1	10.0	0	10.0	0	7.8	LDN
Day is 15 hours	1	13.3	0	11.2	0	9.0	
Night is 9 hours	1	15.0	0	11.8	0	9.5	
	1	16.7	0	12.2	0	10.0	CNR, NEF (number weighting)
	1	20.0	0	13.0	0	10.8	
	1	40.0	0	16.0	0	13.8	
	1.0	1.0	0	0	-6.0	-1.2	LEQ (24 HR)
	3.0	10.0	4.8	10.0	-1.2	8.8	CNEL
Day is 12 hours	5.0	5.0	7.0	7.0	1.0	5.7	
	5.0	10.0	7.0	10.0	1.0	8.8	
Evening is 3 hours	12.6	13.3	11.0	11.2	5.0	10.0	WECPNL (3 period)
Night is 9 hours	10.0	10.0	10.0	10.0	4.0	8.8	
	12.6	4.2	11.0	6.2	5.0	5.0	
	20.0	20.0	13.0	13.0	7.0	11.8	

* The equations relating these weights are given in the text.

TABLE III: FINDINGS FOR ADJUSTED ENERGY SUMMATION MODEL

Study title (Source)	Annoyance judgements: Period judged	Annoyance judgements: Type of question[a] (Appendix A)	Finding reported	Value[b] for w_e, w_n	Comments[a]
METHOD 2: Noise index correlation testing[a]					
1975 British railway (Fields and Walker, 1982: p. 200)	24 hours	Annoyance index[a]	$R_{A \cdot LEQ} \geq R_{A \cdot LDN}$	w_n <5.0	
Manchester traffic (Yeowart, Wilcox and Rossall, 1977: p. 135)	24 hours	Numeric	$R_{A \cdot LEQ} \geq R_{A \cdot LDN}$	w_n <5.0	LEQ is more highly correlated with annoyance averaged over all sites but LDN is more highly correlated with annoyance at the motorway sites.
1969 USA 3 airport (Edmiston and Connor, 1972: p. 15)	24 hours	Activity index[a]	$R_{A \cdot CNR} \geq R_{A \cdot LEQ}$	w_n >5.0	Activity index is mix of day and night activities.
1978-79 Canada 5 railway yard (Dixit and Reburn, 1980: p. 885)	24 hours	Verbal	$R_{A \cdot LDN} > R_{A \cdot LEQ}$	w_n >3.0	
W. Ontario traffic (Bradley and Jonah, 1979a: p. 595; 1979b: p. 398; 1979c: p. 412)	Both 24 hour and periods	Annoyance index[a]	$R_{A \cdot LDN} > R_{A \cdot LEQ}$	w_n >3.0	Annoyance index is mix of day and night questions.

TABLE III (cont.)

Study title (Source)	Annoyance judgements: Period judged	Annoyance judgements: Type of question (Appendix A)	Finding reported	Value[a] for w_e, w_n	Comments
1980 Australian 5 airport (Bullen and Hede, 1983: Table 2)	24 hours	Annoyance/ index[a]	Noise index with D_e=3 and D_n=1, is more highly correlated with annoyance than indices with D_e=1, D_e=6, D_n=3, D_n=0 D_n=0	$0<w_e<4$ (significantly different from w_e=16 but not from w_e=0) $0<w_n,<2$ (significantly different from w_n=4) (p =.05)	1. Annoyance index is mix of 24 hour annoyance questions and day and night activity questions. 2. Weightings examined in 3 dB steps.
Method 3: Period response comparison[b]					
1972 Heathrow (Ollerhead, 1978: p. 75)	Day, Evening Night	Number of events which bother	Day and evening lines separated by 6 dB (peak noise level). Night response not related to number of noise events.	w_e = 4 w_n < 1	Basis is strictly number of times disturbed. Amount of disturbance for each day and night event is not differentiated.
U.S. Army impulse noise (Schomer, 1983: p. 554)	Day, Night	Verbal	Equal period annoyance scores if 9 dB LEQ shift in exposure.	w_n=13.2	Separate questions about day and evening were added for "day". Weekday and weekend questions were weighted to estimate assumed total response.
W. Ontario traffic (Bradley, 1979: p. 120)	Day, Night	Numeric	Day and night reactions are separated by 9 dB LEQ.	w_n=13.2	Questions about shorter periods were combined to form day and night period responses.
1978 Zurich time-of-day (Wehrli, et al., 1978: p. 142)	Day, Night	Numeric	Threshold at which annoyance begins is about 5 dB LEQ higher for day than night. (Difference between reactions decreases to 2 dB at 70 LEQ)	w_n= app.6	The analysis was not designed to estimate a time-of-day weighting.

TABLE III (cont.)

Study title (source)	Annoyance judgements: Period judged	Annoyance judgements: Type of question (Appendix A)	Finding reported	Value for w_e, w_n	Comments
Method 4: Respondent ranking					
1961 Heathrow (Wilson, 1963: p. 215)	Day, Night	Period Ranking	Approximately equal annoyance even though night peak levels 8 dB lower and 1/4 as many aircraft	$w_n = 25$	Most "day" worst respondents said "evening" worst. The 24% "day" (ie day and evening) is only approximately equal to the 28% night.
1972 Heathrow (Ollerhead, 1978: p. 75)	"an" aircraft in day, evening	Ranking of "an" aircraft	Day worse than evenings. Day worse than night.	$w_e<1$ $w_n<1$	1. Evening result is inconsistent with findings using Method 2. 2. Author suggests that respondents did not realize question was about single aircraft.
1975 British railway (Fields and Walker, 1982: p. 195)	Day, Evening Night	Period Ranking	Day annoyance is less, but evening and night LEQ are lower.	$w_e > 1$ $w_n > 1$	No numerical estimate.
1980 Australian 5 airport (Bullen and Hede, 1983: p. 1628)	Day, Evening	Period Ranking	Annoyance is worse for evening and night 3 hr. periods even though day LEQ values for 3 hr. periods are 10.6 dB above night and 7.8 above evening LEQ values	$w_e > 6.0$ $w_n > 11.5$	1. Authors not certain if respondents interpret questions as ratings of actual exposure or of hypothetically equal exposures. 2. No attempt to specify anything but lower bounds for w_i since these results are inconsistent with Method 2 estimate.

TABLE III (cont.)

Study title (Source)	Annoyance judgements: Period judged	Annoyance judgements: Type of question (Appendix A)	Finding reported	Value for w_e, w_n	Comments
1977 Zurich traffic (Wanner et al., 1977: p. 112)	Day, Night	Period Ranking	Night annoyance is worse even though the daytime values for LEQ are 8 dB higher.	w_e >12.6	

a. The use of the term index in annoyance "index" or activity "index" means that several different annoyance questions have been combined to provide a single scale (index) of annoyance.

b. All time period annoyance judgements, unless otherwise specified, are assumed to be per period (i.e., take into account the length of the period) (see discussion under "Problems" for the period comparison method in the "CRITIQUE OF METHODS" section).

TABLE IV: FINDINGS FOR ADDITIONAL MODELS

Study title	Annoyance judgements		Finding reported	Comments
	Period	Type of question		
Model 2: Independent effects				
1975 British railway (Fields and Walker, 1982: p. 196)	24 hours	Annoyance index	$A = C + 0.089\ LEQ_d - 0.017\ LEQ_e + 0.035\ LEQ_n$, Day impacts annoyance most.	None of the coefficients in this full equation are statistically significant.
1969 USA three airport (Edmiston and Connor, 1972: p. 21)	24 hours	Activity index	$A = C - 0.89\ LEQ_d + 1.34\ LEQ_n$, Only night noise increases annoyance	Activity index is mix of day and night activities.
Model 3: Decibel difference				
W. Ontario traffic (Bradley, 1979: p. 119)	24 hours	Annoyance index	ADJD = -1.1 $A = C + LEQ_{24} -1.1 \cdot (LEQ_d - LEQ_n)$	Annoyance index is mixture of day and night questions.
Model 4: Ratio of numbers				
1972 JFK (Borsky, 1976: p. 21)	Day, evening	Numeric	ADJN = 2 Each night flight is equal to 2 day flights.	Assume that respondents interpret period question as annoyance per hour.
USA Army impulse noise (Schomer, 1983: p. 546)	Day, night	Verbal	(Weekday results) Artillery ADJN = 2.5 Airplanes ADJN = 2.8 Helicopters ADJN = 5.3 Traffic ADJN = 4-7	1. Added day and evening responses to estimate 15 hour day response. 2. Measure of annoyance is number of people bothered, not number of times bothered.

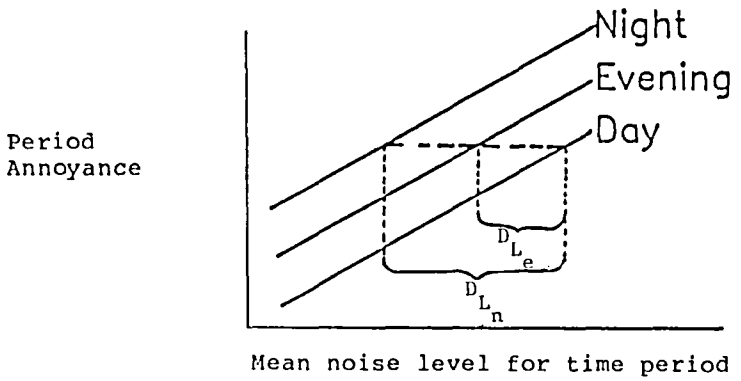

Figure 1: The derivation of decibel weights using the period period response comparison method. (Hypothetical example in which respondents rate an average hour for each period).

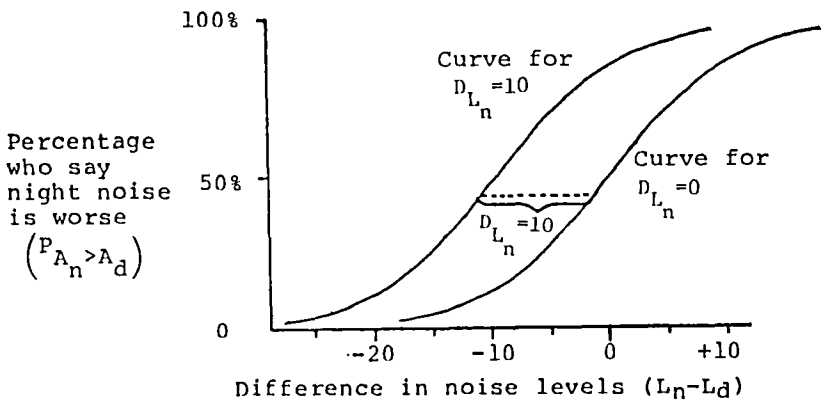

Figure 2: A continuous relationship between respondents' rankings and the differences in period noise levels. (Hypothetical example).

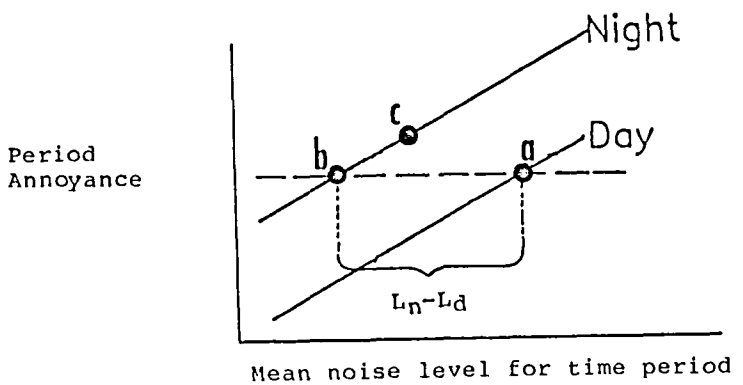

Figure 3: Period dose-response relations which are the basis for annoyance rankings. (Hypothetical example).

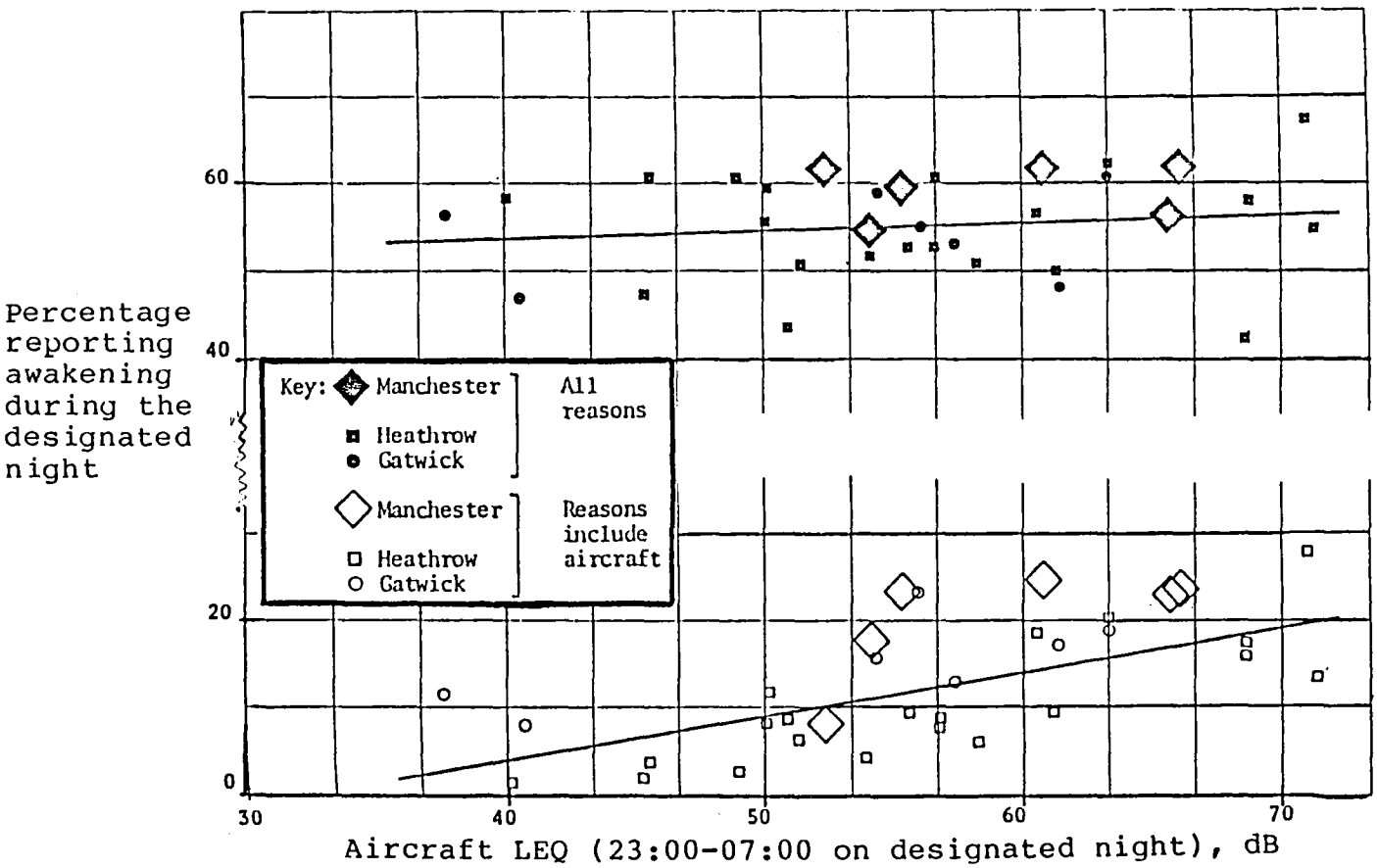

Figure 4: Awakenings for all reasons and awakenings attributed to aircraft during designated nights around three English airports.

(Source: Brooker and Nurse, 1982; Fig. 9.
Question:
Q.a Did you wake at all during <u>that night</u>? (Yes, No)

<u>IF YES</u>
Q.b What were the reasons you woke that night? (PLEASE TICK ALL WHICH APPLY) Road traffic noise/ Aircraft noise, Noise from people outside/neighbours, Other noise (inside or outside), Ill health, Worry/nerves, Need to use toilet, Other reason, no particular reason)

(Note: Regression lines exclude Manchester).

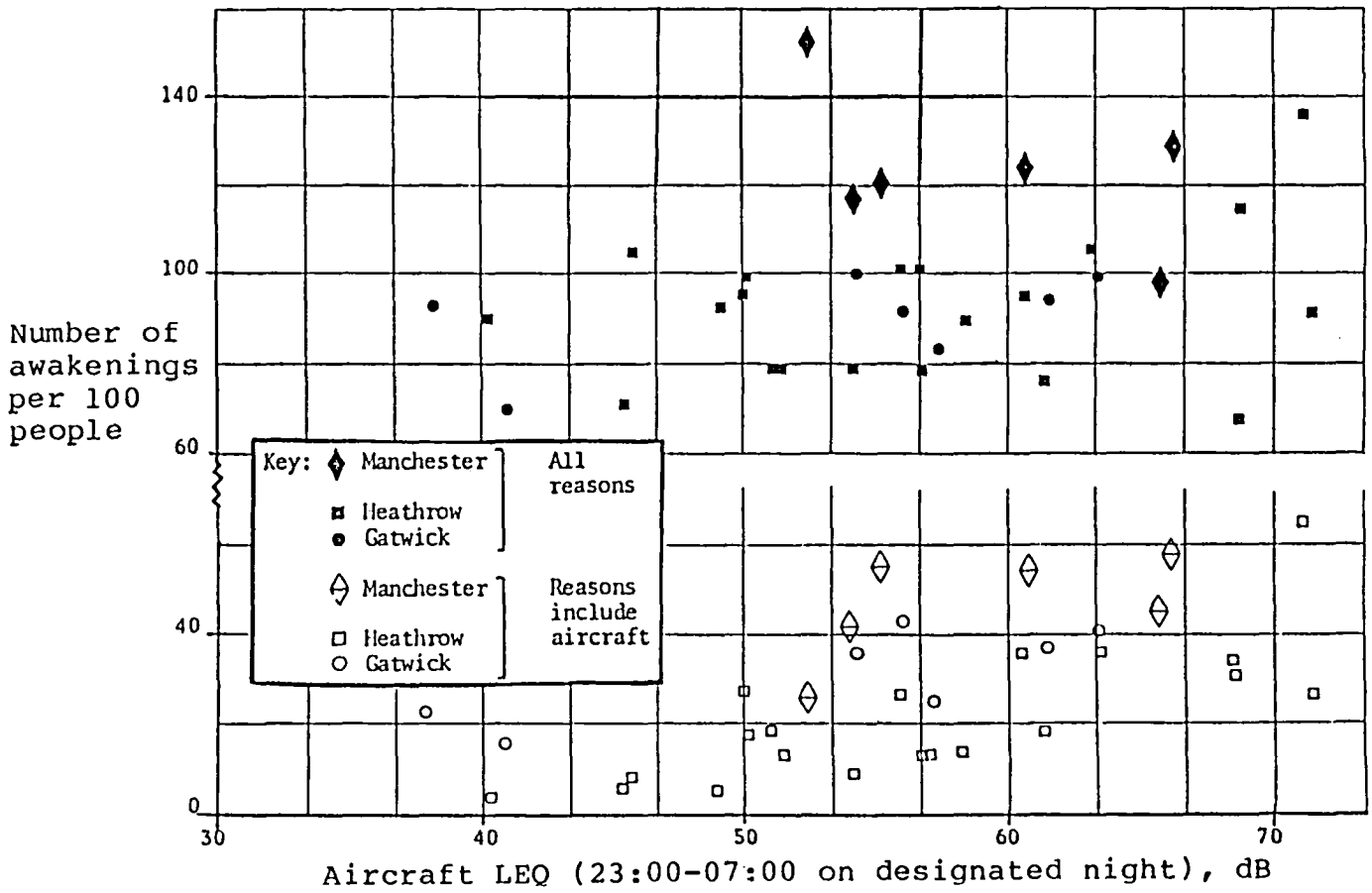

Figure 5: Numbers of awakenings for all reasons and awakenings attributed to aircraft during designated nights around three English airports

(Source: Brooker and Nurse, 1982; Fig. 10.
Question:
Q.a Did you wake at all during <u>that night</u>? (Yes, No)

<u>IF YES</u>
Q.b How many times did you wake during that night (PLEASE TICK ONE ONLY) Once, Twice, 3 or 4 times, 5 or more times)

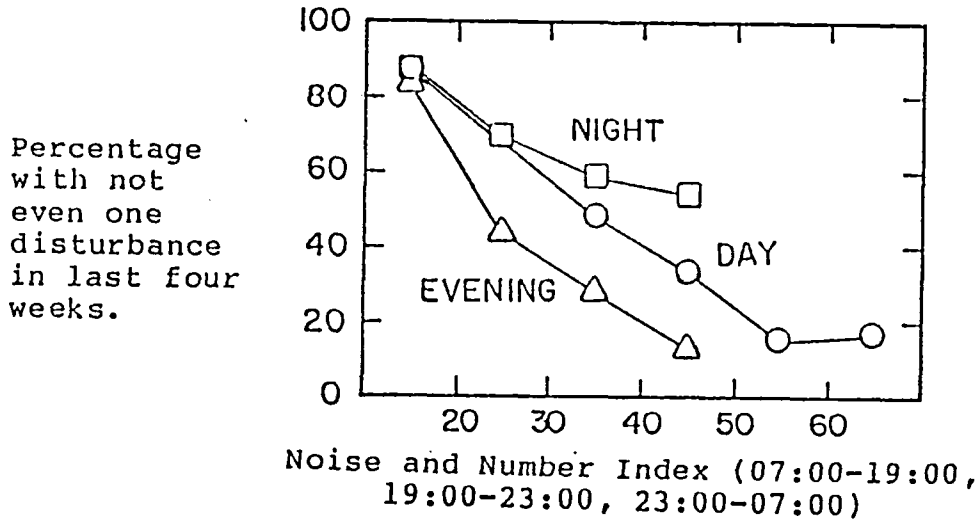

Figure 6: Reports of no disturbance by noise level in three time periods (1972 Heathrow survey).

(Source: Ollerhead, 1978; Fig. 4.
Question: This question about frequency of annoyance is reproduced in Appendix A).

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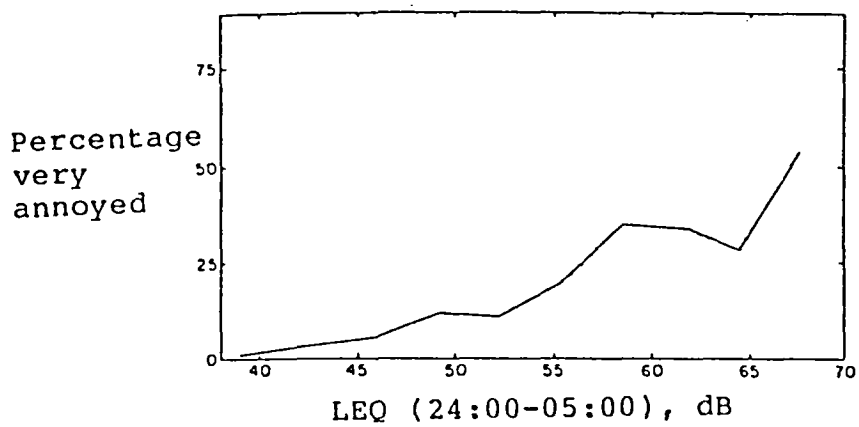


Figure 7a. Relationship between nighttime annoyance and nighttime noise (1979 French behavioral effects of road traffic noise study).

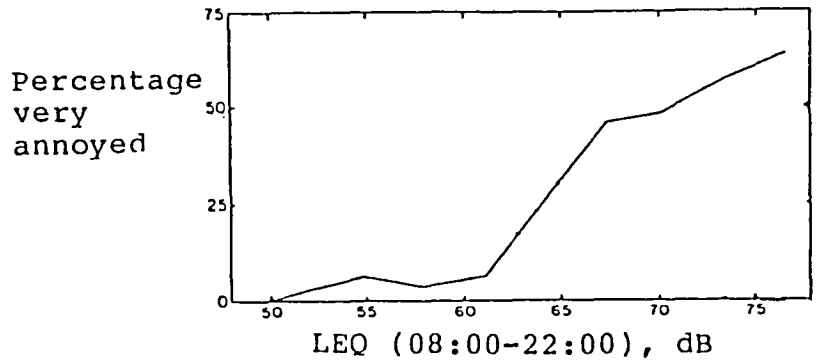


Figure 7b. Relationship between daytime annoyance and daytime noise (1979 French behavioral effects of road traffic survey).

(Source: Lambert, Simonnet and Vallet, 1984; Fig. 3 and 4.
Question:
At night (...During the daytime...) do you find the traffic noise is very annoying, fairly annoying, a little annoying or not at all annoying?

[Q.21 - Dans la journee, estimez-vous que le bruit de la circulation est: tres genant, assez genant, peu genant, pas do tout genant?

Q.92 - La nuit, trouvez-vous que le bruit de la circulation est: tres genant, assez genant, peu genant, pas genant du tout?])

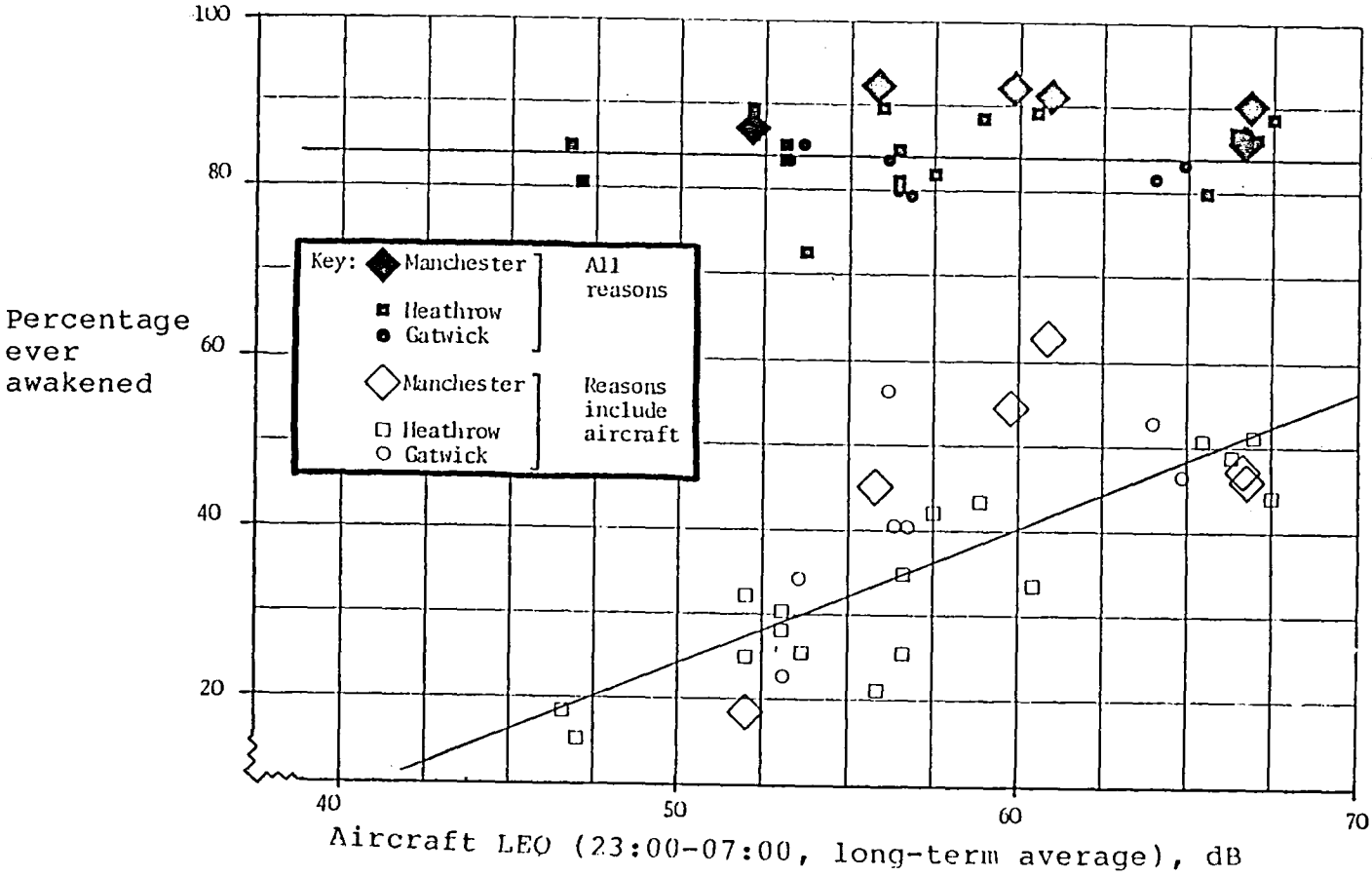


Figure 8: Awakenings for all reasons and awakenings attributed to aircraft over the last three months around three English airports

(Source: Brooker and Nurse, 1982; Fig. 11.
Q.a Still thinking about the past three months or so, have you ever been woken up once you were asleep? (Yes, No)

IF YES
Q.b What were the main things that woke you once you were sleep? (PLEASE TICK ALL WHICH APPLY) Road traffic noise, Aircraft noise, Noise from people outside/neighbours, Other noise (inside or outside), Ill health, Worry/nerves, Need to use toilet, Other reason, No particular reason)

(Note: Regression lines exclude Manchester).

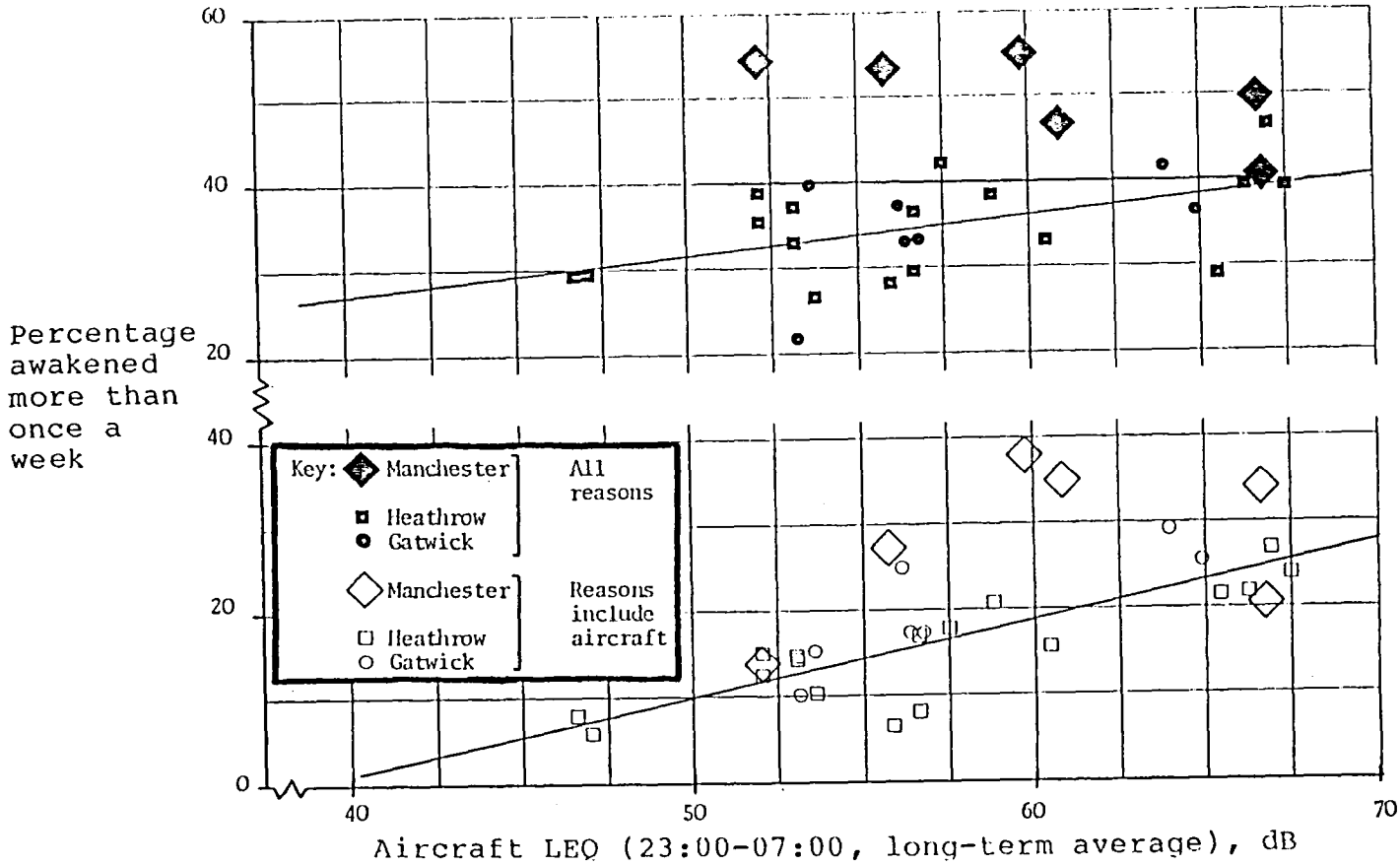


Figure 9: Percentage of people reporting awakenings for all reasons and awakenings attributed to aircraft which occur more than once a week around three English airports

(Source: Brooker and Nurse, 1982; Fig. 12.
Question:
Q.a Still thinking about the past three months or so, have you ever been woken up once you were asleep? (Yes, No)

IF YES
Q.b On about how many nights were you woken up once you were asleep? (PLEASE TICK ONE ONLY) Less than one night a month, One or two nights a month, About one night a week, 2 or 3 nights a week, Almost every night)

(Note: Regression lines exclude Manchester).

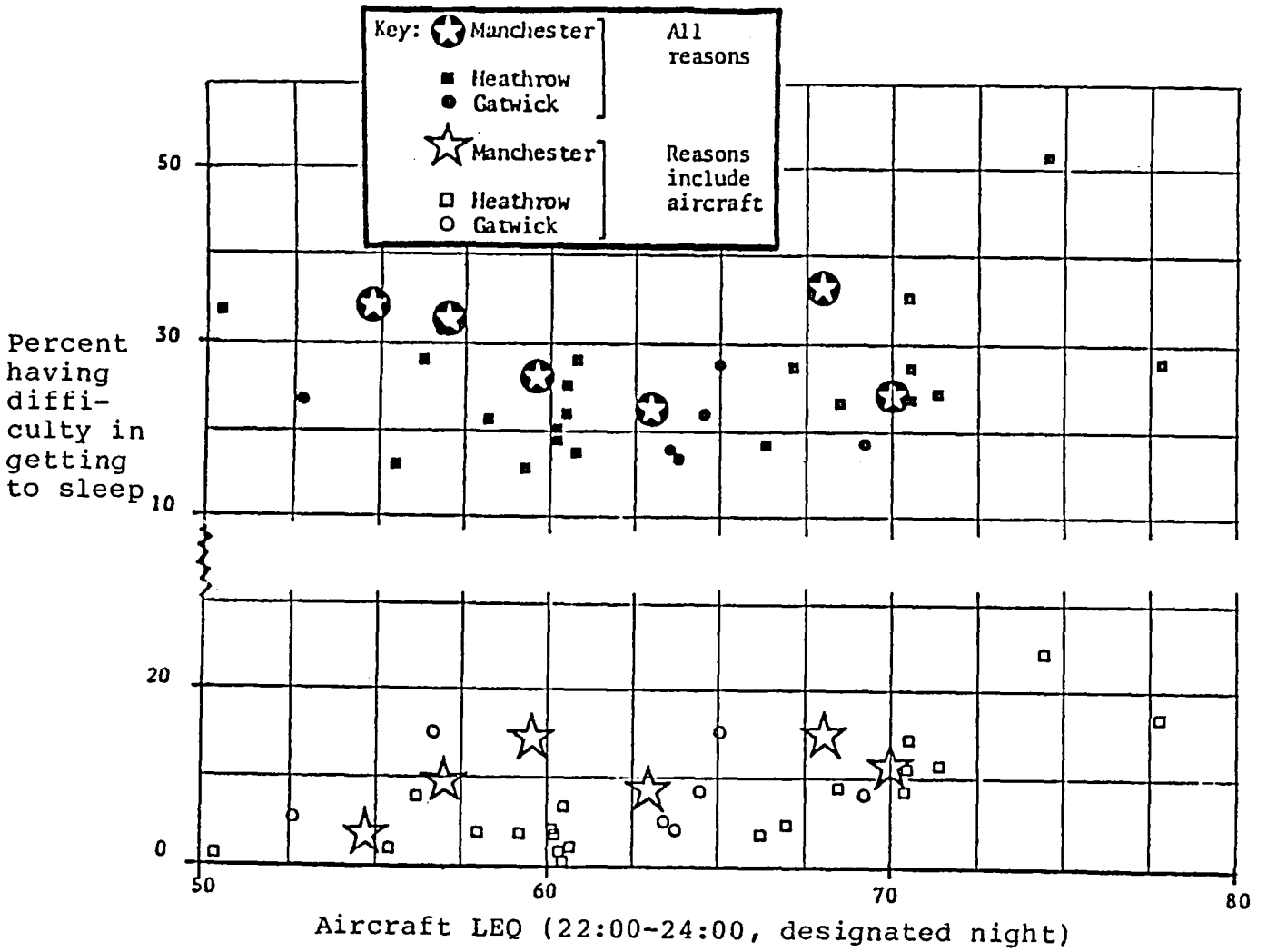


Figure 10: Difficulties in getting to sleep for all reasons and because of aircraft noise on designated nights around three English airports

(Source: Brooker and Nurse, 1982; Fig. 14
Q.a Still thinking only of that night, did you have any difficulty getting to sleep? (Yes, No)

IF YES
Q.b What was the main reason you had difficulty getting to sleep that night? (PLEASE TICK ONE ONLY). Road traffic noise, Aircraft noise, Noise from people outside/ neighbours, Other noise (inside or outside), Ill health, Worry/nerves, Other reason, no particular reason)

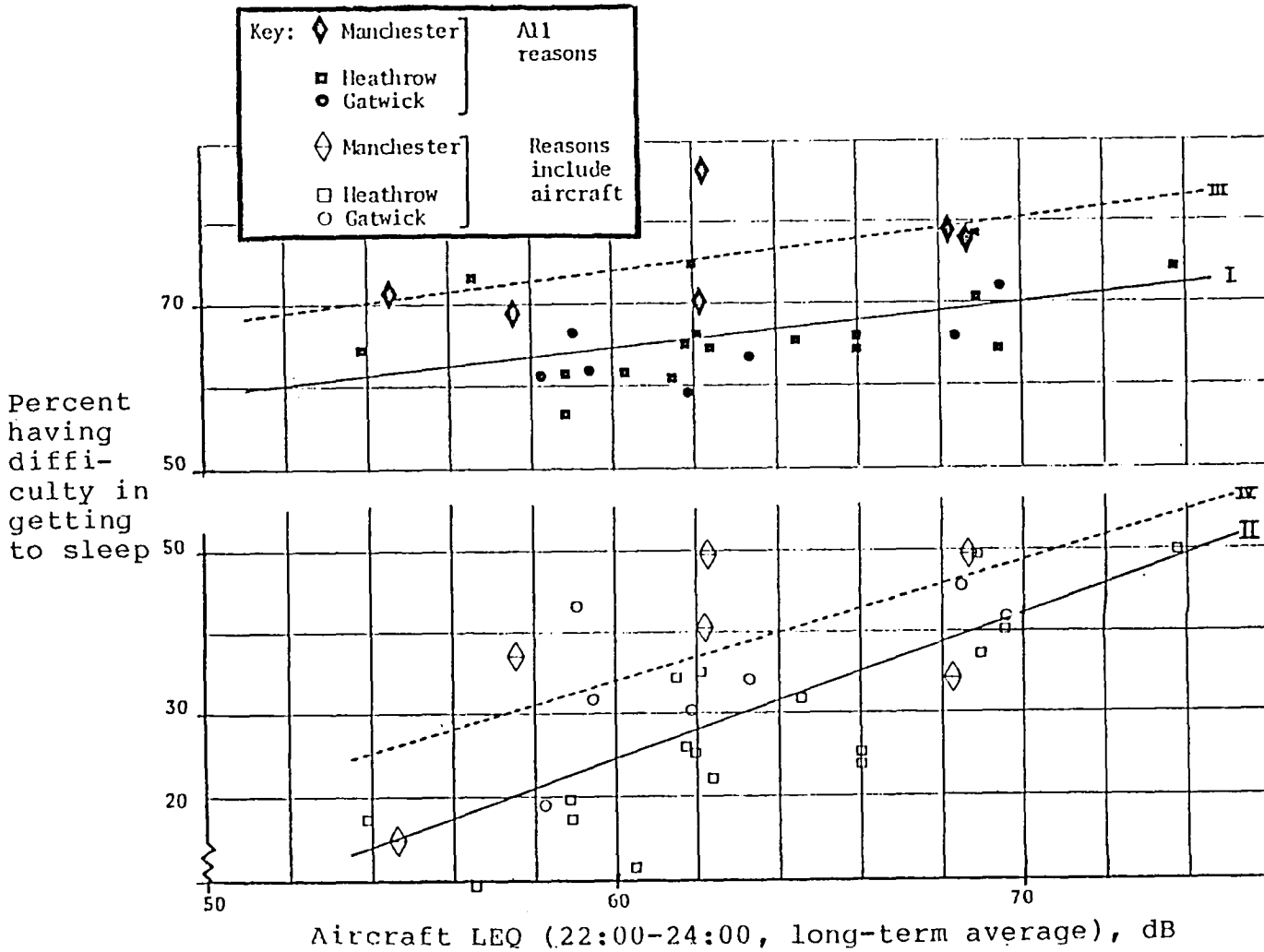


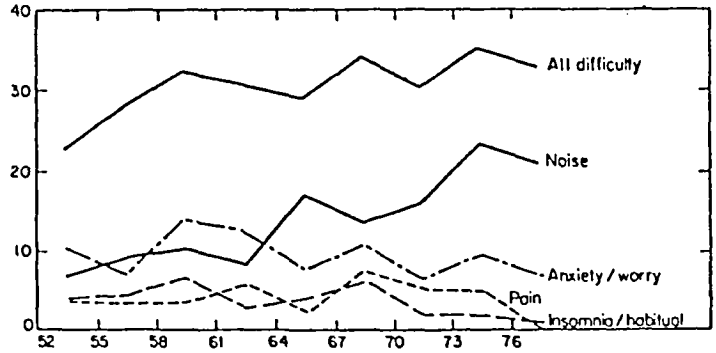
Figure 11: Reports of difficulty in getting to sleep for all reasons and because of aircraft over last 3 months around three English airports

(Source: Brooker and Nurse, 1982; Fig. 13.
Question:
Q.a Thinking back over, say, the past three months, have you ever had difficulty in getting to sleep? (Yes, No)

IF YES
Q.b What were the main things that made it difficult for you to get to sleep? (PLEASE TICK ALL WHICH APPLY) Road traffic noise, Aircraft noise, Noise from people outside/ neighbours, Other noise (inside or outside), Ill health, Worry/ nerves, Other reason, No particular reason)

(Note: Solid regression lines are for Heathrow and Gatwick. Broken lines are for Manchester).

Percentage mentioning reason for not being able to get to sleep.



L_{10} (22:00-06:00), dB

Figure 12: Reasons given for difficulty in getting to sleep (1972 London road traffic survey).

(Source: Langdon and Buller, 1977; Fig. 3.
Question:

Q.a I'd like to ask you some questions about going to sleep. Do you yourself have trouble getting to sleep? ALWAYS/VERY OFTEN, SOMETIMES, NEVER/HARDLY EVER, DON'T KNOW?

<u>ALL ANSWERING "ALWAYS", "VERY OFTEN" OR "SOMETIMES"</u>

Q.b What do you think is the main reason? NOISE FROM OUTSIDE, PAIN/PHYSICAL DISCOMFORT/ILLNESS, WORRY/TENSION/ EXHAUSTION, ALWAYS FOUND IT DIFFICULT, OTHER REASON, DON'T KNOW)

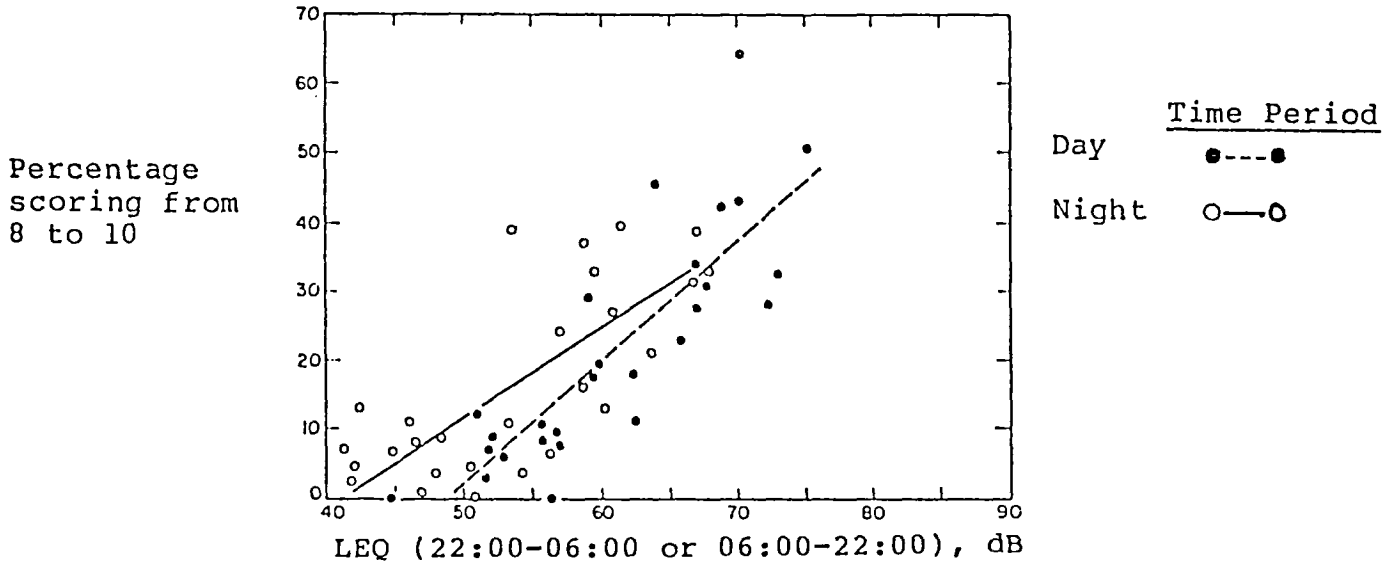


Figure 13: Percentages giving high annoyance ratings for day and for night noise by time period noise level (1978 Zurich nighttime survey). (For day % = -87.88 + 1.80 LEQ: for night, % = -49.03 + 1.23 LEQ)

(Source: Nemecek, et. al., 1981; Fig. 3.
Question: The 0 to 10 point numerical scale is reproduced in Appendix A).

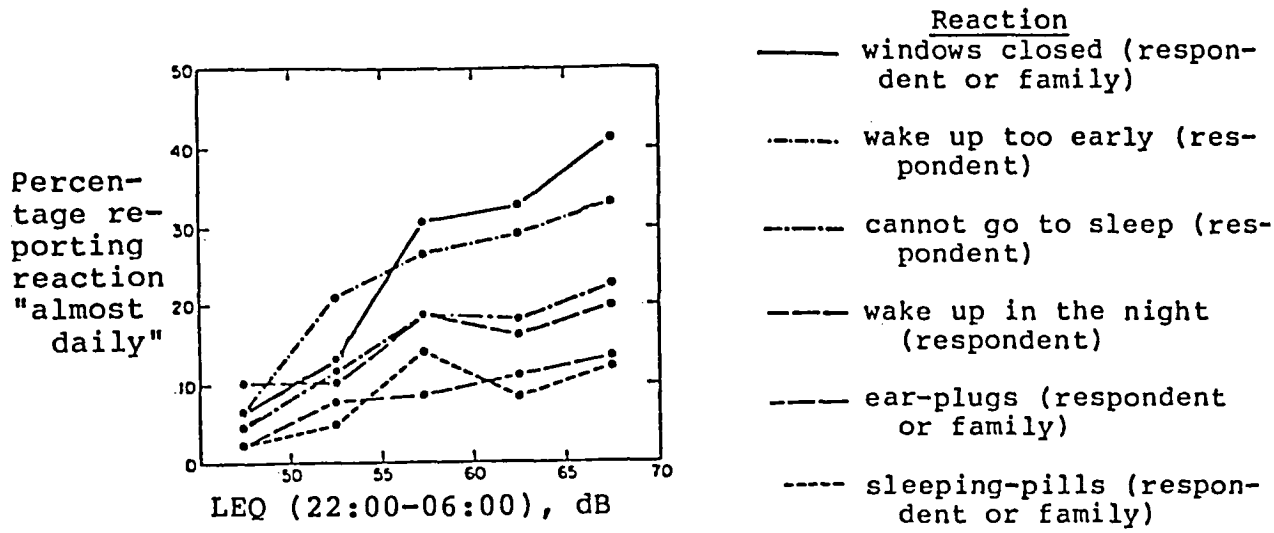


Figure 14: Indications of nighttime disturbance (1978 Zurich nighttime survey).

(Source: Nemecek, et. al., 1981; Fig. 5. These figures appeared in bar chart form as Figures 6 and 7 in an earlier publication

(Wehrli et al., 1978) in which the reaction is dichotomized between "several times a week" and "almost daily". Question: (Note that this follows in a series of questions about road traffic noise).

Q.20 Are there times when you or members of your family:
(a) put cotton, earplugs, or something similiar in during the night?
(b) take sleeping pills or sedatives
(c) keep the bedroom windows closed during the night
(Almost daily, several times a week, sometimes, never)

[Q.20 Kommt es vor, dass Sie oder Ihre Angehorigen wegen des Verkehrslarms:
(a) in der Nacht Watte, Ohropax oder ahnliche Mittel verwenden
(b) Schlaf - oder Beruhigungsmittel einnehmen
(c) in der Nacht das Schlafzimmer fenster geschlossen halten
(fast taglich, nehrmals pro Woche, hie & da, nie)]

Q.24 Does it happen that because of the traffic noise at home you:
(a) cannot fall asleep
(b) wake up suddenly during the night
(c) wake up too early in the morning
(almost every night, several times per week, sometimes, never)

[Q.24 Kommt es vor, dass Sie zuhause wegen des Verkehrslarms:
(a) nicht einschlafen konnen
(b) nachts plotzlich aufwachen
(c) morgens zu fruh erwachen
(fast jede Nacht, mehrmals pro Woche, hie & da, nie)]

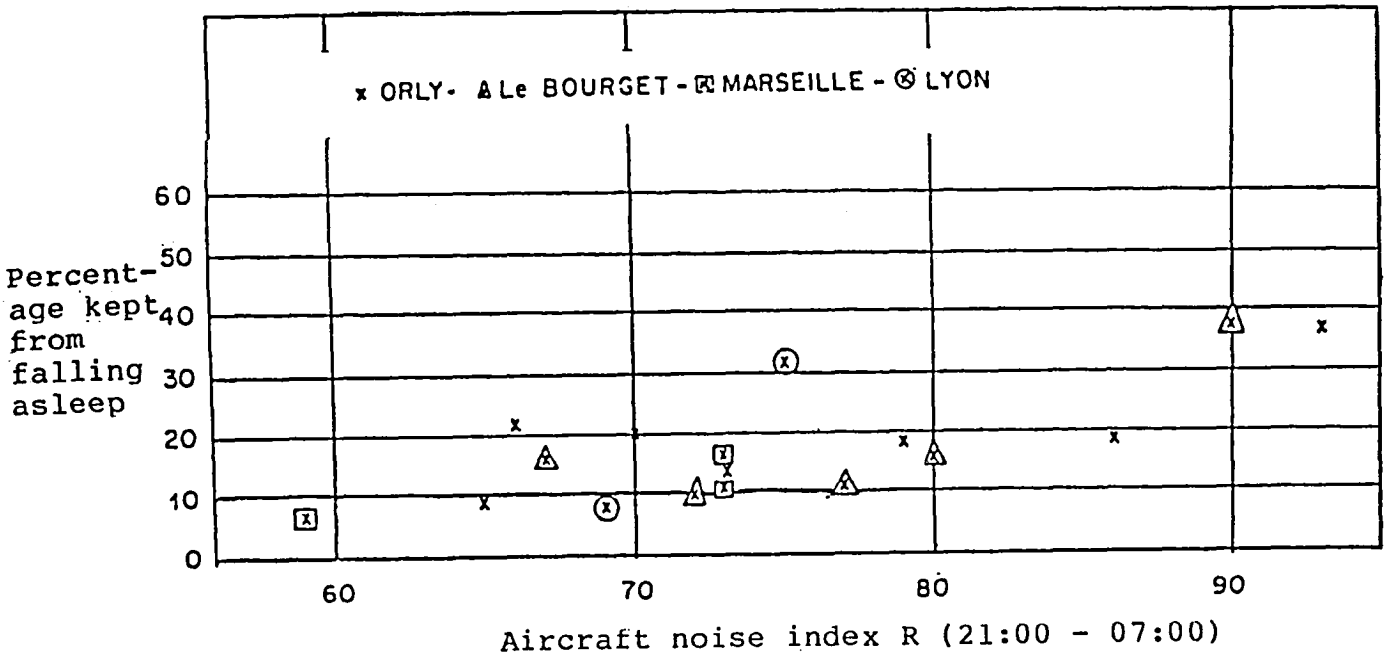


Figure 15: Effect of aircraft noise on falling asleep

(Source: La Gene Causes Par le Bruit Atour des Aeroports, 1968: p. 93

Question:

Q. Does aircraft noise do the following to you . . . stop you from falling asleep? (No, Sometimes, Quite Often)

[Q. Arrive-t-il que le bruit des avions . . . vous empeche de vous endormir? (Non, Parfois, Assez souvent)])

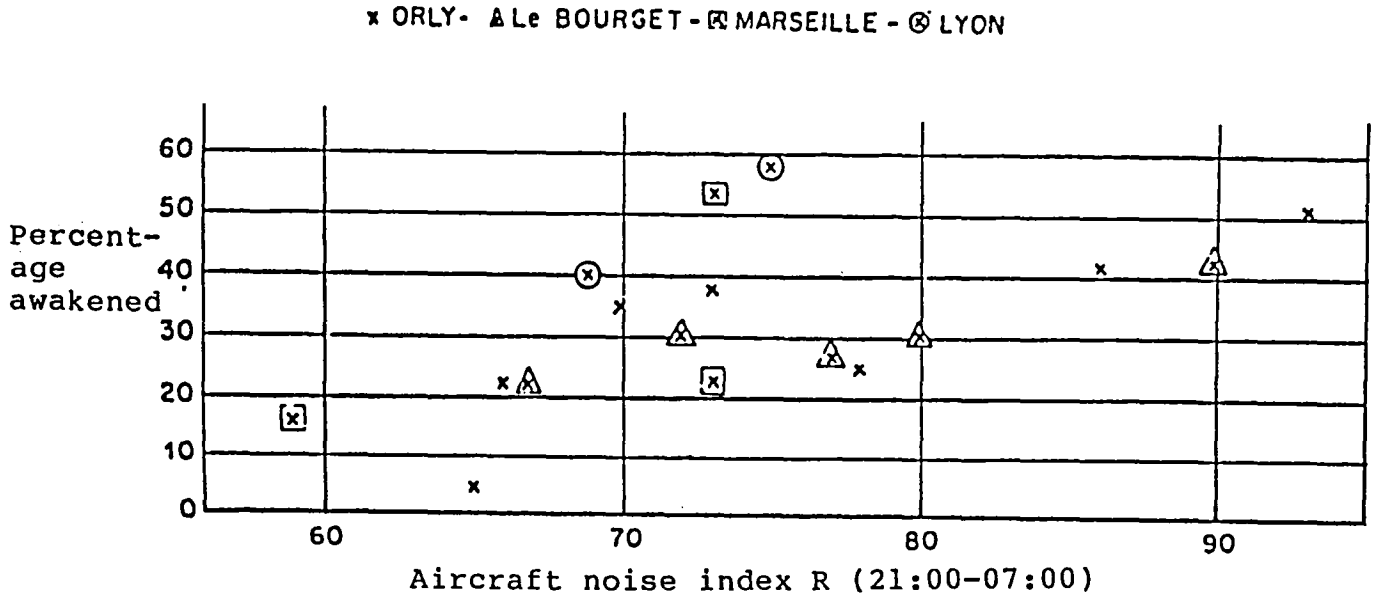


Figure 16: Effect of aircraft noise on being awakened

(Source: La Gene Causes Par le Bruit Atour des Aeroports, 1968: p. 93

Question:

Q. Does aircraft noise do the following to you . . . wake you up? (No, Sometimes, Quite Often)

[Q. Arrive-t-il que le bruit des avions . . . vous reveille? (Non, Parfois, Assez souvent)])

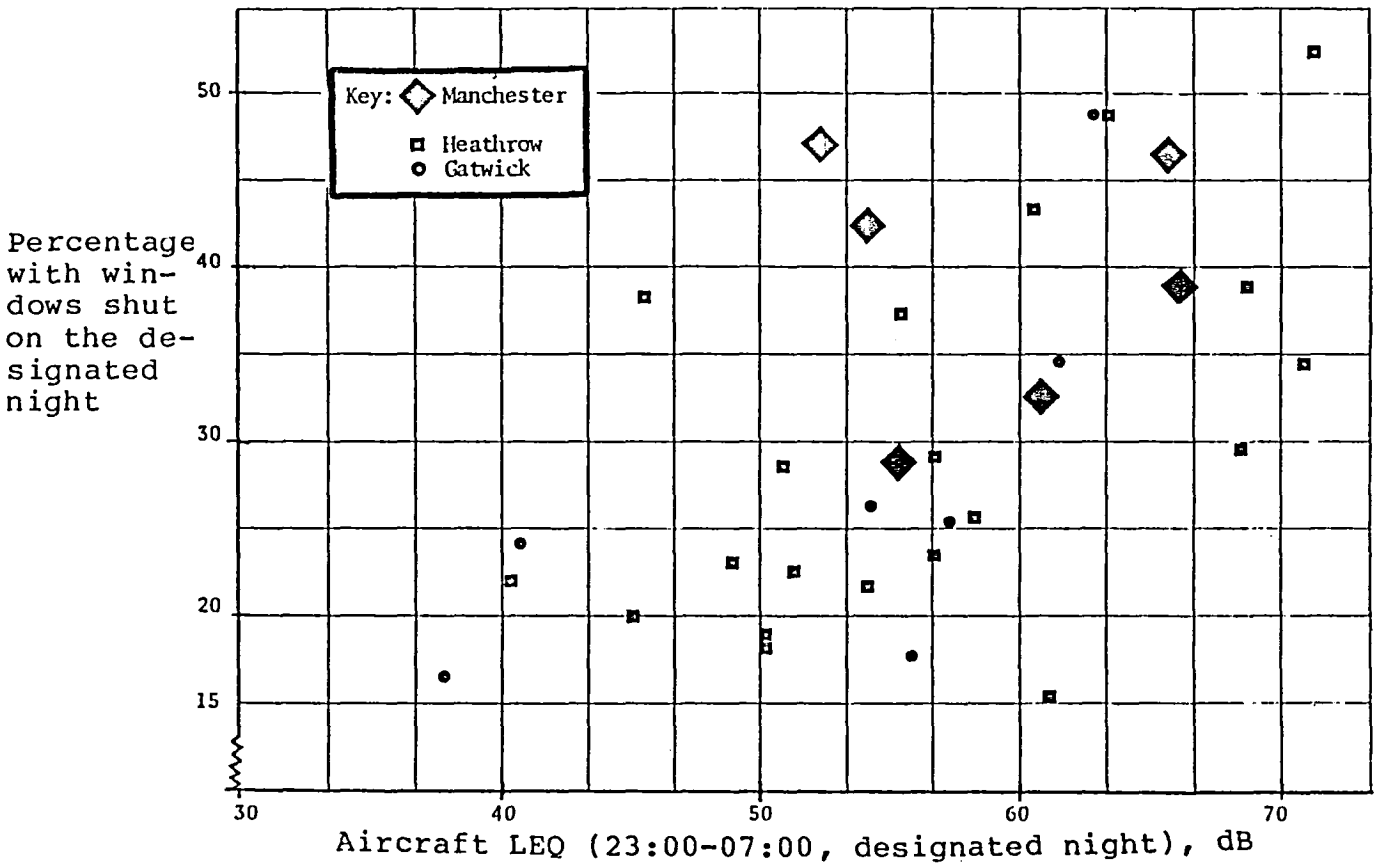


Figure 17: Noise level on reports of sleeping with windows shut on designated nights around three English airports

(Source: Brooker and Nurse, 1982; Fig. 7.
Question:
Q. Did you sleep with your bedroom windows open or shut <u>that night</u>? (PLEASE TICK ONE BOX ONLY) (All or some open, All shut)

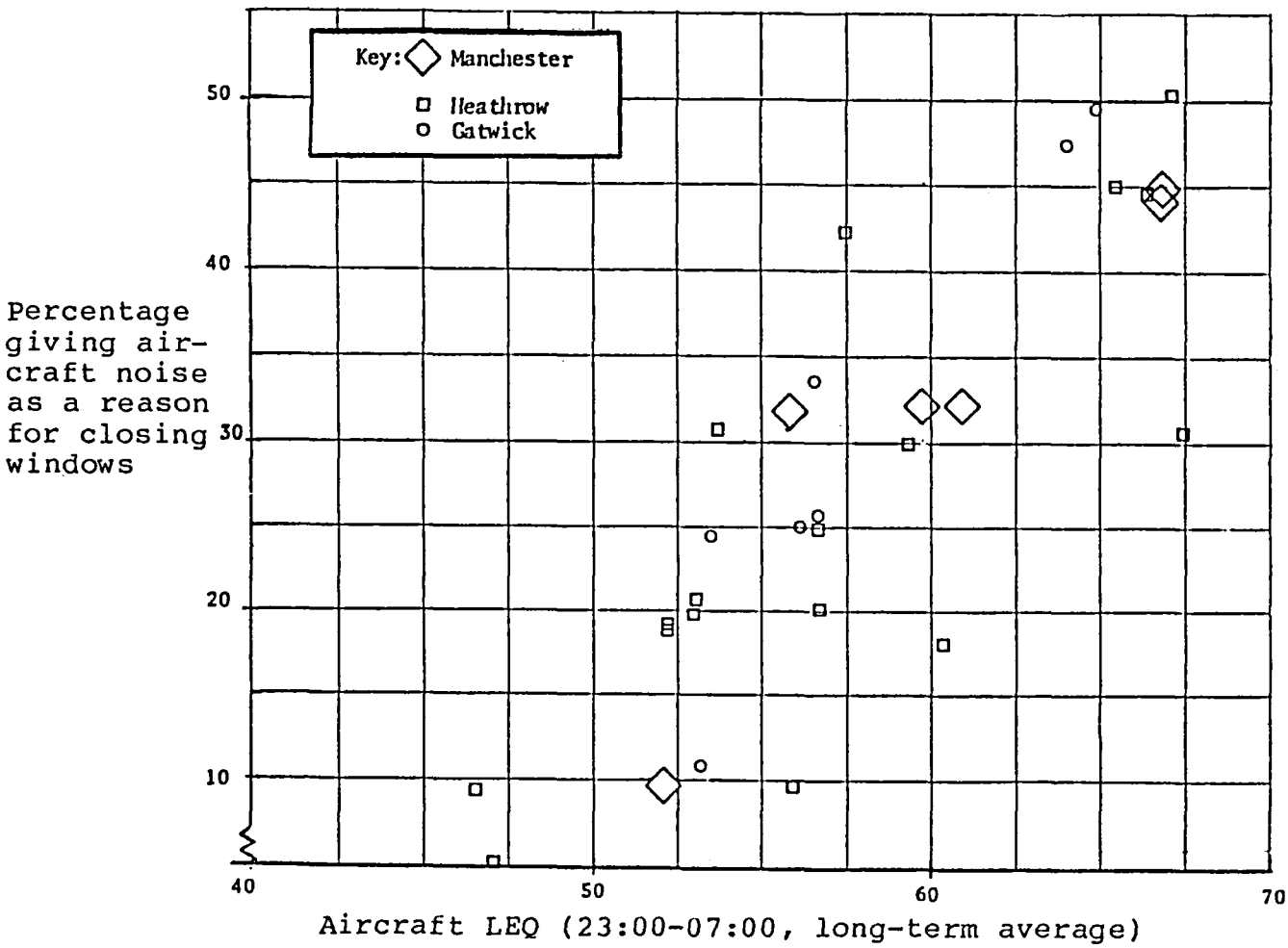


Figure 18: Percentage checking aircraft noise as a main reason for bedroom windows being shut at night over the last three months

(Source: Brooker and Nurse, 1982; Fig. 8.
Question:

Q.a Over the past three months or so, have you usually slept with your bedroom windows open or shut? (Open - some or all, Shut - all)

IF OPEN

Q.b During that time have you ever slept with all your bedroom windows shut? (Yes, No)

IF OPEN ON a OR b

Q.c What are the main reasons you slept with all your bedroom windows shut? (PLEASE TICK ALL WHICH APPLY) Road traffic noise, Aircraft noise, Noise from people outside/ neighbours, Other noise (inside or outside), Weather/ temperature, Security, Other reason, No particular reason)

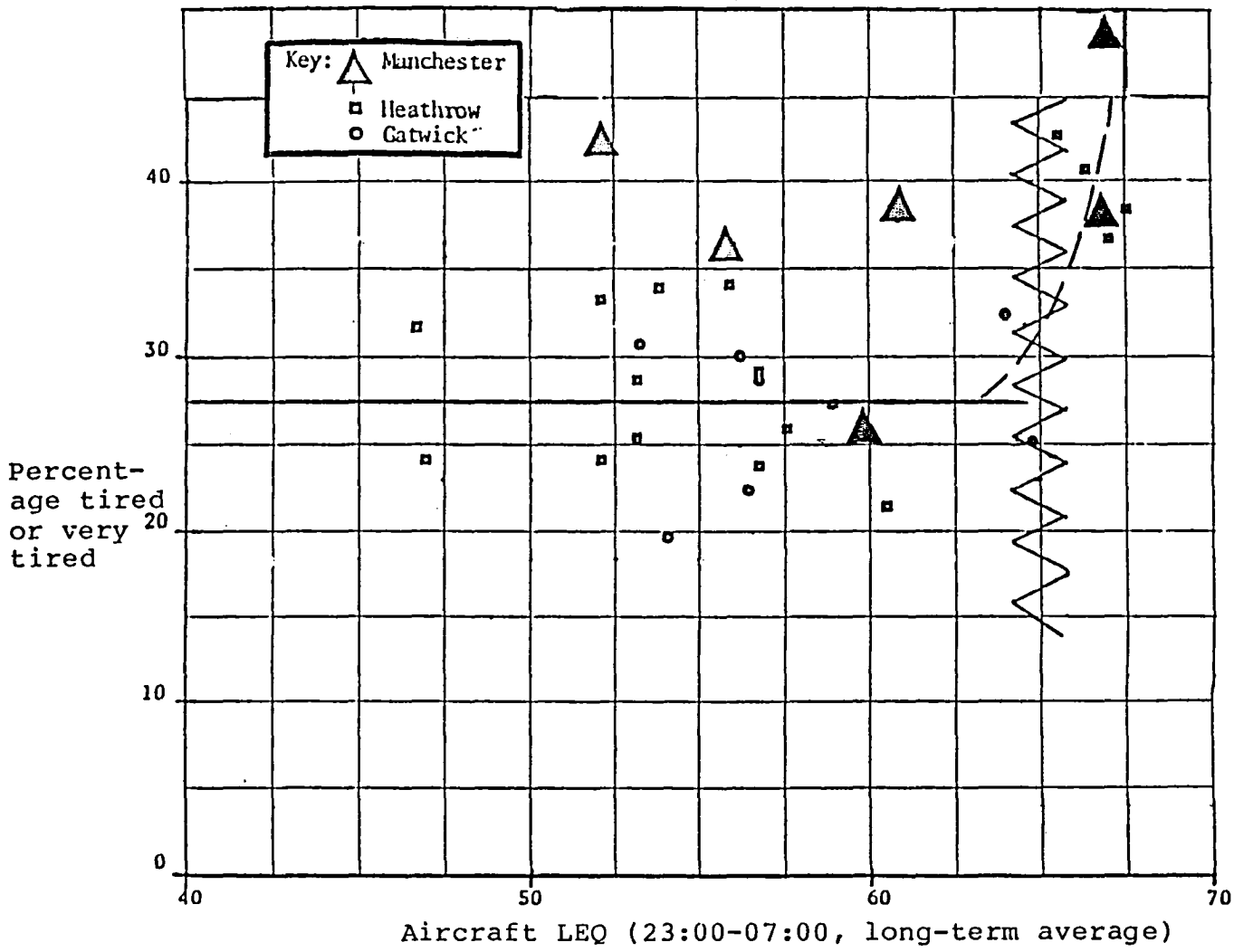


Figure 19: Reports of feelings after a typical night's sleep around three English airports

(Source: Brooker and Nurse, 1982; Fig. 15.
Question: When you wake up in the morning, after a typical night's sleep, how do you feel? (PLEASE TICK ONE ONLY) Very refreshed, Refreshed, Neither refreshed nor tired, Tired, Very tired)

(Note: The solid line is the mean response around Heathrow and Gatwick below 65 LEQ).

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15. Supplementary Notes

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16. Abstract

Social surveys of residents' responses to noise at different times of day are reviewed. Some of the discrepancies in published reports about the importance of noise at different times of day are reduced when the research findings are classified according to the type of time-of-day reaction model, the type of time-of-day weight calculated and the method which is used to estimate the weight. When the estimates of nighttime weights from 12 studies are normalized, it is found that they still disagree, but do not support stronger nighttime weights than those used in existing noise indices. Challenges to common assumptions in nighttime response models are evaluated. Two of these challenges receive enough support to warrant further investigation: the impact of changes in numbers of noise events may be less at night than in the day and nighttime annoyance may be affected by noise levels in other periods. All existing social survey results in which averages of nighttime responses were plotted by nighttime noise levels are reproduced in this report.

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