University of Salford
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HUMAN RESPONSE TO VIBRATION IN RESIDENTIAL ENVIRONMENTS (NANR209)

TECHNICAL REPORT 6

DETERMINATION OF EXPOSURE-RESPONSE RELATIONSHIPS

31 MARCH 2011

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Foreword

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The views and analysis expressed in this report are those of the authors and do not necessarily reflect those of the Department for Environment Food and Rural Affairs.

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Preface

This document is one component of the Defra project NANR209 'Human response to vibration in residential environments' final report.

The NANR209 Final Report consists of the following documents:
- Executive summary
- Final project report
- Technical report 1: Measurement of vibration exposure
- Technical report 2: Measurement of response
- Technical report 3: Calculation of vibration exposure
- Technical report 4: Measurement and calculation of noise exposure
- Technical report 5: Analysis of the social survey findings
- Technical report 6: Determination of exposure-response relationships

The project was performed at the University of Salford between January 2008 and March 2011. During that time the following University of Salford researchers worked on the project. David Waddington, Andy Moorhouse, Mags Adams, Geoff Kerry, Rodolfo Venegas, Andy Elliott, Victoria Henshaw, Eulalia Peris, Phil Brown, Andy Steele, Jenna Condie, Gennaro Sica, James Woodcock, Deborah Atkin, Nathan Whittle, Zbigniew Koziel, George Perkins, Natalia Szczepanczyk, Sharron Henning, Ryan Woolrych, Heather Dawes, Amy Martin, Maria Beatrice Aquino-Petkos, Laura Jane Buckley, Catherine McGee, Andrew Caunce, Valentin Le Bescond, Stephanie Jones, Dawn Smail, Andrew King, Lauren Hunt, Michael Gerard Smith, Tomos Evans.

The work by the University of Salford benefited from guidance by the Defra project steering group. The Defra project steering group consisted of Richard Perkins and Colin Grimwood on behalf of Defra, Colin Stanworth representing the interests of the British Standards Institution working group for BS6472, Rupert Thornely-Taylor representing the interests of the Association of Noise Consultants, and Henk Miedema, Sabine Janssen and Henk Vos from TNO (Netherlands Organization for Applied Scientific Research).

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The peer review of the railway questionnaire was performed by Jim Fields, Larry Finegold, Evy Öhrström, Peter Brooker, and Gary J Raw.

This research would not have been possible without the kind cooperation of the residents that took part in the field trials.

The work presented is research performed by the University of Salford funded by Defra.

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1 INTRODUCTION

This technical report aims to present the development of exposure-response relationships for the human response to vibration in residential environments. The data used to formulate the relationships presented in this report are those which were collected for the Defra funded project "NANR209: Human response to vibration in residential environments", the main aim of which was the development of exposure-response relationships. Vibration caused by railway traffic, construction work, and internal sources outside of the residents' control were considered. Response data was collected via face to face interviews with residents in their own homes. The questionnaire was presented as a neighbourhood satisfaction survey and gathered information on, among other things, annoyance caused by vibration and noise exposure. Development and implementation of the questionnaire used for the collection of response data is discussed in Technical Report 2 and Technical Report 5. Vibration exposure was determined via measurement and prediction in such a way that, where possible, an estimation of internal vibration exposure was established for each residence in which a questionnaire was completed. The measurement procedures and methods employed to estimate vibration exposure are detailed in Technical Report 1 and Technical Report 3. Estimations of noise exposure were also derived for each residence using the methods detailed in Technical Report 4.

The first section of this report will consist of a review of literature related to human response to vibration and noise exposure. Following this, a discussion of the most appropriate descriptor for vibration exposure with regards to human response in residential environments will be presented. Finally, exposure-response curves will be presented for the different sources of vibration and noise considered in this project.

The relationships presented in this report have been derived in terms of vibration and noise exposure. Because of this, only the relationship between the total amount of vibration energy to which a respondent could potentially be subjected to and annoyance are described. This is in contrast to vibration dose which is defined as the total amount of vibration energy absorbed by a respondent over a given time period. From a policy or planning viewpoint, exposure-response relationships are probably more useful than dose-response relationships as information relating to the activities of the community such as the times of day that people are in their properties is likely to be unavailable.

A laboratory study to assess the feasibility of using the methods of paired-comparison testing and multidimensional scaling analysis to investigate the perception of whole body vibration is presented in Appendix I of this report.

2 LITERATURE REVIEW

2.1 INTRODUCTION

This section aims to provide an overview of literature relating to human response to vibration and noise in residential environments. It will begin with a brief overview of the work which has been carried out to determine exposure-response relationships for community response to noise. Following this, a discussion of the current guidance for the evaluation of vibration with regard to human response in residential environments will be provided. An overview of research into community response to vibration in residential environments will then be presented along with a review of factors influencing community response to noise and vibration exposure.

2.2 COMMUNITY RESPONSE TO NOISE

Perhaps the most fitting analogue to the project discussed in this report is that of community response to noise. A wealth of literature is available on the subject of annoyance due to noise exposure. This section will focus on literature relating to the development of exposure-response relationships for human response to environmental noise (transportation noise in particular). It is felt that by providing an overview of the work and criticisms thereof in the area of human response to noise exposure, a solid basis for the work detailed in this report can be established.

The work of (Schultz 1978) is generally regarded as the seminal work in this field. Schultz presented an exposure-response relationship based on the synthesis of data collected for eleven social surveys considering the relationship between noise exposure and annoyance. As a measure of annoyance, Schultz selected a percentile-based metric which described the proportion of respondents expressing annoyance in the upper 28% of the annoyance scale. This metric was termed "Percent Highly Annoyed" (%HA). The decision to use a percentile-based metric was driven in part by the poor correlation observed between individual annoyance responses and noise exposures. Schultz observes that, in areas exhibiting high noise exposure, there is less scatter in the annoyance responses than in those areas which exhibit comparatively lower noise exposure. Schultz postulates that, "when people are highly annoyed by the noise, the effects of non-acoustical variables are reduced, and the correlation between the noise exposure and the expressed subjective reaction is high, both for individuals and for groups". It is also argued that, although measurements of noise may have been conducted, it is not known if respondents were actually exposed to the measured level of noise exposure (i.e. because of shielding, distance from the source, etc.) so by considering only the "highly annoyed" part of the population, there is more certainty that those considered have been exposed to the measured noise level[1].

[1] It should be noted that this argument was based on surveys for which external measurements of noise were taken.

Finally, it is argued that %HA is a more useful and interpretable measure of community annoyance from a policy point of view than the mean or median of annoyance responses. Of the eleven social surveys Schultz considered, the relationship between noise exposure and %HA was found to be highly consistent between the studies. The overall synthesis curve presented by Schultz was expressed as a third order polynomial fit with %HA as the dependent variable and L_{dn} (dB) as the noise exposure descriptor. It was shown that as the magnitude of noise exposure increases, the proportion of respondents reporting high annoyance also increases. (Fidell 1989) presented an updated version of the Schultz curve by incorporating an additional 292 data points into the curve. The updated curve was found to be very similar to the original curve presented by Schultz.

The Schultz curve drew considerable criticism (Kryter 1982), partly due to the fact that the relationship did not consider different sources of noise separately. It was shown by Kryter that the curve under-predicts annoyance caused by aircraft noise and over-predicts annoyance caused by road and rail traffic noise. Separate synthesis curves for different transportation noise sources (aircraft, road traffic, and railway traffic) have been derived by Miedema and Vos (H. Miedema & Vos 1998). The results of this study were obtained through analysis of the same datasets used by Schultz and Fidell plus an additional 34 datasets. Attempts were made in this study to find 95% confidence intervals for the exposure-response curves by fitting a multilevel model to the data. It was found from this study that, for a given exposure, %HA was highest for aircraft noise followed by road traffic noise followed by rail traffic noise.

Miedema and Oudshoorn (H. Miedema & Oudshoorn 2001) presented an improved exposure-response model based on the same dataset analyzed by Miedema and Vos. The model used in this study (Groothuis-Oudshoorn & H. Miedema 2006) models the entire annoyance distribution meaning any annoyance measure which summarizes the distribution can be calculated. Another benefit of this model is that the standard error can be estimated meaning robust confidence limits can be established. Updated curves for aircraft, road, and rail traffic noise were presented as a function of noise exposure and percent “highly annoyed”, percent “annoyed”, and percent “a little annoyed”. At the time of writing, the model presented in this study can be considered current best practice for the determination of exposure-response relationships for community response to noise exposure, this model is discussed in more detail in section 4.1.3.

It is generally found in studies of this nature that the calculated exposure-response relationships leave a large proportion of the variance in the response data unaccounted for. Several personal, attitudinal and situational factors have been considered as covariates in exposure-response models for annoyance due to transportation noise (J. Fields 1979; J. M. Fields & Walker 1982; J. M. Fields 1993; H. Miedema & Vos 1999; H. Miedema & Vos 2003; Klćboe et al. 2004; Paunovic et al. 2009; Van Gerven et al. 2009).

In general, demographic factors have been shown to have little influence on annoyance due to transportation noise (J. M. Fields 1993; H. Miedema & Vos 1999). Age has been found to have a significant influence in these relationships where the largest proportion respondents expressing high annoyance have been found to be in the middle age ranges (Van Gerven et al. 2009). It has been found that those reporting some degree of fear towards the noise source report a higher degree of annoyance than those who do not express fear (J. M. Fields 1993; H. Miedema & Vos 1999). Those reporting a high degree of sensitivity to noise have been found to report a higher degree of annoyance than those reporting a lower degree of sensitivity (H. Miedema & Vos 2003; Paunovic et al. 2009).

2.3 RESPONSE TO VIBRATION

2.3.1 PERCEPTION AND ASSESSMENT OF VIBRATION EXPOSURE

There have been a number of laboratory studies conducted which aim to determine vibration perception thresholds. The results of some of these studies are summarized by Griffin (M. J. Griffin 1996) as shown in Figure 1. As can be seen, although there is some agreement between the threshold curves, a large amount of scatter can be observed between studies.

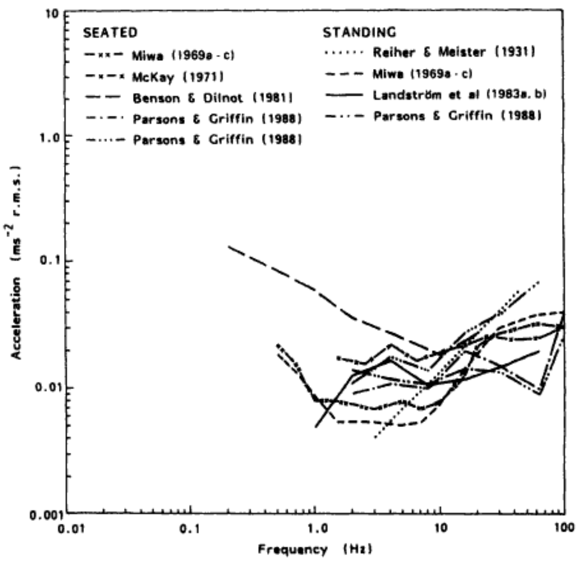

Figure 1 Vibration perception thresholds in the vertical direction for a number of laboratory studies as presented in "Handbook of Human Vibration", (M. J. Griffin 1996).

Vibration perception threshold base curves are provided in a number of national and international standards. Figure 2 shows the base curves presented in ISO 2631-2:2003 and ANSI S2.71-1983 (R2006), these curves were also presented in BS 6472-1:1992 but have been omitted from later revisions of the standard. These base curves are intended to represent the threshold at which 50% of the population will be able to perceive vibration.

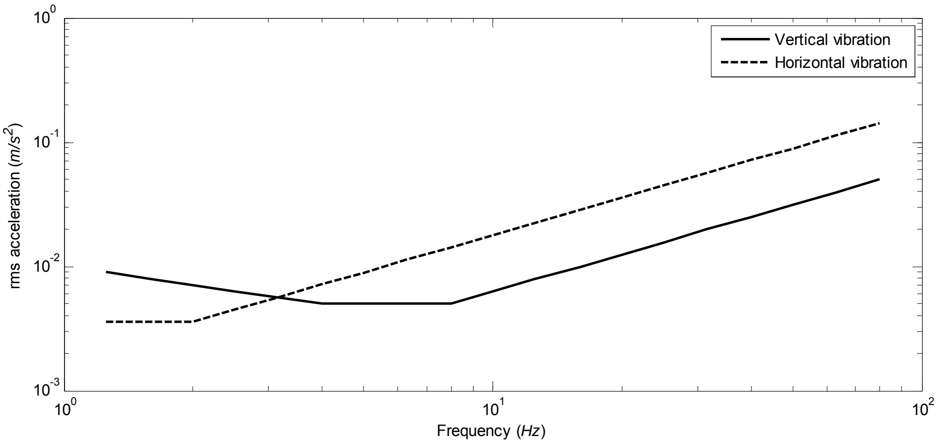

Figure 2 Vibration perception base curves.

It should be noted that the perception thresholds and base curves highlighted in this section are the results of laboratory studies and therefore may not be appropriate for the perception of vibration in residential environments. Most of the studies from which these perception curves are derived were based on steady state or random vibrations. A laboratory study by (Wiss & Parmelee 1974) described in (Murray 1979) has developed a relationship for the subjective response to transient vibrations based on frequency, amplitude, and floor damping. It was found that an increase in perception threshold was observed for transient vibration compared with the threshold for steady state vibration. It should be noted that these results were expressed as peak vibration values. The same result may not be expected for energy type vibration descriptors such as *rms* acceleration.

There are a number of national and international standards which provide guidance on the evaluation of vibration exposure with respect to human response. Guidance is typically in given in the form of frequency weighting curves and averaging methods. BS 6472-1:2008 recommends two frequency weighting curves. These weighting curves, which are applied to acceleration signals, are intended to reflect the sensitivity of humans to the perception of vibration at different frequencies. The W_b and W_d weighting curves presented in the standard apply to vertical and horizontal vibration respectively. The W_b weighting curve demonstrates maximum sensitivity to vertical acceleration in the frequency range 4Hz to 12.5Hz. The W_d weighting curve demonstrates maximum sensitivity to horizontal acceleration in the frequency range 1Hz to 2Hz. ISO 2631-1:1997 recommends the use of the W_k weighting curve for acceleration signals in the vertical direction and the W_d curve for acceleration signals in the horizontal direction. The W_k weighting curve differs only slightly from the W_b weighting defined in BS 6472-1:2008. ISO 2631-2:2003 recommends the use of the W_m weighting curve, this curve is applied to acceleration signals in any direction. DIN 4150-2, the German national standard, recommends the use of the *KB* weighting curve applied to velocity signals. If the *KB* weighting is transformed so as to be applied to an acceleration signal, it is equal to the W_m weighting curve. The W_b, W_d, W_k, and W_m weighting curves are illustrated in Figure 3.

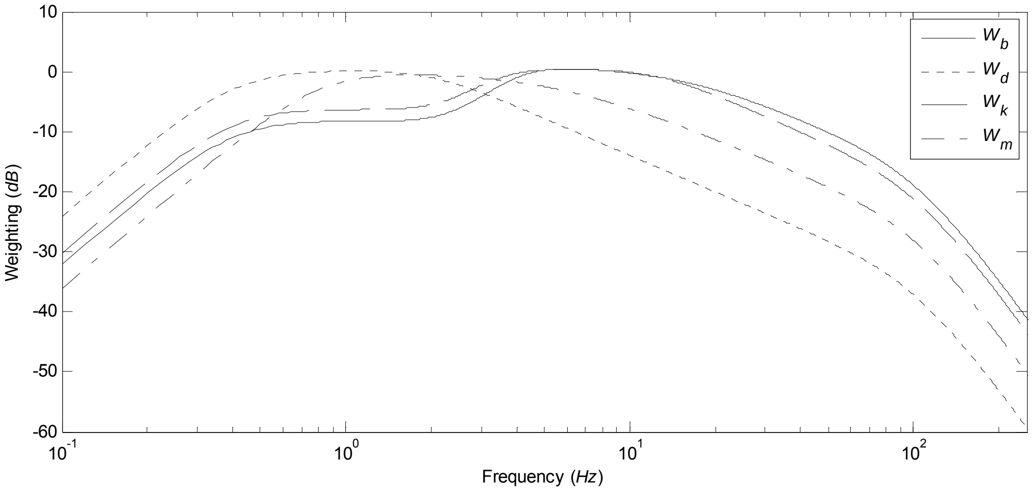

Figure 3 Weighting curves as defined in BS 6472-1:2008, ISO 2631-1:1997, and ISO 2631-2:2003.

BS 6472-1:2008 suggests the use of vibration dose value (*VDV*) to quantify vibration exposure with regards to human response. *VDV* is defined with the subscripts b/d to refer to W_b and W_d weighting respectively and day/night to refer to a 16 hour daytime period and an 8 hour night time period respectively (i.e. $\mathrm{VDV}_{b,day}$). *VDV* is a forth power integration of acceleration and is defined in the equation below:

$$\ddot{x}_{VDV} = \sqrt[4]{\int_0^T \ddot{x}^4(t)dt}$$ **Equation 1**

Where $\ddot{x}(t)$ is an acceleration signal, and T is the evaluation period in seconds. *VDV* has the units $m/s^{1.75}$.

The rationale for the use of vibration dose value is derived from a laboratory study (H. Howarth & M.J. Griffin 1988) into the relationship between vibration magnitude and number of events with regards to human annoyance. This study produced the following relationship:

$$NV^4 \propto annoyance$$ **Equation 2**

Where N is the number of vibration events and V is the vibration magnitude.

ISO 2631-1:1997 suggests the use of root-mean-square acceleration (*rms*) which is defined in the equation below. *VDV* is also defined in this standard.

$$\ddot{x}_{rms} = \sqrt{\frac{1}{T}\int_0^T \ddot{x}^2(t)dt}$$ **Equation 3**

Where $\ddot{x}(t)$ is an acceleration signal, and *T* is the evaluation period in seconds.

Norwegian standard NS 8176 suggests the use of the statistical maximum weighted acceleration or velocity level ($a_{w,95}$ or $v_{w,95}$) from 1 second averages of acceleration or velocity signals. These descriptors are calculated as follows:

$$v_{w,95} = \overline{v_{w,\max}} + 1.8\sigma_v$$
$$a_{w,95} = \overline{a_{w,\max}} + 1.8\sigma_a$$

Equation 4

Where $v_{w,\max}$ and $a_{w,\max}$ are the maximum 1-second average weighted velocity or acceleration level for a single train passby. $\overline{v_{w,\max}}$ and $\overline{a_{w,\max}}$ are the mean value of the maximum weighted velocity and acceleration respectively for all train passbys. σ_v and σ_a are the standard deviation of the maximum 1-second average weighted velocity or acceleration level for all train passbys.

The German national standard DIN 4150 suggests the use of KB_{FTr}:

$$KB_{FTr} = \sqrt{\frac{1}{T_r}\sum_j T_{e,j} KB_{FTm,j}^2}$$

Equation 5

Where T_r is the evaluation period (day or night), $T_{e,j}$ is the exposure period of the j^{th} event, and $KB^2_{FTm,j}$ is the average of the maximum 0.125 *s* running average *rms* velocity for each 30 second period of an event.

Little guidance is provided in national and international standards as to the probable annoyance caused by a given vibration exposure. ISO 2631 -1:1997 suggests that "… occupants of residential buildings are likely to complain if the vibration magnitudes are only slightly above the perception threshold". BS 6472-1:2008 indicates the possibility of adverse comment for five ranges of *VDV*, however there is no indication as to how these values were arrived at. It is also unclear as to what is meant by "adverse comment".

Place and time	Low probability of adverse comment[2] $m/s^{1.75}$	Adverse comment possible $m/s^{1.75}$	Adverse comment probable[3] $m/s^{1.75}$
Residential buildings 16*hr* day	0.2 – 0.4	0.4 – 0.8	0.8 – 1.6
Residential buildings 8*hr* night	0.1 – 0.2	0.2 – 0.4	0.4 – 0.8

Table 1 Vibration dose value ranges which might result in various probabilities of adverse comment within residential buildings. Taken from BS 6472-1:2008.

2.3.2 COMMUNITY RESPONSE

The main source of literature concerned with the human response to vibration in residential environments derives from studies into annoyance caused by railway vibration. In a field survey conducted in Scotland (Woodroof & M.J. Griffin 1987), annoyance caused by railway induced building vibration was evaluated via a questionnaire with residents and measurements of vibration within a limited number of properties. The aim of this study was to determine the number of people who noticed or were annoyed by railway induced groundborne vibration. 459 questionnaires were conducted with residents along with 52 measurements of 24 hour vibration within dwellings. The vibration measurements were conducted in three orthogonal directions. Of the 459 respondents interviewed, 35% reported feeling vibration. By correlating different measures of vibration exposure against reported annoyance, it was found that the most appropriate descriptor for describing annoyance for this study was the number of train passes which occurred in a 24-hour period with annoyance found to increase with the number of train passes.

A study by the Transport Research Laboratory was conducted in which residents in 50 sites in the United Kingdom were questioned about nuisance related to traffic induced vibration (Watts 1984). Noise exposure at the most exposed façade of the respondent's property was found to correlate reasonably well with nuisance caused by vibration. In a subsequent study (Watts 1987), measurements of vibration were conducted at respondent's properties both internally and externally.

A large scale field study has been conducted in Norway (Turunen-Rise et al. 2003; Klæboe et al. 2003; Klaeboe et al. 2003) with the aim of deriving an exposure-response relationship for the community response to vibration caused by road and

[2] Below these ranges adverse comment is not expected.

[3] Above these ranges adverse comment is very likely.

railway traffic in Norway. In this study, a social survey was conducted via telephone interview with 1503 respondents to determine people's reaction to vibration experienced within their own homes along with the prediction of vibration exposure in each respondent's property. Twelve study areas were selected with the aim of sampling participants for the study which were exposed to a wide range of vibration magnitudes (between 0 and 3 mm/s vibration velocity values ($v_{w,95}$)). The survey was presented as a study of neighbourhood quality followed by questions relating to annoyance caused by vibration from road and railway traffic. Vibration exposure in each residence ($v_{w,95}$) was estimated via a semi-empirical model (Madshus et al. 1996). Logistic and ordinal logit regression models were then used to develop exposure-response relationships for annoyance caused by road and railway induced vibration (see Figure 4). As can be seen from this figure, it was found that as the magnitude of vibration exposure increases so does the proportion of people reporting annoyance. Relationships were also reported for disturbance of activities such as communication and watching TV and also for how the perception of vibration manifested itself (i.e. rattling of furniture). An important finding from this study was that there were no significant differences in annoyance caused by road and railway vibration sources.

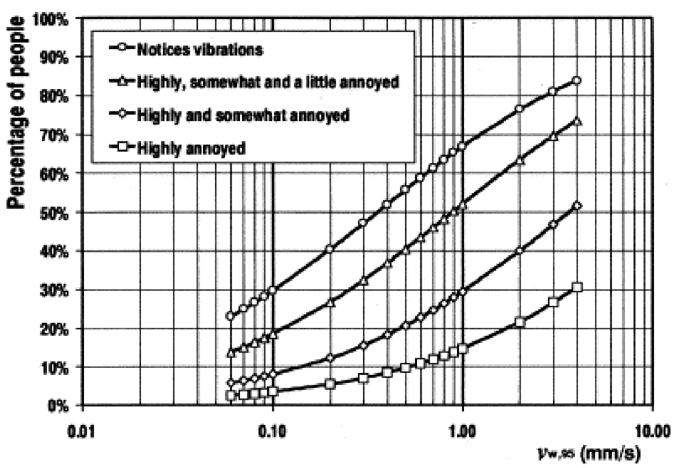

Figure 4 Exposure-response relationship for the cumulative percentage of people expressing different degrees of annoyance for a given vibration exposure (Klæboe et al. 2003).

In a recent study by the Transit Cooperative Research Program (Zapfe et al. 2009), a field study was implemented in North America and Canada with a view to developing criteria for acceptable levels of railway induced groundborne noise and vibration in residential buildings. The main aim of this study was to develop an exposure response relationship for predicting community annoyance due to groundborne vibration caused by railway systems. The study consisted of questionnaires administered via telephone with 1306 respondents along with measurements of external vibration. In this study, around 200 different noise and vibration metrics were considered as potential independent variables for an exposure-response relationship. It was found that all of the calculated metrics were highly correlated with each other and it was therefore concluded that any one of the metrics would be as good a predictor as any other of annoyance. Exposure-response relationships calculated using a logistic regression model were presented for groundborne vibration using highest magnitude of vibration velocity (*Vdb*) level in any given 1/3 octave band as a predictor. Frequency weightings were not applied to the vibration signals. Relationships were also presented for annoyance caused by groundborne noise using A-weighted vibration velocity (*Vdb*) level as a predictor. For the groundborne vibration and noise relationships, the exposure descriptor was expressed both as a mean value and also as a mean value plus two standard deviations; the second of these two methods is intended to represent the statistical highest magnitude event. For both groundborne noise and vibration, the proportion of people expressing a given annoyance was found to increase with noise and vibration exposure respectively.

2.3.3 Exposure time and sleep distubance

It has been suggested that exposure to vibration during the night elicits a higher annoyance response than exposure during the evening or day (Ohrström 1997; Peris et al. 2010) with a number of studies agreeing that environmental vibration from transportation sources causes disturbance to rest and sleep (Arnberg et al. 1990; Klæboe & Fyhri 1999; Peris et al. 2010). Field and laboratory studies (simulating railway vibrations with combined noise) have shown that railway vibrations have a significant impact on sleep quality (Öhrström et al. 2009; Ögren & Öhrström 2009).

2.3.4 Combined effects of vibration and noise

In a study conducted in Sweden (Ohrström & Skånberg 1996; Ohrström 1997), a field survey was carried out to investigate the effects of exposure to noise and vibration from railway traffic. The aim of this study with regards to vibration exposure was to compare annoyance due to noise in the presence of strong vibration levels with annoyance due to noise alone. In this study, areas were defined as having strong vibration if the vibration caused by railway traffic exceeded 2 *mm/s* and weak vibration if the vibration was less than 1 *mm/s*. It was found that in areas in which strong vibration was observed, a greater annoyance due to noise for a given exposure was elicited than in areas with weak vibration for the same noise exposure. It is suggested that, in order for annoyance to be equal, noise exposure should be 10 *dB(A)* lower in areas in which vibration in present. In a field study to investigate the combined effect of railway induced noise and vibration with regards to human response (Knall 1996), a social survey of 1056 respondents from 565 households was conducted along with measurements of internal noise and vibration. It is not clear from this paper how noise and vibration were measured. One of the main aims of this study was to investigate how noise influences the response to vibration. The results of this investigation suggest that the vibration perception threshold is increased in the presence of high noise exposure (> 55 *dB(A)*). Similar interactions between noise and vibration exposure have been observed in laboratory studies (H. V. C. Howarth &

Michael J Griffin 1991; H. Howarth & M.J. Griffin 1990; H. Howarth & M. J. Griffin 1990; Paulsen & Kastka 1995).

In a laboratory study to investigate the subjective response to combined noise and vibration exposure (H. Howarth & M. J. Griffin 1990), subjects were presented with simulations of noise and vibration caused by railway traffic. Six magnitudes of vibration and noise were considered. The study was split into three sessions in which subjects were presented with every possible combination of the noise and vibration stimuli. In the first session, subjects were asked to rate annoyance caused by vibration. In the second session subjects were asked to rate annoyance caused by noise. In the third session subjects were asked to rate annoyance cause by combined noise and vibration. The magnitude of noise exposure was found to have a significant effect on the on the judgment of annoyance caused by vibration. No significant effect of vibration exposure was found on the judgment of annoyance caused by exposure to noise. From the results of the third session, relationships were developed between annoyance and combined vibration and noise exposure.

In a similar study, laboratory tests were conducted with the aim of investigating the combined effects of noise and vibration (Paulsen & Kastka 1995). Four magnitudes of vibration and noise were presented to subjects in every possible combination and subjects were asked to make a judgment on reported intensity and annoyance and also whether the stimulus was perceived. The phrasing of the questions posed to subjects was found to have a strong influence on annoyance judgments. It was found that if subjects were asked to judge annoyance caused by vibration, then their annoyance judgments for a given vibration exposure were largely independent of the magnitude of noise exposure. However, it was found that if subjects were explicitly asked about annoyance due to noise exposure the magnitude of vibration exposure had an influence on their annoyance rating. Relationships were developed between annoyance and combined noise and vibration exposure. The gradient of the vibration exposure term in the relationship was found to be shallower that that reported by (H. Howarth & M. J. Griffin 1990).

2.3.5 Response to groundborne noise

As opposed to airborne noise, comparatively little research has been conducted on the human response to groundborne noise. The term groundborne noise generally refers to structurally reradiated noise in the 30 *Hz* to 250 *Hz* frequency range (Thompson 2009). In a survey of environmental noise and vibration caused by London Underground operations (Edwards 1996), it was estimated that around 56,000 residences in London were subject to groundborne noise levels of over L_{AmaxS} 40 *dB(A)* during a train pass. Laboratory and fields studies have been carried out to investigate human response to groundborne noise (Walker & Chan 1996; Vadillo et al. 1996). It was concluded from the field study (Vadillo et al. 1996) that at noise levels below L_{AmaxF} 32 *dB(A)* residents are not bothered by noise or vibration, at levels between 32 and 42 *dB(A)* some residents were bothered by noise but none by vibration, and at levels above 42 *dB(A)* all residents were bothered by both noise and vibration with vibration deemed to be the most annoying factor. In a complementary laboratory study (Walker & Chan 1996), it was found that annoyance due to groundborne noise was related to frequency content, level of the noise, and background noise levels. A study conducted in Norway (Aasvang et al. 2007) found that noise annoyance and self reported sleep disturbance were significantly related to groundborne noise levels.

3 DESCRIPTORS FOR VIBRATION EXPOSURE

3.1 INTRODUCTION

One of the key challenges in the formulation of an exposure-response relationship for this project is the determination of the most appropriate descriptor of vibration exposure. Broadly, the two main considerations which go into the selection of the most appropriate descriptor are the type of averaging and frequency weighting. This section will present the vibration exposure descriptors considered and provide recommendations for the most appropriate descriptor to be used for the final exposure-response relationship. The analyses presented in this section were conducted on the database of vibration measurements and responses collected for railway induced vibration. This database was considered the most appropriate to carry out the analyses presented in this section as it encompasses 932 responses and 497 estimations of internal vibration exposure which are based on measured data.

3.2 VIBRATION DESCRIPTORS

Numerous descriptors of vibration exposure were calculated from 24-hour acceleration time histories of internal vibration obtained using the methods described in Technical Reports 1 and Technical Report 3. Table 2 provides a summary of the vibration descriptors considered. For railway vibration, these descriptors were calculated for each case study using all train events recorded during a 24 hour period; a train event was defined by its 10 dB down points. Additional to the descriptors presented in Table 2, 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentiles were also calculated. Figure 5 shows the distribution of an acceleration time history of all train events recorded during a 24 hour period along with how the various descriptors calculated fall on the distribution. It can be seen from this figure that the descriptors considered cover the whole range of the distribution.

Descriptor	**Calculation**
Root mean square (*m/s²*)	$\ddot{x}_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^2}$
Root mean quad (*m/s²*)	$\ddot{x}_{rmq} = \sqrt[4]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$
Root mean hex (*m/s²*)	$\ddot{x}_{rmh} = \sqrt[6]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^6}$
Root mean oct (*m/s²*)	$\ddot{x}_{rmo} = \sqrt[8]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^8}$

Vibration dose value ($m/s^{1.75}$)	$\ddot{x}_{VDV} = \sqrt[4]{\frac{T}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$
Mean (m/s^2)	$\bar{x} = \frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)$
Standard deviation	$\sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\ddot{x}(n)-\bar{x})^2}$
Skewness	$S_k = \frac{1}{N\cdot\sigma^3}\sum_{n=1}^{N}(\ddot{x}(n)-\bar{x})^3$
Kurtosis	$K_t = \frac{1}{N\cdot\sigma^4}\sum_{n=1}^{N}(\ddot{x}(n)-\bar{x})^4$
Peak particle acceleration (m/s^2)	Maximum deviation of the time series from the mean
L_{max} (*dB re 1x10*$^{-6}$ m/s^2)	Maximum 1 second exponential average *rms* over an event
L_{eq} (*dB re 1x10*$^{-6}$ m/s^2)	$L_{eq} = 20\log_{10}\left(\frac{\ddot{x}_{rms}}{1E-6}\right)$
L_E (*dB re 1x10*$^{-6}$ m/s^2)	$L_E = 20\log_{10}\left(\frac{\ddot{x}_{rms}}{1E-6}\right)+10\log_{10}(T)$

Table 2 Summary of vibration exposure descriptors considered. Where $\ddot{x}(n)$ an acceleration time series, *N* is the number of samples in the acceleration time series, and *T* is the duration of the event in seconds.

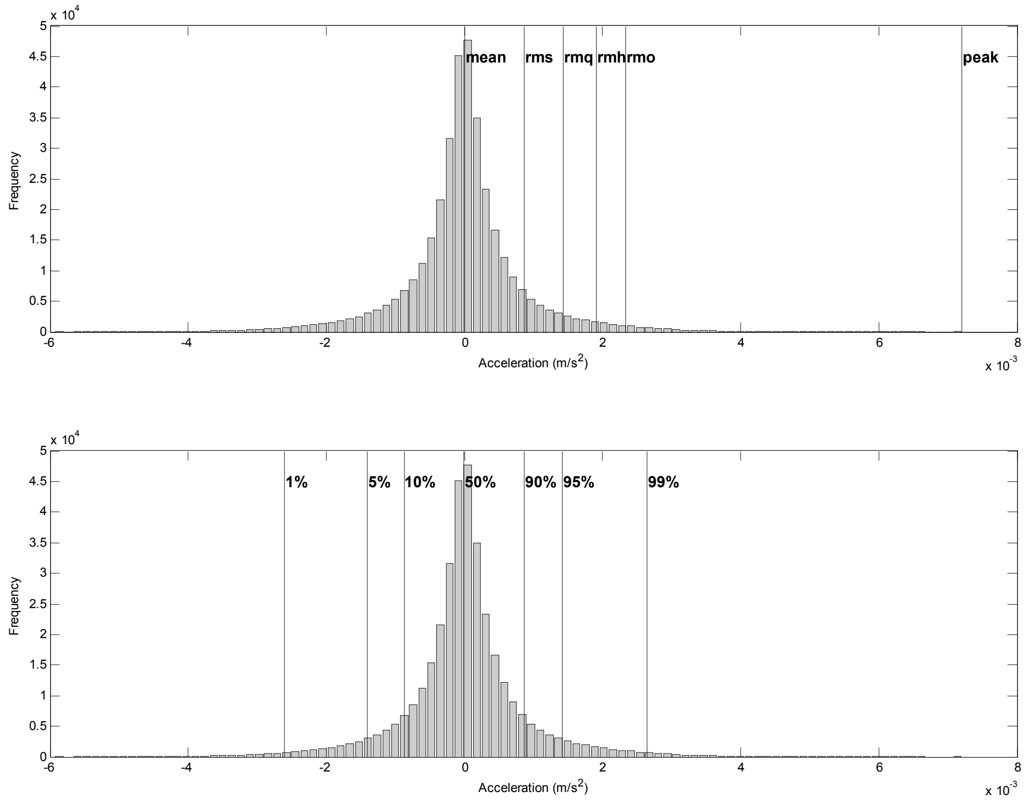

Figure 5 Distribution of 24 hour acceleration time history for railway vibration.

To attempt to reduce the number of descriptors considered, a principal component analysis was carried out on the descriptor space. Figure 6 shows the amount of variance explained by each of the calculated principal components. It can be seen from this figure that more than 75% of the variance in the component space is accounted for in the first principal component. Figure 7 shows the principal component coefficients for each of the calculated metrics for the first two principal components. These coefficients indicate the weighting each descriptor has on a principal component. It can be seen from this figure that, apart from the skewness, kurtosis, and arguably the mean and 50th percentile, each of the descriptors considered have a similar weighting on the first principal component indicating that the descriptors are well correlated with each other (please note, because of this many of the labels in this figure are overlapped).

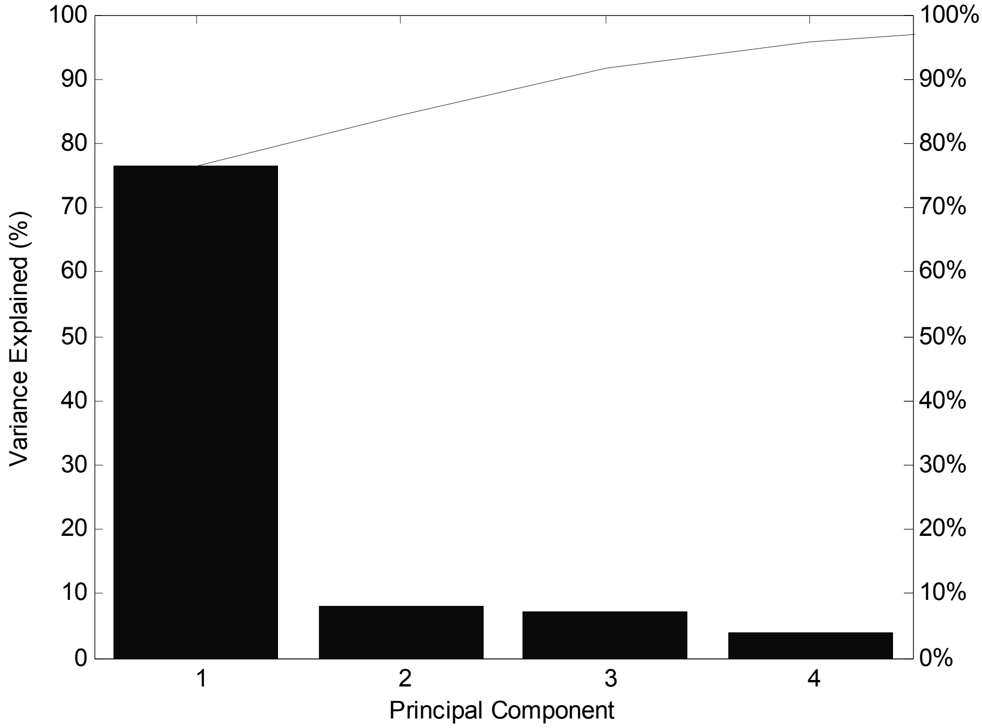

Figure 6 Scree plot of the percentage of variance explained by each principal component.

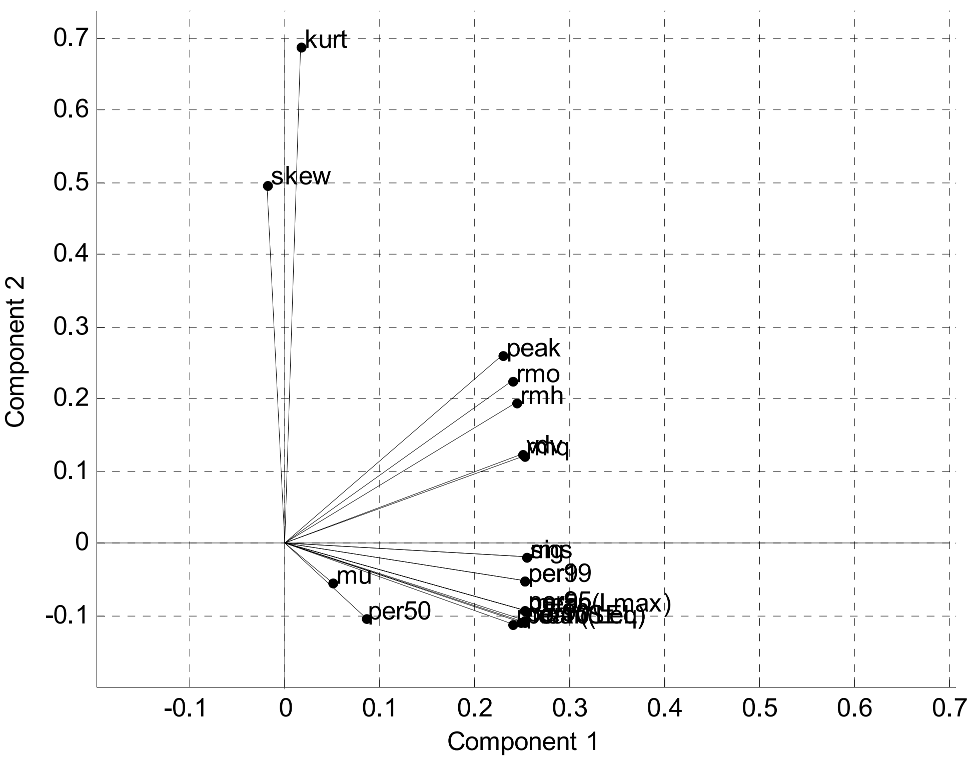

Figure 7 Principal component coefficients for each of the calculated metrics.

The results of the principal component analysis can be verified by examining the Spearman's rank correlation coefficient between the different vibration exposure descriptors and self reported annoyance. Spearman's rank correlation coefficient was used as the response data is categorical. It can be seen from Table 3 that, excluding skewness, kurtosis, and mean, each of the vibration exposure descriptors considered exhibits a similar magnitude of correlation with self reported annoyance.

Descriptor	5-point scale	11-point scale
Root mean square (*m/s²*)	0.08*	0.09*
Root mean quad (*m/s²*)	0.09*	0.08*
Root mean hex (*m/s²*)	0.10**	0.09*
Root mean oct (*m/s²*)	0.10**	0.09*
Vibration dose value ($m/s^{1.75}$)	0.10**	0.10**
Mean (m/s^2)	--	--
Standard deviation	0.08*	0.09*
Skewness	--	--
Kurtosis	--	--
Peak particle acceleration (m/s^2)	0.11**	0.10**
L_{max} ($dB\ re\ 1x10^{-6}\ m/s^2$)	0.10**	0.10**
L_{eq} ($dB\ re\ 1x10^{-6}\ m/s^2$)	0.08*	0.11**
SEL ($dB\ re\ 1x10^{-6}\ m/s^2$)	0.08*	0.12**

Table 3 Spearman's correlation coefficient between different descriptors of 24-hour vibration exposure and self reported annoyance (N = 751). * $p<0.05$, ** $p<0.01$, *** $p<< 0.001$, -- : not significant.

The results presented in this section suggest that, for the dataset of railway induced vibration under analysis, the type of averaging used is unimportant. This result is consistent with similar studies into the human response to groundborne vibration (Zapfe et al. 2009). The choice of averaging method is therefore dictated by a number of factors including ease of calculation, interpretability, current practice, and the measurement capability of the user of the exposure-response relationship. BS 6472-1:2008 suggests the use of VDV ($m/s^{1.75}$) for reporting whole body vibration exposure and ISO 2631-1:1997 suggests the use of *rms* acceleration (m/s^2). The exposure-response relationships presented later in this report will therefore be presented in terms of both *VDV* and *rms* acceleration.

3.3 FREQUENCY WEIGHTINGS AND DIRECTION OF EXCITATION

When considering frequency weightings, it is important to ensure that respondents were exposed to excitations with a range of different frequency content. Figure 8 and Figure 9 show boxplots of the distribution of *rms* acceleration in each 1/3 octave band for 751 estimates of internal vibration exposure in the vertical and horizontal directions respectively. It can be seen from these figures that each 1/3 octave band exhibits a wide dynamic range of exposures. These magnitudes are also compared to the perception threshold base curves presented in previous versions of BS 6472-1. It can be seen that these exposures are generally at or below the thresholds indicated by the base curves. However, as was highlighted in previous sections, the perception threshold base curves are derived from laboratory studies and therefore may not be directly applicable to vibration perception in residential environments.

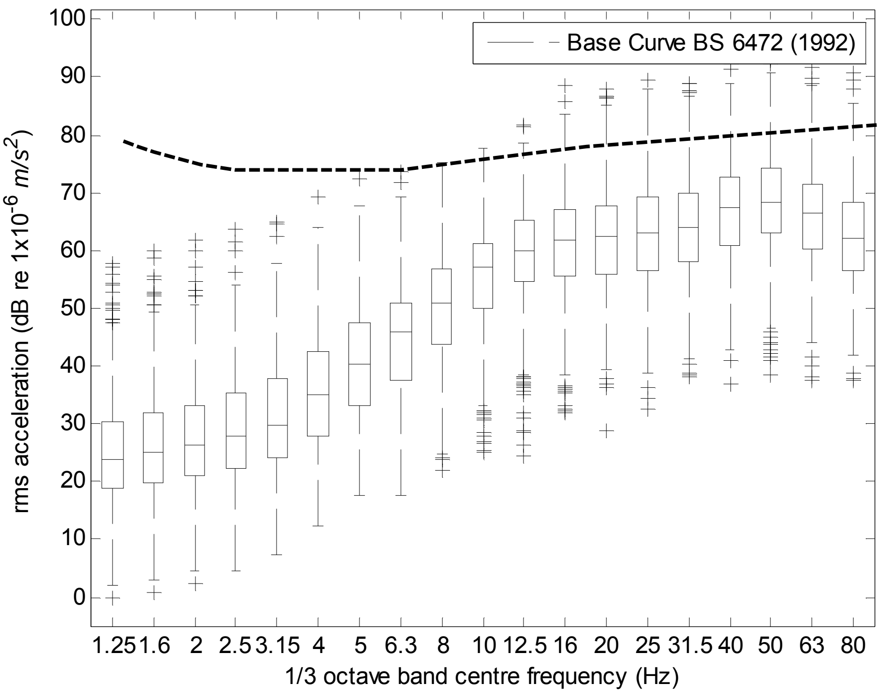

Figure 8 Boxplot illustrating the distribution of *rms* acceleration in 1/3 octave bands in the vertical direction for 751 estimations of internal vibration exposure. Also shown is the vibration perception base curve from (the now superseded) BS 6472-1:1992.

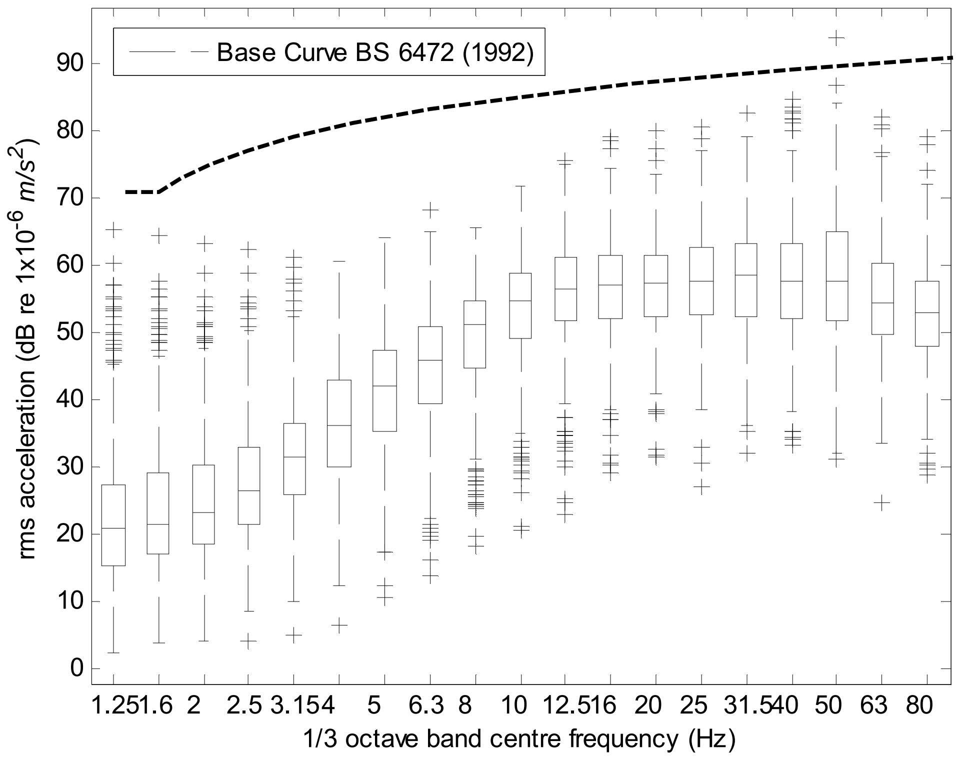

Figure 9 Boxplot illustrating the distribution of *rms* acceleration in 1/3 octave bands in the horizontal direction for 751 estimations of internal vibration exposure. Also shown is the vibration perception base curve from(the now superseded) BS 6472- 1:1992.

As well as a wide range of exposure magnitudes, it is also important to ensure respondents have been exposed to excitations with different spectral content. To determine the range of frequency content to which respondents were exposed, spectral centroid was calculated for 496 estimations of internal vibration exposure in the vertical and horizontal directions. Spectral centroid is a single figure measure of the spectral content of a signal. High values of spectral centroid indicate that energy is concentrated in the high frequency components of the spectrum and whereas low values indicate energy is concentrated in the low frequency components of the spectrum. Spectral centroid is defined by the equation below:

$$f_{cent} = \frac{\sum_{n=1}^{N} f(n) \cdot \left|\ddot{X}(n)\right|}{\sum_{n=1}^{N} \left|\ddot{X}(n)\right|}$$

Equation 6

Where *f(n)* is the centre frequency of the n^{th} spectral bin (*Hz*) and $\left|\ddot{X}(n)\right|$ is the magnitude Fourier coefficient of the n^{th} spectral bin.

Figure 10 shows the distribution of spectral centroid for 496 estimations of 24-hour railway induced vibration in the vertical direction. Figure 11, Figure 12, and Figure 13 show magnitude Fourier spectra of 24-hour internal vibration exposures with spectral centroids of 27 *Hz*, 43 *Hz,* and 64 *Hz* respectively. Figure 14, Figure 15, Figure 16, and Figure 17 show the same results for vibration in the horizontal direction. The broad spread in spectral centroid values indicates that respondents were exposed to excitations with a range of different spectral content indicating that the data generated by this project may be appropriate for an investigation into different frequency weightings. The cause of the peak at around 49 *Hz* in the spectrum shown in Figure 13 is unknown, however it can be seen from the boxplot in Figure 8 that there is no overall dominant peak in the exposures around that frequency.

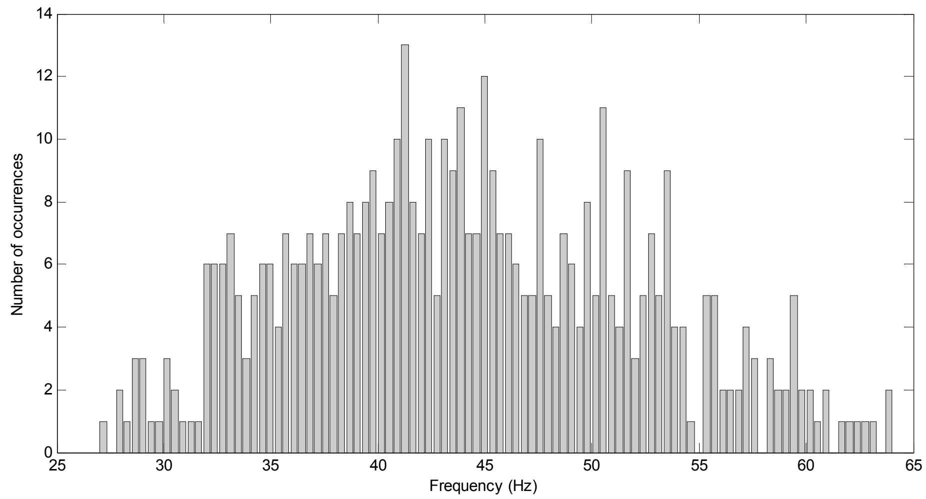

Figure 10 Distribution of spectral centroid for 496 estimations of internal vibration exposure in the vertical direction.

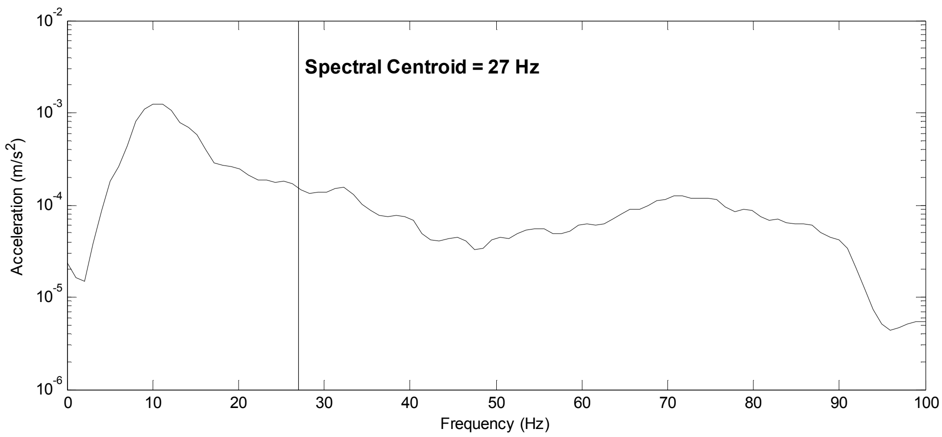

Figure 11 Magnitude Fourier spectrum of 24-hour internal vibration exposure in the vertical direction exhibiting 27 *Hz* spectral centroid.

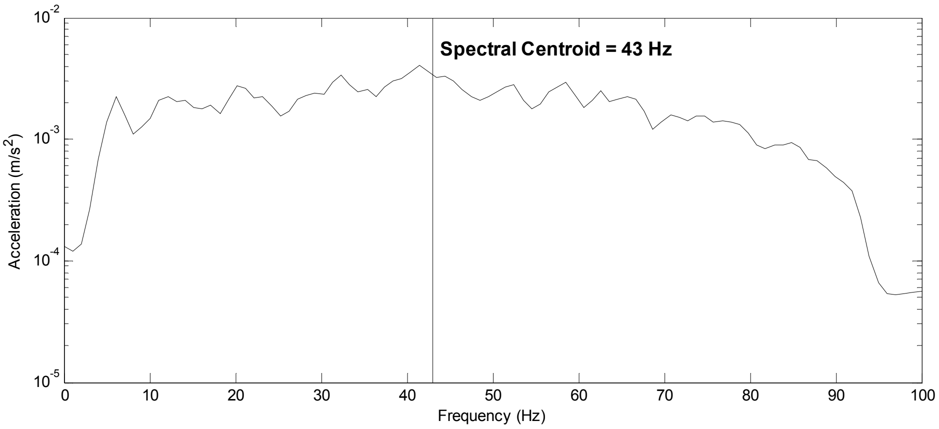

Figure 12 Magnitude Fourier spectrum of 24-hour internal vibration exposure in the vertical direction exhibiting 43 *Hz* spectral centroid.

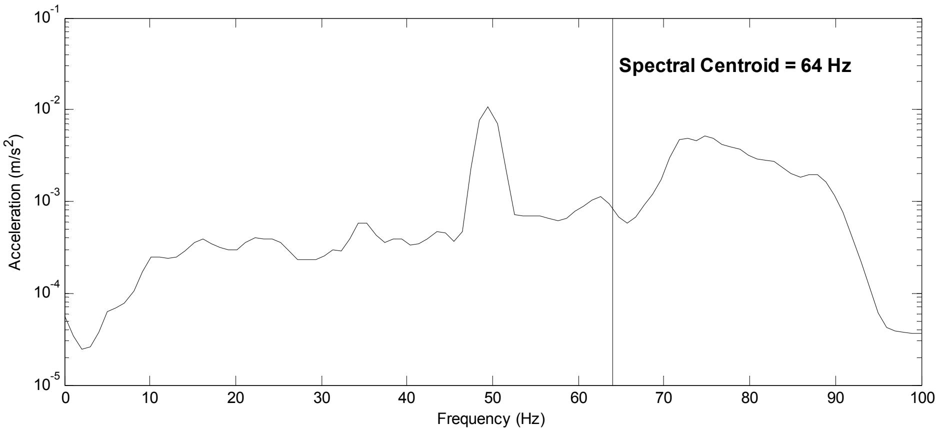

Figure 13 Magnitude Fourier spectrum of 24-hour internal vibration exposure in the vertical direction exhibiting 64 *Hz* spectral centroid.

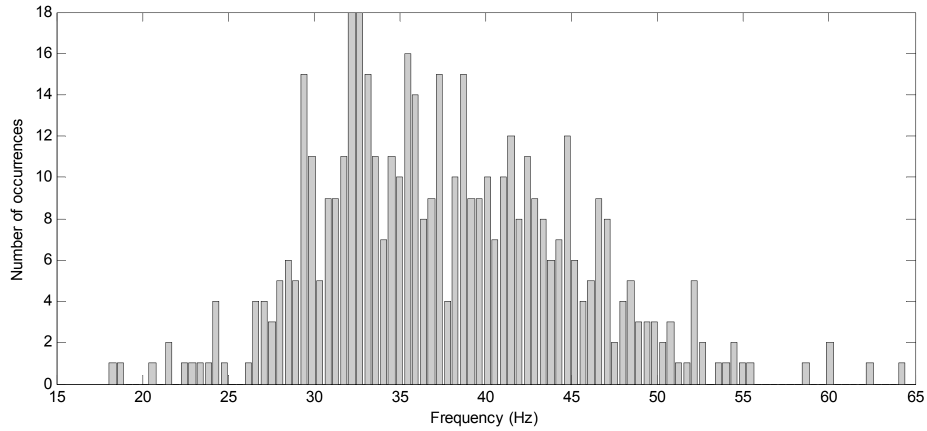

Figure 14 Distribution of spectral centroid for 496 estimations of internal vibration exposure in the horizontal direction.

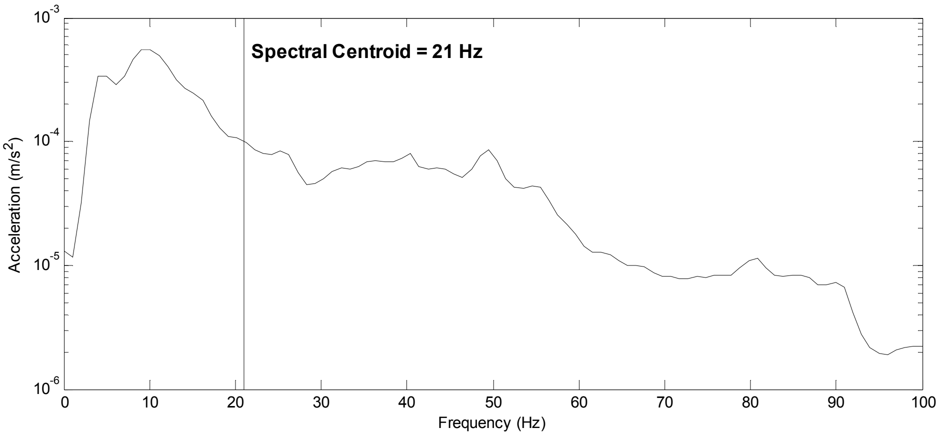

Figure 15 Magnitude Fourier spectrum of 24-hour internal vibration exposure in the horizontal direction exhibiting 21 *Hz* spectral centroid.

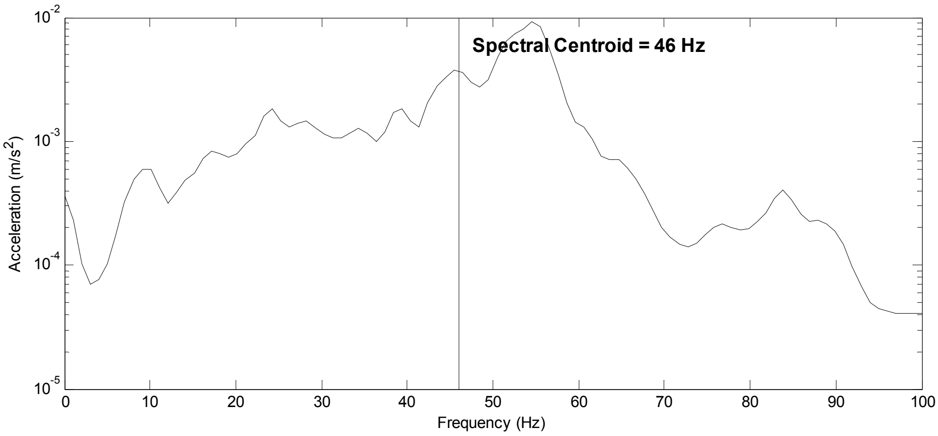

Figure 16 Magnitude Fourier spectrum of 24-hour internal vibration exposure in the horizontal direction exhibiting 46 *Hz* spectral centroid.

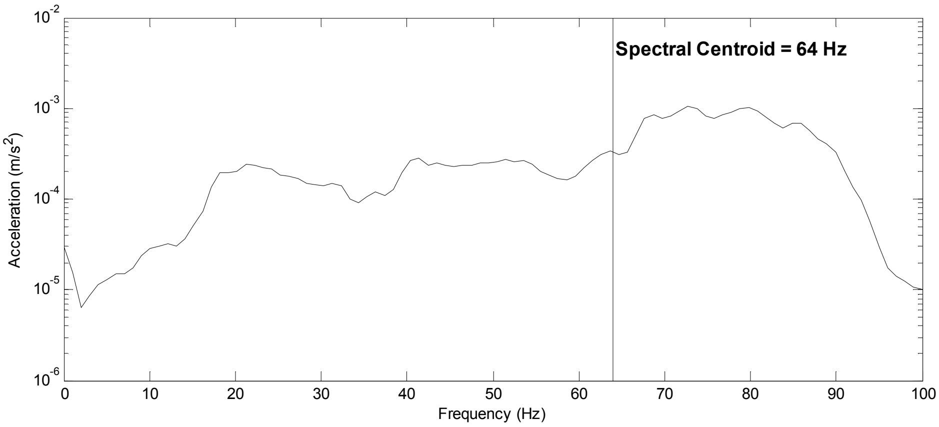

Figure 17 Magnitude Fourier spectrum of 24-hour internal vibration exposure in the horizontal direction exhibiting 64 *Hz* spectral centroid.

To investigate the relationship between frequency weightings and direction of excitation with respect to the annoyance data collected in this project, Spearman's correlation coefficient was calculated for self reported annoyance and vibration exposure expressed in terms of *rms* in the vertical and horizontal directions for acceleration, velocity, in 1/3 octave bands, and using the appropriate frequency weightings defined in BS 6472-1:2008, ISO 2631-1:1997, and ISO 2631-2:2003 (see section 2.3.1).

The frequency weightings were realized by means of a digital infinite impulse response (IIR) filter response implemented in Matlab as defined in BS 6841:1987 and ISO 8041:2005. To determine that the filters have been implemented correctly, the magnitude frequency response of the filters has been checked against the asymptotic approximations provided in the relevant standards. It can be seen from Figure 18 that the IIR implementation of the W_b weighting filter agrees well with the asymptotic approximation provided in BS 6472-1:2008.

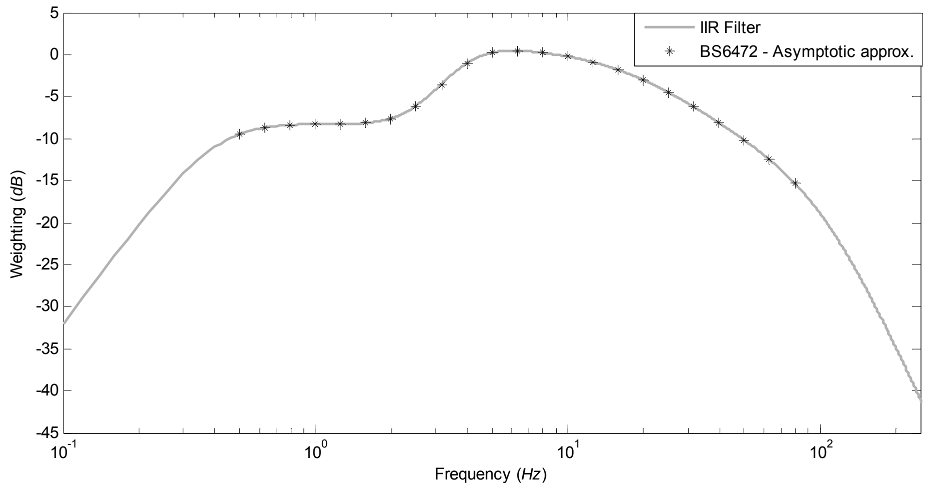

Figure 18 Magnitude frequency response of the IIR implementation of the W_b weighting filter compared with the asymptotic approximation presented in BS6472-1:2008.

As time domain parameters are such as *VDV* and peak are under consideration in this project, it is important that the weighting filters do not introduce a significant amount of phase distortion. Figure 19 shows the phase response of the IIR implementation of the W_b weighting filter. It can be seen from this figure that the phase deviation is broadly proportional to frequency indicating a constant time delay and no significant phase distortion. This curve is similar to the phase response of the weighting filters reported in ISO 8041:2005.

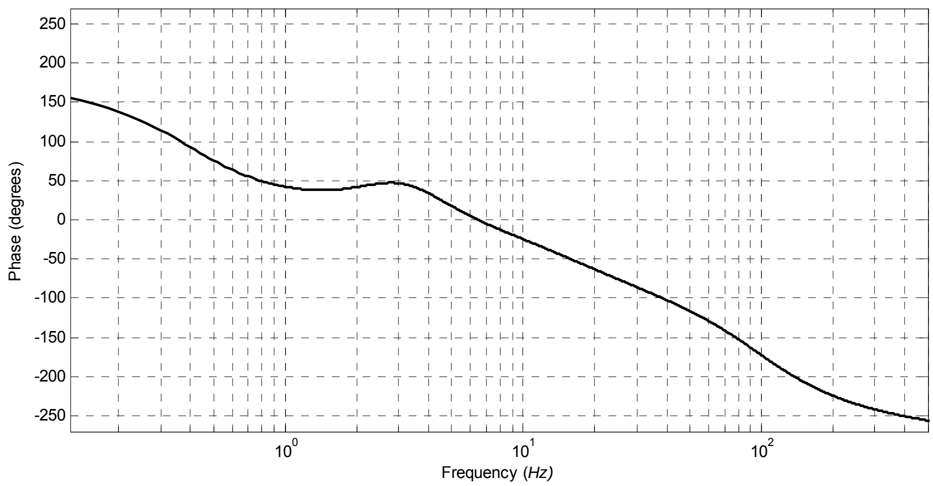

Figure 19 Phase response of the IIR implementation of the W_b weighting filter.

Acceleration time histories were converted to velocity by means of the equation below:

$$\dot{X}(f) = \frac{\ddot{X}(f)}{j\omega}$$ **Equation 7**

Where $\dot{X}(f)$ is the complex velocity Fourier spectrum, $\ddot{X}(f)$ is the complex acceleration Fourier spectrum, $\omega = 2 \cdot \pi \cdot f$ where *f* is frequency in *Hz.*

By taking the inverse Fourier transform of $\dot{X}(f)$, the velocity time history $\dot{x}(t)$ is obtained. A high pass filter at 2 *Hz* was applied to the calculated velocity time histories to remove the low frequency artefacts associated with this type of transformation (Mercer 2006).

Table 4 presents Spearman's correlation coefficient between the two annoyance rating scales and *rms* vibration calculated using different frequency weightings in the vertical and horizontal directions. It can be seen from this table that an improvement in correlation is observed when the appropriate frequency weightings are applied in both the vertical and horizontal directions of excitation. Similarly, expressing vibration exposure in terms of velocity results in a higher correlation than if the exposure is expressed in terms of acceleration; this result is perhaps unsurprising as, for vibration in the vertical direction, the frequency weighting curves approximate velocity at frequencies above around 16 *Hz*. It can also be noted that vibration exposure in the horizontal direction exhibits a higher correlation than vibration in the vertical direction expressed using the same descriptor.

	5-point scale	**11-point scale**
Vertical acceleration (*m/s*^{2})	0.08 *	0.09 *
Weighted vertical acceleration (W_b) (*m/s*^{2})	0.12 ***	0.12 ***
Weighted vertical acceleration (W_k) (*m/s*^{2})	0.13 ***	0.13 ***
Weighted vertical acceleration (W_m) (*m/s*^{2})	0.12**	0.13***
Vertical velocity (*m/s*)	0.13 ***	0.13 ***
Horizontal acceleration (*m/s*^{2})	0.08 *	0.11 **
Weighted Horizontal acceleration (W_d) (*m/s*^{2})	0.17 ***	0.18 ***
Weighted Horizontal acceleration (W_m) (*m/s*^{2})	0.15***	0.16***
Horizontal velocity (*m/s*)	0.14 ***	0.16 ***

Table 4 Spearman's correlation coefficient between vibration exposure expressed as *rms* with different frequency weightings and reported annoyance (N = 751). * $p<0.05$, ** $p<0.01$, *** $p< 0.001$.

Figure 20 and Figure 21 present Spearman's correlation coefficients between self reported annoyance and 24-hour *rms* (m/s^2) internal vibration exposure in individual 1/3 octave bands in the vertical and horizontal directions respectively. It can be seen from Figure 20 that there is a clear peak in the correlation between vibration exposure in the vertical direction and self reported annoyance when vibration exposure is expressed in the 6.3 *Hz* and 8 *Hz* 1/3 octave bands. Similarly, Figure 21 exhibits a peak in the correlation at 8 *Hz* as well as a peak at the 3.15 *Hz* 1/3 octave band. Comparing the maximum correlation coefficients in these figures with the correlation coefficients presented in Table 4, it can be seen that an improvement in the magnitude of the correlation can be achieved by expressing the vibration exposure in 1/3 octave bands.

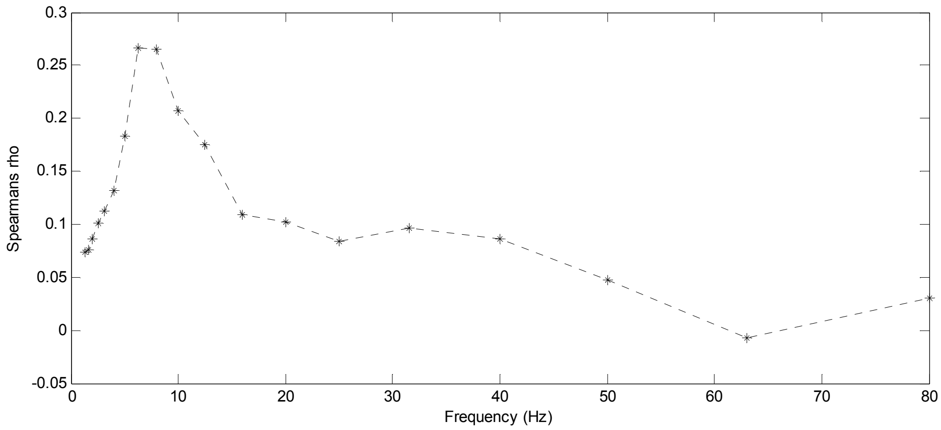

Figure 20 Spearman's correlation coefficient between self reported annoyance and 24-hour vertical rms acceleration in 1/3 octave bands (N = 751).

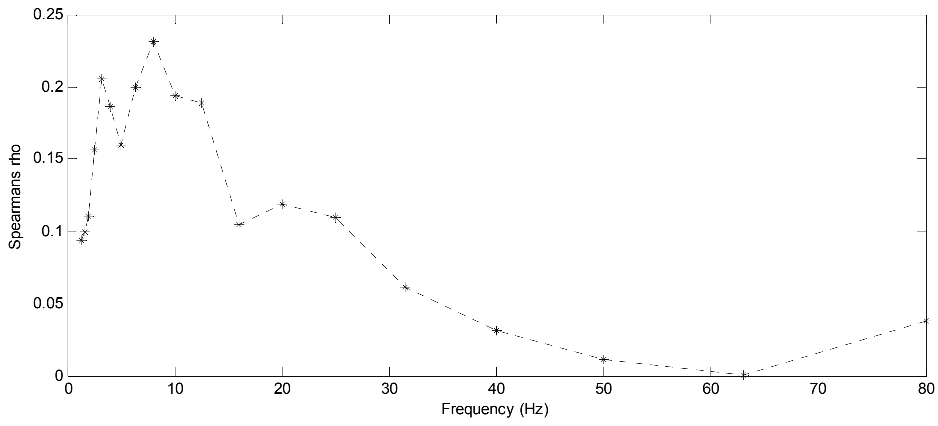

Figure 21 Spearman's correlation coefficient between self reported annoyance and 24-hour horizontal rms acceleration in 1/3 octave bands (N = 751).

Figure 22 and Figure 23 provide a comparison between the Spearman's correlation coefficients in 1/3 octave bands and the W_b and W_d weighting curves for vertical and horizontal vibration respectively In these figures, the Spearman's correlation coefficients have been normalized so that the maximum correlation has a value of one for the purpose of comparison with the frequency weighting curves. It can be seen from Figure 22 that the frequency dependent correlation coefficients for the vertical direction show similar frequency dependence as the W_b weighting curve (although it should be appreciated that they are essentially different phenomena). The correlation coefficients for horizontal excitation agree less well with the W_d weighting curve (see Figure 23) than the vertical excitation case. The discrepancy in the horizontal direction may be explained by the absence of energy in the 1 – 2 *Hz* region of the spectrum where the W_d weighting curve exhibits the highest weighting (see Figure 15, Figure 16, and Figure 17).

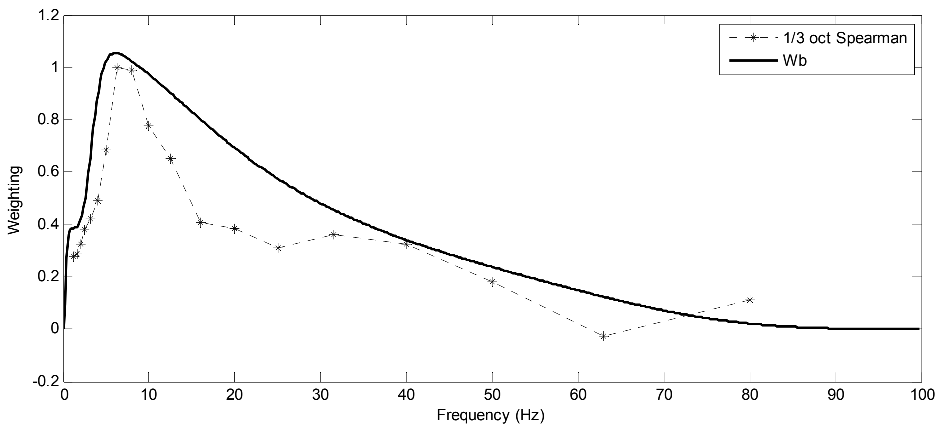

Figure 22 Spearman's correlation coefficient between self reported annoyance and 24-hour vertical rms acceleration in 1/3 octave bands compared with W_b weighting curve (correlation coefficients normalized) (N = 751).

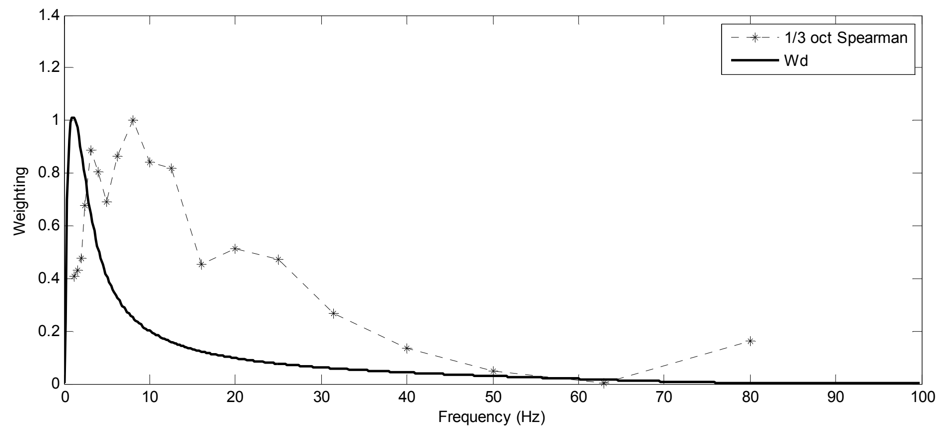

Figure 23 Spearman's correlation coefficient between self reported annoyance and 24-hour horizontal rms acceleration in 1/3 octave bands compared with W_d weighting curve (correlation coefficients normalized) (N = 751).

3.4 OTHER FACTORS CONSIDERED

Additional to the vibration descriptors detailed in the previous sections, a number of other factors were considered as correlates to self reported annoyance to railway induced vibration. The mean and maximum duration (*s*) of all train passes in a 24-hour period were calculated for each case study. The duration of a train pass was defined as its 10 *dB* down points. The number of train passes during a 24-hour period was considered as well as the distance of each respondent's property from the source. Only the distance of a respondent's property from the source was found to be significantly correlated with self reported annoyance ($\rho = -0.08$, $p < 0.05$ for the five point scale and $\rho = -0.11$, $p < 0.01$); it can be noted that the magnitude of this correlation is of a similar magnitude to that of unweighted acceleration (see Table 4).

3.5 RESPONSE SCALE

As can be seen from Table 3 in section 3.2, the 5-point and 11-point annoyance scale display a similar magnitude of correlation with vibration exposure. The exposure-response models presented in this report have been calculated using the 5-point semantic scale. Any respondent stating that they cannot feel vibration are recoded to the lowest category of the annoyance scale (i.e. "Not at all") (H. Miedema & Oudshoorn 2001).

3.6 SUMMARY AND RECOMMENDATIONS

This section has aimed to determine the most effective descriptor of vibration exposure with regards to self reported annoyance. The effectiveness of a descriptor has been assessed using Spearman's rank correlation coefficient. It was found that the type of averaging used to express vibration exposure was largely unimportant as descriptors calculated using different averaging methods were found to be highly correlated with each other. The choice of averaging method is therefore dictated by ease of calculation, interpretability, current practice, and measurement capability of the user of the exposure-response relationship. Exposure-response relationships presented later in this report will therefore be reported using *VDV* and *rms* acceleration in line with current British and International Standards. This section has also explored the effect of expressing vibration exposure using different frequency weightings. It has been found that the application of the frequency weightings recommended in BS 6472-1:2008, ISO 2631-1:1997, and ISO 2631-2:2003 leads to an increase in the magnitude of correlation between vibration exposure and self reported annoyance. Vibration exposure has been calculated in 1/3 octave bands and it has been found that by expressing vibration exposure in the 6.3 *Hz* and 8 *Hz* an improvement in correlation with self reported annoyance can be achieved over the frequency weightings recommended in National and International Standards. Vibration exposure expressed in 1/3 octave bands have not been used for the derivation of exposure-response relationships as these descriptors describe only a fraction of the vibration energy to which respondents were exposed and therefore do not provide a measure of the overall exposure. It should be noted that the results presented in this section are only directly applicable to the database from which they were derived, however the improvement in correlation observed by expressing vibration exposure in 1/3 octave bands suggests that further research into frequency weightings could yield a more robust descriptor for the human response to vibration in residential environments than those which are recommended in current standards.

4 MODELS FOR EXPOSURE-RESPONSE RELATIONSHIPS

4.1.1 INTRODUCTION

A major consideration associated with the formulation of exposure-response relationships for this project is the form of the statistical model used to derive the relationships. As the vibration exposure data is continuous and the response data collected via the social survey is categorical, ordinary least squares regression models cannot be used. When the dependent variable of a regression model is categorical, the assumptions of ordinary least squared regression are violated (Weisberg 2005; Long 1997; Agresti 1990). There are a number of well established methods for regressing continuous data onto categorical data which overcome the problems associated with OLS.

Based upon published literature, current best practice for the determination of exposure-response relationships relating self reported annoyance to exposure to an environmental stressor appears to be that proposed by (Groothuis-Oudshoorn & H. Miedema 2006). As opposed to previous exposure response relationships for noise which deal with proportions (Schultz 1978), the response distribution is fully described in this model as a function of an exposure descriptor such that any measure that summarises the distribution can be calculated from the model. This method has previously been applied to establish the EU-endorsed (EC/DG Environment. 2002) relationships between transportation noise exposure and annoyance (H. Miedema & Oudshoorn 2001). Other studies aiming to derive exposure-response relationships for the human response to vibration in residential environments have used similar statistical models (Klæboe et al. 2003; Zapfe et al. 2009), namely logistic regression and ordinal logit models.

Although not essential for the understanding of the exposure-response relationships presented in this report, a brief description of these models will be provided. These models may not be well known among the vibration and noise community and therefore may be of some interest. As a starting point, a binary regression model will be presented to highlight the short comings of using ordinary least squares regression to regress continuous data onto a categorical variable. This model will be used to formulate exposure-response relationships for responses which elicit a binary outcome. The binary regression model will then be extended to an ordinal regression model which will be used to formulate exposure-response relationships for responses which elicit an ordinal categorical outcome.

4.1.2 BINARY PROBIT

Figure 24 shows the regression of a continuous independent variable on a binary dependent variable using ordinary least squares regression. The regression line is of the form:

$$y_i = \mathbf{x_i}\boldsymbol{\beta} + \varepsilon \qquad \textbf{Equation 8}$$

where $\mathbf{x_i}$ is a vector of values for the i^{th} observation, $\boldsymbol{\beta}$ is a vector of parameters to be estimated, and ε is the error term.

The conditional value of y given x is $E\left(y_i \middle| \mathbf{x_i}\right) = \mathbf{x_i}\boldsymbol{\beta}$ which is shown as the solid line in Figure 24.

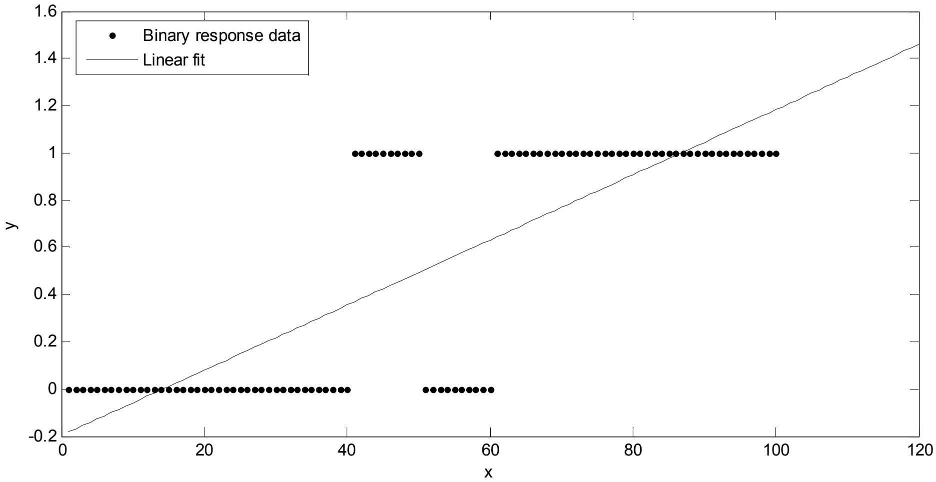

Figure 24 Ordinary least squares regression of a continuous independent variable on a binary dependent variable.

This figure illustrates one of the major the shortcomings of using ordinary least squares regression to handle categorical dependent variables. When y is a binary variable, the expectation of y_i conditional on $\mathbf{x_i}$ is the probability that $y_i = 1$:

$$\begin{aligned} E\left(y_i \middle| \mathbf{x_i}\right) &= \Pr\left(y_i = 1 \middle| \mathbf{x_i}\right) \\ &= \mathbf{x_i}\boldsymbol{\beta} \end{aligned} \qquad \textbf{Equation 9}$$

As can be seen from Figure 24, by fitting an ordinary least squares regression model to this data, $\Pr\left(y_i = 1 \middle| \mathbf{x_i}\right)$ can take on values above 1 and below 0.

To overcome this issue, a latent variable, y_i^*, is assumed to exist such that:

$$y_i^* = \mathbf{x_i}\boldsymbol{\beta} + \varepsilon \qquad \textbf{Equation 10}$$

The latent variable y_i^* is linked to the observed variable y_i by the following relationship:

$$y_i = \begin{cases} 1 & if\ y_i^* > \tau \\ 0 & if\ y_i^* \le \tau \end{cases} \qquad \textbf{Equation 11}$$

where τ is a category cutpoint. For the case of a binary dependent variable, $\tau = 0$.

It follows that:

$$\begin{aligned}\Pr\left(y=1\middle|\mathbf{x}\right) &= \Pr\left(y^*>0\middle|\mathbf{x}\right)\\ &= \Pr\left(\mathbf{x}\boldsymbol{\beta}+\varepsilon>0\middle|\mathbf{x}\right)\\ &= \Pr\left(\varepsilon>-\mathbf{x}\boldsymbol{\beta}\middle|\mathbf{x}\right)\\ &= \Pr\left(\varepsilon\le\mathbf{x}\boldsymbol{\beta}\middle|\mathbf{x}\right)\end{aligned}$$ **Equation 12**

If the error term of the latent variable is assumed to be normally distributed:

$$\Pr\left(y=1\middle|\mathbf{x}\right)=\Phi(\mathbf{x}\boldsymbol{\beta})$$ **Equation 13**

where Φ is the cumulative normal distribution function.

This model is termed a "binary probit model". The $\boldsymbol{\beta}$ parameters of this model can then be estimated via maximum likelihood. The likelihood function for this model is:

$$L\left(\boldsymbol{\beta}\middle|\mathbf{y},\mathbf{X}\right)=\prod_{y=1}\Phi(\mathbf{x}\boldsymbol{\beta})\prod_{y=0}\left[1-\Phi(\mathbf{x}\boldsymbol{\beta})\right]$$ **Equation 14**

Figure 25 show the application of the binary probit model to the data shown in Figure 24. It can be seen that, unlike the case of ordinary least squares regression, this model is bound between zero and one.

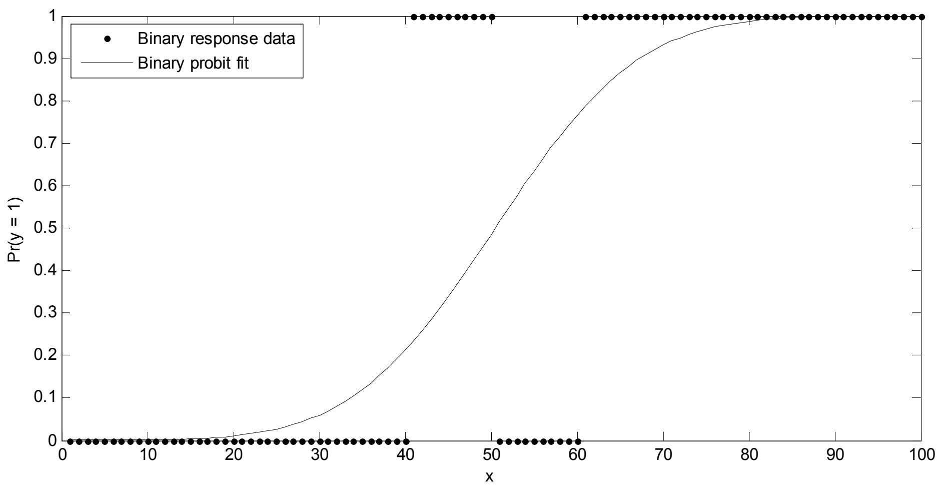

Figure 25 Binary probit regression of a continuous independent variable on a binary dependent variable.

The basic ideas of this model can be extended to polychotomous categorical variables which will be shown in the following section.

4.1.3 *GROUPED REGRESSION MODEL*

In this section, an ordinal probit model with fixed thresholds is presented which is adapted from (Groothuis-Oudshoorn & H. Miedema 2006). This case of an ordinal probit model is termed a "*grouped regression model*". This model will be described in terms of vibration exposure and self reported annoyance recorded on a scale of 0 to 100. The category cutpoints τ_j are assumed to be fixed and known. Annoyance response scales with any number of categories can be rescaled to a range of 0 – 100 using the following relation:

$$\tau_j = 100 j / m$$ **Equation 15**

where *j* is the rank number of the category with 0 assigned to the lowest category and *m* is the total number of categories. The annoyance data, *A*, is then centered to the midpoints of these categories.

For the data presented in this report, self reported annoyance (A_i) was recorded on an ordinal scale with *J* categories. As with the binary regression model outlined in the previous section, a latent variable A^* which is assumed to be a linear combination of vibration exposure (*X*) and a random error component ε is assumed to underlie the categorical annoyance variable *A*.

$$A_i^* = \mathbf{X_i \beta} + \varepsilon$$ **Equation 16**

where $\boldsymbol{\beta}$ is a vector of parameters to be estimated.

The latent variable A_i^* is linked to the observed variable A_i by the following relationship:

$$A_i = \begin{cases} 0 & \text{if } A_i^* < 0 \\ A_i^* & \text{if } A_i^* \in [0,100] \\ 100 & \text{if } A_i^* > 100 \end{cases}$$ **Equation 17**

It is common practice to define annoyance as the proportion of people who respond above a certain annoyance level *C* (H. Miedema & Oudshoorn 2001). Three values of *C* are often reported: *C* = 72 (*percent highly annoyed*), *C* = 50 (*percent annoyed*), and *C* = 28 (*percent slightly annoyed*). The probability that an individual exposed to a certain magnitude of exposure (*V*) responds with an annoyance level above a cutoff *C* ($p_C(V)$) can be expressed as:

$$\begin{aligned} p_C(V) &= \text{Prob}(A^* \geq C) \\ &= \text{Prob}(\mathbf{X\beta} + \varepsilon \geq C) \\ &= \text{Prob}(\varepsilon \geq C - \mathbf{X\beta}) \end{aligned}$$ **Equation 18**

where Φ represents the cumulative normal distribution function and σ represents the standard error.

As with the binary regression model, the error term ε is assumed to be normally distributed:

$$p_C(V) = \text{Prob}(1 - \Phi\left[\frac{C - \mathbf{X\beta}}{\sigma}\right])$$ **Equation 19**

The parameters of this model can be estimated via maximum likelihood. The likelihood function for this model is:

$$L(\boldsymbol{\beta}, \boldsymbol{\tau} | \mathbf{y}, \mathbf{X}) = \prod_{j=1}^{J} \prod_{y_i = j} \left[\Phi\left(\tau_j - \mathbf{x_i}\boldsymbol{\beta}\right) - \Phi\left(\tau_{j-1} - \mathbf{x_i}\boldsymbol{\beta}\right) \right]$$ **Equation 20**

where τ_j it the cutpoint of the j^{th} category of the ordinal dependent variable.

By varying the cutoff point *C*, the distribution of responses at different annoyance levels can be expressed.

The 95% upper and lower confidence limits of this model at a given exposure level *X* can be given as:

$$C_{LU} = \mathbf{x}^{\mathbf{T}}\mathbf{b} \pm Z\sqrt{(\mathbf{x}^{\mathbf{T}}\boldsymbol{\Sigma}_b\mathbf{x})}$$ **Equation 21**

where $\mathbf{x}^{\mathbf{T}}$ is the transpose of the vector (1, *X*), $\boldsymbol{\Sigma}_b$ is the covariance matrix of the $\boldsymbol{\beta}$ coefficients, and **b** is a vector of the estimates of the $\boldsymbol{\beta}$ coefficients. Z = 1.96 for a standard normal distribution.

The confidence limits for $p_C(V)$ can then be expressed as:

$$1 - \Phi\left(\frac{C - C_{L,U}}{\sigma}\right)$$ **Equation 22**

4.1.4 GOODNESS-OF-FIT AND TESTS OF SIGNIFICANCE

Unlike ordinary least squares regression, there is no universally accepted method of assessing the goodness-of-fit of a categorical regression model. The goodness-of-fit of an ordinary least squares regression model is generally assessed in terms of the R^2 value associated with the model (see Equation 23). R^2 ranges between 0 and 1 with higher values indicating a better model fit. A common interpretation of the R^2 value is the proportion of variance in the response variable explained by the model.

$$R^2 = 1 - \frac{\sum_{i=1}^{N} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{N} (y_i - \overline{y}_i)^2}$$

Equation 23

where y_i are the measured responses, $\overline{y}_i$ is the mean of the measured responses, and $\hat{y}_i$ are the responses predicted by the regression model.

As categorical regression models are calculated via maximum likelihood rather than minimization of variance, R^2 cannot be calculated as an indicator of goodness-of-fit. There are many "*R^2 like*" indicators which have been developed to attempt to describe the goodness-of-fit of a regression model estimated via maximum likelihood (Agresti 1990; Long 1997). Of these *pseudo-R^2* values, there is no consensus as to which is the most appropriate to use. For the models presented in the remainder of this report, McFadden's pseudo-R^2 will be reported.

McFadden's pseudo-R^2 considers the likelihood of the full model (L_{full}) compared to the likelihood of a model in which only the intercept term is considered ($L_{intercept}$). L_{full} is considered to be analogous to the sum of squared errors (numerator in Equation 23). $L_{intercept}$ is considered to be analogous to the total sum of squares (denominator in Equation 23).

$$R^2_{pseudo} = 1 - \frac{\ln(L_{full})}{\ln(L_{\text{intercept}})}$$

Equation 24

As can be seen from Equation 24, for models based on the same data, McFadden's pseudo-R^2 would be higher for the model with the greater likelihood.

5 RAILWAY SOURCES

5.1 INTRODUCTION

In this section, exposure-response relationships will be presented for railway induced vibration. From the findings detailed in previous sections, exposure-response relationships will be presented in line with BS 6472-1:2008 and ISO 2631-1:1997. Relationships for concern of damage to property and time of day of vibration exposure are also presented.

The relationships presented in the following section have been derived in terms of vibration exposure. Because of this, only the relationship between the total amount of vibration energy to which a respondent could potentially be subjected to and annoyance are described. This is in contrast to vibration dose which is defined as the total amount of vibration energy absorbed by a respondent over a given time period. From a policy or planning viewpoint, exposure-response relationships are probably more useful than dose-response relationships as information relating to the activities of the community such as the times of day that people are in their properties is likely to be unavailable.

The exposure-response relationships will take the form of curves indicating the percentage of people expressing annoyance above a given threshold for a given vibration exposure. The annoyance thresholds reported will be 28%, 50%, and 72% of the annoyance scale which will be referred to "*percent slightly annoyed*" *(%SA*), "*percent annoyed*" (%A), and "*percent highly annoyed*" (*%HA*) respectively throughout the remainder of this report. Relationships presenting the percentage of people able to feel vibration for a given exposure will also be presented. The relationships presented in this section were derived using the models detailed in section 4 (Groothuis-Oudshoorn & H. Miedema 2006).

It should be noted that, although 932 social survey questionnaires were completed, the relationships presented in this section are derived from a smaller sample. This is due to situations where it was not possible to derive an estimate of vibration or noise exposure for a respondent due to an inability to gain access to a property to conduct measurements, equipment malfunction, or the lack of an estimation of vibration at a similar property type from which to estimate the respondent's vibration exposure.

5.2 FUNCTIONAL FORM OF VIBRATION EXPOSURE DESCRIPTOR

Models were tested with the exposure descriptor described in absolute units and $10*\log_{10}(exposure)$. The likelihoods of the two models were evaluated and in all cases the descriptor expressed in logarithmic form was to result in a significant increase in the likelihood of the model. This result is consisted with the findings of (Klæboe et al. 2003). Unless otherwise stated, the relationships presented in the rest of this report have been calculated using the exposure descriptor in logarithmic form.

5.3 MODEL BASED ON GUIDANCE FROM BS 6472-1:2008

Figure 26 and Figure 27 show exposure-response relationships for the proportion of respondents reporting feeling vibration and the proportion of respondents reporting annoyance above a given threshold. Vibration exposure was calculated based on guidance form BS 6472-1:2008. The relationships are shown in terms of $VDV_{b,24hr}$ for vibration in the vertical direction and $VDV_{d,24hr}$ for vibration in the horizontal direction.

From Figure 26 it can be seen that approximately 50% of respondents report feeling vibration at exposures of around 7×10^{-3} *m/s*$^{1.75}$ in the vertical direction and at around 1×10^{-3} *m/s*$^{1.75}$ in the horizontal direction. At these magnitudes of vibration exposure, it can be seen from Figure 27 around 3% of respondents report being highly annoyed by vibration. At exposures of 0.3 *m/s*$^{1.75}$ in the vertical direction and 0.02 *m/s*$^{1.75}$ in the horizontal direction, around 10% of respondents report being highly annoyed, 22% report being annoyed, and 41% report being slightly annoyed.

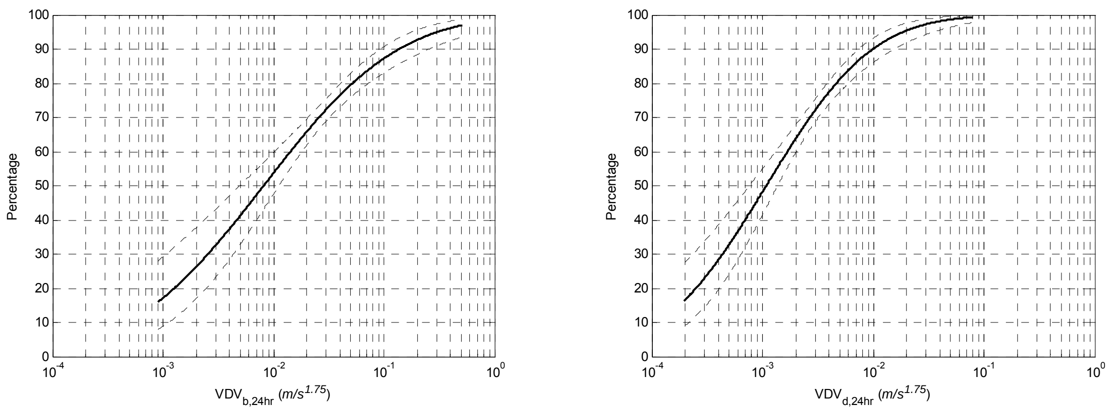

Figure 26 Exposure-response relationship showing the proportion of people reporting feeling vibration for a given vibration exposure. Left pane: Vertical vibration. Right pane: Horizontal vibration.

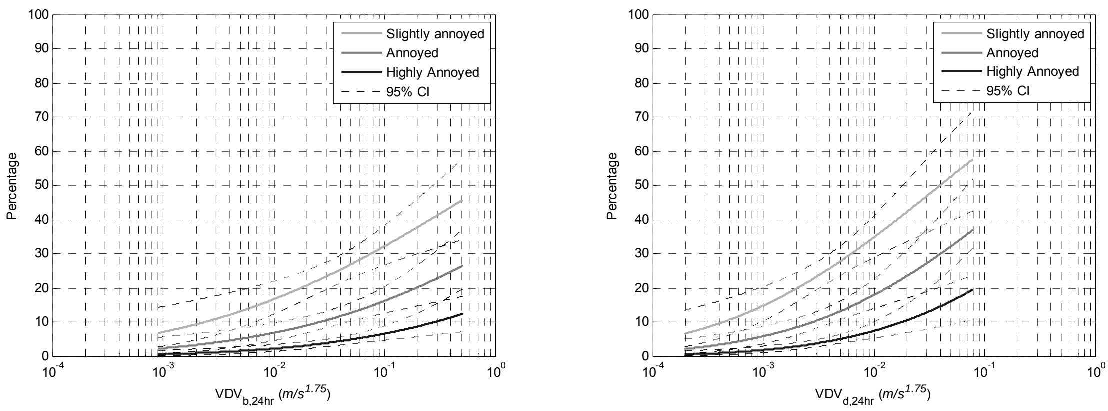

Figure 27 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure. Curves are shown in their 95% confidence intervals. Left pane: Vertical vibration Right pane: Horizontal vibration.

The following tables provide parameter estimates and polynomial approximations[4] for the relationships provided in this section. These models must not be used outside of the ranges 8.96×10^{-4} and 0.51 $VDV_{b,24hr}$ in the vertical direction and 1.95×10^{-4} and 0.078 $VDV_{d,24hr}$ in the horizontal direction.

Response: Feel/Don't feel			N =	752	Polynomial Approximations
Scale: Binary			p-Value	<0.0001	$\%Feel = -2.167X^3 - 3.702X^2 + 29.746X + 66.406$
Direction of excitation: Vertical			R^2_{pseudo} =	0.04	$CU_{feel} = -2.016X^3 - 2.501X^2 + 26.215X + 71.084$
Parameter	β Estimate	Standard Error		p-Value	$CL_{feel} = -2.759X^3 - 4.461X^2 + 32.761X + 61.409$
Intercept	2.1801	0.2234		<0.0001	
$10\log(VDV_{b,24hr})$	0.1044	0.0139		<0.0001	

Table 5 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 26.

Where $X = \dfrac{10\log_{10}(VDV_{b,24hr}) + 16.7}{8.0}$

	β_0	β_1
β_0	0.0499	0.0030
β_1	0.0030	0.0002

Table 6 Estimated covariance matrix for the relationships presented in the left pane of Figure 26.

Response: Feel/Don't feel			N =	752	Polynomial Approximations
Scale: Binary			p-Value	<0.0001	$\%Feel = -2.070X^3 - 6.904X^2 + 30.122X + 75.944$
Direction of excitation: Horizontal			R^2_{pseudo} =	0.05	$CU_{feel} = -2.376X^3 - 5.931X^2 + 27.558X + 79.691$
Parameter	β Estimate	Standard Error		p-Value	$CL_{feel} = -1.970X^3 - 7.416X^2 + 31.961X + 71.564$
Intercept	3.9388	0.4165		<0.0001	
$10\log(VDV_{d,24hr})$	0.1328	0.0161		<0.0001	

Table 7 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 26.

Where $X = \dfrac{10\log_{10}(VDV_{d,24hr}) + 24.1}{7.5}$

[4] *%Feel* – Percentage of respondents stating they can feel vibration, *%HA* – Percent highly annoyed, *%A* – Percent annoyed, *%LA* – Percent slightly annoyed, *CU* – Upper 95% confidence interval, *CL* – Lower 95% confidence interval

	β0	β1
β0	0.1735	0.0067
β1	0.0067	0.0003

Table 8 Estimated covariance matrix for the relationships presented in the left pane of Figure 26.

Response: Annoyance railway			*N =*	752
Scale: 5 point semantic			*p-Value*	*<0.001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.01*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	29.64	7.88		<0.001
10log($VDV_{b,24h}$)	2.12	0.53		<0.0001
σ	41.99	2.5		<0.0001

Polynomial Approximations
$\%LA = -0.114X^3 + 1.725X^2 + 11.600X + 21.136$
$CU_{LA} = +0.654X^3 + 3.624X^2 + 10.832X + 25.740$
$CL_{LA} = -0.955X^3 + 0.364X^2 + 11.699X + 17.110$
$\%A = +0.116X^3 + 1.693X^2 + 6.651X + 9.246$
$CU_{A} = +0.854X^3 + 3.213X^2 + 6.716X + 11.883$
$CL_{A} = -0.484X^3 + 0.678X^2 + 6.173X + 7.106$
$\%HA = +0.176X^3 + 1.085X^2 + 2.895X + 3.205$
$CU_{HA} = +0.712X^3 + 2.089X^2 + 3.124X + 4.322$
$CL_{HA} = -0.165X^3 + 0.467X^2 + 2.491X + 2.351$

Table 9 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 27.

Where $X = \frac{10\log_{10}(VDV_{b,24hr}) + 16.7}{8.0}$

	β0	β1
β0	62.05	3.91
β1	3.91	0.28

Table 10 Estimated covariance matrix for the relationships presented in the right pane of Figure 27.

Response: Annoyance railway			*N =*	752
Scale: 5 point semantic			*p-Value*	*<0.0001*
Direction of excitation: Horizontal			R^2_{pseudo} =	*0.02*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	66.07	14.61		<0.0001
10log($VDV_{d,24hr}$)	2.72	0.61		<0.0001
σ	41.64	2.52		<0.0001

Polynomial Approximations
$\%LA = -0.344X^3 + 2.257X^2 + 15.787X + 25.525$
$CU_{LA} = -0.028X^3 + 4.494X^2 + 17.114X + 30.480$
$CL_{LA} = -0.975X^3 + 0.312X^2 + 14.183X + 21.078$
$\%A = +0.112X^3 + 2.613X^2 + 9.721X + 11.785$
$CU_{A} = +0.739X^3 + 4.822X^2 + 11.515X + 14.844$
$CL_{A} = -0.507X^3 + 0.921X^2 + 7.987X + 9.235$
$\%HA = +0.312X^3 + 1.887X^2 + 4.524X + 4.300$
$CU_{HA} = +1.004X^3 + 3.668X^2 + 5.792X + 5.660$
$CL_{HA} = -0.156X^3 + 0.715X^2 + 3.423X + 3.219$

Table 11 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 27.

Where $X = \frac{10\log_{10}(VDV_{d,24hr}) + 24.1}{7.5}$

	β_0	β_1
β_0	213.44	8.7
β_1	8.7	0.37

Table 12 Estimated covariance matrix for the relationships presented in the right pane of Figure 27.

5.4 Model based on guidance from ISO 2631-1:1997

Figure 28 and Figure 29 show exposure-response relationships for the proportion of respondents reporting feeling vibration and the proportion of respondents reporting annoyance above a given threshold. Vibration exposure was calculated based on guidance form ISO 2631-1:1997. The relationships are shown for *rms* acceleration in the vertical and horizontal directions weighted with the W_k and W_d frequency weighting curves respectively.

From Figure 28 it can be seen that approximately 50% of respondents report feeling vibration at exposures of around 7x10^{-4} m/s^2 in the vertical direction and at around 1x10^{-4} m/s^2 in the horizontal direction. At these magnitudes of vibration exposure, it can be seen from Figure 29 that around 3% of respondents report being highly annoyed by vibration. At exposures of 2x10^{-2} m/s^2 in the vertical direction and 2x10^{-3} m/s^2 in the horizontal direction, around 10% of respondents report being highly annoyed, 20% report being annoyed, and 40% report being slightly annoyed.

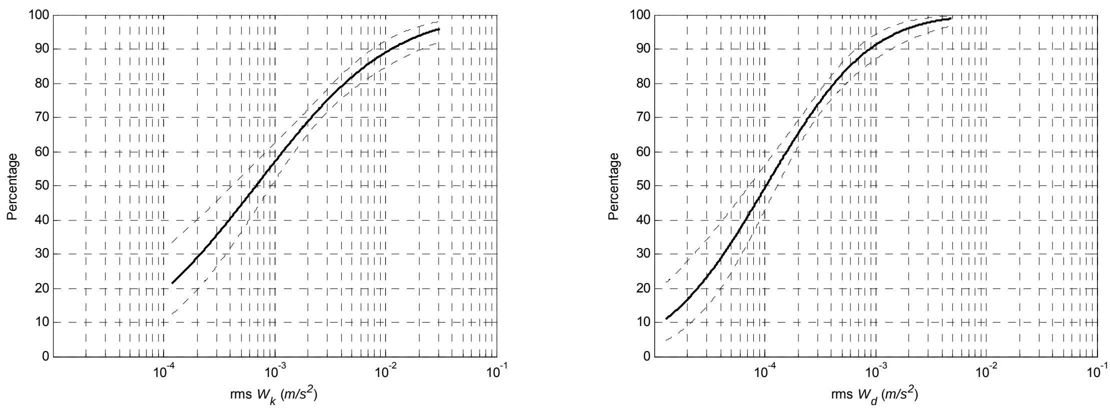

Figure 28 Exposure-response relationship showing the proportion of people reporting feeling vibration for a given vibration exposure. Left pane: Vertical vibration. Right pane: Horizontal vibration.

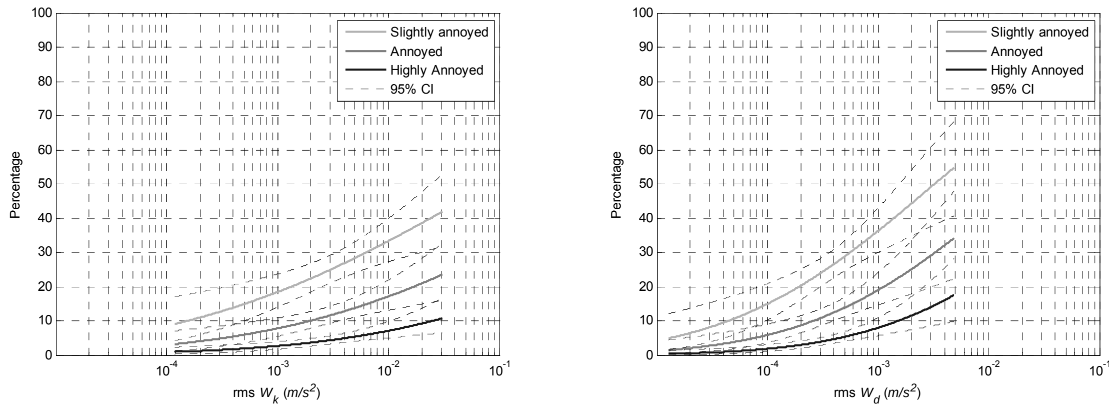

Figure 29 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure. Curves are shown in their 95% confidence intervals. Left pane: Vertical vibration. Right pane: Horizontal vibration.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the ranges 1.33x10^{-4} and 0.037 W_k weighted *rms* acceleration in the vertical direction and 1.23x10^{-5} and 0.0049 W_d weighted *rms* acceleration in the horizontal direction.

Response: Feel/Don't feel			*N =*	752
Scale: Binary			*p-Value*	*<0.0001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.04*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	3.3194	0.3740		<0.001
10log(*rms Wk* (m/s^2))	0.1048	0.0140		<0.0001

Polynomial Approximations

$$\%Feel = -1.505X^3 - 3.313X^2 + 25.977X + 67.705$$
$$CU_{feel} = -1.563X^3 - 2.030X^2 + 23.203X + 72.053$$
$$CL_{feel} = -1.818X^3 - 4.342X^2 + 28.417X + 63.045$$

Table 13 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 28.

Where $X = \dfrac{10\log_{10}(rms_{k,24hr}) + 27.2}{7.0}$

	β₀	**β₁**
β₀	0.1399	0.0052
β₁	0.0052	0.0002

Table 14 Estimated covariance matrix for the relationships presented in the left pane of Figure 28.

Response: Feel/Don't Feel			*N =*	752	Polynomial Approximations
Scale: Binary			*p-Value*	*<0.0001*	$\%Feel = -3.164X^3 - 5.454X^2 + 34.557X + 69.049$
Direction of excitation: Horizontal			R^2_{pseudo} =	*0.05*	$CU_{feel} = -2.969X^3 - 4.623X^2 + 30.857X + 73.659$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{feel} = -3.697X^3 - 5.678X^2 + 37.386X + 63.988$
Intercept	5.4369	0.6152		<0.0001	
10log(*rms Wd* (m/s^2))	0.1363	0.0170		<0.0001	

Table 15 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 28.

Where $X = \dfrac{10\log_{10}(rms_{k,24hr}) + 36.0}{7.5}$

	β_0	β_1
β_0	0.3785	0.0104
β_1	0.0104	0.0003

Table 16 Estimated covariance matrix for the relationships presented in the right pane of Figure 28.

Response: Annoyance railway			*N =*	752	Polynomial Approximations
Scale: 5 point semantic			*p-Value*	*<0.001*	$\%LA = -0.071X^3 + 1.160X^2 + 9.711X + 22.071$
Direction of excitation: Vertical			R^2_{pseudo} =	*0.01*	$CU_{LA} = +0.542X^3 + 2.901X^2 + 8.857X + 26.669$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LA} = -0.748X^3 - 0.078X^2 + 10.010X + 17.988$
Intercept	49.41	13.63		<0.001	$\%A = +0.060X^3 + 1.165X^2 + 5.697X + 9.880$
10log(*rms Wk* (m/s^2))	1.99	0.54		<0.0001	$CU_A = +0.635X^3 + 2.471X^2 + 5.605X + 12.612$
σ	42.42	2.56		<0.0001	$CL_A = -0.419X^3 + 0.323X^2 + 5.417X + 7.624$
					$\%HA = +0.099X^3 + 0.759X^2 + 2.553X + 3.532$
					$CU_{HA} = +0.500X^3 + 1.566X^2 + 2.689X + 4.756$
					$CL_{HA} = -0.165X^3 + 0.280X^2 + 2.249X + 2.585$

Table 17 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 29.

Where $X = \dfrac{10\log_{10}(rms_{k,24hr}) + 27.2}{7.0}$

	β_0	β_1
β_0	185.73	7.2
β_1	7.2	0.29

Table 18 Estimated covariance matrix for the relationships presented in the left pane of Figure 29.

Response: Annoyance railway			$N =$	752	Polynomial Approximations
Scale: 5 point semantic			*p-Value*	*<0.0001*	$\%LA = -0.278X^3 + 2.626X^2 + 15.254X + 22.264$
Direction of excitation: Horizontal			$R^2_{pseudo} =$	*0.02*	$CU_{LA} = +0.603X^3 + 4.761X^2 + 14.803X + 27.188$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LA} = -1.322X^3 + 0.978X^2 + 14.905X + 18.015$
Intercept	99.26	22.45		<0.0001	$\%A = +0.197X^3 + 2.725X^2 + 8.890X + 9.829$
10log(*rms Wd* (m/s^2))	2.87	0.66		<0.0001	$CU_A = +1.160X^3 + 4.714X^2 + 9.398X + 12.639$
σ	41.66	2.59		<0.0001	$CL_A = -0.613X^3 + 1.275X^2 + 7.961X + 7.588$
					$\%HA = +0.353X^3 + 1.835X^2 + 3.912X + 3.410$
					$CU_{HA} = +1.162X^3 + 3.363X^2 + 4.424X + 4.553$
					$CL_{HA} = -0.169X^3 + 0.836X^2 + 3.249X + 2.541$

Table 19 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 29.

Where $X = \frac{10\log_{10}(rms_{k,24hr}) + 36.0}{7.5}$

	β_0	β_1
β_0	503.87	14.68
β_1	14.68	0.43

Table 20 Estimated covariance matrix for the relationships presented in the right pane of Figure 29.

5.5 SENSITIVITY OF RELATIONSHIPS TO OUTLIERS, SITE EFFECTS, AND RESPONSE SCALE

To investigate the sensitivity of the calculated models to outliers, the exposure-response model presented in section 5.3 was recalculated using only the data in the 5 to 95 percentile range of the vibration exposure. Figure 30 provides a comparison between the full model and the subset model. It can be seen from this figure that the full model and the subset model show good agreement indicating that the exposure response relationship is not sensitive to outliers.

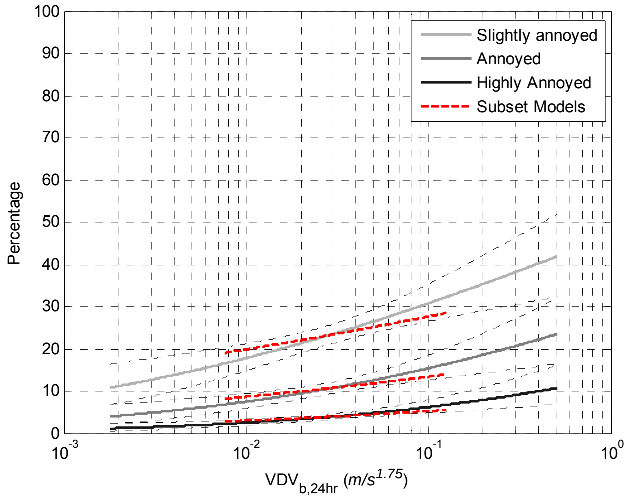

Figure 30 Exposure-response relationship for annoyance caused by railway induced vibration recalculated on a subset of responses.

To investigate the influence of potential differences between measurement sites, the exposure-response relationship was calculated with data from each site removed sequentially. Figure 31 show the %HA relationship for the model calculated using data from all sites (solid line) compared with the relationship calculated with data with different sites removed. The agreement between the full model and the subset model indicates that measurement location has no significant influence on the model.

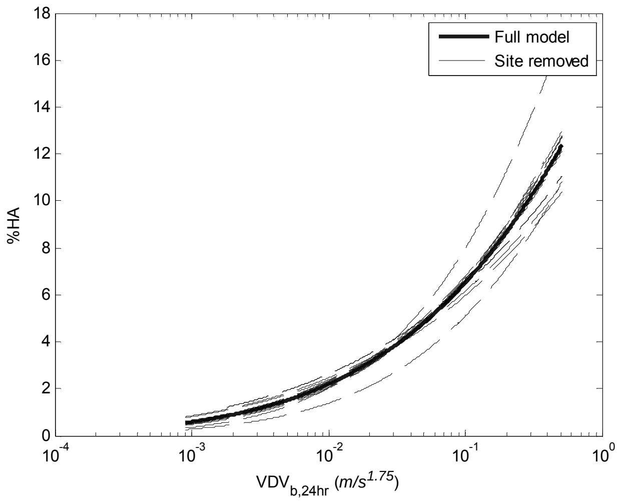

Figure 31 Exposure-response relationship illustrating site effects.

To investigate potential differences in the way respondents rate annoyance due to different annoyance scales, an exposure-response model was calculated using both the 5-point semantic and 11-point numerical response scales. Figure 32 provides a comparison between the relationships calculated using the two different response scales. It can be seen from this figure that the choice of response scale has little influence on the derived relationship.

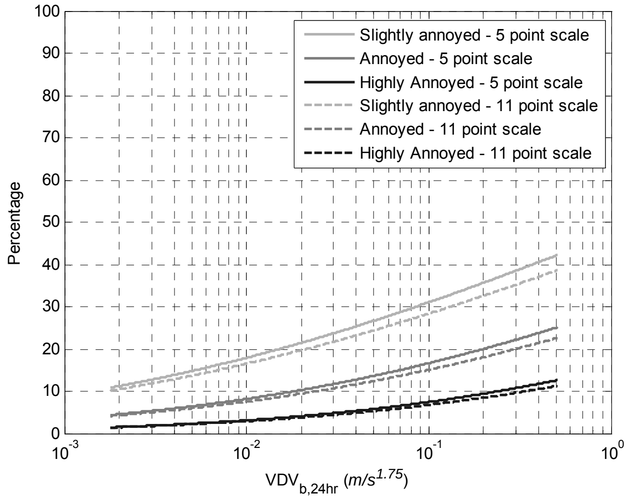

Figure 32 Exposure-response relationship for annoyance due to railway induced vibration calculated using the 5-point semantic and 11-point numerical response scales.

5.6 DISTANCE ONLY MODEL

Figure 33 presents an exposure-response relationship for annoyance caused by railway induced vibration using only the distance from the source as an independent variable. As highlighted in section 3.4, Spearman's correlation between distance from the source and self reported annoyance was similar to that of unweighted vibration exposure expressed in acceleration. Although not as effective a predictor of annoyance than measurements of vibration exposure, this result suggests that a fair approximation of community response to railway induced vibration can be obtained by considering only the distance of a residence from the source.

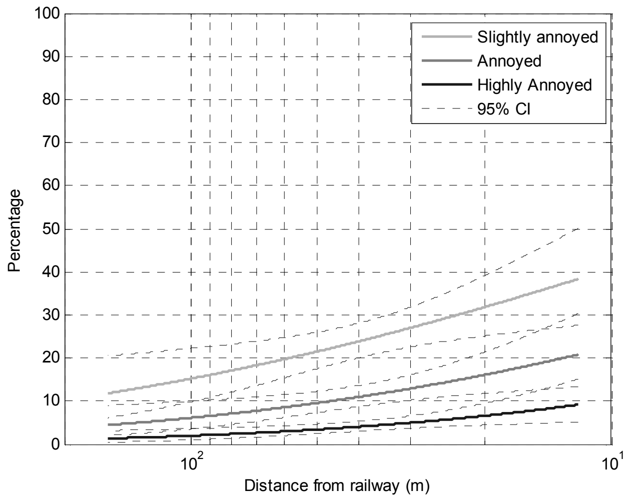

Figure 33 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given distance from the railway line. Curves are shown in their 95% confidence intervals.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the range 10 m and 160 m.

Response: Annoyance railway			*N =*	752	**Polynomial Approximations**
Scale: 5 point semantic			*p-Value*	*<0.01*	$\%LA = +0.039X^3 + 0.716X^2 - 7.795X + 22.978$
			R^2_{pseudo} =	*0.01*	$CU_{LA} = -0.385X^3 + 2.800X^2 - 7.534X + 27.511$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LA} = +0.548X^3 - 0.815X^2 - 7.735X + 18.884$
Intercept	51.87	18.77		<0.01	$\%A = -0.027X^3 + 0.736X^2 - 4.653X + 10.443$
10log(Distance)	-3.38	1.18		<0.0001	$CU_A = -0.475X^3 + 2.260X^2 - 4.852X + 13.202$
σ	42.54	2.57		<0.0001	$CL_A = +0.352X^3 - 0.220X^2 - 4.253X + 8.113$
					$\%HA = -0.049X^3 + 0.485X^2 - 2.126X + 3.803$
					$CU_{HA} = -0.378X^3 + 1.380X^2 - 2.379X + 5.075$
					$CL_{HA} = +0.161X^3 - 0.005X^2 - 1.793X + 2.791$

Table 21 Parameter estimates and polynomial approximations for the curves presented in Figure 33.

Where $X = \frac{10\log_{10}(\text{Distance}) - 16.4}{3.2}$

	β_0	β_1
β_0	352.17	-21.82
β_1	-21.82	1.38

Table 22 Estimated covariance matrix for the relationships presented in Figure 33.

5.7 DAY, EVENING, NIGHT EFFECTS

Table 23 presents Spearman's correlation coefficients between self reported annoyance and day, evening, and night vibration exposure in the vertical and horizontal directions. Daytime is defined between 7:00 – 19:00, evening is defined between 19:00 – 23:00, and night is defined between 23:00 – 7:00. Vibration exposure expressed as VDV_b in the vertical direction and VDV_d in the horizontal direction were calculated over the three different time periods. It can be seen from this table that there is a significant correlation between self reported annoyance in the day, evening, and night for vibration exposures calculated over these time periods for both the vertical and horizontal directions. As with annoyance due to 24-hour vibration exposure (see Table 4), exposures calculated in the horizontal direction exhibit a slightly higher magnitude of correlation than exposures calculated in the vertical direction.

	Day	Evening	Night
VDV_b in vertical direction ($m/s^{1.75}$)	0.11 **	0.10***	0.15 ***
VDV_d in horizontal direction ($m/s^{1.75}$)	0.13 ***	0.15***	0.19 ***

Table 23 Spearman's correlation coefficient between vibration exposure expressed as *VDV* in the vertical and horizontal directions for different times of day (N = 751). * $p<0.05$, ** $p<0.01$, *** $p< 0.001$.

Figure 34, Figure 35, and Figure 36 show exposure-response relationships for the proportion of respondents reporting annoyance above a given threshold for vibration exposure during the day, evening, and night respectively. It can be seen that, for a given vibration exposure, the percentage of respondents expressing annoyance above a given threshold is higher for night than it is for evening and higher for evening than it is for day. For a vibration exposure of 0.1 $m/s^{1.75}$ VDV_b, the proportion of respondents expressing high annoyance is around 2% in the daytime, 4% in the evening, and 12% during the night. These results suggest that a day-evening-night type descriptor (similar to the L_{DEN} descriptor used for the assessment of noise exposure) may be appropriate for the assessment of vibration exposure with respect to human response. Similar results have been observed for annoyance due to noise exposure where evening and nighttime noise exposure have been found to have a greater impact on annoyance than daytime noise exposure (J. Fields 1986a; J. Fields 1986b; J. Fields 2001; H. Miedema 2000).

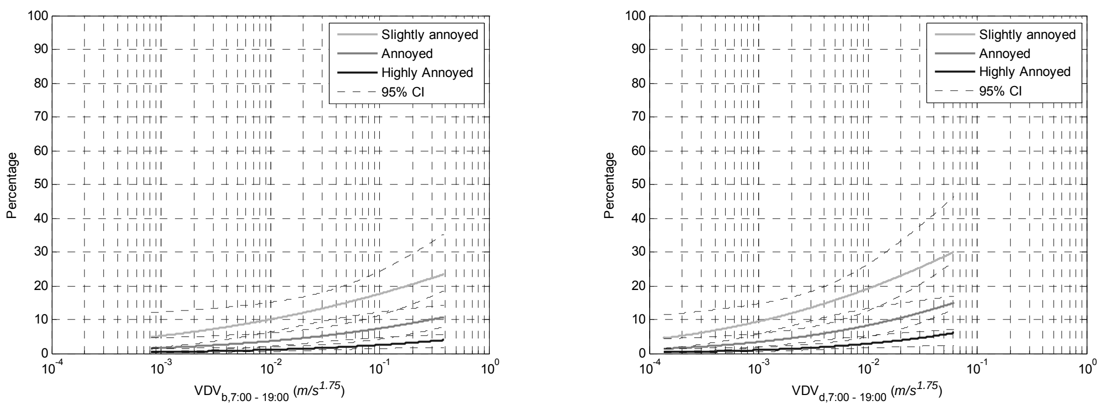

Figure 34 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure during the day. Curves are shown in their 95% confidence intervals. Left pane: Vertical vibration. Right pane: Horizontal vibration.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the ranges 8.16×10^{-4} and 0.38 $VDV_{b,7:00-19:00}$ in the vertical direction and 1.35×10^{-4} and 0.062 $VDV_{d,7:00-19:00}$ in the horizontal direction.

Response: Annoyance railway			N =	752	Polynomial Approximations
Scale: 5 point semantic			p-Value	<0.0001	$\%LA = +0.025X^3 + 0.831X^2 + 5.287X + 11.634$
Direction of excitation: Vertical			R^2_{pseudo} =	0.09	$CU_{LA} = +0.593X^3 + 2.462X^2 + 5.028X + 16.419$
Parameter	β Estimate	Standard Error		p-Value	$CL_{LA} = -0.449X^3 - 0.043X^2 + 4.891X + 7.947$
Intercept	3.25	9.62		n.s.	$\%A = +0.056X^3 + 0.575X^2 + 2.494X + 4.353$
10log(VDV$_{b,7:00-19:00}$)	1.49	0.59		<0.0001	$CU_{A} = +0.483X^3 + 1.602X^2 + 2.635X + 6.700$
σ	42.52	3.33		n.s.	$CL_{A} = -0.198X^3 + 0.091X^2 + 2.056X + 2.726$
					$\%HA = +0.043X^3 + 0.279X^2 + 0.900X + 1.290$
					$CU_{HA} = +0.283X^3 + 0.793X^2 + 1.047X + 2.163$
					$CL_{HA} = -0.064X^3 + 0.063X^2 + 0.663X + 0.741$

Table 24 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 34.

Where $X = \frac{10\log_{10}(\text{VDV}_{b,7:00-19:00}) + 17.5}{7.7}$

	β0	β1
β0	92.45	5.08
β1	5.08	0.35

Table 25 Estimated covariance matrix for the relationships presented in the left pane of Figure 34.

Response: Annoyance railway			N =	752	Polynomial Approximations
Scale: 5 point semantic			p-Value	<0.0001	$\%LA = +0.026X^3 + 1.323X^2 + 7.312X + 13.322$
Direction of excitation: Horizontal			R^2_{pseudo} =	0.09	$CU_{LA} = +0.628X^3 + 3.695X^2 + 8.392X + 18.372$
Parameter	β Estimate	Standard Error		p-Value	$CL_{LA} = -0.539X^3 - 0.127X^2 + 5.980X + 9.323$
Intercept	28.45	17.25		n.s.	$\%A = +0.107X^3 + 0.989X^2 + 3.618X + 5.195$
10log(VDV$_{d,7:00-19:00}$)	1.89	0.69		<0.0001	$CU_{A} = +0.708X^3 + 2.717X^2 + 4.623X + 7.754$
σ	42.77	3.38		<0.0001	$CL_{A} = -0.251X^3 + 0.099X^2 + 2.631X + 3.349$
					$\%HA = +0.093X^3 + 0.517X^2 + 1.372X + 1.608$
					$CU_{HA} = +0.514X^3 + 1.516X^2 + 1.927X + 2.579$
					$CL_{HA} = -0.085X^3 + 0.083X^2 + 0.892X + 0.958$

Table 26 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 34.

Where $X = \frac{10\log_{10}(\text{VDV}_{d,7:00-19:00}) + 25.4}{7.7}$

	β_0	β_1
β_0	297.5	11.45
β_1	11.45	0.47

Table 27 Estimated covariance matrix for the relationships presented in the right pane of Figure 34.

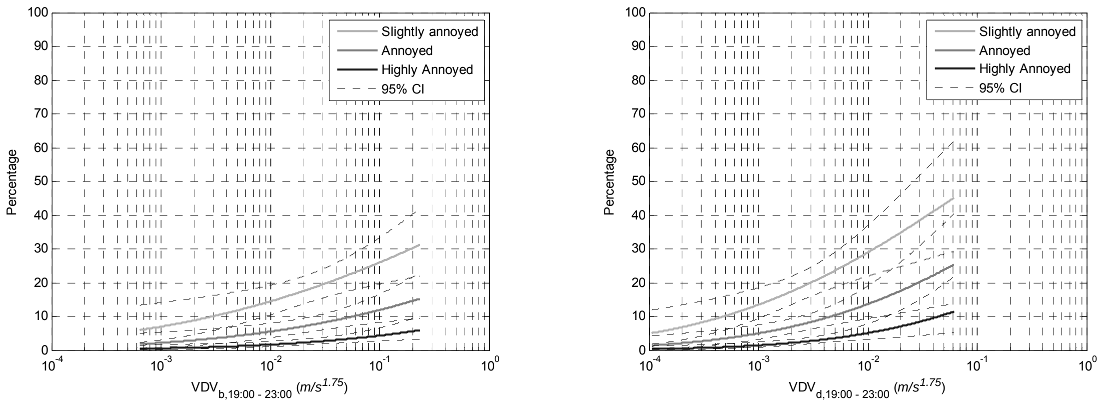

Figure 35 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure during the evening. Curves are shown in their 95% confidence intervals. Left pane: Vertical vibration. Right pane: Horizontal vibration.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the ranges 6.43x10^{-4} and 0.23 $VDV_{b,19:00-23:00}$ in the vertical direction and 1.06x10^{-4} and 0.061 $VDV_{d,19:00-23:00}$ in the horizontal direction.

Response: Annoyance railway			N =	751
Scale: 5 point semantic			p-Value	<0.0001
Direction of excitation: Vertical			R^2_{pseudo} =	0.03
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	18.66	9.02		<0.05
10log(VDV$_{b,19:00-23:00}$)	1.71	0.54		<0.0001
σ	40.99	2.75		<0.0001

Polynomial Approximations
$\%LA = +0.002X^3 + 1.105X^2 + 7.266X + 15.250$
$CU_{LA} = +0.687X^3 + 2.619X^2 + 6.282X + 19.931$
$CL_{LA} = -0.632X^3 + 0.206X^2 + 7.434X + 11.403$
$\%A = +0.078X^3 + 0.863X^2 + 3.629X + 5.906$
$CU_A = +0.598X^3 + 1.863X^2 + 3.434X + 8.303$
$CL_A = -0.286X^3 + 0.313X^2 + 3.365X + 4.113$
$\%HA = +0.072X^3 + 0.451X^2 + 1.358X + 1.784$
$CU_{HA} = +0.367X^3 + 0.979X^2 + 1.393X + 2.694$
$CL_{HA} = -0.090X^3 + 0.180X^2 + 1.147X + 1.160$

Table 28 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 35.

Where $X = \frac{10\log_{10}(\text{VDV}_{b,19:00-23:00}) + 19.1}{7.4}$

	β_0	β_1
β_0	81.4	4.56
β_1	4.56	0.29

Table 29 Estimated covariance matrix for the relationships presented in the left pane of Figure 35.

Response: Annoyance railway			*N =*	751	**Polynomial Approximations**
Scale: 5 point semantic			*p-Value*	*<0.0001*	$\%LA = -0.095X^3 + 2.101X^2 + 11.869X + 18.915$
Direction of excitation: Horizontal			R^2_{pseudo} =	*0.03*	$CU_{LA} = +0.464X^3 + 4.683X^2 + 13.232X + 23.957$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LA} = -0.829X^3 + 0.152X^2 + 10.235X + 14.627$
Intercept	50.04	16.03		<0.01	$\%A = +0.179X^3 + 1.906X^2 + 6.370X + 7.737$
10log(VDV$_{d,19:00-23:00}$)	2.23	0.62		<0.0001	$CU_A = +0.932X^3 + 4.128X^2 + 7.850X + 10.447$
σ	40.63	2.77		<0.0001	$CL_A = -0.393X^3 + 0.472X^2 + 4.947X + 5.610$
					$\%HA = +0.220X^3 + 1.128X^2 + 2.545X + 2.455$
					$CU_{HA} = +0.866X^3 + 2.631X^2 + 3.411X + 3.484$
					$CL_{HA} = -0.122X^3 + 0.312X^2 + 1.795X + 1.682$

Table 30 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 35.

Where $X = \frac{10\log_{10}(\text{VDV}_{d,19:00-23:00}) + 25.9}{8.0}$

	β_0	β_1
β_0	256.83	9.78
β_1	9.78	0.39

Table 31 Estimated covariance matrix for the relationships presented in the right pane of Figure 35.

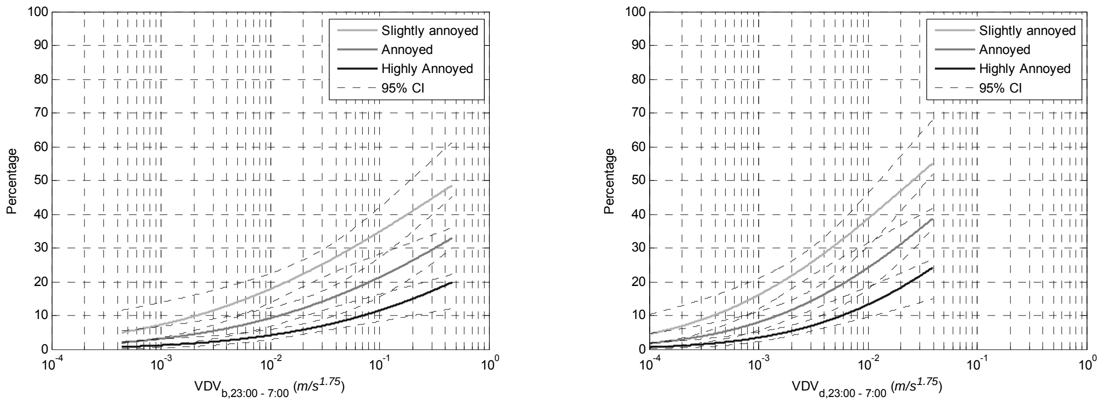

Figure 36 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure during the night. Curves are shown in their 95% confidence intervals. Left pane: Vertical vibration. Right pane: Horizontal vibration.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the ranges 4.40x10^{-4} and 0.46 $VDV_{b,23:00-7:00}$ in the vertical direction and 7.95x10^{-5} and 0.040 $VDV_{d,23:00-7:00}$ in the horizontal direction.

Response: Annoyance railway			N =	752
Scale: 5 point semantic			*p-Value*	*<0.0001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.03*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	35.69	11.02		<0.01
10log(VDV$_{b,23:00-7:00}$)	2.89	0.67		<0.0001
σ	54.24	3.18		<0.0001

Polynomial Approximations
$\%LA = -0.146X^3 + 2.300X^2 + 13.021X + 20.029$
$CU_{LA} = +0.690X^3 + 4.213X^2 + 12.569X + 24.635$
$CL_{LA} = -1.055X^3 + 0.885X^2 + 12.758X + 16.072$
$\%A = +0.132X^3 + 2.314X^2 + 8.540X + 10.634$
$CU_A = +0.983X^3 + 4.044X^2 + 8.784X + 13.633$
$CL_A = -0.593X^3 + 1.083X^2 + 7.835X + 8.208$
$\%HA = +0.261X^3 + 1.791X^2 + 4.748X + 4.911$
$CU_{HA} = +1.000X^3 + 3.197X^2 + 5.162X + 6.532$
$CL_{HA} = -0.253X^3 + 0.852X^2 + 4.101X + 3.662$

Table 32 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 36.

Where $X = \frac{10\log_{10}(\mathrm{VDV}_{b,23:00-7:00}) + 18.5}{8.7}$

	β$_0$	β$_1$
β$_0$	121.54	6.97
β$_1$	6.97	0.45

Table 33 Estimated covariance matrix for the relationships presented in the left pane of Figure 36.

Response: Annoyance railway			*N =*	*752*	Polynomial Approximations
Scale: 5 point semantic			*p-Value*	*<0.0001*	$\%LA = -0.269X^3 + 3.021X^2 + 15.582X + 20.717$
Direction of excitation: Horizontal			R^2_{pseudo} =	*0.03*	$CU_{LA} = +0.531X^3 + 4.784X^2 + 15.555X + 25.446$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LA} = -1.178X^3 + 1.602X^2 + 14.895X + 16.674$
Intercept	87.17	19.28		<0.0001	$\%A = +0.181X^3 + 3.124X^2 + 10.228X + 10.932$
10log($VDV_{d,23:00-7:00}$)	3.73	0.75		<0.0001	$CU_A = +1.047X^3 + 4.900X^2 + 10.918X + 13.995$
σ	53.15	3.2		<0.0001	$CL_A = -0.587X^3 + 1.739X^2 + 9.146X + 8.477$
					$\%HA = +0.402X^3 + 2.463X^2 + 5.650X + 4.977$
					$CU_{HA} = +1.216X^3 + 4.048X^2 + 6.389X + 6.596$
					$CL_{HA} = -0.186X^3 + 1.318X^2 + 4.760X + 3.742$

Table 34 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 36.

Where $X = \frac{10\log_{10}(\text{VDV}_{d,23:00-7:00}) + 27.5}{7.8}$

	β_0	β_1
β_0	121.54	6.97
β_1	6.97	0.45

Table 35 Estimated covariance matrix for the relationships presented in the right pane of Figure 36.

5.8 CONCERN OF DAMAGE TO PROPERTY

In the social survey questionnaire, respondents were asked to quantify the extent to which they felt concerned that vibration caused by railway activity was causing damage to their property on a five-point semantic scale. An exposure-response model was calculated for three thresholds of concern, *highly concerned* (upper 28% of the concern scale), *concerned* (upper 50% of the concern scale), and *slightly concerned* (upper 72% of the concern scale). This model is presented in Figure 37. It can be seen from this figure that as vibration exposure increases, the proportion of respondents expressing concern of damage to their property increases.

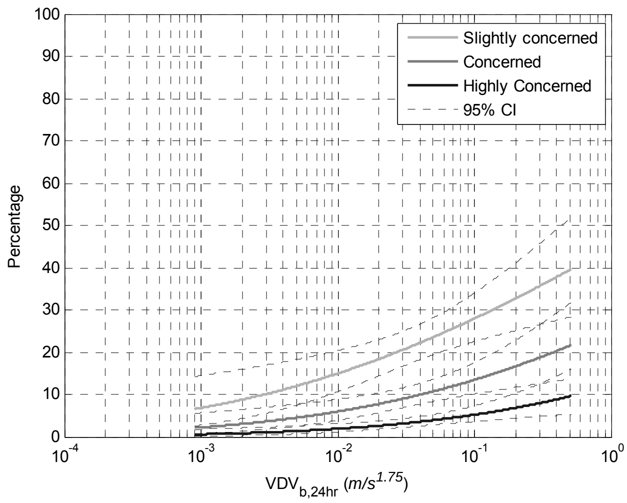

Figure 37 Exposure-response relationship showing the proportion of people reporting different degrees of concern of damage to property for a given vibration exposure from railway activities. Curves are shown in their 95% confidence intervals.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the ranges 8.96x10^{-4} and 0.51 $VDV_{b,24hr}$ in the vertical.

Response: Concern railway			*N =*	752	**Polynomial Approximations**
Scale: 5 point semantic			*p-Value*	*<0.0001*	$\%LC = -0.049X^3 + 1.466X^2 + 9.702X + 18.702$
Direction of excitation: Vertical			R^2_{pseudo} =	*0.02*	$CU_{LC} = +0.706X^3 + 3.362X^2 + 8.950X + 23.417$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LC} = -0.827X^3 + 0.194X^2 + 9.739X + 14.670$
Intercept	22.41	8.11		<0.01	$\%C = +0.103X^3 + 1.319X^2 + 5.340X + 7.936$
10log($VDV_{b,24hr}$)	1.92	0.54		<0.0001	$CU_C = +0.781X^3 + 2.741X^2 + 5.350X + 10.554$
σ	42.29	2.71		<0.0001	$CL_C = -0.415X^3 + 0.443X^2 + 4.903X + 5.869$
					$\%HC = +0.127X^3 + 0.794X^2 + 2.240X + 2.674$
					$CU_{HC} = +0.586X^3 + 1.666X^2 + 2.410X + 3.760$
					$CL_{HC} = -0.146X^3 + 0.301X^2 + 1.893X + 1.872$

Table 36 Parameter estimates and polynomial approximations for the curves presented in Figure 37.

Where $X = \dfrac{10\log_{10}(\mathrm{VDV}_{b,24hr}) + 16.7}{8.0}$

	β_0	β_1
β_0	65.75	4.09
β_1	4.09	0.3

Table 37 Estimated covariance matrix for the relationships presented in Figure 37.

Respondents were also asked to specify what damage they were concerned about via "*Yes*" and "*No*" responses. Figure 38 presents relationships between vibration exposure and different aspects of concern of damage.

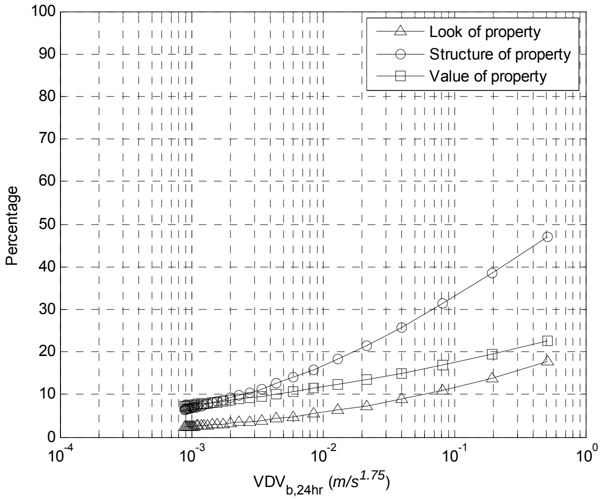

Figure 38 Exposure-response relationship showing the proportion of people reporting different aspects of concern of damage for a given vibration exposure.

The results presented in this section mirror the relationship between annoyance due to noise exposure and "*fear associated with the source*" (J. Fields 1979; J. Fields & Walker 1982; H. Miedema & Vos 1999). Miedema and Vos (1999) concluded that respondents who express fear associated with the activity that causes noise are expected to be more annoyed at the same exposure level than those who do not express fear.

5.9 SLEEP DISTURBANCE

The social survey questionnaire asked respondents to state if their sleep was ever disturbed by vibration caused by railway activity. The response to this question was either "*Yes*" or "*No*". Figure 39 shows the proportion of respondents reporting sleep disturbance for a given magnitude of vibration exposure.

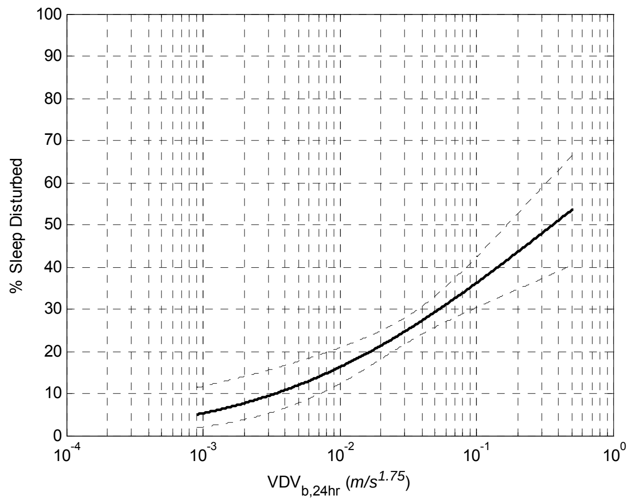

Figure 39 Exposure-response relationship showing the proportion of people reporting sleep disturbance for a given vibration exposure. (N = 755).

5.10 RESPONSE TO NOISE

In addition to annoyance caused by vibration exposure, respondents were also asked to rate annoyance caused by noise exposure on a 5-point semantic and 11-point numerical scale. Exposure to railway noise for each residence was calculated via CRN (see Technical Report 4). It should be noted that the speed of trains used in the calculation were taken as the speed limit of the railway line, therefore these noise exposures may be overestimated. Figure 40 shows the proportion of respondent expressing annoyance above a given threshold for different noise exposures.

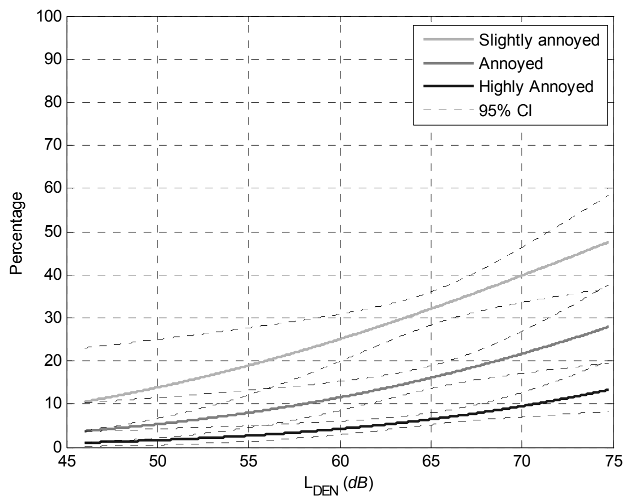

Figure 40 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance due to noise for a given noise exposure from railway activities. Curves are shown in their 95% confidence intervals.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the range 45 and 75 L_{DEN} (*dB*).

Response: Annoyance noise railway			*N =*	698
Scale: 5 point semantic			*p-Value*	*<0.0001*
			R^2_{pseudo} =	*0.02*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	-104.32	36.60		<0.01
L_{DEN}	1.74	0.56		<0.0001
σ	41.88	2.25		<0.0001

Table 38 Parameter estimates for the relationships presented in Figure 40.

	β_0	β_1
β_0	1339.8	-20.47
β_1	-20.47	0.31

Table 39 Estimated covariance matrix for the relationships presented in Figure 40.

Figure 41 presents a comparison between the noise exposure-response curves and the synthesis curves presented by Miedema and Oudshoorn (H. Miedema & Oudshoorn 2001). It can be seen from this figure that the exposure-response curves derived from the data collected in this project predict lower levels of annoyance than those presented by Miedema and Oudshoorn. As was noted previously, this may be due in part to an overestimation of noise exposure due to the assumption that all trains were travelling at the speed limit of the railway line in the calculation of railway noise.

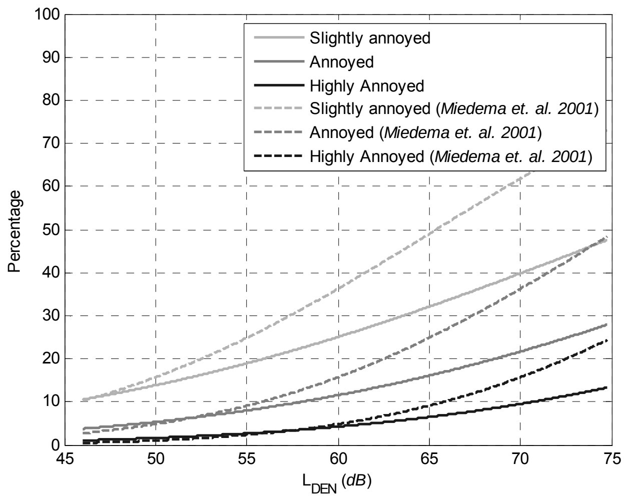

Figure 41 Comparison of exposure-response relationship for annoyance due to noise exposure with synthesis curves presented by (H. Miedema & Oudshoorn 2001).

5.11 Response to combined noise and vibration

As was highlighted in section 2.3.4, field and laboratory studies have consistently found an interaction between vibration and noise with regards to self reported annoyance to both stimuli. Exposure-response models were calculated for annoyance caused by vibration and annoyance caused by noise using vibration exposure ($VDV_{b,24hr}$ $m/s^{1.75}$) and noise exposure (L_{DEN} dB) as independent variables. For the vibration annoyance model, the improvement in likelihood when noise exposure was included as an independent variable was found to be significant ($p < 0.05$). The same result was observed for the noise annoyance model when vibration exposure was included as an independent variable.

Figure 42 shows the proportion of respondents reporting high annoyance due to *vibration* for different vibration and noise exposures. It can be seen from this figure that annoyance due to *vibration* increases with increases in both noise and vibration exposure. This result suggests an interaction effect between noise and vibration exposure on the total annoyance caused by vibration although it can be seen that vibration exposure has a greater influence. Figure 43 shows sections through the curved surface presented in Figure 42 at different values of noise exposure (left pane) and vibration exposure (right pane).

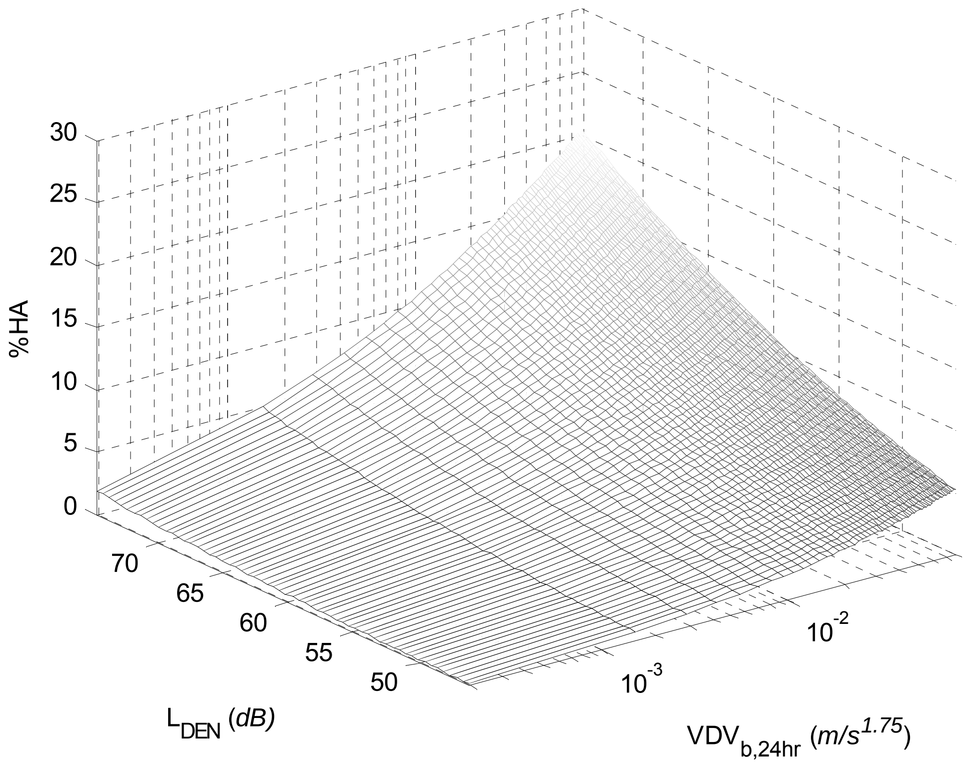

Figure 42 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance caused by vibration for a given vibration exposure and different levels of noise exposure.

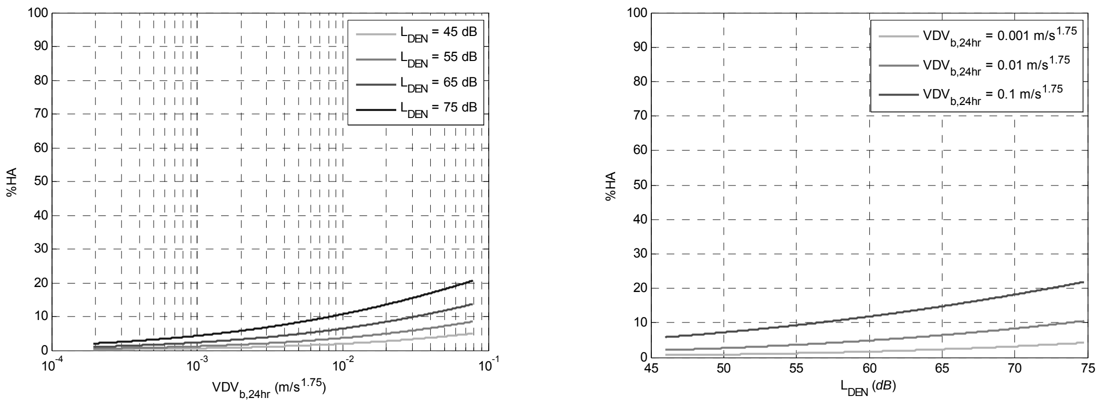

Figure 43 Sections through the curved surface presented in Figure 42 at different values of noise exposure (left pane) and vibration exposure (right pane).

Response: Annoyance vibration railway			*N =*	698
Scale: 5 point semantic			*p-Value*	*<0.0001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.01*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	-27.17	49.69		n.s.
10log($VDV_{b,24hr}$)	2.00	0.67		<0.0001
L_{DEN}	1.16	0.64		<0.0001
σ	41.94	2.60		<0.0001

Table 40 Parameter estimates for the relationship presented in Figure 42.

Figure 44 shows the proportion of respondents reporting high annoyance due to *noise* for different vibration and noise exposures. Similar to the relationship presented in Figure 42, it can be seen that annoyance due to *noise* increases with increases in both noise and vibration exposure. Again, this result suggests an interaction effect between noise and vibration exposure on self reported annoyance however in this case noise exposure can be seen to have a greater influence on the overall annoyance. Figure 45 shows sections through the curved surface presented in Figure 44 at different values of noise exposure (left pane) and vibration exposure (right pane).

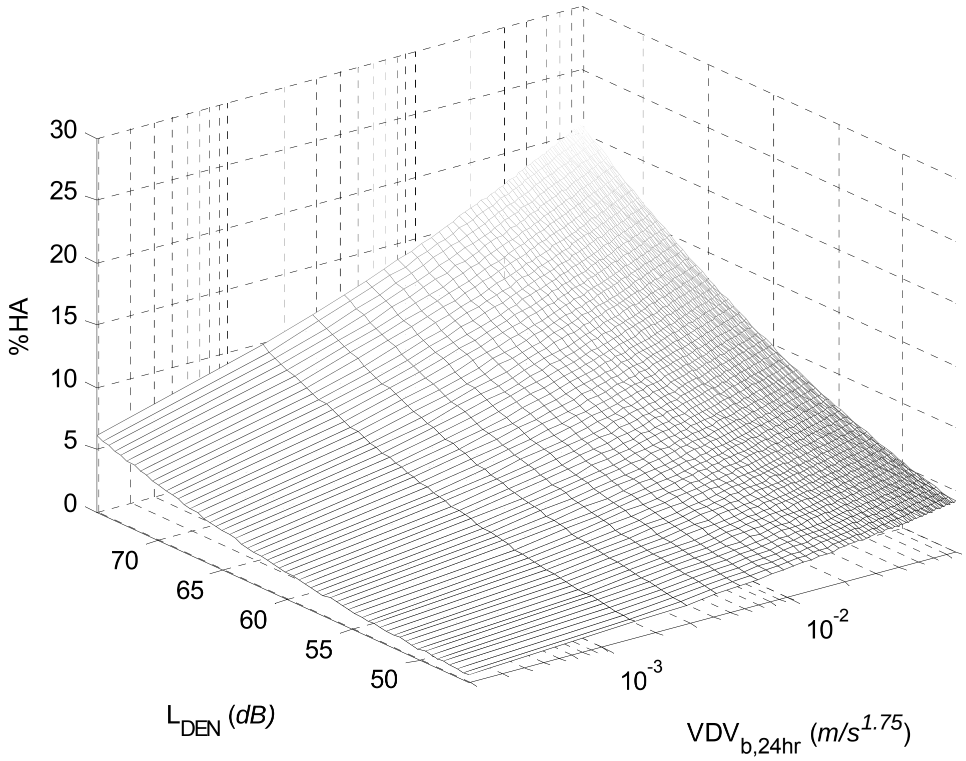

Figure 44 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance caused by noise for a given noise exposure and different levels of vibration exposure.

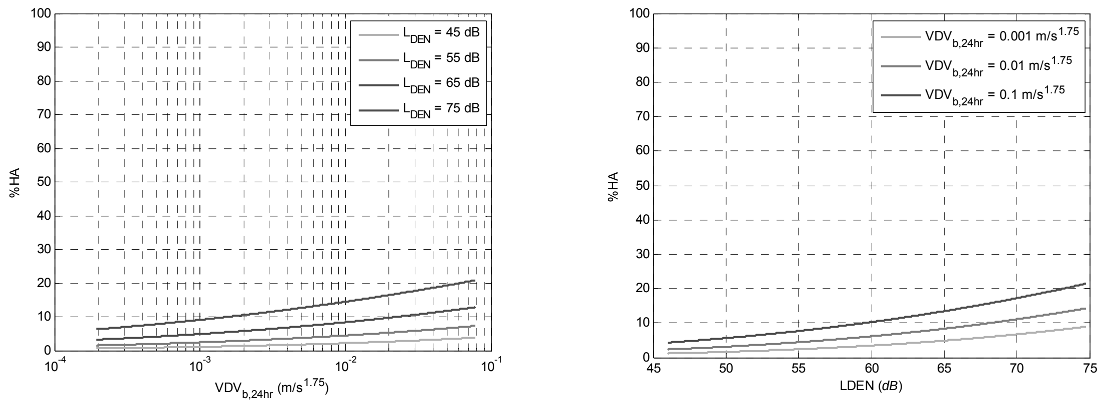

Figure 45 Sections through the curved surface presented in Figure 44 at different values of noise exposure (left pane) and vibration exposure (right pane).

Response: Annoyance noise railway			N =	698
Scale: 5 point semantic			*p-Value*	*<0.0001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.02*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	-49.14	46.12		n.s.
10log($VDV_{b,24hr}$)	1.15	0.61		<0.0001
L_{DEN}	1.33	0.59		<0.0001
σ	41.53	2.26		<0.0001

Table 41 Parameter estimates for the relationship presented in Figure 44.

6 CONSTRUCTION SOURCES

6.1 INTRODUCTION

In this section, exposure-response relationships are presented for annoyance caused by vibration from construction activities. The methods employed to estimate vibration exposure are detailed in Technical Report 3. Exposure-response relationships are presented with vibration exposure evaluated in line with BS 6472-1:2008 and ISO 2631-1:1997. Relationships for concern of damage to property are presented along with exposure-response relationships for annoyance due to construction noise exposure.

6.2 INFLUENCE OF CONSTRUCTION ACTIVITIES

The data used for the exposure response relationships were generated from construction sites which exhibited different construction activities. To determine if the data from the different sites could be pooled together to form one exposure-response relationship, a dummy variable was created for "*site*". The likelihood for the models with and without the "*site*" dummy variable was calculated. Inclusion of the "*site*" variable did not result in a significant increase in the likelihood of the model indicating it was appropriate to combine the datasets from different sites.

6.3 MODEL BASED ON GUIDANCE FROM BS 6472-1:2008

Figure 46 shows an exposure-response relationship for annoyance caused by vibration exposure from construction sources as a function of VDV_b ($m/s^{1.75}$).

From Figure 46 it can be seen that approximately 50% of respondents report feeling vibration at exposures of around 0.01 $m/s^{1.75}$. At this magnitude of vibration exposure, it can be seen that around 10% of respondents report being highly annoyed by vibration from construction activities. At exposures of 0.1 $m/s^{1.75}$, around 50% of respondents report being highly annoyed, 60% report being annoyed, and 70% report being slightly annoyed.

Comparing this relationship with the exposure-response relationship derived for railway induced vibration (see Figure 26 and Figure 27), it can be seen that the point at which 50% of respondents report feeling vibration is similar for the two different sources; however, the proportion of respondents reporting annoyance for this exposure raises from below 5% for railway induced vibration to more than 10% for construction induced vibration. The proportion of respondents reporting annoyance rises much more rapidly for construction vibration than for railway vibration. At exposures of 0.1 $m/s^{1.75}$, 50% of respondents report being highly annoyed by vibration from construction sources compared with 10% of respondents for the same exposure from railway sources.

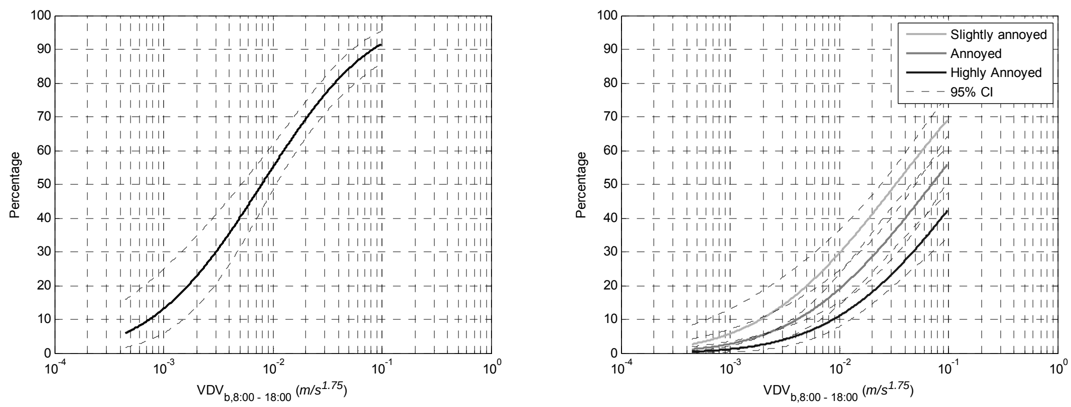

Figure 46 Exposure-response relationships for construction vibration exposure. Left pane: Proportion of people reporting feeling vibration for a given vibration exposure. Right Pane: Proportion of people reporting different degrees of annoyance for a given vibration exposure.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the range 4.45×10^{-4} and 0.10 $VDV_{b,8:00-18:00}$ in the vertical direction.

Response: Feel/Don't Feel			*N =*	321
Scale: Binary			*p-Value*	*<0.0001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.09*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	2.6337	0.3193		<0.0001
$VDV_{b,8:00-18:00}$	0.1253	0.0174		<0.0001

Polynomial Approximations
$\%Feel = -2.861X^3 + 0.920X^2 + 32.990X + 46.189$
$CU_{feel} = -1.691X^3 + 0.583X^2 + 28.127X + 54.694$
$CL_{feel} = -4.117X^3 + 1.913X^2 + 35.757X + 38.207$

Table 42 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 46.

Where $X = \frac{10\log_{10}(\mathrm{VDV}_{b,8:00-18:00}) + 21.8}{6.8}$

	β_0	β_1
β_0	0.1019	0.0054
β_1	0.0054	0.0003

Table 43 Estimated covariance matrix for the relationships presented in the left pane of Figure 46.

Response: Annoyance construction			N =	321	Polynomial Approximations
Scale: 5 point semantic			*p-Value*	*<0.0001*	$\%LA = -0.809X^3 + 4.290X^2 + 21.567X + 23.728$
Direction of excitation: Vertical			R^2_{pseudo} =	*0.09*	$CU_{LA} = +0.150X^3 + 3.891X^2 + 19.399X + 31.042$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LA} = -1.507X^3 + 4.847X^2 + 21.731X + 17.792$
Intercept	126.24	15.93		<0.0001	$\%A = -0.024X^3 + 4.922X^2 + 15.950X + 14.483$
10log($VDV_{b,8:00-18:00}$)	6.62	0.98		<0.0001	$CU_A = +0.736X^3 + 4.850X^2 + 15.378X + 19.938$
σ	63.6	4.94		<0.0001	$CL_A = -0.508X^3 + 4.927X^2 + 15.092X + 10.385$
					$\%HA = +0.558X^3 + 4.587X^2 + 10.468X + 7.971$
					$CU_{HA} = +1.177X^3 + 4.892X^2 + 10.756X + 11.567$
					$CL_{HA} = +0.169X^3 + 4.177X^2 + 9.358X + 5.466$

Table 44 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 46.

Where $X = \frac{10\log_{10}(\mathrm{VDV}_{b,8:00-18:00}) + 21.8}{6.8}$

	β_0	β_1
β_0	253.66	14.98
β_1	14.98	0.96

Table 45 Estimated covariance matrix for the relationships presented in the right pane of Figure 46.

6.4 MODEL BASED ON GUIDANCE FROM ISO 2631-1:1997

Figure 47 shows an exposure response relationship for annoyance caused by vibration exposure from construction sources as a function of W_b weighted *rms* acceleration (m/s^2). It can be seen that, as the magnitude of vibration exposure increases, the proportion of respondents expressing annoyance increases.

From Figure 47 it can be seen that approximately 50% of respondents report feeling vibration at exposures of around 4×10^{-5} m/s^2. At this magnitude of vibration exposure, it can be seen that around 10% of respondents report being highly annoyed by vibration from construction activities. At exposures of 1×10^{-3} m/s^2, around 60% of respondents report being highly annoyed, 70% report being annoyed, and 80% report being slightly annoyed.

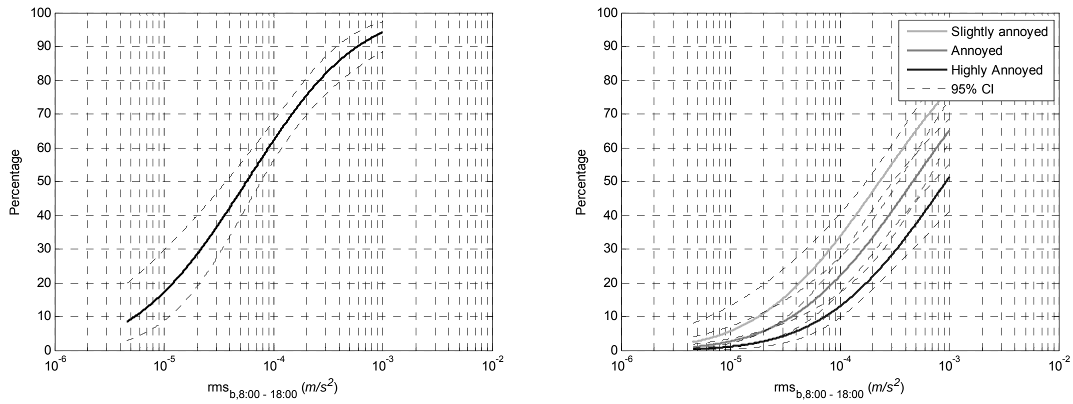

Figure 47 Exposure-response relationships for construction vibration exposure. Left pane: Proportion of people reporting feeling vibration for a given vibration exposure. Right Pane: Proportion of people reporting different degrees of annoyance for a given vibration exposure.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the range 4.55x10^{-6} and 0.10x10^{-4} $rms_{b,8:00-18:00}$ acceleration in the vertical direction.

Response: Feel/Don't Feel			*N =*	321
Scale: Binary			*p-Value*	*<0.0001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.09*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	5.3402	0.7245		<0.0001
10log($rms_{b,8:00-18:00}$)	0.1258	0.0183		<0.0001

Polynomial Approximations
$\%Feel = -2.895X^3 - 0.860X^2 + 33.139X + 53.541$
$CU_{feel} = -2.112X^3 - 0.595X^2 + 28.651X + 61.165$
$CL_{feel} = -4.025X^3 - 0.474X^2 + 36.037X + 45.973$

Table 46 Parameter estimates and polynomial approximations for the curves presented in the left pane of Figure 47.

Where $X = \dfrac{10\log_{10}(\mathrm{rms}_{b,8:00-18:00}) + 41.7}{6.8}$

	β_0	β_1
β_0	0.5249	0.0132
β_1	0.0132	0.0003

Table 47 Estimated covariance matrix for the relationships presented in the right pane of Figure 47.

Response: Annoyance construction			*N* =	321
Scale: 5 point semantic			*p-Value*	*<0.0001*
Direction of excitation: Vertical			R^2_{pseudo} =	*0.11*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	291.29	39.11		<0.0001
10log(rms$_{b,8:00-18:00}$)	7.24	1.06		<0.0001
σ	62.22	5.23		<0.0001

Polynomial Approximations
$\%LA = -1.416X^3 + 4.558X^2 + 25.749X + 27.198$
$CU_{LA} = -0.309X^3 + 4.242X^2 + 23.311X + 34.556$
$CL_{LA} = -2.311X^3 + 5.014X^2 + 26.091X + 21.113$
$\%A = -0.364X^3 + 5.755X^2 + 19.672X + 16.962$
$CU_A = +0.544X^3 + 5.847X^2 + 19.096X + 22.559$
$CL_A = -1.026X^3 + 5.547X^2 + 18.739X + 12.678$
$\%HA = +0.528X^3 + 5.726X^2 + 13.287X + 9.508$
$CU_{HA} = +1.323X^3 + 6.326X^2 + 13.731X + 13.239$
$CL_{HA} = -0.049X^3 + 4.990X^2 + 11.987X + 6.857$

Table 48 Parameter estimates and polynomial approximations for the curves presented in the right pane of Figure 47.

Where $X = \frac{10\log_{10}(\text{rms}_{b,8:00-18:00}) + 41.7}{6.8}$

	β₀	β₁
β₀	1529.87	41.22
β₁	41.22	1.12

Table 49 Estimated covariance matrix for the relationships presented in the right pane of Figure 47.

6.5 DISTANCE FROM SOURCE

Figure 48 shows an exposure response relationship for annoyance caused by vibration exposure from construction sources as a function of the distance from the source. It can be seen that, as the distance from the source increases, the proportion of respondents expressing annoyance decreases.

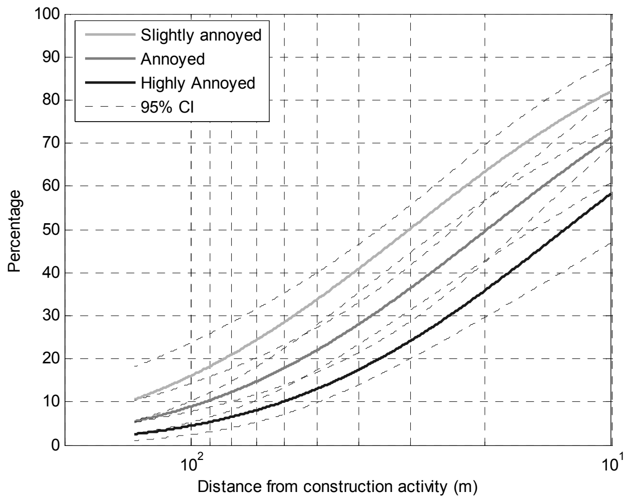

Figure 48 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given distance from the construction activity. Curves are shown in their 95% confidence intervals.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the range 10 m and 130 m.

Response: Annoyance construction			*N =*	321	**Polynomial Approximations**
Scale: 5 point semantic			*p-Value*	*<0.0001*	$\%LA = +1.300X^3 + 0.987X^2 - 24.460X + 43.604$
			R^2_{pseudo} =	*0.11*	$CU_{LA} = +1.179X^3 + 1.582X^2 - 23.885X + 49.597$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LA} = +1.654X^3 + 0.466X^2 - 24.359X + 37.793$
Intercept	204.45	24.21		<0.0001	
10log(Distance)	-11.91	1.57		<0.0001	$\%A = +0.919X^3 + 2.822X^2 - 21.767X + 30.512$
σ	62.41	4.9		<0.0001	$CU_A = +0.739X^3 + 3.541X^2 - 22.540X + 35.945$
					$CL_A = +1.275X^3 + 2.092X^2 - 20.458X + 25.540$
					$\%HA = +0.326X^3 + 3.866X^2 - 17.149X + 19.496$
					$CU_{HA} = +0.052X^3 + 4.869X^2 - 18.806X + 23.831$
					$CL_{HA} = +0.707X^3 + 2.859X^2 - 15.239X + 15.747$

Table 50 Parameter estimates and polynomial approximations for the curves presented in Figure 49.

Where $X = \frac{10\log_{10}(\text{Distance}) - 15.7}{3.3}$

	β_0	β_1
β_0	586.16	-37.47
β_1	-37.47	2.48

Table 51 Estimated covariance matrix for the relationships presented in Figure 49.

6.6 CONCERN OF DAMAGE TO PROPERTY

Figure 49 presents an exposure-response relationship illustrating the proportion of respondents expressing concern of damage to property above a given threshold for a given vibration exposure from construction activities. The thresholds used are the same as those used for the concern of damage to property from railway induced vibration presented in section 5.8.

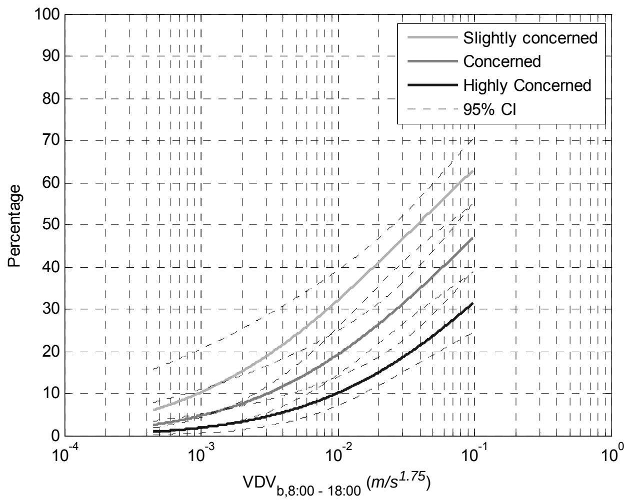

Figure 49 Exposure-response relationship showing the proportion of people reporting different degrees of concern of damage to property for a given vibration exposure from construction activities. Curves are shown in their 95% confidence intervals.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the range 4.45×10^{-4} and 0.10 $VDV_{b,8:00-18:00}$ in the vertical direction.

Response: Concern construction			N =	321	**Polynomial Approximations**
Scale: 5 point semantic			*p-Value*	*<0.0001*	$\%LC = -0.511X^3 + 2.539X^2 + 17.907X + 27.109$
Direction of excitation: Vertical			R^2_{pseudo} =	*0.07*	$CU_{LC} = +0.490X^3 + 2.714X^2 + 14.524X + 35.032$
Parameter	**β Estimate**	**Standard Error**		**p-Value**	$CL_{LC} = -1.416X^3 + 2.888X^2 + 19.311X + 20.425$
Intercept	89.61	13.04		<0.0001	$\%C = -0.033X^3 + 3.150X^2 + 12.917X + 15.537$
$10\log(VDV_{b,8:00-18:00})$	4.35	0.81		<0.0001	$CU_C = +0.806X^3 + 3.358X^2 + 11.398X + 21.387$
σ	54.28	4.34		<0.0001	$CL_C = -0.646X^3 + 3.155X^2 + 12.853X + 11.055$
					$\%HC = +0.309X^3 + 2.844X^2 + 7.907X + 7.779$
					$CU_{HC} = +0.952X^3 + 3.194X^2 + 7.544X + 11.430$
					$CL_{HC} = -0.100X^3 + 2.565X^2 + 7.309X + 5.228$

Table 52 Parameter estimates and polynomial approximations for the curves presented in Figure 49.

Where $X = \dfrac{10\log_{10}(\mathrm{VDV}_{d,8:00-18:00}) + 21.8}{6.8}$

	β₀	**β₁**
β₀	170.04	10.04
β₁	10.04	0.65

Table 53 Estimated covariance matrix for the relationships presented in Figure 49.

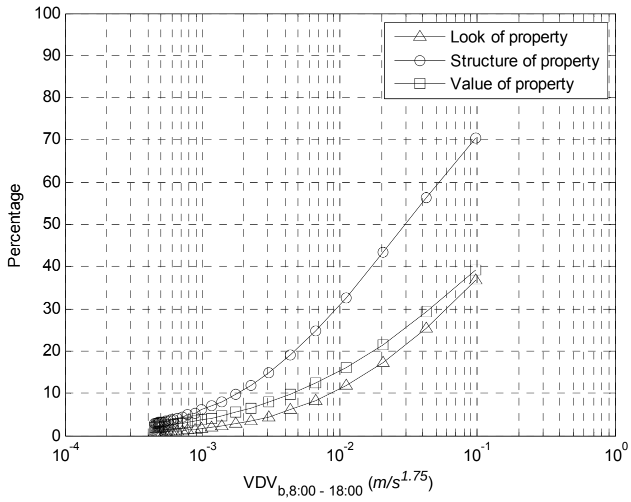

Figure 50 Exposure-response relationship showing the proportion of people reporting different aspects of concern of damage for a given vibration exposure from construction activities.

6.7 RESPONSE TO NOISE

Figure 51 shows an exposure-response relationship for annoyance due to exposure to noise from construction activities. Noise exposure was estimated using the methods detailed in Technical Report 4.

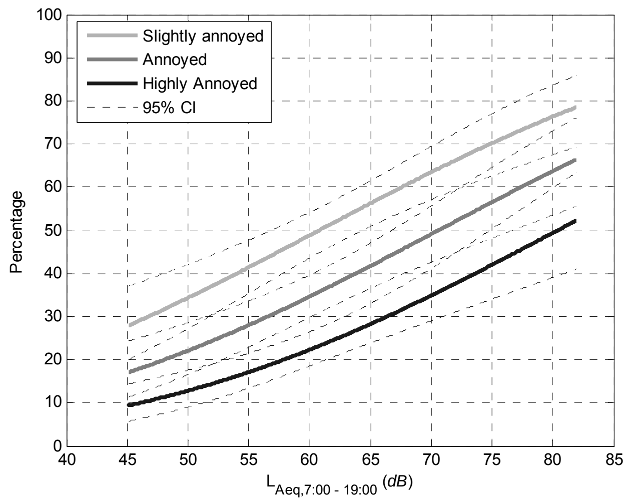

Figure 51 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance due to noise for a given noise exposure from construction activities. Curves are shown in their 95% confidence intervals.

The following tables provide parameter estimates and polynomial approximations for the relationships provided in this section. These models must not be used outside of the range 45 and 82 $L_{Aeq,7:00} - 19{:}00$.

Response: Annoyance noise construction			N =	321
Scale: 5 point semantic			*p-Value*	*<0.0001*
			R^2_{pseudo} =	*0.10*
Parameter	**β Estimate**	**Standard Error**		**p-Value**
Intercept	-108.45	24.83		<0.0001
$L_{Aeq,7:00-19:00}$	2.24	0.39		<0.0001
σ	60.07	4.82		<0.0001

Table 54 Parameter estimates for the relationships presented in Figure 51.

	β_0	β_1
β_0	616.51	-9.65
β_1	-9.65	0.16

Table 55 Estimated covariance matrix for the relationships presented in Figure 51.

7 INTERNAL SOURCES

For the case of internal vibration sources outside of respondents' control, 151 case studies were conducted. Only 19% of this sample reported being able to feel vibration. None of the residents interviewed reported high annoyance due to vibration exposure. The mean annoyance rating for this sample calculated from the 5-point semantic scale was 0.18. The vibration exposures measured for internal sources ranged from 1.7×10^{-4} to 6.7×10^{-4} m/s^2 W_b weighted 24-hour *rms*. Due to the low proportion of respondents reporting annoyance and the limited range of vibration exposures, this dataset was considered unsuitable for the derivation of an exposure-response relationship for annoyance caused by internal vibration sources.

8 EXPOSURE-RESPONSE RELATIONSHIPS FOR MIXED SOURCES

In previous studies, exposure-response relationships for the human response to vibration in residential environments have been derived for mixed sources (Klæboe et al. 2003), namely railway induced vibration and road traffic induced vibration. To investigate in influence of the vibration source type on self reported annoyance due to vibration exposure, data from the railway and construction source types were pooled together and a dummy variable was created for source type. Exposure-response models were calculated with and without the source type variable. The improvement in likelihood for the model with the source variable was found to be significant ($p \ll 0.001$). This result suggests that the exposure-response relationships for railway and construction sources cannot be combined and a separate relationship is needed for the two different sources. However, it should be noted that differences in the methodology for the estimation of vibration exposure for the two sources may have had an influence on this result.

As with the exposure-response relationships for annoyance caused by vibration from different sources, a "*source*" dummy variable was created for the noise from railway and construction datasets. The improvement in likelihood for the model with the source variable was found to be significant ($p \ll 0.001$) again indicating that annoyance due to noise exposure from railway and construction sources should be considered separately.

9 COMPARISON WITH PUBLISHED GUIDANCE

9.1 BS 6472-1:2008 AND ANC GUIDELINES

BS 6472:2008 suggests the probability of adverse comment for five categories of vibration exposure (see Table 56). A similar table is included in the ANC guidelines (Association of Noise Consultants, 2001) in which the categories for daytime exposure are the same as in BS 6472:2008 but the categories for night-time exposure are expressed as single figure values (these values are shown in brackets in Table 56). As it is not stated what is meant by "adverse comment", it is difficult to assess the suitability of this guidance. Table 57 presents the range of percentage of respondents expressing high annoyance within these five categories for railway and construction vibration. For railway induced vibration, it can be seen that the top three categories in the daytime and the top two categories at night are outside of the range of measured exposures.

Place and time	**Low probability of adverse comment**[5] $m/s^{1.75}$	**Adverse comment possible** $m/s^{1.75}$	**Adverse comment probable**[6] $m/s^{1.75}$
Residential buildings 16*hr* day	0.2 – 0.4	0.4 – 0.8	0.8 – 1.6
Residential buildings 8*hr* night	0.1 – 0.2 (0.13)	0.2 – 0.4 (0.26)	0.4 – 0.8 (0.51)

Table 56 Probability of adverse comment for a range of vibration exposures as suggested in BS 6472:2008. Values provided in the ANC guidelines are shown in brackets.

[5] Below these ranges adverse comment is not expected.

[6] Above these ranges adverse comment is very likely.

Exposure	%HA Railway	%HA Construction
< 0.2 $VDV_{b,day}$	0 – 3	0 - > 43*
0.2 – 0.4 $VDV_{b,day}$	3 – 4	> 43*
0.4 – 0.8 $VDV_{b,day}$	> 4 *	> 43*
0.8 – 1.6 $VDV_{b,day}$	> 4 *	> 43*
> 1.6 $VDV_{b,day}$	> 4 *	> 43*
< 0.1 $VDV_{b,night}$	0 – 12	N/A
0.1 – 0.2 $VDV_{b,night}$	12 – 15	N/A
0.2 – 0.4 $VDV_{b,night}$	15 – 19	N/A
0.4 – 0.8 $VDV_{b,night}$	> 19 *	N/A
> 0.8 $VDV_{b,night}$	> 19 *	N/A

Table 57 Percentage of respondents expressing high annoyance for vibration exposure in the limits provided in Table 56. (* - outside range of measured exposures).

For railway *noise* exposure, PPG24 recommends the limit of 55 $L_{Aeq,16hr}$ dB(A) during the daytime and 45 $L_{Aeq,8hr}$ dB(A) during the night-time. These figures are based on guidance from the World Health Organisation that state "general daytime outdoor noise levels of less than 55 dB(A) L_{eq} are desirable to prevent any significant community annoyance". These limits combined would result in a day-night level of 53.5 dB(A) which would equate to around 2% of the population being *highly annoyed* according to published exposure-response curves for noise exposure (H. Miedema & Oudshoorn 2001). Based on this, the lowest category of the guidance provided by BS6472-1:2008 which equates to around 0 – 3% highly annoyed according to the relationships presented in this report seems reasonable.

In the bottom two categories for which measured exposures are available for both daytime and night-time exposure, there is little agreement between the ranges of *highly annoyed* respondents in the daytime and night-time periods. Along with the results presented in section 5.7, this strongly suggests that a day-evening-night type descriptor (similar to the L_{DEN} descriptor used for noise exposure) would be useful for the assessment of 24 hour vibration exposure.

It is also apparent from the results presented in Table 57, based upon the guidance provided in BS6472-1:2008, adverse comment due to construction vibration exposure is severely underestimated. This indicates that, as with noise exposure, source specific guidance needed.

9.2 BS 5228-2:2009

BS5228-2:2009 provides guidance on the effect of vibration from construction activities in residential environments (see Table 58). This guidance is provided in terms of peak particle velocity (*ppv*). As only peak particle acceleration was available for construction, *ppv* was estimated as the maximum peak particle acceleration in any 1/3 octave band divided by ω_c (where ω_c is 2π multiplied by the octave band centre frequency). Figure 52 shows the exposure-response relationship for annoyance due to construction vibration in terms of estimated *ppv*. Table 59 shows the percentage of respondents expressing high annoyance in the categories defined in BS5228-2:2009.

Vibration level (mm/s)	Effect
0.14	Vibration might be just perceptible in the most sensitive situations for most vibration frequencies associated with construction. At lower frequencies, people are less sensitive to vibration
0.3	Vibration might be just perceptible in residential environments
1.0	It is likely that vibration of this level in residential environments will cause complaint, but can be tolerated if prior warning and explanation has been given to residents
10	Vibration is likely to be intolerable for any more than a very brief exposure to this level

Table 58 Guidance of effects of construction vibration levels as stated in BS5228-2:2009.

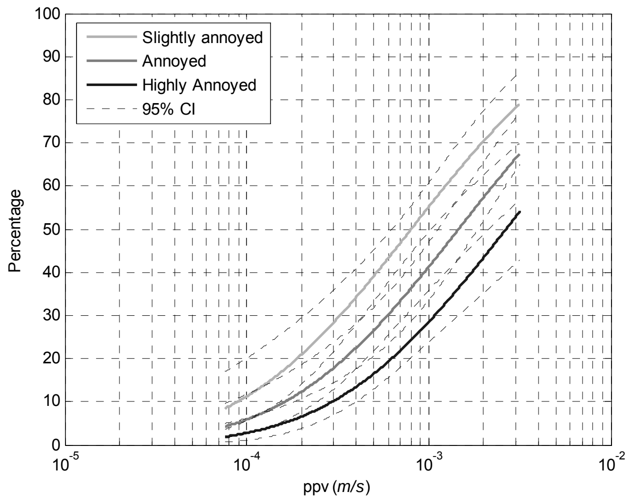

Figure 52 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure.

Exposure	%HA Construction
< 0.14 mm/s (*ppv*)	0 – 4.0
0.14 – 0.3 mm/s (*ppv*)	4.0 – 10.2
0.3 – 1.0 mm/s (*ppv*)	10.2 – 28.4
1.0 – 10 mm/s (*ppv*)	>28.4*

Table 59 Percentage of respondents reporting high annoyance in the categories defined in BS5228-2:2009 (* - Outside range of measured exposures).

9.3 Norwegian socio-vibration study

Based on the exposure response relationships derived from the Norwegian socio-vibration study (Klæboe et al. 2003), guidance was provided for classification of dwelling based on four categories of statistical maximum weighted velocity and acceleration (Turunen-Rise et al. 2003). This guidance is summarised in Table 60. Class C, which corresponds to 7 – 8% of people highly annoyed, was suggested as the minimum vibration requirement for new residential buildings. Figure 53 shows the exposure-response relationships for the railway dataset under investigation in this report expressed in terms of $a_{w,95}$. Comparing this relationship to the guidance provided in Table 60, it can be seen that at 11 mm/s^2 ($a_{w,95}$) (which corresponds to a Class C dwelling) around 12% of the population report high annoyance. Within the confidence limits reported in Figure 53, this result is in line with the findings of the Norwegian study.

Type of vibration value	Class A	Class B	Class C	Class D
Statistical maximum value for weighted velocity $v_{w,95}$ (mm/s)	0.1	0.15	0.3	0.6
Statistical maximum value for weighted acceleration $a_{w,95}$ (mm/s^2)	3.6	5.4	11	21

Table 60 Guidance classification of dwellings with the upper limits for the statistical maximum value for weighted velocity $v_{w,95}$ or acceleration $a_{w,95}$ (taken from (Turunen-Rise et al. 2003)).

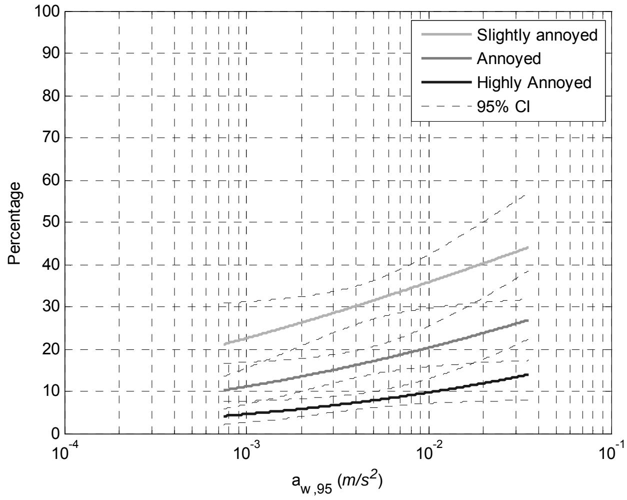

Figure 53 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure.

10 CONCLUSIONS

This report has aimed to present the development of exposure-response relationships for the human response to vibration in residential environments. An analysis of the most appropriate vibration exposure descriptor to describe self reported annoyance has been undertaken. This analysis focused on determining the most appropriate averaging method and frequency weighting. It was found that, for the dataset under analysis in this report, the type of averaging used was largely unimportant with regards to human response. The application of frequency weightings defined in BS 6472- 1:2008, ISO 2631-1:1997, and ISO 2631- 2:2003 were found to improve the magnitude of correlation between vibration exposure and self reported annoyance. The highest magnitude of correlation with self reported annoyance was exhibited by vibration exposure in the 8 *Hz* 1/3 octave band. It should be noted that this result is only directly applicable to the data from which it was derived, however the improvement in correlation observed by expressing vibration exposure in 1/3 octave bands suggests that further research into frequency weightings for the human response to vibration in residential environments could yield a more robust descriptor than those which are recommended in current standards.

Exposure-response relationships have been developed for the human response to railway and construction induced groundborne vibration. These relationships have been expressed in *VDV* as per the guidance provided in BS 6472- 1:2008 and in weighted *rms* acceleration as per the guidance provided in ISO 2631-1:1997. In all of the derived relationships it was found that, as the magnitude of vibration exposure increases so does the proportion of respondents reporting annoyance above a given threshold. It was found for both railway and construction sources, the distance of a residence from the source of vibration is a useful proxy for vibration exposure in the absence of measured data.

Other factors relating to the human response to vibration have been assessed. The time of day of exposure has been shown to have an affect on the degree of annoyance caused by a given vibration exposure with exposure at night been shown to elicit a stronger response than exposure in the evening and exposure in the evening been shown to elicit a stronger response than annoyance during the day. Relationships have been derived for self reported concern of damage to property, as with annoyance, concern of damage was found to rise with increased vibration exposure. It was investigated whether a synthesis curve could be developed from the relationships derived for railway and construction sources. This analysis suggested that the human response to railway and construction vibration should be considered separately, however, it should be noted that differences in the methodology for the estimation of vibration exposure for the two sources may have had an influence on this result.

Internal sources of vibration outside of residents' control were also considered. Due to the narrow vibration exposures recorded for these sources along with the low proportion of respondents expressing annoyance, the data collected for this source was considered unsuitable for the formulation of an exposure-response relationship.

Additional to exposure-response relationships for self reported annoyance, relationships have been derived for sleep disturbance due to vibration exposure. It was found that the proportion of respondents reporting sleep disturbance increased as the magnitude of vibration exposure increased.

Exposure-response relationships for combined noise and vibration exposure have been derived. These curves are expressed in the form of *VDV* for the vibration exposure and L_{DEN} for the noise exposure. It was found that, for a given vibration exposure, annoyance caused by vibration increases with increasing noise exposure. Similarly, it was found that for a given noise exposure, annoyance due to noise increases with increasing vibration exposure.

11 References

11.1 Papers

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12 Appendix I – Laboratory tests

12.1 Introduction

This report presents a laboratory study designed to assess the feasibility of using the method of paired comparisons and multidimensional scaling to investigate the perception of whole body vibration. Multidimensional scaling is a powerful data exploration technique which, when combined with paired comparison tests of similarity, makes it possible to identify the underlying perceptual dimensions of a group of stimuli. The methods of paired comparisons and multidimensional scaling have been used extensively in areas such as the perception of musical timbre (Grey 1977; McAdams et al. 1995), the perception of concert hall quality (Schroeder et al. 1974), and product sound quality (Parizet et al. 2008). In Grey's study, subjects were presented with every possible pairing of a group of synthesised musical tones and asked to judge how similar they perceived the tones to be. By analysing these pairwise judgements of similarity via multidimensional scaling, it was revealed that the perception of musical timbre can be described by three perceptual dimensions. Through analysis of a number of objective acoustical features of the test signals, Grey determined that the perceptual dimensions revealed through the multidimensional scaling analysis were related to spectral energy distribution, spectral fluctuation and high frequency energy in the attack section of the tones. In the case of product sound quality, the aim of these tests is usually to relate the perceptual dimensions revealed through multidimensional scaling to some judgment of product sound quality in order to build a model to predict perceived sound quality based on objective acoustical features of the sound emitted by the product in question.

It can be seen in the literature that these techniques have been highly successful in uncovering the underlying perceptual dimensions of groups of auditory stimuli. The multidimensional nature of sound perception is highlighted by the rich vocabulary available for the description of auditory perception. For example, frequency characteristics of a sound can be described as "*bright*", "*sharp*", or "*dull*"; amplitude characteristics can be described as "*loud*" or "*quiet*"; and temporal characteristics can be described "*fluctuating*", "*peaky*", or "*undulating*". In comparison to the perception of auditory stimuli, the vocabulary at our disposal for describing the perception of vibratory stimuli is rather limited. This suggests that the acuity of human perception of vibration is much less that that of the perception of sound. The main aim of the work detailed in this report is to determine if the perception of vibration is multidimensional in nature.

The suitability of the method of paired comparisons and multidimensional scaling is assessed via the following criteria:

- The test procedure was simple and readily understood by subjects

- Data collected via the test was suitable for multi-dimensional scaling analysis
- The axes revealed through the multidimensional scaling analysis related to a perceptual continuum
- The axes revealed through the multidimensional scaling analysis could be related to self reported annoyance

12.2 MULTIDIMENSIONAL SCALING

NOTE: This section provides an overview of multidimensional scaling techniques, an understanding of which is not vital to interpret the results presented in this report. The reader may wish to skip the content in this section.

Multidimensional scaling (MDS) is a method by which it is possible to reduce the dimensionality of a matrix of pairwise data. By considering pairwise judgments of similarity or dissimilarity obtained through perceptual testing, it is possible to obtain a configuration of points in low-dimensional space which represent the "*perceptual distance*" between the stimuli considered in the perceptual test. The greater the distance between two points in the MDS configuration the greater the judged dissimilarity of the two stimuli. As the dimensions of the configuration obtained through MDS are orthogonal, it is not unreasonable to assume that each dimension relates to a continuum of a unique perceptual attribute within the group of stimuli studied. By finding objective correlates to the axes revealed through MDS, it is possible to reveal the perceptual dimensions which underlie a group of stimuli.

Multidimensional scaling refers to a family of multivariate data analysis techniques which aims to reduce the dimensionality of multidimensional data. MDS attempts to determine a configuration for a group objects in a low-dimensional multidimensional space to provide a visual representation of pairwise distances or (dis)similarities between the objects in the group. If a test has been conducted in which subjects were presented with every possible pairing (r, s) of n objects and asked to judge how dissimilar ($\delta_{r,s}$) they perceive the pair of objects to be, a matrix of pairwise dissimilarities can be formed $\{\delta_{r,s}\}$. The dissimilarity matrix $\{\delta_{r,s}\}$ can then be subjected to MDS analysis which aims to find the best representation of the n objects in a Euclidean space of a user defined number of dimensions (R) with a large distance ($d_{r,s}$) between objects in the MDS configuration representing a large judged dissimilarity ($\delta_{r,s}$) and vice versa. By studying the configuration of points in multidimensional space it is possible to identify the perceptual attributes which underlie a group of objects, each of the R dimensions being orthogonal and therefore representative of a salient perceptual attribute underlying the group of n objects. A classic illustration of multidimensional scaling presented in many texts is to analyse a matrix of pairwise distances between cities; a two dimensional solution yields a representation of the cities as they would appear on a two dimensional map (see Figure A - 1).

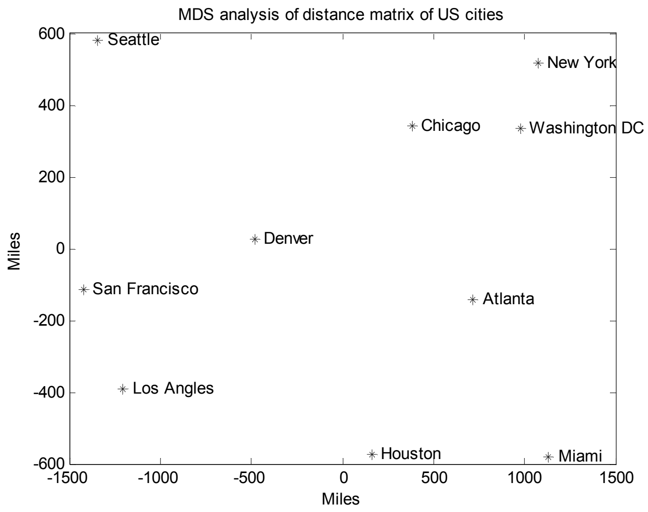

Figure A - 1 Results of MDS analysis on pairwise distances between US cities.

There are numerous different MDS models and selecting which model is appropriate for the task is largely dependent upon the type of data under analysis. Data for MDS analysis are often described in terms of *ways* and *modes*. The number of *ways* refers to the dimensionality of the dataset; magnitude judgements of preference on a group of sounds would be classified as *one-way* data whereas a matrix describing pairwise preference judgements of a group of sounds would be described as *two-way* data, a three-dimensional matrix containing pairwise judgments from a number of different subjects would be *three-way* data. The number of *ways*, however, gives no indication as to the form of the data (i.e. square, rectangular, etc. matrices) as magnitude judgements of preference of a group of objects made by multiple subjects (a two dimensional rectangular matrix) would give rise to the same number of *ways* as pairwise comparison data for one subject (a two dimensional, symmetric square matrix). The avoid these possible ambiguities, *modes* are used to describe the number of “entities” contributing to the dataset. For example, multiple subjects judging the dissimilarities between a group of vibration stimuli ($\delta_{r,s,i}$) would produce *three-way two-mode* data; the two *modes* being the group of vibration stimuli and the set of subjects undertaking the perceptual tests and the three *ways* being the pairwise dissimilarity judgements (r and s) from a number of subjects (i).

12.2.1 Metric and non-metric scaling

Metric MDS aims to find a configuration of points in low dimensional Euclidean space where distances between points ($d_{r,s}$) are approximately equal to $f(\delta_{r,s})$ where f is a continuous parametric monotonic function and $\delta_{r,s}$ are measured pairwise distances. This is commonly achieved by fitting distances $\{d_{r,s}\}$ by least squares to $\{f(\delta_{r,s})\}$. For example, a configuration may be sought which minimises the loss function given in Equation 1 where α and β are positive constants to be found (M. A. A. Cox & T. F. Cox 2008).

$$\frac{\sum_r \sum_s (d_{rs} - (\alpha + \beta \delta_{rs}))^2}{\sum_r \sum_s d_{rs}}$$ **Equation 1**

where $d_{r,s}$ are the reproduced distances, and $\delta_{r,s}$ are measured distances.

Non metric scaling can be used when the input data are judged dissimilarities; as dissimilarities are non-metric but can be thought of as "*distance like*", only the rank order of the dissimilarities is taken into consideration during the analysis. The transform *f* can therefore now be arbitrary but must still be monotonic. In contrast to metric scaling which attempts to find a configuration of points in low-dimensional Euclidean space which preserves the measured distances between objects, non-metric multidimensional scaling attempts to provide a configuration in which the distances between points preserves the rank order of judged dissimilarities. In-depth discussions of metric and non-metric MDS models can be found in a number of publications (Coxon et al. 1985; M. A. A. Cox & T. F. Cox 2008; Borg & Groenen 2005).

12.2.2 Individual Difference Scaling

When data is obtained from many different subjects, the issue of how to aggregate the data arises. By averaging responses across the subject group, any information about intra-subject variability is lost. Carroll and Chang (Carroll & Chang 1970) proposed a multidimensional scaling algorithm in which intra-subject differences could be preserved by defining both a "*group space"* which provides an MDS configuration which is common to all subjects and a "*subject space"* which represents the weighting each subject attributes to each dimension of the group space. Using this information a "*private space"* can be derived for each subject. This procedure is termed the INDSCAL model (INdividual Difference SCALing), an in-depth description of which can be found in Chapter 7 of Coxon (Coxon et al. 1985).

Some basic features of INDSCAL analysis are illustrated in Figure A - 2 (from (Coxon et al. 1985)). This figure was generated using data collected from pairwise dissimilarity ratings made by sixteen subjects on three objects. It can be seen that the group space (**X**) calculated via the INDSCAL routine forms an approximate equilateral triangle. The subject space (**W**) illustrates the relative weighting each subject attributes to the two dimensions of the group space. The angle formed between a subject's vector in the *subject space* relates to the relative weighting the subject attributes to that dimension. The magnitude of a subject's vector from the origin relates to how well the subject's data is represented in the group space. Subjects 4, 5, and 6 in the *subject space* presented in Figure A - 2 place an equal weighting on each dimension in the *group space*. However, the magnitude of subject 4, 5, and 6's vectors from the origin in the subject space show that, although equal salience is attributed to each dimension, only subject 6's dissimilarity judgement's are well reproduced by the configuration of points in the group space. Subjects 1 and 2 place almost exclusive salience upon dimensions II and I of the group space respectively.

The magnitude of their vectors for subjects 1 and 2 from the origin in the subject space show that their dissimilarity judgements are well represented by the configuration of points in the group space. The private spaces (**Y**) of each subject can be derived by scaling the dimensions of the *group space* with respect to the square root of the weightings shown in the *subject space*:

$$y_{ja}^{(i)} = \sqrt{w_a^{(i)}} x_{ja}$$

Equation 2

where $y_{ja}^{(i)}$ is the coordinate of the *j*th object on the *a*th dimension in the *i*th subject's private space, $w_a^{(i)}$ is the *i*th subject's weighting for the *a*th dimension, and x_{ja} is the coordinate of the *j*th object on the *a*th dimension in the group space.

It follows that the distance between object *j* and *k* in subject *i*'s *private space* ($d_{jk}^{(i)}$) will be:

$$d_{jk}^{(i)} = \sqrt{\sum_a \left(\sqrt{w_a^{(i)}} x_{ja} - \sqrt{w_a^{(i)}} x_{ka}\right)^2}$$

Equation 3

$$d_{jk}^{(i)} = \sqrt{\sum_a w_a^{(i)} \left(x_{ja} - x_{ka}\right)^2}$$

Private spaces for subjects 1 and 2 are shown in Figure A - 2. Individual difference scaling is a useful technique when analysing data collected from multiple subjects as it removes the need to average data across the subject group and hence removes the risk of losing important features due to variation in subjective responses.

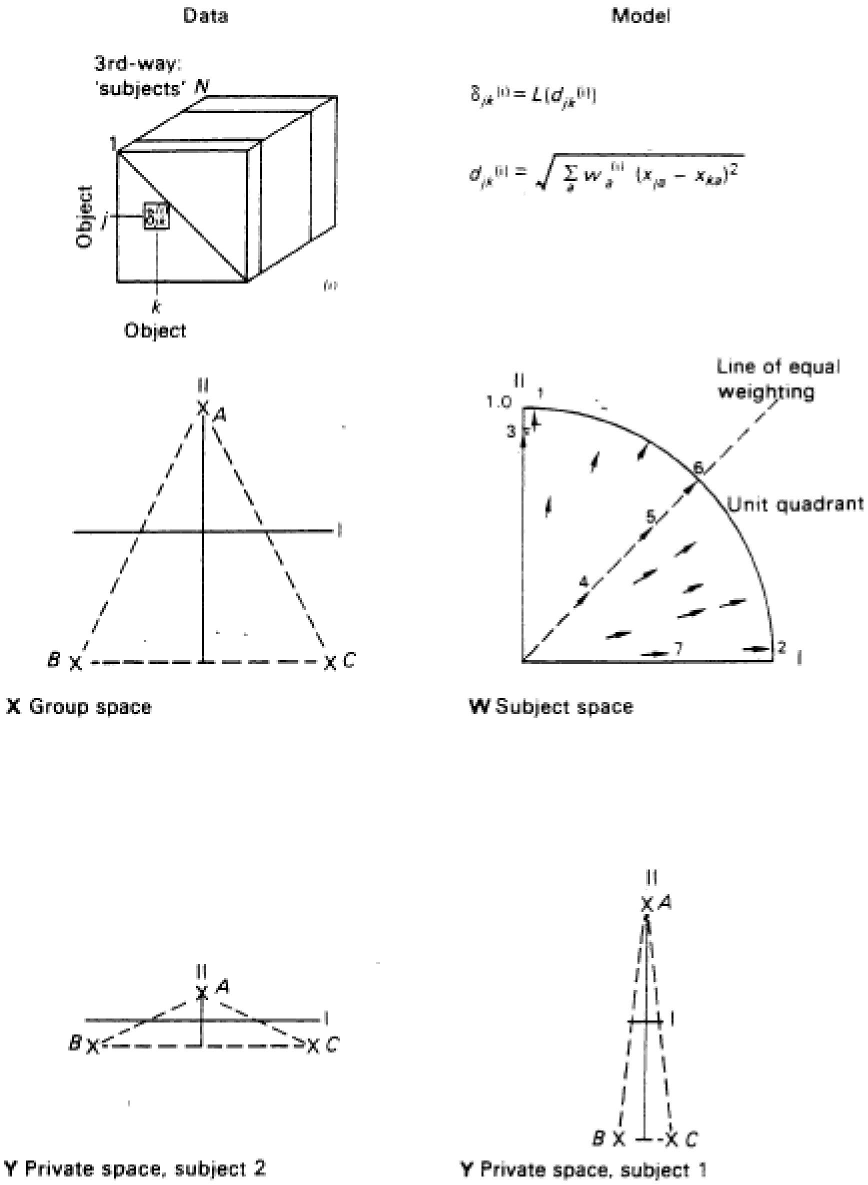

Figure A - 2 Illustration of some basic features of the INDSCAL model (taken from (Coxon et al. 1985)).

12.3 PAIRED COMPARISON TESTING

The method of paired comparisons is a test methodology whereby stimuli are presented in pairs to one or more subject. In a balanced paired comparison experiment, each subject is presented with every possible pairing of stimuli and is typically asked to state a preference or judge how dissimilar they perceive the pair of objects to be. This method has the advantage of removing the influence of stimuli outside of the pair under judgement and is particularly useful when the perceptual differences between the stimuli may be small. It has been shown that paired comparison tests result in much more consistent results than tests such as magnitude estimation (Parizet et al. 2005).

12.4 TEST METHODOLOGY

12.4.1 TEST RIG

The test rig consisted of a tactile transducer (Buttkicker LFE) rigidly attached to the underside of a chair with four bolts. This transducer is a commercially available electro-dynamic shaker generally sold for home cinema type applications and is powered by a 1000 *W* amplifier. The rig was calibrated by measuring the transfer function measured between the voltage into the transducer and the acceleration measured at the seat of the chair. This transfer function was applied to the signals used in the subjective testing by means of a minimum phase filter designed using the Yule-Walker method (Friedlander & Porat 2007). Figure A - 4 shows the magnitude Fourier spectra of acceleration measured at the seat of the chair for a white noise input with and without the calibration transfer function applied to the input signal. It can be seen from this figure that by applying this correction a relatively flat response can be achieved in the 10 *Hz* to 80 *Hz* region.

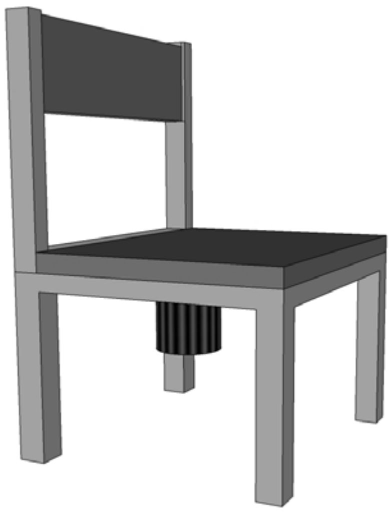

Figure A - 3 Tactile transducer attached to the underside of a chair.

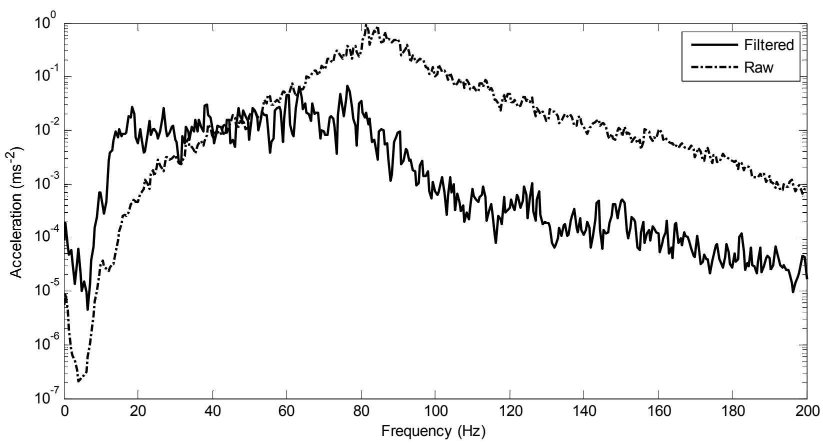

Figure A - 4 Response of test rig measured at the seat for a white noise input before and after calibration.

12.4.2 STIMULI

Twelve vibration stimuli were synthesized by combining signals with three types of frequency content (see Figure A - 5), two time windows (see Figure A - 6), and two different durations (3 seconds and 5 seconds). Table 1 shows how the twelve stimuli were synthesized from these three attributes. The resulting time histories of the stimuli are shown in Figure A - 7.

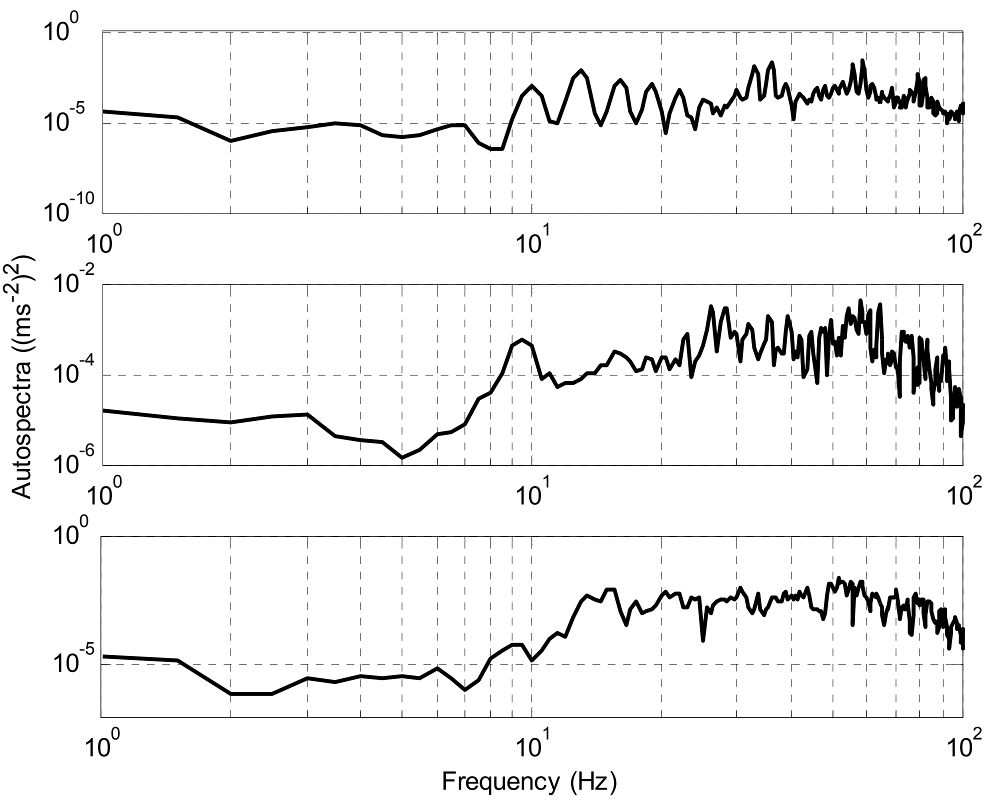

Figure A - 5 Frequency content of vibration stimuli.

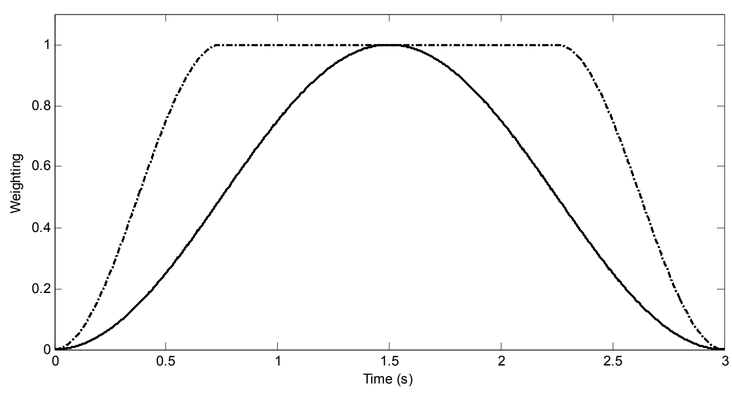

Figure A - 6 Time windows applied to vibration stimuli.

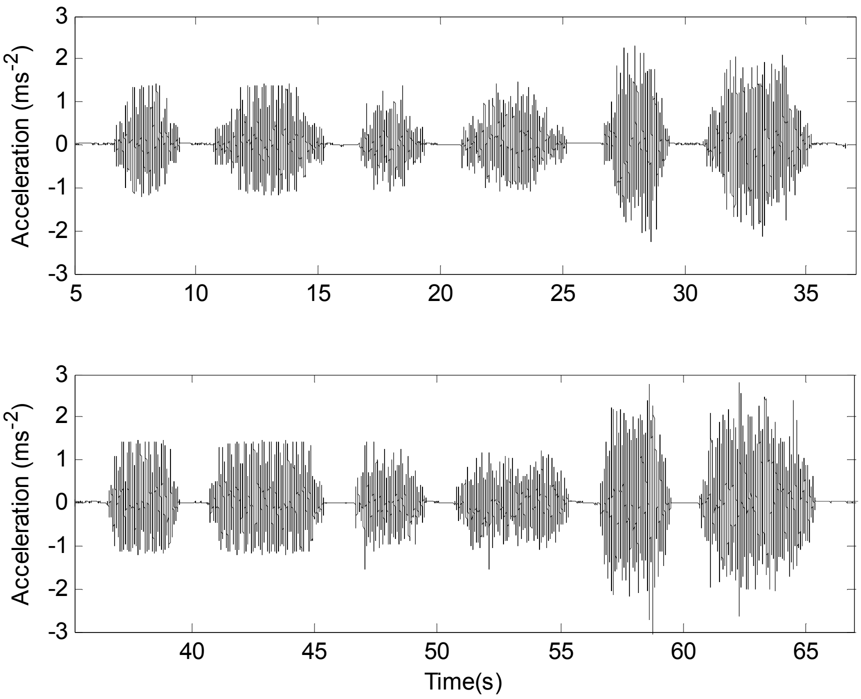

Figure A - 7 Acceleration time history of the twelve vibration stimuli.

Stimulus	Noise	Window	Duration
1	Harmonic	Hanning	3 sec
2	Harmonic	Hanning	5 sec
3	Noise 1	Hanning	3 sec
4	Noise 1	Hanning	5 sec
5	Noise 2	Hanning	3 sec
6	Noise 2	Hanning	5 sec
7	Harmonic	Custom	3 sec
8	Harmonic	Custom	5 sec
9	Noise 1	Custom	3 sec
10	Noise 1	Custom	5 sec
11	Noise 2	Custom	3 sec
12	Noise 2	Custom	5 sec

Table 1 Characteristics of the twelve stimuli.

12.4.3 TEST PROCEDURE

Eleven subjects participated in paired comparison tests. These tests were conducted in the University of Salford listening room. Prior to the start of the test, subjects were given verbal instructions informing them of what was required:

"*In this test, you will be presented with 66 pairs of vibration signals. The vibration will be reproduced via a chair. When presented with the vibration signals, you will be shown two sliders. Using the first slider, please indicate how similar you perceive the pair of vibration signals to be. Using the second slider, please indicate which of the vibration signals you would find more annoying if you were to experience them in your own home."*

Subjects were asked to assume a comfortable upright posture with their backs supported by the backrest of the chair and to maintain this posture as far as possible throughout the test. The tests were conducted via a graphical user interface presented on a laptop. Subjects were first presented with a screen from which they were allowed to feel the twelve stimuli as many times as they wished. The purpose of this stage of the test was to allow subjects to familiarize themselves with the group of stimuli on which they would be making judgments. To allow subjects to familiarize themselves with the test interface, five trial paired comparison judgments were performed prior to the main test. Figure A - 8 shows the main test interface for the paired comparison tests. The interface was developed in MATLAB using the graphical user interface design tool "*GUIDE*". Using the first slider, subjects were asked to make a judgment upon how similar they perceived the pair of vibration stimuli to be. One extremity of the slider is labelled "*Very Different"* and the other extremity is labelled "*Very Similar*". The slider is continuous and logs a score from 0 (*Very Similar*) to 1 (*Very Different*). Using the second slider subjects were asked to make a judgment upon which of the two vibration stimuli was more annoying. One extremity of the slider is labelled "*Stimulus 1"*, the centre of the slider is labelled "*Neither"* and the other extremity is labelled "*Stimulus 2*". This slider is continuous and logs a score from -0.5 (*Stimulus 1*) to 0.5 (*Stimulus 2*). The option of *"Neither*" was included as it has been shown in paired comparison tests to assess sound quality that allowing a tie minimises circular errors (Parizet 2002).

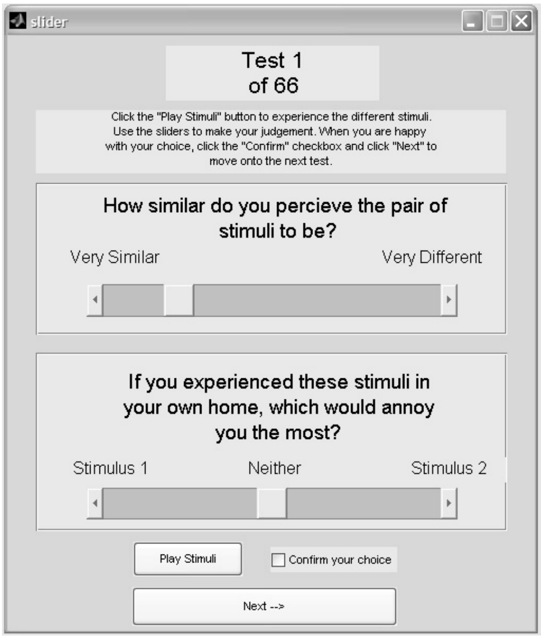

Figure A - 8 Graphical interface for subjective test.

When the "*Play Stimuli*" button was clicked, subjects were presented with a pair of vibration stimuli separated by around 1*s*. Subjects were allowed to feel each pair of stimuli as many times as they wished. The order in which the stimuli were presented to the subjects was defined by a Ross series (David 1988). The Ross series ensures the greatest separation of pairs with a common stimulus. Once the subject was happy with their assessment, the next pair of vibration signals could be assessed by clicking the "*Next*" button. Each test took around 30 minutes in total.

12.5 RESULTS AND DISCUSSION

12.5.1 PERCEPTUAL SPACE

The goodness-of-fit of a MDS solution can be assessed by examining the *stress* of the configuration. A lower stress value for a MDS configuration indicates a better fit to the original pairwise data. The optimal number of dimensions of an MDS configuration for a given dataset can be evaluated by calculating configurations in different numbers of dimensions to determine how the stress changes with respect to the number of dimensions in the configuration. The visualization of this data is known as a scree-plot. The optimal number of dimensions in a MDS configuration is generally assessed by looking for a "*knee*" in the scree-plot (i.e. the point at which the stress is not significantly reduced by an increase in dimensionality). Figure A - 9 shows stress for non-metric MDS configurations calculated in 2 to 8 dimensions for the results of the perceptual tests outlined in section 12.4. It can be seen from this figure that there is no obvious "*knee*" in the curve. As a rule of thumb, stress of around 0.1 represents a fair fit (Borg & Groenen 2005). For the purpose of this study, a four dimensional INDSCAL configuration will be analysed.

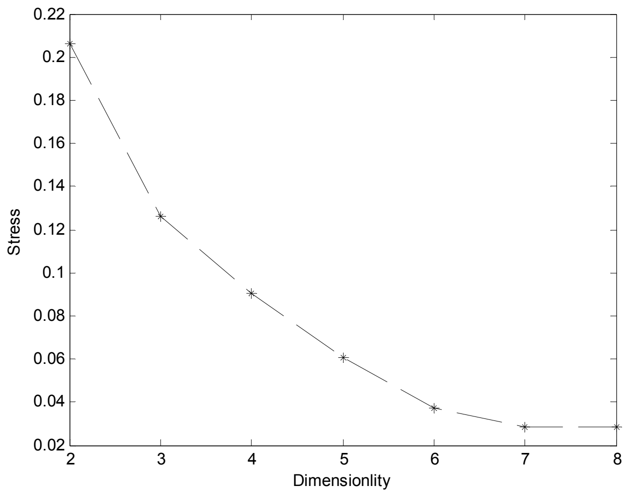

Figure A - 9 Relationship between stress and the number of calculated dimensions.

Figure A - 10, Figure A - 11, and Figure A - 12 show the group and subject spaces of an INSCAL solution calculated in 4 dimensions. Each point in the group space represents a vibration stimulus and each point in the subject space represents a subject. From the group space it can be seen that the stimuli are well spread across each of the dimensions suggesting that subjects were rating dissimilarities based on a perceptual continuum and not simply categorizing the stimuli. As was discussed in section 12.2.2, the angle between a subject's vector and a given dimension in the subject space relates to the relative importance the subject places on the dimension with regards to the perception of the group of stimuli. The magnitude of a subject's vector relates to how well the similarity judgements for the subject are reproduced in the group space. It can be seen that, although there is some scatter on the relative weighting each subject attributes to a given dimension, each subject's data is generally well represented by the configuration presented in the group space. It should be noted that objective correlates to these axes have not yet been identified. Some initial analysis has suggested that the first two axes may be related to the frequency content and energy of the vibratory stimuli.

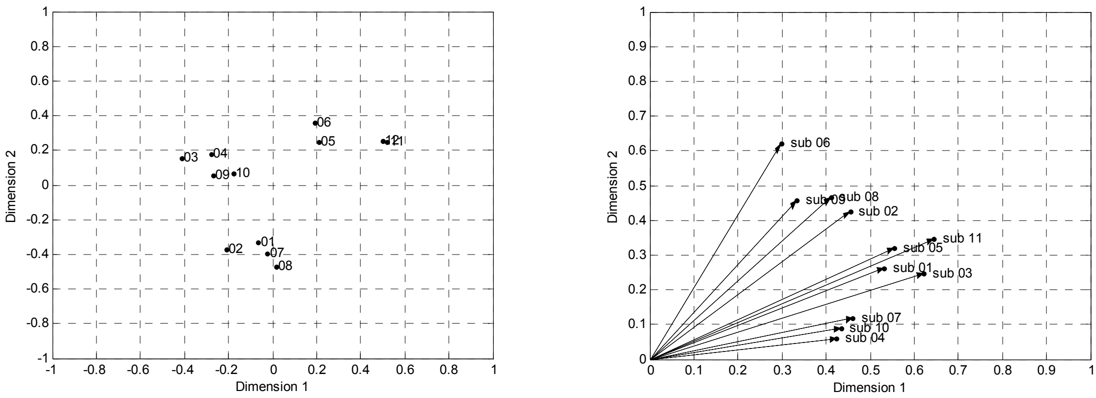

Figure A - 10 Dimension 1 and Dimension 2 INDSCAL solution. Left pane: Group space. Right pane: Subject space.

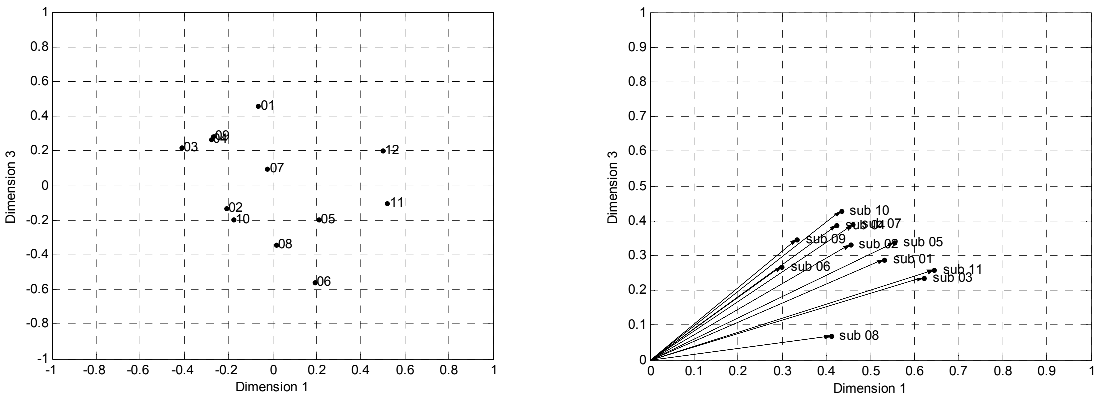

Figure A - 11 Dimension 1 and Dimension 3 INDSCAL solution. Left pane: Group space. Right pane: Subject space.

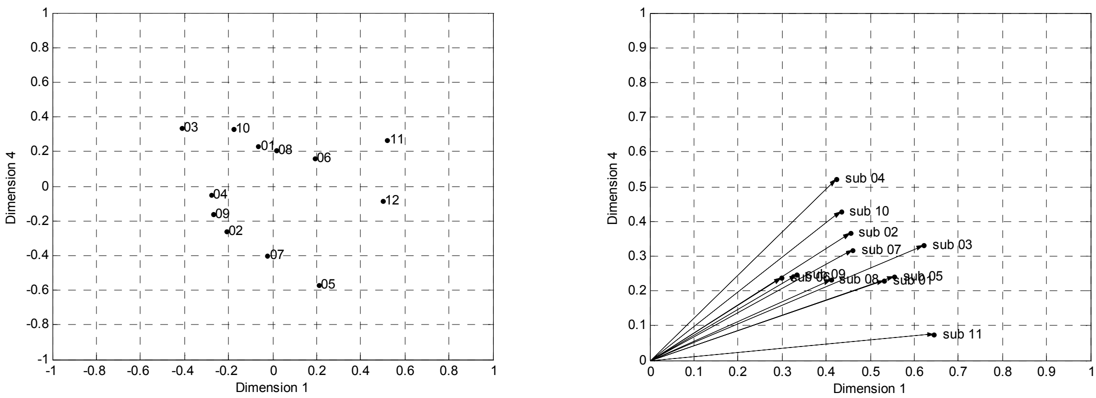

Figure A - 12 Dimension 1 and Dimension 4 INDSCAL solution. Left pane: Group space. Right pane: Subject space.

12.5.2 SINGLE FIGURE ANNOYNACE SCORES

Single figure annoyance scores were calculated from the paired comparison of annoyance ratings. The single figure scores (A_i) were averaged across the subject group linearly:

$$A_i = \frac{1}{N}\sum_{j \neq i} P_{j,i}$$ **Equation 4**

where A_i is the single figure preference score, N is the number of subjects and P_{ji} is the summation of preference scores for sounds *i* and *j* across the subject group.

Figure A - 13 shows the single figure annoyance scores for each of the twelve vibration stimuli. A high score indicates a high degree of annoyance. It should be noted that this scale is relative, therefore, although stimulus 12 has been judged to be more annoying than stimulus 3, the overall magnitude of annoyance cannot be known. The relatively narrow confidence intervals shown in this figure suggest that annoyance ratings were consistent between subjects.

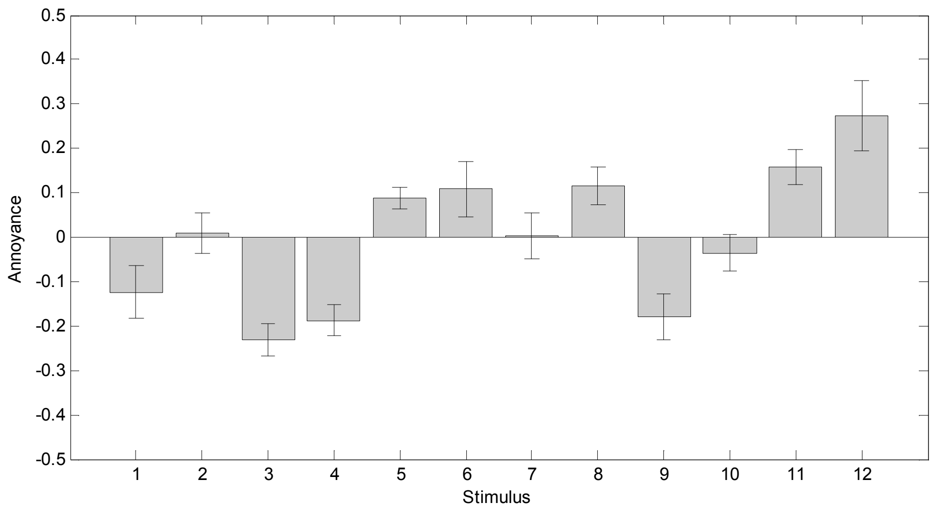

Figure A - 13 Single figure annoyance scores shown in their 95% confidence intervals ($N = 11$).

12.5.3 INTER-SUBJECT CONSISTENCY

The consistency of a subject's responses can be assessed by the calculation of circular error rate. If a subject is presented with every possible pairing of three stimuli (*A,B*) (*A,C*) (*B,C*) and asked to judge which of the pair they find more annoying there are eight possible outcomes. Six of these outcomes are of the form [2 1 0] whereby one object is judged to be more annoying twice, one is judged to be more annoying once and the remaining stimulus is not judged to be annoying in any of the tests. The remaining two outcomes are of the form [1 1 1] whereby each of the three stimuli has been stated as being the most annoying once; in these cases an inconsistency, or *circular error*, has occurred as the subject has stated, for example, that *A* is more annoying than *B*, *B* is more annoying than *C*, and *C* is more annoying than *A*.

Figure A - 14 shows the circular error rate for the eleven subjects that took part in the test. In paired comparison tests using auditory stimuli, circular error rates are typically of a similar order as those presented in Figure A - 14 (Parizet 2002). These results suggest that subjects were relatively consistent in rating perceived annoyance due to whole body vibration. Considering the relative acuity of vibration perception compared with the perception of sound, it is surprising that these figures are similar to those obtained from studies into the perception of sound.

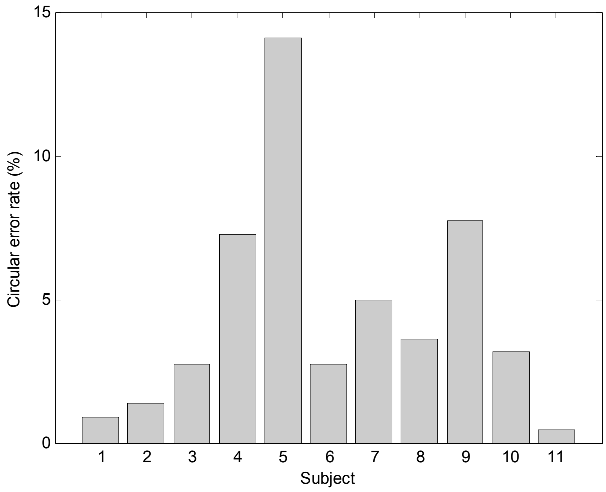

Figure A - 14 Circular error rate for each subject.

12.5.4 ANNOYANCE MODEL

From the results of the MDS analysis presented in section 12.5.1 and the single figure annoyance scores presented in section 12.5.2, multiple regression has been used to develop a model for the prediction of self reported annoyance due to whole body vibration. Multiple regression is a technique whereby several predictor variables are used to model a single response variable (Weisberg 2005). The form of the model is shown in matrix form in the equation below:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} \qquad \textbf{Equation 5}$$

where $\mathbf{Y}$ is a vector of responses, $\mathbf{X}$ is a matrix of predictor variables, and $\boldsymbol{\beta}$ is a vector of parameters to be estimated.

The $\boldsymbol{\beta}$ parameters are estimated via a least squares estimation. This is achieved by minimizing the function shown below:

$$RSS(\boldsymbol{\beta}) = \sum (y_i - \mathbf{x_i}^{\mathbf{T}}\boldsymbol{\beta})^2 \qquad \textbf{Equation 6}$$

where RSS is the residual sum of squares, y_i is the i^{th} response, and $\mathbf{x_i}^{\mathbf{T}}$ is the transpose of the i^{th} row of **X.**

The result of the multiple regression conducted using single figure annoyance as the response variable and the positions of the vibration stimuli on the perceptual axes revealed through the multidimensional scaling analysis is shown in the equation below:

$$A = 0 + 0.45D_1 - 0.10D_2 - 0.15D_3 - 0.03D_4$$ **Equation 7**

where A is the predicted single figure annoyance and D_n is the position of the vibration stimulus on the n^{th} perceptual axis.

Figure A - 15 shows the relationship between the single figure annoyance scores measured through the subjective test and the single figure annoyance scores predicted using Equation 7. It can be seen from this figure that there is a good agreement (R^2=0.92) between the measured and predicted single figure annoyance scores. This result suggests that, if objective features of the vibration stimuli can be found which correlate with the perceptual dimensions revealed through the multidimensional scaling analysis, an efficient model to predict self reported annoyance due to whole body vibration exposure based on objective features of the vibration stimulus can be formulated.

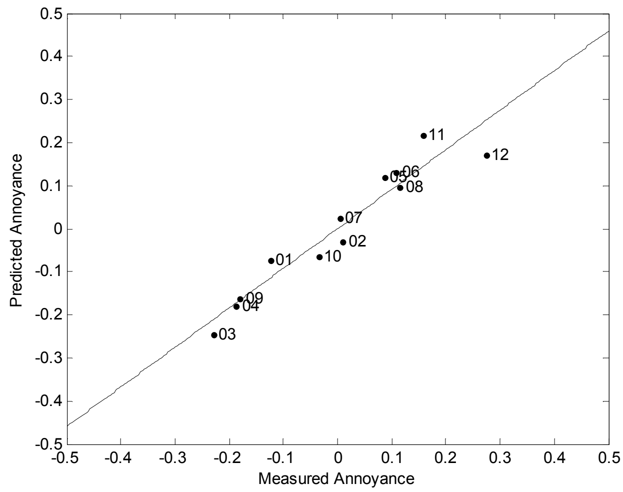

Figure A - 15 Measured and predicted single figure annoyance scores. (N = 11) (R^2=0.92, p<0.001).

12.6 CONCLUSIONS

This section has presented the results of a study designed to test the feasibility of using the methods of paired comparison testing and multidimensional scaling analysis to investigate the perception of whole body vibration. Paired comparison tests of similarity and annoyance were conducted using twelve synthesised vibration stimuli. A multidimensional scaling analysis of the paired comparison of similarity data was conducted. Analysis of a four dimensional solution showed that the vibration stimuli were well spread in perceptual space indicating that subjects were basing their similarity ratings on perceptual continua and not simply categorizing the stimuli.

These results give confidence that objective features of the vibration stimuli can be found as correlates to the perceptual axes revealed through the multidimensional scaling analysis.

Single value annoyance scores for each of the vibration stimuli were calculated from the paired comparison of annoyance tests. Circular error rates for each subject and 95% confidence intervals for the single figure annoyance scores were calculated to assess intra- and inter-subject consistency respectively. It was found that subjects were consistent with their annoyance ratings suggesting that subjects found the test easily realizable.

The perceptual axes revealed through the multidimensional scaling analysis were related to the single figure annoyance scores via multiple regression. This model was found to be an efficient predictor of the single figure annoyance scores (R^2=0.92, $p < 0.001$).

The results presented in this report suggest that the methods of paired comparison testing and multidimensional scaling can provide a valuable insight into the perception of whole body vibration. Further work is needed to relate the perceptual dimensions to objective features of vibration stimuli. The high correlation found between measured and predicted annoyance scores suggest that, if these objective correlates can be found, an effective model for the prediction of annoyance caused by whole body vibration can be formulated using the methods outlined in this report.

12.7 References

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