Sleep Disturbance Due To Environmental Noise: A Proposed Assessment Index

Robert Bullen
ERM Mitchell McCotter Pty Ltd,
24 Falcon St, Crows Nest, NSW 2065

Andrew Hede
Sunshine Coast University College,
Locked Bag 4, Maroochydore South, QLD 4558

Tony Williams
Environmental Impact Reports Pty Ltd,
214a Old South Head Rd, Vaucluse NSW 2030

Abstract: Traditional methods of assessing the impact of environmental noise are generally based on the use of "equal-energy" measures of noise exposure, such as $L_{Aeq,24hr}$ or ANEF. These have been derived from studies of the annoyance generated by the noise. This paper presents a proposed methodology for directly assessing the level of sleep disturbance due to intermittent night-time noise, independent of the degree of annoyance caused. The procedure is based on calculation of a Sleep Disturbance Index (SDI) which is numerically approximately equal to the average number of awakenings per night due to the noise. Typical values of SDI would range from less than 0.2, representing a relatively insignificant level of disturbance, to greater than 5, representing a very high level. Details of calculation procedures, and possible criterion values in terms of SDI, are discussed. The use of this methodology in addition to traditional "equal-energy" noise indices should allow for a more comprehensive assessment of the impact of night-time noise on residential communities.

1. INTRODUCTION

This paper describes a proposed methodology for direct assessment of the impact of certain types of environmental noise on sleep. The method described is intended to provide a practical tool for regulators and practitioners, and is seen as being complementary to existing assessment procedures which are based largely on studies of the annoyance (or similar psychological constructs) generated by the noise.

Throughout the world, existing regulatory procedures for assessment of environmental noise are based on the calculation of noise exposure indices, such $L_{Aeq,24hr}$ or ANEF, and comparison of these values with specified "criterion" levels. In almost all cases, indices based on the "equal-energy" principle (such as the two above) are used. A useful review of noise exposure indices and criterion levels which are adopted in various countries is provided by Gottlob (1995).

The use of "equal-energy" noise exposure indices is based on results from a series of studies (e.g. Fields, 1984; Bullen & Hede, 1986) which indicate that they provide the most appropriate basis for prediction of the annoyance generated by various types of environmental noise - or, at least, no alternative methodology provides a significantly better prediction of annoyance. Since most people describe their reaction to environmental noise in terms related to annoyance, this appears to be a reasonable procedure.

However, there has been continuing concern, both in the published literature (e.g. Ohrstrom & Bjorkman, 1988) and among the general community, that certain impacts of noise are not adequately predicted by "equal-energy" noise indices - or in other words, they are not adequately described by the "annoyance" generated by the noise. Chief among these additional impacts is sleep disturbance. It is argued that sleep disturbance may be associated with physiological or other effects of which a respondent may not be fully aware, and which would therefore not be reflected in their reported annoyance. This raises a particularly emotive issue, which has been the subject of considerable debate (see, for example, Stansfeld, 1992). Recent results in this field are summarised by Kawada (1995).

The present paper introduces a new index, and a methodology by which the extent of potential sleep disturbance due to noise may be assessed, independent of the degree of annoyance caused by the noise. Annoyance should still be assessed using standard "equal-energy" descriptors. The methodology applies only to intermittent noise which can be regarded as consisting of a series of isolated "events". However, this is the form of noise which is most commonly associated with disturbance to sleep.

2. MEASURES OF SLEEP DISTURBANCE

In studies of the effect of noise on sleep, the degree of disturbance may be assessed by a number of methods, including:

- the number of awakenings due to the noise, which may be measured using an electro-encephalograph (EEG); recorded using a device such as a button which subjects are required to push; or simply reported by subjects the following morning;
- the number and type of changes in sleep state which occur during the night, as recorded using an EEG;
- the number of body movements during the night, recorded using an actimeter;
- measures of performance the following morning, such as simple unprepared reaction time; and
- subjective reports of sleep quality.

These measures are all reasonably well correlated. However, the first two are most directly related to actual sleep quality. Body movements are difficult to interpret, since they occur in normal dreaming (REM) sleep as well as in periods when sleep is disturbed. Performance measures are related to a number of factors other than quality of sleep, and scales for reporting subjective sleep quality have not been standardised, so results from different studies are difficult to compare.

Of the first two measures, numbers of changes in sleep state are highly correlated with numbers of awakenings (awakenings are a subset of changes in state). While total changes in sleep state may provide a more sensitive measure of noise effects than awakenings, the significance of sleep state changes for overall sleep quality is not clear. In addition, because awakenings are reported in a large number of studies, conclusions concerning the frequency of awakenings can be drawn with greater certainty.

For this reason, in the proposed methodology, assessment of the impact of noise on sleep is based on prediction of the number of awakenings which would be caused by the noise per night.

As noted above, awakenings may be recorded in various ways. In situations where subjects are not exposed to noise, an EEG typically records seven to nine awakenings per night, whereas only one to two awakenings are remembered or are recorded by pushing a button. However, results from Eberhardt et al (1988) indicate that the number of EEG awakenings due to noise (that is, the number of additional awakenings in a noisy environment) is approximately the same as the number of remembered awakenings due to noise. In other words, although most EEG awakenings are not remembered the following morning, those which are caused by a noise event are generally remembered. This result allows data from various studies using different methodologies to be combined, giving greater confidence in the results.

3. COMPARISON OF RESULTS FROM PUBLISHED STUDIES

Studies of sleep disturbance due to noise have almost exclusively involved intermittent noise, consisting of a series of discrete events - generally actual or recorded passbys of aircraft, trains or road vehicles. The noise level of these events is typically characterised by the maximum A-weighted level, "Fast" speed. The number of events per night and/or their maximum noise level are varied, and the effect on sleep quality is assessed. In most cases, maximum noise levels of events are well above the ambient level - at least 20 dB higher. Figure 1 shows a comparison of results from a number of studies. The Appendix indicates the major characteristics of each of these studies.

Studies included in this comparison include all published studies which could be located for which the number of awakenings per night experienced by subjects could be related to a maximum noise level and a number of events per night. They include both laboratory and field studies, and subjects cover a range of demographic groups. In the case of laboratory studies, only results obtained after at least several nights' acclimatisation are included.

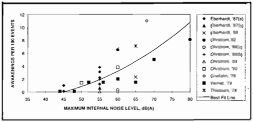

Figure 1. Probability of awakening - results of 11 studies.

In Fig. 1, the number of awakenings recorded has been standardised as the number per 100 events - or equivalently, the percentage probability of awakening per event. This form of analysis tacitly assumes that the number of awakenings per night is directly proportional to the number of events heard. There is some indication from results in Ohrstrom (1990) that for large numbers of noise-related awakenings (greater than approximately five per night) the actual number of awakenings may be lower than predicted from a direct relationship. At this point, subjects simply become too tired to wake up even for loud events. However, this level of disturbance would be well beyond reasonable criterion limits, and it can be assumed that for lower levels of disturbance there is a direct relationship between number of events and number of awakenings.

The scatter of results shown in Figure 1 is due to many factors, including differences in experimental methodology, types of subjects studied, differences between laboratory and field studies, differences between response to various types of noise, and statistical variation resulting from limited sample sizes. There is some suggestion from these data that recorded numbers of awakenings are lower for field studies than for laboratory studies. However, the difference is not statistically significant at the .05 level. It is also likely that differences in age, gender and other characteristics of the subjects are associated with some difference in susceptibility to awakening. However, data to confirm this are not available, and the implications foro planning purposes are in any case not clear.

The degree of agreement between studies shown in Figure 1 is considered to be sufficient to warrant the use of a best-fit line, as shown, to summarise the results. This relationship explains 50% of the total variance in number of awakenings, and the standard error of estimate is 2.6 awakenings per 100 events.

It should be noted that results in Figure 1 represent an average across all subjects. Very little information is available on inter-subject differences, but these can be expected to be large. Based on available data, criteria would need to be determined from these results for an "average" subject, recognising that some individuals will experience more, or less, disturbance than indicated.

4. PROPOSED ASSESSMENT METHODOLOGY

The proposed methodology is based on calculation of a "Sleep Disturbance Index" (SDI) which is numerically equal to the estimated average number of awakenings per night which would be caused by the noise in question. Typical values of SDI would range from less than 0.2, representing a relatively insignificant level of disturbance, to greater than 5, representing a very high level. Possible criterion values, expressed in terms of SDI, are discussed below.

The value of the Sleep Disturbance Index depends on the number of individual noise events heard per night; the maximum noise levels of events; and the "emergence" of events above the ambient noise. Calculation of the index is based on the results discussed above, and is described in detail below.

4.1 Basic Procedure

If there are N events per night, all with a maximum internal noise level of L_{max} dB(A), "Fast" speed, then the Sleep Disturbance Index is

$$SDI = N \cdot W(L_{max}) / 100$$

where W(L) is the weighting factor for a noise level of L. To calculate W(L) precisely, use

$$W(L) = 0.142\ (L - 45) + 0.00473\ (L - 45)^2 \text{ if } L > 45 \quad (1a)$$

$$W(L) = 0 \qquad \text{if } L <= 45 \quad (1b)$$

which is the formula representing the best-fit line shown in Fig. 1. Alternatively, Table 1 can be used. If there are several types of noise event with different levels, a partial SDI for each type should be calculated, and these should be added to give the total SDI.

Table 1 Weighting factors for calculating SDI

Maximum Internal Noise Level, L - dB(A)	Weighting Factor, W(L)
< 45	0
45 - 49	0.4
50 - 54	1.3
55 - 59	2.5
60 - 64	3.9
65 - 69	5.6
70 - 74	7.5
75 - 79	9.6
80 - 84	12.0

4.2 Example 1

Suppose a service station has 40 customers per night between 10 pm and 6 am. For each customer there are three separate audible events at the nearest residence - driving in at 62 dB(A), starting up at 70 dB(A) and driving away at 65 dB(A). It will be assumed that the residence has open windows, and that the internal noise level is 10 dB below the external level. (In practice, the difference between internal and external noise levels may vary depending on the degree of opening of windows, and may also differ between noise metrics. These factors would need to be considered in applying this methodology in practice.) The SDI due to these events is shown in Table 2.

Table 2 Example calculation of SDI

Event	Number Per Night	Max. Noise Level, dB(A)		Weighting Factor	Partial SDI
		External	Internal	(Calculated)	
Drive In	40	62	52	1.23	0.5
Start-Up	40	70	60	3.19	1.3
Drive Away	40	65	55	1.89	0.8
TOTAL SDI					2.6

4.3 Modified SDI

The above procedure does not take account of the emergence of noise events, i.e. the difference between the level of the event and the general ambient noise level. For large numbers of events with low noise levels, it gives values of SDI which are anomalously high.

Of the available studies, only Eberhardt et al. (1987) provides direct information on this effect. Indications from this paper are that the above procedure is applicable if the noise level of events is well above the overall L_{eq} noise level - say 20 dB higher than L_{eq}. If events are within 5 dB of the L_{eq}, the sleep disturbance due to the individual events reduces to almost zero.

This can be handled by modifying the weighting factors above. Modified weighting factors can be defined, using the factors found from Equation 1 or Table 1, by

$$W_{mod}(L_{max}) = W(L_{max}) \qquad \text{if } L_{max} >= L_{eq} + 20 \quad (2a)$$

$$W_{mod}(L_{max}) = W(L_{max}) * (L_{max} - L_{eq} - 5)/15 \qquad \text{if } L_{eq} + 5 < L_{max} < L_{eq} + 20 \quad (2b)$$

$$W_{mod}(L_{max}) = 0 \qquad \text{if } L_{max} <= L_{eq} + 5 \quad (2c)$$

where L_{eq} is the internal $L_{Aeq,8hr}$ noise level for the entire night-time period 10 pm - 6 am.

A problem with this formulation is that a measured $L_{Aeq,8hr}$ noise level may include noise from the events themselves as well as the ambient noise, and this may have some influence on the measured "ambient" level. Where events are definite and individually definable - such as in the case of rail traffic or aircraft noise - noise from these events should be excluded when measuring or calculating the ambient L_{Aeq} noise level. However, a special case exists for road traffic noise, which in practice consists of a series of noise events ranging continuously from infrequent high-level events which may result in sleep disturbance to a large number of low-level events which effectively constitute the "ambient" noise level. It is not clear which events should constitute "sleep disturbance" events and which should constitute the "ambient". In this case, preliminary indications are that an appropriate value for SDI may be found by using the overall measured (or calculated) L_{Aeq} noise level to represent the "ambient" from which higher noise level events arise.

4.4 Example 2

Suppose noise events from traffic are recorded throughout a night, outside a residence. Assume the bedroom window is open, and the external noise level is 10 dB higher than the internal level. The number of measured events with noise levels in various ranges is shown in Table 3. The measured $L_{Aeq,8hr}$ noise level was 53 dB(A). Table 3 shows the modified procedure for calculating SDI. A refinement of this assessment procedure would be to calculate the modified weighting factor separately for events in each hour, using the $L_{eq,1hr}$ value for that hour. This would be necessary if the L_{eq} noise level changed significantly during the night.

Table 3 Calculation of modified SDI

Noise Level Range, dB(A) (External)	Number of Recorded Events	Internal Noise Level, dB(A)	Weighting Factor		Partial SDI
			Basic	Modified	
75 - 79	2	65 - 69	5.6	5.6	0.1
70 - 74	12	60 - 64	3.9	3.6	0.4
65 - 69	53	55 - 59	2.5	1.5	0.8
60 - 64	206	50 - 54	1.3	0.35	0.7
55 - 59	316	45 - 49	0.4	0	0
TOTAL SDI					2.0

5. MEASUREMENT OF SDI

5.1 Definition of an "Event"

The value of SDI at a measurement location can be calculated directly from measured noise levels, provided one has a suitable definition of what constitutes a "noise event". For the purpose of measurement, an "event" is defined to occur when:

- the noise level reaches a maximum;
- the noise level drops by at least 5 dB between this and any other maximum; and
- the maximum is separated from any other maximum by at least 15 seconds.

The period of 15 seconds relates to the definition of an "awakening" in an EEG trace - to be counted, the subject should be in an awakened state for at least 15 seconds.

5.2 Equipment Required

Isolated noise events can be simply measured using a sound level meter on "Fast" speed, noting the maximum level and the number of events per night.

Quasi-continuous noise such as traffic noise is slightly more difficult. Using current measurement equipment, events can most easily be detected with a chart recorder, applying the above definition to the recorded trace. The recorder needs to run all night. Events can then be counted and assigned to ranges according to their L_{max} values. However, with appropriate software it would not be difficult to detect events automatically and save their maximum levels in a logger.

The value of SDI for a particular measurement night can be calculated directly as indicated in Table 3. From experience, values appear relatively stable between nights, but perhaps averaging over a number of nights would be useful.

6. PREDICTION OF SDI

For isolated events, prediction of the value of the Sleep Disturbance Index is relatively simple, requiring only a prediction of the maximum level and number of events per night, as well as knowledge or prediction of the ambient L_{eq} level.

For traffic noise, it would be necessary to divide vehicles into classes and predict maximum levels and numbers for each class. Maximum levels from individual vehicles can be predicted relatively easily, using ENM or any other appropriate model. The standard FHWA procedure can be easily modified to predict maximum levels rather than L_{eq} values. Predicted maximum levels would probably be more accurate than predicted L_{eq} levels using the standard CORTN or FHWA procedures.

If the traffic volume is high enough (or the distance from the road is large enough), there is a possibility that noise events may be due to more than one vehicle being present at the same time. This situation is more difficult to handle, and would require a statistical model to predict maximum levels accurately. However, such situations are not as important as the case of isolated events, because in these cases the maximum level is not greatly above the L_{eq} level, and hence the partial SDI from the events is low.

7. CRITERION LEVELS

Like any assessment methodology, the calculation of SDI represents a method of gauging the extent of sleep disturbance due to noise, and does not presuppose any specific values which should be adopted as criteria. The setting of criterion levels is primarily the responsibility of relevant regulatory authorities, based on judgements regarding the benefits and costs of various noise control strategies.

Nevertheless, some consideration of the level of impact associated with various values of SDI is appropriate, to define a level which could, for example, be described as "unacceptable" for planning purposes. One point of reference is the fact that studies indicate subjects experience an average of approximately 1.5 (remembered) awakenings per night for reasons unrelated to noise. Thus, an SDI of 1.5 would represent approximately a doubling of the "ambient" level of sleep disturbance. Such a level may be considered an appropriate criterion for transportation-related noise sources, where some consideration is traditionally given to the benefit of the noise source to the community and the cost to the community of noise mitigation measures.

For other noise sources, such as industrial sources or those associated with entertainment, more stringent criteria are traditionally applied, representing a point at which the impact of a new noise does not add significantly to existing impacts. A value of 0.5 for SDI (representing one additional awakening every two nights) may be considered an appropriate criterion under these circumstances.

In further refining these values, consideration would need to be given to the appropriateness of defining different criteria for existing and new sources, and of controlling the cumulative sleep disturbance due to a number of sources.

8. CONCLUSION

This paper presents a proposed methodology for assessment of sleep disturbance due to intermittent environmental noise. It is based on published research data, and takes account of the three factors which have been identified as being most important in determining the extent of this impact, namely:

- the number of individual noise events heard per night;
- the maximum noise levels of events; and
- the "emergence" of events above the ambient noise.

To the authors' knowledge, no existing alternative system allows all these factors to be considered in a systematic and quantifiable way.

Other acoustic factors, such as duration, rise time and information content of the noise, as well as non-acoustic factors such as age and personal sensitivity, will also affect the level of disturbance in any particular case. Corrections for such effects could conceivably be included in the methodology at a later date. However, reliable data to allow such corrections are currently unavailable.

The Sleep Disturbance Index, as defined above, is presented as a viable method for assessment of sleep disturbance from most types of night-time noise. Criteria of acceptability, in terms of the index, may be determined by relevant authorities. Possible criterion values are suggested for consideration in Section 7 above.

The methodology advanced in this paper now needs to be applied by practitioners in real situations. It is believed that use of the Sleep Disturbance Index in addition to an appropriate "equal-energy" index will result in a more comprehensive assessment of the impact of night-time noise on residential communities.

REFERENCES

Bullen, R.B. and Hede, A.J. 1996. Comparison of the effectiveness of measures of aircraft noise exposure using social survey data. *J. Sound Vibr.* 108, 227-245.

Eberhardt, J.L. 1988. The influence of road traffic noise on sleep. *J. Sound Vibr.* 127(3), 449-455

Eberhardt, J.L. and Akelsson, K.R. 1987a. The disturbance by road traffic noise of the sleep of young male adults as recorded in the home. *J. Sound Vibr.* 114(3), 417-434.

Eberhardt, J.L. Strale, L.-O. and. Berlin, M.H 1987 b. The influence of continuous and intermittent traffic noise on sleep. *J. Sound Vibr.* 116(3), 445-464

Fields, J.M. 1984. The effect of numbers of noise events on people's reaction to noise: An analysis of existing survey data. *J. Acoust. Soc. Am.* 75(2), 447-467

Gottlob, D. 1995. Regulations for community noise. *Noise/News International,* December 1995, 223-236

Griefahn, B. and Muzet, A. 1978. Noise-induced sleep disturbances and their effects on health. *J. Sound Vibr.* 59(1), 99-106

Kawada, T. 1995. Effects of traffic noise on sleep: A review. *Japanese Journal of Hygiene,* 50(5), 932-938.

Ohrstrom, E. 1989. Sleep disturbance, psycho-social and medical symptoms - A pilot survey among persons exposed to high levels of road traffic noise. *J. Sound Vibr.* 133(1), 117-128.

Ohrstrom, E. and Bjorkman, M. 1988a. Effects of noise-disturbed sleep - A laboratory study on habituation and subjective noise sensitivity. *J. Sound Vibr.* 122(2), 277-290.

Ohrstrom, E. and Rylander, R. 1982. Sleep disturbance effects of traffic noise - A laboratory study on after effects. *J. Sound Vibr.* 84(1), 87-103.

Ohrstrom, E. and Rylander, R. 1990. Sleep disturbance by road traffic noise - A laboratory study on number of noise events. *J. Sound Vibr.* 143(1) 93-101.

Ohrstrom, E. Rylander, R. and Bjorkman, M. 1988 b. Effects of night time road traffic noise - An overview of laboratory and field studies on noise dose and subjective noise sensitivity. *J. Sound Vibr.* 127(3), 441-448.

Stansfeld, S.A 1992. Noise, noise sensitivity and psychiatric disorder: epidemiological and psychophysiological studies. *Psychological Medicine,* Suppl 22, 1-44.

Thiessen, G.J. 1978. Disturbance of sleep by noise. *J. Acoust. Soc. Am.* 64(1), 216-222

Vernet, M. 1979. Effect of train noise on sleep for people living in houses bordering the railway line. *J. Sound Vibr.* 66(3), 483-492.

APPENDIX
SUMMARY STUDIES CONSIDERED IN SYNTHESIS

Reference	Type of study	Noise Source	Measure of Awakenings	Maximum noise levels, dB(A)	Numbers of events	Comments
Eberhardt et al, 1987	Laboratory	Recorded traffic	EEG and reported	45 - 55	50 per night	Includes data on effect of emergence
Eberhardt & Akselsson, 1987	In subjects' homes	Existing traffic noise	EEG	Range of normal traffic	45 per night with max. level > 50	Data used not obvious from paper - requires calculation.
Eberhardt, 1988	In subjects' homes - children 6 - 11 yrs	Recorded truck passages	EEG	65	68 per night	Brief report in referenced paper
Ohrstrom & Rylander, 1982	Laboratory	Recorded traffic	Self-reported	60 - 80	37 per night	
Ohrstrom & Bjorkman, 1988	Laboratory	Recorded traffic	Self-reported	60	57 per night	Subjects grouped as noise-sensitive and not sensitive - mean value used
Ohrstrom et al, 1988	In subjects' homes - comparison of two areas	Existing traffic	Self-reported	Range of normal traffic	54 per night with max. level > 55	Plotted change in number of awakenings vs number of events > 55 dB(A)
Ohrstrom, 1989	In subjects ' homes - comparison of two areas	Existing traffic	Self-reported	Range of normal traffic	97 per night with max. level > 55	Plotted change in number of awakenings vs number of events > 55 dB(A)
Ohrstrom & Rylander, 1990	Laboratory	Recorded traffic	Self-reported	50 - 60	4 - 64 per night	Plotted data for 64 events per night
Thiessen, 1978	Laboratory	Recorded traffic	Pressing button	65	7 per night	Plotted data are after adaptation for at least 12 nights
Griefahn & Muzet, 1978	Summary of laboratory studies	Various	EEG	68 - 87	Not stated	Summary line shown in report; plotted values for 60 dB(A) and 68 dB(A) which are mentioned in text
Vernet, 1979	In subjects' homes	Existing train noise, two sites	EEG	40 - 70	80 per night one site, 10 per night the other	