1. INTRODUCTION

1.1. Public response to noise from surface and air transportation has been widely studied in a number of social and noise measurement surveys over the last thirty years. Effects of vibration have been studied to a lesser extent. The results of these surveys have been used both to predict likely effects from transportation developments, in terms of the numbers of people affected (e.g. annoyed) to varying extents, and to set standards.

1.7. London has one of the largest and oldest underground railway systems in the world, and the indications have been that although underground train noise is heard in many locations, the effect on people is small.

1.9. In the summer of 1993, CrossRail sought to carry out a social/noise and vibration survey of people living above underground lines in London. Since CrossRail is concerned with a project to construct a circular bored tunnel, the survey was restricted to people living above 'tube' lines, and excluded cut-and-cover lines which have different characteristics. Because the CrossRail scheme is a major project which may be perceived by a substantial number of people as having a potential impact, it was decided to conduct the survey in areas well away from the CrossRail alignment. Survey addresses were selected according to their position relative to the alignment of tube lines, including areas where comparatively high noise levels were known to occur.

2. THE SOCIAL AND NOISE SURVEYS

2.1. The social survey was carried out by a contractor, British Market Research Bureau (BMRB), and, following behind the social survey, the noise survey was carried out by separate contractors, Sound Research Laboratories Ltd (SRL).

2.2. A total of 646 survey addresses were initially selected by BMRB from areas designated by CrossRail. It was expected that there would be a success rate of about 65% and that 400 interviews would be achieved. The success rate in the event proved to be only 38%, and after increasing the number of addresses issued, this yielded a total of 277 interviews. Of the 277 addresses, in only 117 were measurements possible largely because of refusals. In half the addresses the levels of noise and vibration were too low to be measured. Vibration was more measurable than noise, and vibration measurements were achieved in more locations than were noise measurements. Nevertheless, the total number of measurements of either vibration, noise, or both, was very small. As a result, statistical confidence levels in the survey results are very low.

2.4. Because of the small number of results, the survey does not serve to establish, with the degree of confidence which attaches to the surveys of noise from above-ground transportation, the relationship between noise from underground trains and its effect on people. It nevertheless adds to the existing small database on the subject although any interpretation placed on the results must be treated with caution.

4. CONCLUSIONS

4.1 Because of the small size of the sample of interviewees for whom both noise and social surveys were achieved, the confidence limits of the results are very low.

4.2 Nevertheless, two strong general conclusions emerged of a kind which probably would still obtain were a much larger sample studied. These were firstly that of reported annoyance due to noise, only a tiny proportion of the annoyance is explained by measured noise level. Significant correlations between noise annoyance and physical measurements are only obtained when both noise and vibration are included as independent variables. As a result, the conclusion is that with no vibration, annoyance due to noise is very low, and that noise annoyance, for the same noise level, increases with increase in vibration. The correlation between *noise* annoyance and *vibration* alone is not much lower than that between *vibration* annoyance and vibration alone.

4.3 Because of the low correlation between noise and annoyance, the differences between the capabilities of various noise metrics (e.g. $L_{Amax,S}$ and $L_{Amax,F}$) to predict annoyance are insignificant.

2.5. The fact that such a small proportion of people allowed the noise survey to be carried out leads to the suggestion that a degree of self-selection in the survey sample may have taken place. Among the population of the social survey as a whole, 7% of people were annoyed by noise from underground trains (of which 3% were very annoyed). Among the population subjected to the measurement survey 7% were annoyed (of which 3.5% were very annoyed, which does not suggest strongly that a bias of this kind did occur.

3. SUMMARY OF THE CONCLUSIONS OF THE SURVEY.

3.1. In all surveys of this kind, a feature of the results is the wide distribution of noise levels for any given level of annoyance. Some people are not annoyed at quite high levels of noise, and vice-versa. This means that correlations between noise metrics and measures of annoyance are never perfect. In the CrossRail survey the correlations between noise measurements and annoyance due to noise were particularly low. While the small size of the sample is one cause of this, the low correlation between noise (as opposed to vibration) and annoyance may be indicative of a result that would be obtained in a larger survey.

3.2. The survey studied annoyance in two ways. The first used a four point semantic scale: not at all annoyed; not very annoyed; quite annoyed and very annoyed. Semantic scales suffer from the drawback that the words have different shades of meaning to different people. The second method involved asking people about the effect of the noise (e.g. wakes you up; makes you go into another room). The effects are tabulated in ascending order of severity so that in general, a positive answer to a question high up the table would also be accompanied by a positive answer to each of the questions below it. One point is scored for each positive answer.

3.3. The striking conclusion of the survey is that the only reasonable correlations are between vibration and reported annoyance, and as far as annoyance due to *noise* is concerned, the best correlation was with measured *vibration*.

3.4. An insignificant proportion of the annoyance could be explained by the noise level alone. The correlations were too low for any significant distinction to be made between the various noise measures; $L_{Amax,\ S}$ gave a marginally better, but still insignificant, correlation than $L_{Amax,\ F}$; L_{Aeq} (24 hour) gave a marginally better correlation than L_{Amax}, but the correlation was still so poor that no attempt has been made to consider whether refinements to the L_{Aeq} computation period (e.g. 24 hour versus day and night). The observed relationship between $L_{Amax,\ S}$ and $L_{Amax,F}$, indicated that the latter may be taken as 3 dB greater than the former for existing underground tube lines.

3.6. It is sometimes suggested that underground train noise would be more annoying in homes with low background noise levels. In fact, trains were marginally more annoying in areas with higher background noise.

Published by the Institute of Environmental Epidemiology, Ministry of the Environment, Environment Building, 40 Scotts Road #22-00, Singapore 228 231, Tel: +65 731 9754, Fax: +65 734 8287, Email: ENV_IEE@ENV.gov.sg

ISBN: 9971-88-770-3

of the probability of obtaining a response (Griefahn 1977; *cf.* Berglund & Lindvall 1995). Another possible factor is the person's age, with older persons having an increased probability of awakening. However, one field study showed that noise-induced awakenings are independent of age (Reyner & Horne 1995).

For a good sleep, it is believed that indoor sound pressure levels should not exceed approximately 45 dB LAmax more than 10–15 times per night (Vallet & Vernet 1991), and most studies show an increase in the percentage of awakenings at SEL values of 55–60 dBA (Passchier-Vermeer 1993; Finegold et al. 1994; Pearsons et al. 1995). For intermittent events that approximate aircraft noise, with an effective duration of 10–30 s, SEL values of 55–60 dBA correspond to a LAmax value of 45 dB. Ten to 15 of these events during an eight-hour night-time implies an LAeq,8h of 20–25 dB. This is 5–10 dB below the LAeq,8h of 30 dB for continuous night-time noise exposure, and shows that the intermittent character of noise has to be taken into account when setting night-time limits for noise exposure. For example, this can be achieved by considering the number of noise events and the difference between the maximum sound pressure level and the background level of these events.

Special attention should also be given to the following considerations:

a. Noise sources in an environment with a low background noise level. For example, night-traffic in suburban residential areas.

b. Environments where a combination of noise and vibrations are produced. For example, railway noise, heavy duty vehicles.

c. Sources with low-frequency components. Disturbances may occur even though the sound pressure level during exposure is below 30 dBA.

If negative effects on sleep are to be avoided the equivalent sound pressure level should not exceed 30 dBA indoors for continuous noise. If the noise is not continuous, sleep disturbance correlates best with LAmax and effects have been observed at 45 dB or less. This is particularly true if the background level is low. Noise events exceeding 45 dBA should therefore be limited if possible. For sensitive people an even lower limit would be preferred. It should be noted that it should be possible to sleep with a bedroom window slightly open (a reduction from outside to inside of 15 dB). To prevent sleep disturbances, one should thus consider the equivalent sound pressure level and the number and level of sound events. Mitigation targeted to the first part of the night is believed to be effective for the ability to fall asleep.

messages (at school, listening to foreign languages, telephone conversation), it is recommended that the signal-to-noise ratio should be at least 15 dBA. Thus, with a speech level of 50 dBA, (at 1 m distance this level corresponds to a casual speech level of both women and men), the sound pressure level of interfering noise should not exceed 35 dBA. For vulnerable groups even lower background levels are needed. If it is not possible to meet the strictest criteria for vulnerable persons in sensitive situations (e.g. in classrooms), one should strive for as low background levels as possible.

3.4. Sleep Disturbance

Uninterrupted sleep is known to be a prerequisite for good physiological and mental functioning of healthy persons (Hobson 1989); sleep disturbance, on the other hand, is considered to be a major environmental noise effect. It is estimated that 80-90% of the reported cases of sleep disturbance in noisy environments are for reasons other than noise originating outdoors. For example, sanitary needs; indoor noises from other occupants; worries; illness; and climate (e.g. Reyner & Horne 1995). Our understanding of the impact of noise exposure on sleep stems mainly from experimental research in controlled environments. Field studies conducted with people in their normal living situations are scarce. Most of the more recent field research on sleep disturbance has been conducted for aircraft noise (Fidell et al. 1994 1995a,b 1998; Horne et al. 1994 1995; Maschke et al. 1995 1996; Ollerhead et al. 1992; Passchier-Vermeer 1999). Other field studies have examined the effects of road traffic and railway noise (Griefahn et al. 1996 1998).

The primary sleep disturbance effects are: difficulty in falling asleep (increased sleep latency time); awakenings; and alterations of sleep stages or depth, especially a reduction in the proportion of REM-sleep (REM = rapid eye movement) (Hobson 1989). Other primary physiological effects can also be induced by noise during sleep, including increased blood pressure; increased heart rate; increased finger pulse amplitude; vasoconstriction; changes in respiration; cardiac arrhythmia; and an increase in body movements (cf. Berglund & Lindvall 1995). For each of these physiological effects, both the noise threshold and the noise-response relationships may be different. Different noises may also have different information content and this also could affect physiological threshold and noise-response relationships (Edworthy 1998).

Exposure to night-time noise also induces secondary effects, or so-called after effects. These are effects that can be measured the day following the night-time exposure, while the individual is awake. The secondary effects include reduced perceived sleep quality; increased fatigue; depressed mood or well-being; and decreased performance (Öhrström 1993a; Passchier-Vermeer 1993; Carter 1996; Pearsons et al. 1995; Pearsons 1998).

Long-term effects on psychosocial well-being have also been related to noise exposure during the night (Öhrström 1991). Noise annoyance during the night-time increased the total noise annoyance expressed by people in the following 24 h. Various studies have also shown that people living in areas exposed to night-time noise have an increased use of sedatives or sleeping pills. Other frequently reported behavioural effects of night-time noise include closed bedroom windows and use of personal hearing protection. Sensitive groups include the elderly, shift workers, persons especially vulnerable to physical or mental disorders and other individuals with

Many studies have compared the accuracy of predictions based on A-weighted levels with those based on other frequency weightings, as well as more complex measures such as loudness levels and perceived noise levels (see also Berglund & Lindvall 1995). The comparisons depend on the particular effect that is being predicted, but generally the correlation between the more complex measures and subjective scales are a little stronger. A-weighted measures have been particularly criticized as not being accurate indicators of the disturbing effects of noises with strong low-frequency components (Kjellberg et al. 1984; Persson & Björkman 1988; Broner & Leventhall 1993; Goldstein 1994). However, these differences in prediction accuracy are usually smaller than the variability of responses among groups of people (Fields 1986; see also Berglund & Lindvall 1995). Thus, in practical situations the limitations of A-weighted measures may not be so important.

In addition to equal-loudness contours, equal-noisiness contours have also been developed for calculating perceived noise levels (PNL) (Kryter 1959; Kryter 1994; see also section 2.7.2). Critics have pointed out that in addition to equal-loudness and equal-noisiness contours, we could have many other families of equal-sensation contours corresponding to other attributes of the noises (Molino 1974). There seems to be no limit to the possible complexity and number of such measures.

2.3.4. Influence of ambient noise level

A number of studies have suggested that the annoyance effect of a particular noise would depend on how much that noise exceeded the level of ambient noise. This has been shown to be true for noises that are relatively constant in level (Bradley 1993), but has not been consistently found for time-varying noises such as aircraft noise (Gjestland et al. 1990; Fields 1998). Because at some time during an aircraft fly-over the noise almost always exceeds the ambient level, responses to this type of noise are less likely to be influenced by the level of the ambient noise.

2.3.5. Types of noise

A number of studies have concluded that equal levels of different noise types lead to different annoyance (Hall et al. 1981; Griffiths 1983; Miedema 1993; Bradley 1994a; Miedema & Vos 1998). For example, equal LAeq,T levels of aircraft noise and road traffic noise will not lead to the same mean annoyance in groups of people exposed to these noises. This may indicate that the LAeq,T measure is not a completely satisfactory description of these noises and perhaps does not completely reflect the characteristics of these noises that lead to annoyance. Alternatively, the differences may be attributed to various other factors that are not part of the noise characteristics (e.g. Flindell & Stallen 1999). For example, it has been said that aircraft noise is more disturbing, because of the associated fear of aircraft crashing on people's homes (cf. Berglund & Lindvall 1995).

2.3.6. Individual differences

Finally, there is the problem of individual response differences. Different people will respond quite differently to the same noise stimulus (Job 1988). These individual differences can be

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1. Criteria must be related to a level based upon reliable dose response research

2. Research demonstrates that dose response varies by reference to type of noise source e.g. aircraft, road traffic, rail. Thus, criteria must be based upon research of rail noise dose response.

3. The following supports 40 db LA max:

   (1) Victoria Line experience
   (2) Social surveys conducted in 1990s
   (3) JLE experience

4. 40 db LA max is the criterion adopted on a large range of projects in the past and has been the subject of consideration by a number of tribunals. Most recently it was accepted by the Inspector in the Thameslink2000 Inquiry as the proper criterion to adopt.

5. The 40 dB LA max level is lower than the guideline levels identified by Berglund et al in the WHO document.

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	CTRL (Note that there is a statutory undertaking that operation and construction will be Not Environmentally Worse Than (NEWT) the effects identified in the ES)	**THAMESLINK 2000**	**WEST COAST MAIN LINE**	**JUBILEE LINE EXTENSION**	**ELL**
Operational Groundborne Noise	Residential As Crossrail Non-residential subject to individual assessment if predicted levels exceeded LAmax S of: 25 (studios/concert halls etc) 35 (hospitals/churches etc) 40 (offices/shops etc) 50 (factories/warehouses etc)	As Crossrail	N/A	Desirable level: 35 dB(A) (stated as "peak") but inferred to mean L**Amax** Potential complaint threshold: 40 dB(A) (stated as "peak") but inferred to mean L**Amax**	N/A

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