FIELD AND LABORATORY STUDIES INTO THE HUMAN RESPONSE TO GROUNDBORNE VIBRATION: EXPOSURE-RESPONSE RELATIONSHIPS, PERCEPTUAL DIMENSIONS, AND MODELS OF ANNOYANCE

James WOODCOCK

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James WOODCOCK

Acoustics Research Centre

School of Computing, Science and Engineering

University of Salford, Salford, UK

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DECLARATION

The work presented in Chapter 3, Chapter 4, and Chapter 5 of this thesis is based upon data gathered through a collaborative project funded by the Department of Environment, Food and Rural Affairs to investigate the human response to vibration in residential environments (Waddington et al., 2011). The author's individual contributions to this project were as follows:

- Carried out approximately 20% of the field measurements described in Chapter 3.
- Calculated 24-hour internal vibration exposure for all of the railway dataset.
- Conducted an analysis into vibration exposure descriptors with respect to human response.
- Developed the statistical model for the calculation of exposure-response relationships.
- Derived exposure-response relationships for railway and construction induced vibration.
- Authored a technical report detailing the above work (Woodcock et al., 2011).

The analyses, results, views, and conclusions presented in this thesis are those of the author and do not necessarily represent the views of the Department of Food, Environment and Rural Affairs.

Abstract

With proposed increases in both freight and passenger railway in the United Kingdom and the European Union and the building of new high speed lines, there has been an increase in interest in recent years in the human response to vibration in residential environments. As with exposure to environmental noise, exposure to environmental vibration can result in adverse effects such as annoyance and sleep disturbance. However, unlike exposure to environmental noise, well established relationships to evaluate annoyance caused by vibration in residential environments do not exist. In order to predict and control annoyance caused by vibration from environmental sources, a better understanding is needed of how humans perceive vibration and how their perception relates to measureable, quantifiable features of the vibration exposure.

In the work presented in this thesis, the human response to vibration is considered on both a community and individual level. The first major aim of this work is to develop statistically robust exposure-response relationships for the human response to railway and construction induced vibration in residential environments. This is achieved via a large scale field survey in which 1431 questionnaires were conducted with residents in their own homes along with extensive vibration measurements at internal and external positions. Analysis of the data collected through this field survey shows that all of the vibration exposure descriptors advocated in national and international standards are equally well correlated with annoyance due to railway induced vibration. Using a grouped regression model, exposure-response relationships describing the proportion of respondents expected to express annoyance above a given threshold are derived for railway and construction induced vibration in terms of a variety of vibration exposure descriptors.

The second major aim of this work is to investigate the perception of railway induced vibration on an individual level by investigating the salient dimensions of the perception of whole body vibration. This is achieved via a subjective laboratory test in which paired comparisons of similarity and annoyance are conducted using fourteen measured railway vibration stimuli. Through multidimensional scaling analysis, it is shown that the perception of railway induced vibration is dependent on up to four perceptual dimensions. These dimensions relate to energy in the 16 *Hz* 1/3 octave band, energy in the 32 *Hz* 1/3 octave band, the duration of the train passage, and the modulation frequency of the envelope of the signal. These perceptual dimensions are related to single figure Perceived Annoyance Ratings (*A*) by the following relationship: $A = -0.40 + 4.57\ddot{X}_{RMS,16Hz} + 3.18\ddot{X}_{RMS,32Hz} + 0.02T_{10dB} + 0.02f_{\text{mod}}$. Finally, the single figure Perceived Annoyance Ratings are related to categorical ratings of annoyance via a logistic regression model.

CHAPTER 1

INTRODUCTION

1 INTRODUCTION

1.1 GENERAL INTRODUCTION

At home, in transportation, or at work, perceptible vibration is present in the day-to-day environment of many people. This vibration may be unwanted such as vibration from an environmental source propagating into the home or wanted such as the vibration produced by modern video game controllers and mobile phones. This thesis is concerned with the perception of whole body vibration induced by environmental sources experienced in the home. Like airborne noise, exposure to whole body vibration can result in a number of adverse effects such as annoyance (Guski, 1999; Klæboe et al., 2003b; Woodroof and Griffin, 1987) and sleep disturbance (Arnberg et al., 1990; Ögren and Öhrstrom, 2009). However, unlike airborne noise comparatively little research has been conducted into the adverse effects of whole body vibration exposure in residential environments.

Whole body vibration is broadly defined as occurring when the body is in contact with a vibrating surface and is generally considered in the frequency range 0.5 Hz – 80 Hz (Griffin, 1996). There exists a relatively large body of mainly laboratory based research into the perception of whole body vibration focussing on perception thresholds (Parsons and Griffin, 1988), equal comfort contours (Morioka and Griffin, 2006a), subjective magnitude (Howarth and Griffin, 1988a), and just noticeable differences in magnitude and frequency (Bellmann, 2002). However, due in part to a lack of data under field conditions, there exist no generally accepted exposure-response relationships on which to base guidance and assessment methods for the human response to vibration in residential environments.

Exposure-response relationships are a vital tool for policy makers and planners to enable the prediction of the effect an environmental stressor is likely to have on the population.

Internationally accepted exposure-response relationships have been developed for annoyance due to airborne noise exposure which describe the proportion of the population expected to express annoyance above a given threshold for a given noise exposure. These relationships form the basis of international standards and guidance documents for the assessment of environmental noise. However, there is no such consensus regarding the assessment of annoyance due to whole body vibration in residential environments. This is mirrored in the range of vibration assessment methods recommended in national and international standards. There exist numerous different single figure descriptors and frequency weightings recommended in the different standards to assess whole body vibration exposure. Furthermore, most available guidance is based upon psychophysical tests conducted in laboratory settings which may have little applicability to situations where subjects are exposed to vibration within their own homes.

In the work presented in this thesis, the human perception of environmental vibration is considered on two scales; firstly on a community scale and secondly on an individual scale. The overall aim of the research is therefore twofold. The first major aim of this work is to develop statistically robust exposure-response relationships for the human response to railway and construction induced vibration in residential environments. This is achieved via a large scale field survey to determine both vibration exposure and response for residents in their own homes. The second major aim of this work is to investigate the perception of railway induced vibration on an individual level by an investigation of perceptual dimensions. This is achieved via a laboratory assessment resulting in a model for the prediction of annoyance due to railway induced vibration based on objective features of the vibration signal.

1.2 THESIS OUTLINE

Following the general introduction provided in this chapter, Chapter 2 presents a review of literature relevant to the perception of and response to whole body vibration. It is shown in this chapter that, although a relatively large body of research exists for the human response to vibration in laboratory settings, relatively little is known about the human response to vibration in residential environments.

Chapter 3 details the planning and implementation of a large scale field survey to collect data on exposure and response to vibration in residential environments. In this survey, 1281 questionnaires are conducted face-to-face with residents in their own homes to determine annoyance due to vibration. The development and implementation of a novel measurement approach for the estimation of internal vibration exposure is discussed.

Chapter 4 presents the analysis of the vibration data gathered though the measurements detailed in the previous chapter. An investigation into single figure vibration exposure descriptors is presented and considered with respect to the response data collected through the social survey questionnaire.

In Chapter 5, exposure-response relationships are derived for vibration induced by railway and construction sources using the data collected in the field survey. These relationships are presented in terms of a variety of different single figure vibration exposure descriptors. Differences in the response to the railway and construction sources of vibration are discussed along with relationships for perception and vibration induced rattle.

Chapter 6 presents a pilot laboratory study to determine the feasibility of using the methods of paired comparisons and multidimensional scaling to investigate the perception of whole body vibration. The results of the pilot test suggest that perceptual dimensions for the set of stimuli used in the test can be determined which in turn can be related to self reported annoyance.

Chapter 7 details the design, implementation, and results of the main programme of subjective testing. In this chapter, the perceptual dimensions salient in the perception of whole body vibration from railway induced groundborne vibration are identified. The objective descriptors relating to these perceptual dimensions are then used to develop models for the prediction of annoyance due to railway induced vibration.

Finally, conclusions and recommendations for further work are made in Chapter 8.

1.3 NOVEL ASPECTS OF THE WORK

The following list of outcomes, which are presented in this thesis, are considered by the author to be novel contributions to the field of the human response to vibration:

- Exposure-response relationships for annoyance due to railway induced vibration have been developed for all major vibration exposure descriptors.
- Exposure-response relationships for annoyance due to construction induced vibration have been derived.
- Exposure-response relationships have been derived for various factors such as feeling vibration, vibration induced rattle, and perceptual mechanisms.
- The perception of vibration has been shown to be multidimensional and based on a small number of objective parameters.

- These objective parameters have been used to develop a model for the prediction of individual annoyance due to railway induced groundborne vibration.

1.4 ETHICAL CONSIDERATIONS

The research presented in this thesis was subject to review by the University of Salford's ethical committee.

CHAPTER 2

LITERATURE REVIEW

2 LITERATURE REVIEW

2.1 INTRODUCTION

This chapter aims to examine the current knowledge relating to the human response to vibration in residential environments. The chapter comprises five main sections. The first section provides an overview of the perception of whole body vibration; laboratory studies into subjective magnitude, frequency dependence of vibration perception, and the effect of duration on vibration perception are discussed. Following this, a review of methods currently available for the assessment of vibration in residential environments with regards to human response is presented. The state of the art with regards to human response to environmental noise is then discussed. Finally, field studies into the human response to vibration in residential environments are presented.

2.2 PERCEPTION OF WHOLE BODY VIBRATION

The human body is subjected to vibration in a variety of day-to-day situations ranging from travelling in a vehicle to environmental vibration experienced in the home. Above certain magnitudes and within certain ranges of frequency, vibration can be sensed by humans through the somatic, auditory, and visual systems. Exposure to vibration can occur locally, through the hand-arm system for example, or it can act on the whole body; this thesis is primarily concerned with whole body vibration which is defined as occurring "*when the body is supported on a surface which is vibrating*" (Griffin, 1996). Human exposure to vibration can result in annoyance, discomfort, fear, positive tactile feedback, motion sickness, and injury, the latter occurring only at vibration exposures orders of magnitude higher than those of interest in this thesis. In order to predict or control the effects of vibration on humans, an understanding is needed of how measureable, quantitative aspects of vibration correlate with the sensations they evoke in human subjects. This section aims to give an overview of fundamental psychophysical studies into the human perception of vibration.

2.2.1 PHYSIOLOGICAL MECHANISMS OF VIBRATION PERCEPTION

The perception of vibration is governed in part by mechanoreceptors in the skin which respond to a vibratory excitation by producing a pulse train of action potentials. For a sinusoidal vibration excitation, each pulse corresponds to one cycle of the sinusoidal oscillation. The density of pulses produced by the mechanoreceptors is linearly related to the amplitude of the excitation. There are four main mechanoreceptors which respond to vibration in the frequency range related of interest in this thesis. Merkel disk receptors are sensitive to vibration in the range of frequencies 5 – 15 *Hz*, Meissner's corpuscles are sensitive in the range 20 – 50 *Hz*, Pacinian corpuscles are sensitive in the range 60 – 400 *Hz*, and Ruffian endings are sensitive in the range 100 – 500 *Hz* (Kandel et al., 2000). Vibration can also be perceived visually and by the auditory system. Changes in the relative position of objects on the retina can occur due to low frequency vibration and aural perception can occur at frequencies above 20 *Hz* via airborne pathways and bone conduction.

Whole body vibration may be perceived kinaesthetically via forces and movements within the body. Proprioceptors provide information to the brain regarding the position and forces in joints, muscles, and tendons. Visceral perception may also occur via receptors in the abdomen (Mansfield, 2005). The biodynamic response of the body to vibration has been shown consistently to be non-linear. For example, Fairley and Griffin (1989), Matsumoto and Griffin (2002), and Nawayseh and Griffin (2003) have demonstrated a lowering of the resonance frequency of the seated human body with increasing magnitude of vibratory excitation in the vertical direction. Similar nonlinearities have been demonstrated for vibration excitation in the horizontal directions (Nawayseh and Griffin, 2005) and for standing subjects (Matsumoto and Griffin, 1998).

2.2.2 Subjective Intensity and Discomfort

For over a century psychophysicists have attempted to derive mathematical expressions which describe relationships between the perceived intensity of a stimulus and some objective measureable feature of the stimulus [see for example the psychoacoustical concept of loudness (Fastl and Zwicker, 2007)]. Stevens' power law (Stevens, 1975) is a classical psychophysical relationship quantifying the physical magnitude and perceived intensity of a stimulus. The form of Stevens' power law is given below.

$$\psi = k\vartheta^{n}$$ **Equation 1**

Where ψ is the sensation level, k is a proportionality constant which depends on the units of the physical stimulus, ϑ is the magnitude of the physical stimulus and n is a growth constant.

A number of studies have utilised Stevens' power law to determine psychophysical relationships between the magnitude and perceived intensity or discomfort of vibration exposure. Subjective testing involving magnitude estimation is generally employed to estimate the growth constant n in the equation above. This methodology requires subjects to provide a numerical estimation of the relative subjective intensity or discomfort of two stimuli. Another method by which the growth constant n may be estimated is the method of magnitude production which requires subjects to adjust the magnitude of a stimulus until the perceived intensity or discomfort is a given factor greater than that of a reference stimulus.

One of the earliest studies which aimed to estimate the growth constant *n* for the perceived intensity of vibration was performed by Miwa (1968a). In this study ten male subjects adopting a seated posture were presented with pairs of vibration stimuli. The magnitude of the second stimulus was adjusted by the experimenter until the subject judged it to be half the magnitude of the reference stimulus. This procedure was conducted for sinusoidal vibration at three frequencies (5 Hz, 20 Hz, and 60 Hz) and at six magnitudes of reference stimuli in the vertical and horizontal (fore and aft) directions. The results of this study indicated the growth constant *n* did not differ significantly with frequency; significant differences in the growth constant were however observed at different magnitudes of vibration exposure. As such, two psychophysical relationships were derived in this study. The first relationship, for vibration magnitudes below 1 m/s^2, a growth constant of 0.60 was found whereas the second relationship, for vibration magnitudes above 1 m/s^2, a growth constant of 0.46 was found.

A relatively large amount of research into the perceived intensity and discomfort of whole body vibration followed these early studies the results of which are summarised by Leatherwood and Dempsey (1976). Of the studies summarised, a large amount of inter- and intra-study variability is reported with the results of studies into perceived discomfort varying sometimes by orders of magnitude. Differences in results between studies from this period have been attributed to poor experimental design, unrealistic laboratory environments, use of inadequate rating scales, and small sample sizes. Prompted by the variability observed in the results reported in these studies, Leatherwood and Dempsy (1976) aimed to systematically assess the functional form of the psychophysical relationship underlying the perceived intensity of vibration and also to assess the relationship between subjective intensity and discomfort. Two notable studies are identified in this paper (Jones and Saunders, 1974; Shoenberger and Harris, 1971) which present data that support the hypothesis that subjective intensity obeys Steven's power law with respect to the objective magnitude of vibration and that the growth constant of this power law ranges between 0.86 and 1.04. The fluctuation of the reported growth constant in these studies around unity led Leatherwood and Dempsy to question the functional form of the psychophysical relationship; if the growth constant of Steven's power law is unity then the psychometric relationship is linear. Twenty-four subjects participated in tests of magnitude estimation of subjective intensity and an additional twenty-four subjects participated in magnitude estimation tests of subjective discomfort. Vertical sinusoidal vibration exposures were assessed at 2, 5, 8, 11, 14, 17, 20, 23, 26, and 28 *Hz* with reference magnitudes ranging between 0.49 and 4.41 m/s^2. Four different psychophysical relationships were assessed as potential fits to the data gathered through the perceptual tests:

$$\begin{aligned} \psi &= k\vartheta^n \\ \psi &= k + n\log(\vartheta) \\ \psi &= k10^{n\vartheta} \\ \psi &= k + n\vartheta \end{aligned} \qquad \textbf{Equation 2}$$

The effectiveness of each these relationships was assessed via comparison of the correlation coefficients that resulted from the fit of each of the relationships to the subjective intensity and discomfort data. These correlations were assessed both on the individual level and averaged across the subject group. No significant differences were found between the correlation coefficients for the various relationships. Based on these results, it was proposed that the linear psychophysical relationship ($\psi = k + n\vartheta$) be adopted as there appeared to be scientific basis for using the more complicated power law relationship ($\psi = k\vartheta^n$).

Unity growth constants have also been found in subsequent studies (for example, Hiramatsu and Griffin, 1984; Howarth and Griffin, 1988a). However, a number of studies have indicated that the growth constant is not equal over all frequencies and directions of excitation. Shoenberger and Harris (1971), for example, reported the growth constant of subjective magnitude at 5 *Hz* to be significantly greater than at 7, 15, and 20 *Hz*. More recent studies have also suggested that in the lower frequency range the rate of increase of discomfort is greater than at higher frequencies (Morioka and Griffin, 2006a, 2010; Wyllie and Griffin, 2007).

2.2.3 FREQUENCY DEPENDENCE OF PERCEPTION

Early laboratory studies into the human response to vibration found the perception of vibration to be frequency dependent (Miwa, 1967). Studies into the frequency dependency of vibration perception have generally aimed to determine absolute perception thresholds (for example, Parsons & M. Griffin 1988) or equal sensation and comfort contours (for example, H. V. Howarth & M. J. Griffin 1988). The results of a number of studies into perception thresholds are summarised by Griffin (1996) (see Figure 1). Although there is some agreement between the results of these studies, a large amount of inter-study variance can be observed.

For vertical vibration of seated persons the greatest sensitivity is generally observed in the 5-6 *Hz* region. For horizontal vibration, the greatest sensitivity has generally been found to be in the 1-2 *Hz* region. Recent studies however have indicated that the threshold of perception in the vertical direction is relatively flat with acceleration above around 10 *Hz* (Bellmann, 2002; Morioka and Griffin, 2006b).

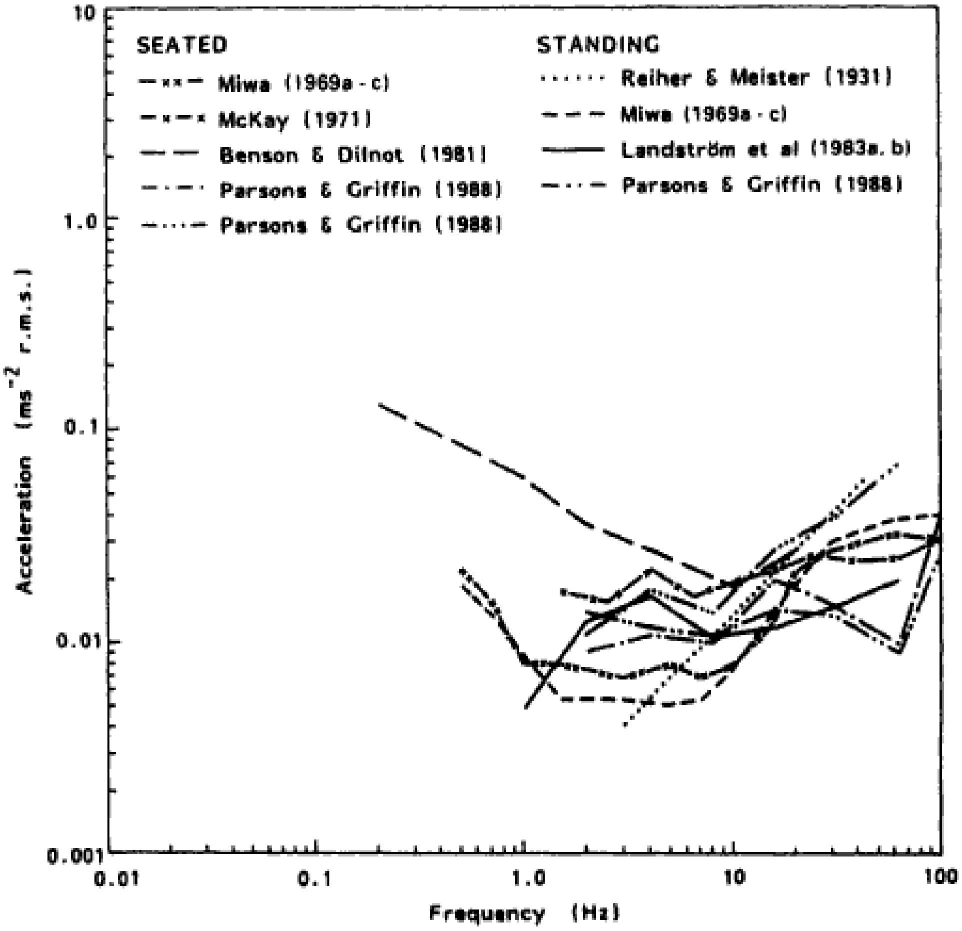


Figure 1 Vibration perception thresholds in the vertical direction for a number of laboratory studies as presented in "Handbook of Human Vibration" (Source: Griffin, 1996).

The perceived discomfort caused by whole body vibration has also been found to be dependent on frequency. Equal comfort contours for different postures and different directions of excitation have been derived in a number of studies (Corbridge and Griffin, 1986; Griffin et al., 1982a, 1982b; Howarth and Griffin, 1988a; Parsons and Griffin, 1982; Parsons et al., 1982) which have generally been found to follow the reciprocal of the perception threshold. Differences found in the rate of growth of subjective intensity and discomfort with respect to frequency (see section 2.2.2) imply that the shape of equivalent comfort contours is magnitude dependent. Figure 2 shows the results of a study investigating the magnitude dependence of equivalent comfort contours for whole body vibration in the vertical direction (Morioka and Griffin, 2006b) in which this magnitude dependency can be observed. The magnitude dependency of equivalent comfort contours has implications on the applicability of the frequency weightings used in the assessment of the human response to vibration discussed in section 2.3.3.

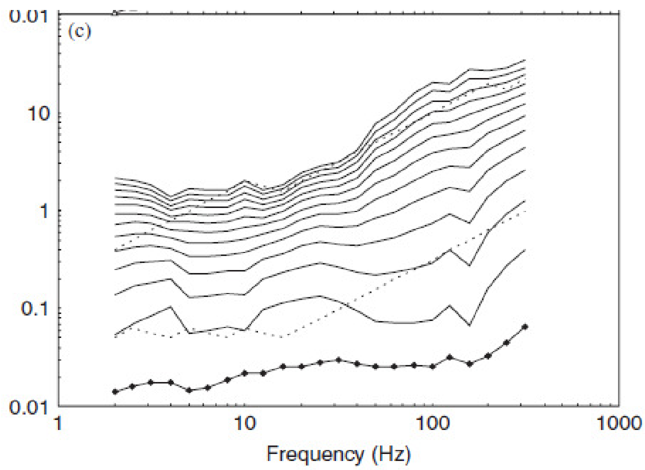


Figure 2 Absolute perception thresholds and equivalent comfort contours for vertical whole body vibration (Source: Morioka and Griffin, 2006b).

2.2.4 DURATION

There is a limited amount of data regarding the effect of vibration duration on discomfort and perception thresholds. An early study into the effect of the duration of vibration exposure on discomfort (Miwa 1968) found that discomfort increases with increasing duration of vibration exposure up to around 2 seconds for vibration in the frequency range 2 – 60 *Hz* and up to around 0.8 seconds for vibration in the frequency range 60 – 200 *Hz*. Parsons & M. Griffin (1988) reported that, for 16 *Hz* sinusoidal vibration exposure, a decrease in the perception threshold is observed for exposures with 4 cycles or greater.

In a study conducted by Griffin and Whitham (1980a, 1980b), the time dependency of discomfort due to vibration was evaluated for sinusoidal excitations in the vertical direction with frequencies of 4, 8, 16, and 32 *Hz* and durations between 1 cycle and 32 seconds. The time dependency of discomfort due to vibration exposure reported in this study was found to approximate a fourth power relationship suggesting that a 16-fold increase in duration would require a two-fold decrease in magnitude to provoke an equivalent discomfort. Hiramatsu & M. J. Griffin (1984) conducted a similar study in which multiple regression techniques were employed to determine a power law to describe the rate of change in discomfort with respect to the duration of vertical sinusoidal vibration exposure. The results of this study suggested a less than second power relationship which contradicted the findings of Griffin and Whitham (1980a, 1980b). It was however suggested that the methodology used in this investigation may have overestimated the effect of vibration duration on discomfort. The fourth power relationship between duration and discomfort found by Griffin and Whitham (1980a, 1980b) is partly the basis of the Vibration Dose Value descriptor advocated in BS6472-1:2008 (see section 2.3.3).

2.2.5 Perception of Transient Vibration

A study by Wiss & Parmelee (1974) [described in Murray (1979)] reported a relationship for the subjective response to transient vibrations based on frequency, amplitude, and floor damping. An increase in perception threshold was observed for transient vibration compared with the threshold for steady state vibration. Howarth and Griffin (1991a) conducted an investigation into the perception of vertical mechanical shocks. Two experiments were conducted in this study the first investigating the perception of single shocks and the second investigating the perception of repeated shocks. For single shocks, the rate of growth of discomfort with respect to vibration magnitude was found to be around unity and was independent of frequency, duration, and the direction of excitation. For multiple shocks, a fourth power relationship was found between discomfort and the number of shocks presented in the stimulus. This result is in agreement with studies into the effect of vibration duration on discomfort (Griffin and Whitham, 1980a, 1980b).

Ahn and Griffin (2008) investigated the human response to mechanical shocks in the vertical direction in terms of frequency, magnitude, damping, and direction. Fifteen seated subjects were exposed to mechanical shocks produced by the response of a one degree-of-freedom mass spring damper system to a half sine input force. Various different excitation waveforms were generated by this model with different fundamental frequencies (from 0.5 to 16 *Hz*), magnitudes (Vibration Dose Values between 0.35 and 2.89 $m/s^{1.75}$), and damping ratios (between 0.05 and 0.4). Subjects performed a magnitude estimation task to determine discomfort for each of the excitations with respect to a reference shock stimuli. These data were used to estimate psychophysical relationships for discomfort due to mechanical shocks based on Stevens' power law (see section 2.2.2). The growth function for the estimated psychophysical relationships was found to decrease from around 1.2 to around 0.6 with decreasing fundamental frequency. Equal comfort contours were determined for the different magnitudes of excitation the shape of which were found to vary with magnitude. The nonlinearity of the equal comfort contours found in this study is consistent with the findings of Morioka and Griffin (2006b) and the nonlinearities observed in the biodynamic response of the human body discussed in section 2.2.1.

2.2.6 *JUST NOTICEABLE DIFFERENCES*

Studies into just noticeable difference aim to determine the smallest perceivable change in some objective measure of a stimulus. The results of studies into just noticeable differences are generally expressed in terms of Weber fractions (Weber, 1834):

$$\frac{\Delta I}{I} = K \qquad \textbf{Equation 3}$$

Where ΔI is the absolute difference threshold, *I* is the magnitude of the reference stimuli, and *K* is a constant.

In a study by Morioka & Griffin (2000), just noticeable difference thresholds for changes in magnitude of vertical whole body vibration were determined. In this study, subjects were presented with pairs of stimuli and asked to judge whether the first or second stimulus had the greater magnitude. This task was conducted for two magnitudes of sinusoidal vibration (0.1 and 0.5 m/s^2) at two frequencies (2 and 20 *Hz*). It was found that the median relative difference threshold for a change in vibration magnitude was around 10%. This difference threshold was found to be independent of the magnitude and frequency of the stimulus. This result suggests that that a change in vibration magnitude of less than around 10% will not be detectable by human subjects.

Bellmann (2002) conducted a number of laboratory studies to investigate just noticeable differences in level and frequency. To determine the just noticeable difference in level, automatic forced choice tests were conducted using sinusoidal stimuli in the vertical direction at 1/3 octave band centre frequencies between 5 and 50 *Hz*. Relative difference thresholds of around 18% were found which were independent of frequency. In a similar experiment, the just noticeable difference in changes of frequency was found to be around 34%.

2.2.7 COMBINED VIBRATION AND NOISE

In a laboratory study to investigate the subjective response to combined noise and vibration exposure (Howarth and Griffin, 1990), subjects were presented with simulations of railway induced noise and vibration. 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, which aimed to investigate the combined effects of noise and vibration (Paulsen and 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 perceived intensity and annoyance. 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 (Howarth and Griffin, 1990).

Parizet et al. (2004) conducted a study into the relative contribution of noise and vibration to comfort in diesel engine cars running at idle. In this study, a test rig was developed capable of reproducing vertical whole body vibration and the vibration of a car steering wheel. In this test setup, sound reproduction was achieved via headphones. Three perceptual tests were conducted using sound and vibration measured in a car as stimuli. In the first test, subjects were required to judge the noise comfort and were exposed to only the sound stimuli. In the second test, subjects were required to judge the noise comfort and were exposed to the noise and vibration stimuli. In the third test, subjects were required to judge the overall comfort and were exposed to the sound and vibration stimuli. From the results of the first two tests, it was concluded that vibration has a small but significant influence on noise perception. The results of the third test suggested two groups of subjects, the first group basing their responses only on vibration and the second group basing their responses on both sound and vibration.

2.3 Measurement and assessment of whole body vibration exposure

2.3.1 Groundborne vibration

The work presented in this thesis is concerned with the human response to groundborne vibration. The generation and propagation of groundborne vibration is a complex topic outside the scope of this thesis, therefore this section aims to provide only a brief overview of the subject. There are two fundamental wave types by which vibration can propagate in an infinite elastic solid; shear waves or dilatational waves (Thompson, 2009). In a medium with a free surface such as the ground, an interaction between these two wave types can occur which results in Rayleigh waves which propagate along the free surface. Of these three wave types, the Rayleigh wave exhibits the slowest wave speed, carries the greatest proportion of the vibration energy, and can propagate the greatest distance outside the near field of the vibration source. As the receivers of vibration in this thesis, namely residents in their own homes, are generally positioned greater than 10 m from the source of vibration, Rayleigh waves are the dominant wave type of interest in this work.

In practice however, the ground is not a homogeneous elastic half space but is a complex medium with layers of varying material properties and discontinuities making the prediction and modelling of groundborne vibration a process with inherently large uncertainties (Jones et al., 2012). Figure 3 shows an example of the transfer mobility across two points spaced 15 m apart. It can be seen from this figure that the transfer mobility varies with frequency with this particular site showing a peak at around 40 Hz. As well as being frequency dependent, the propagation of groundborne vibration is a dispersive phenomenon making accurate time domain predictions problematic. Considering the uncertainties associated with the prediction of groundborne vibration, it is therefore preferable to conduct measurements if possible.

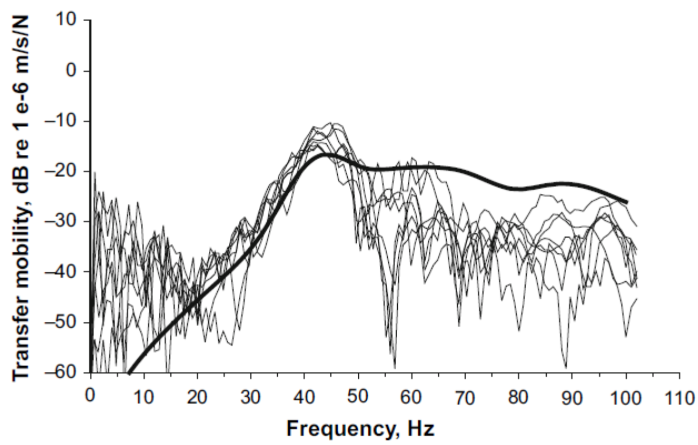


Figure 3 Measured and modelled transfer mobility of ground surface over 15 m [source (Thompson, 2009)].

2.3.2 *Measurement of Vibration Exposure*

The objective of any measurement of vibration with regards to human response is to quantify vibration exposure as close as possible to the 'point of entry' to the human body (BS 6472-1:2008). Different approaches to achieve this objective are detailed in various guidance documents, national and international standards. There is a general agreement between these different approaches that vibration exposure should be quantified at a single position in a room which is likely to represent the 'worst case scenario'. To this end, it is generally advised that measurements of vibration are conducted at the mid-span of the floor of the room of interest (ANC, 2001). The requirements of instrumentation used to measure building vibration with respect to human response are detailed in BS EN ISO 8041:2005.

BS 6472-1:2008 and BS ISO 2631-1:1997 require the measurement of acceleration time histories in three orthogonal directions in the frequency range 0.5 – 80 *Hz*. BS ISO 2631-1 defines these orthogonal directions in a basi-centric coordinate system (see Figure 4) such that the principle axes are defined with respect to the position of the human body. However, the 2008 revision of BS 6472-1 advocates the use of a geo-centric coordinate system such that the principle axes are earth centred.

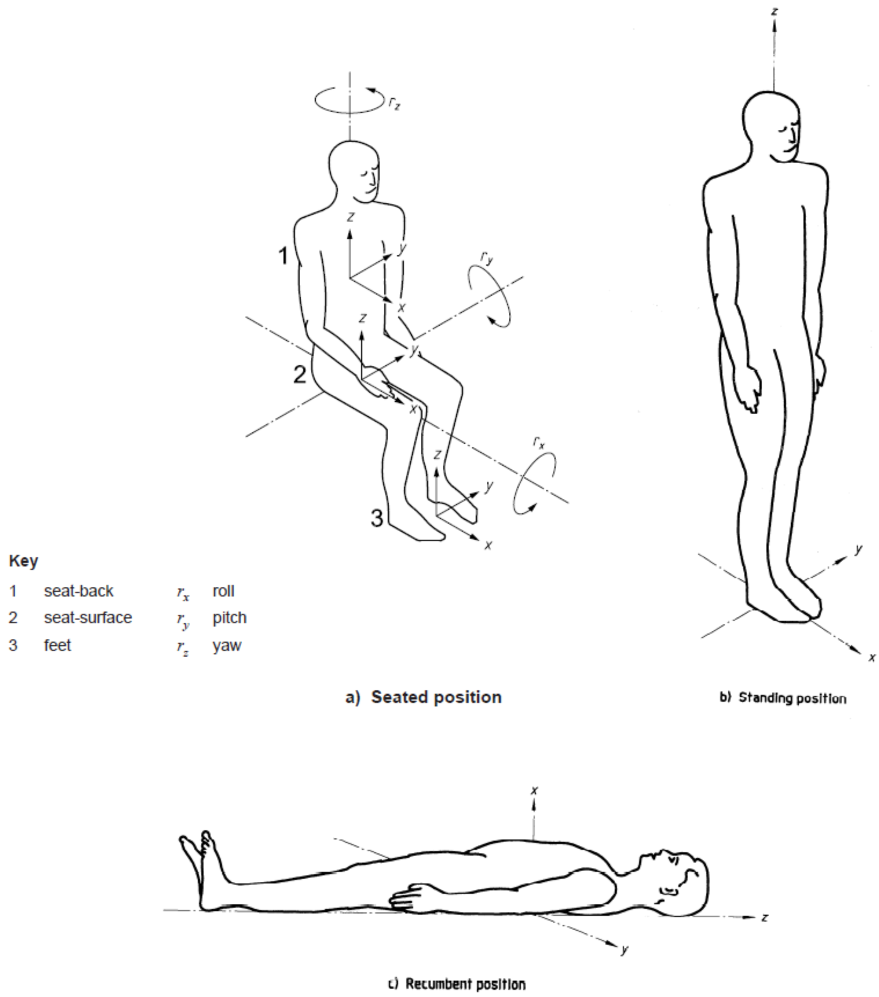


Figure 4 Basi-centric coordinate system (Source: BS ISO 2631-1:1997).

An important consideration in any measurement of vibration is how the transducer is mounted. The ANC (2001) state that transducers should be coupled to the vibrating medium such that they faithfully record the motion relative to the focus of the investigation and special attention should be given to mounting transducers on compliant surfaces such as carpets to ensure any mounting resonances are outside the frequency range of interest.

2.3.3 VIBRATION EXPOSURE METRICS

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 provided in the form of frequency weighting curves and recommendations of single figure metrics. BS 6472-1:2008 recommends two frequency weighting curves, W_b and W_d. 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 weighting curve applies to acceleration measured in the vertical direction and the W_d weighting curve applies to acceleration measured in the horizontal direction. The W_b 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. The moduli of these weightings are based on the laboratory studies into perception thresholds and equal comfort contours discussed in section 2.2.3.

BS 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 slightly from the W_b weighting defined in BS 6472-1:2008, however this difference is less than the inter-subject variability in the laboratory studies on which the weighting curves are based (see section 2.2.3). ISO 2631-2:2003 recommends the use of the W_m weighting curve which is applied to acceleration signals in any direction. The W_m weighting curve is derived from the product of the W_k and W_d curves. DIN 4150-2, the German national standard which is the basis of guidance in much of continental Europe, recommends the use of the K_b weighting curve applied to velocity signals. If the K_b weighting is transformed so as to be applied to an acceleration signal, it is similar to the W_m weighting curve. The magnitudes of the W_b, W_d, W_k, and W_m weighting curves are illustrated in Figure 5.

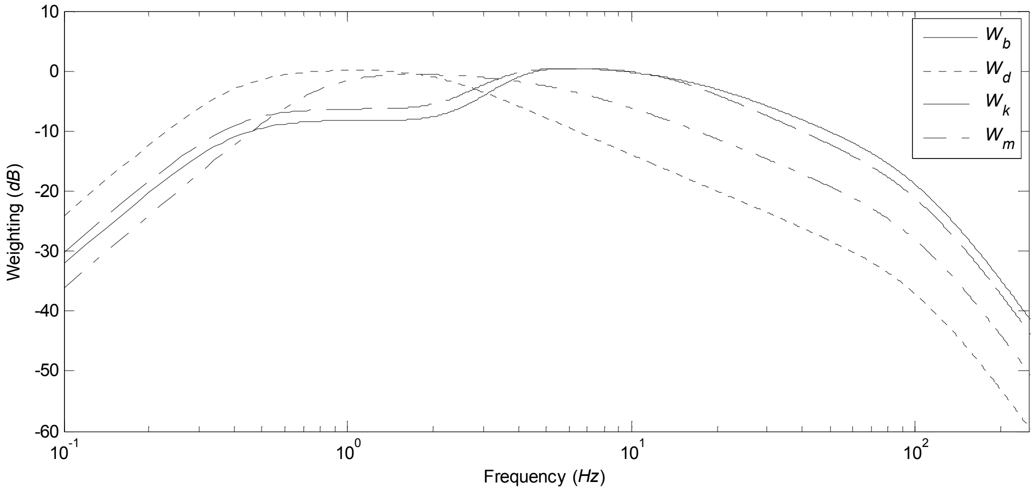


Figure 5 Weighting curves as defined in BS 6472 – 1:2008, BS ISO 2631 – 1:1997, and ISO 2631 – 2:2003.

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. $VDV_{b,day}$). *VDV* is a fourth 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 4**

where $\ddot{x}(t)$ is an acceleration signal, and *T* is the evaluation period in seconds. Due to the fourth power integration, *VDV* has the unconventional units $m/s^{1.75}$.

The rationale for the use of the vibration dose value is derived partly from a laboratory study conducted by Howarth and Griffin (1988b) into the relationship between the magnitude of railway induced vibration and the number of events with regards to human annoyance. This study produced the following relationship:

$$NV^4 \propto annoyance$$ **Equation 5**

where *N* is the number of vibration events and *V* is the vibration magnitude.

The finding of a fourth power relationship between the duration of vibration exposure and perceived discomfort by Griffin and Whitham (1980a, 1980b) is also cited as support for a fourth power metric.

BS ISO 2631-1:1997 suggests the use of frequency weighted root-mean-square acceleration (*RMS*) for the evaluation of low crest factor signals:

$$\ddot{x}_{rms} = \sqrt{\frac{1}{T}\int_0^T \ddot{x}^2(t)dt}$$ **Equation 6**

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

For signals with a crest factor greater than 9, the use of VDV or the maximum transient vibration value (MTVV) is suggested by BS ISO 2631-1:1997. MTVV is defined as the maximum value of the slow weighted (1 *s*) running *RMS* over the evaluation period.

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 7

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.

German national standard DIN 4150 suggests the use of an evaluation procedure for vibration based on two vibration exposure descriptors. Firstly, vibration exposure is evaluated in terms of KB_{Fmax} which is the 0.125 second running exponential RMS KB weighted velocity value over the evaluation period. If KB_{Fmax} is found to exceed a context sensitive threshold, KB_{FTr} is evaluated:

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

Equation 8

where T_r is the evaluation period (day or night), $T_{e,j}$ is the exposure period of the j^{th} event, and $KB_{FTm,j}$ is the average of the maximum 0.125 second running exponential RMS velocity for each 30 second period of an event.

Guidelines from other national standards are summarised by RIVAS (2011). Dutch standard SBR Richtlijn – Deel B 2002, FTA guidelines in the USA, Swedish standard SS 460 48 61:1992, Spanish standard Real Decreto 1367/2007, Italian standard UNI

9614:1990, Japanese Vibration Regulation Law and Austrian standard ONORM S 9012:2010 all recommend some variation of the maximum running average *RMS* velocity or acceleration although there is a variation in the recommended time constant between these standards. The 2009 revision of BS ISO 5228-2 suggests the use of peak particle velocity (*mm/s*) for the assessment of the human response to vibration from construction activities.

2.3.4 CRITERIA AND GUIDANCE

Vibration perception threshold base curves are provided in some national and international standards. Figure 6 illustrates the base curves presented in pre-1992 versions of BS 6472-1 and ANSI S2.71-1983 (R2006). These curves are intended to represent the threshold at which 50% of healthy human subjects will be able to perceive vibration.

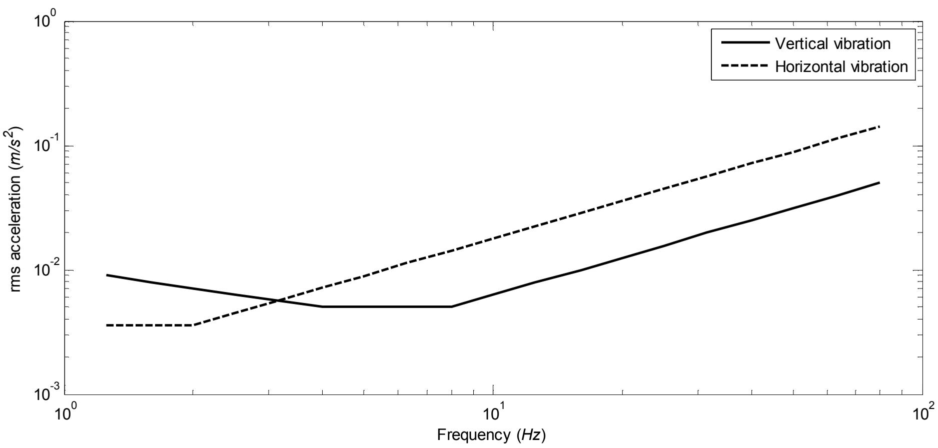


Figure 6 Vibration perception base curves.

Some guidance is available in national and international standards as to the probable annoyance caused by a given vibration exposure. BS 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* (see Table 1), however there is no indication as to how these values were derived and no definition of "*adverse comment*" is provided.

Place and time	Low probability of adverse comment[1] m/s$^{1.75}$	Adverse comment possible m/s$^{1.75}$	Adverse comment probable[2] 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.

Norwegian standard 8176 provides four classes of comfort for dwellings with respect to vibration exposure expressed in $v_{w,95}$ and $a_{w,95}$ (see Table 2). These four classes are based upon the results of a socio-vibrational survey which is described in section 2.5. In a Class A dwelling it is expected that occupants will not notice vibration; in a Class B dwelling it is expected that occupants be disturbed to some extent by vibration; it is expected that 15% of occupants of Class C dwellings be disturbed by vibration; it is expected that 25% of occupants of a Class D dwelling by disturbed by vibration.

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 2 Guidance classification of dwellings with the upper limits for the statistical maximum value for weighted velocity vw,95 or acceleration aw,95 [source (Turunen-Rise et al., 2003)].

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

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

BS ISO 5228-2:2009 provides four categories of Peak Particle Velocities from construction activities along with the expected response in residential environments (see Table 3).

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

2.4 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 the human response to environmental noise (transportation noise in particular). The work of Schultz (1978) is generally regarded as the seminal work in this field. Schultz derived an exposure-response relationship based on the synthesis of data collected in eleven social surveys investigating the relationship between noise exposure and annoyance. As a measure of annoyance, Schultz developed 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 observed that, in areas exhibiting high noise exposure, there was less scatter in the annoyance responses than in areas which exhibited comparatively lower noise exposure. It was also suggested by Schultz 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 was also argued that, although measurements of noise may have been conducted, it is not known if respondents were actually exposed to the measured noise level (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. 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*) [3] as the noise exposure descriptor. It was shown that as the magnitude of noise exposure increased, the proportion of respondents reporting high annoyance also increased. 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 agree well with the original curve derived 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-predicted annoyance caused by aircraft noise and over-predicted annoyance caused by road and rail traffic noise. Separate synthesis curves for different transportation noise sources (aircraft, road traffic, and railway traffic) have since been derived by Miedema & Vos (1998) through analysis of the same datasets used by Schultz

[3] L_{dn} is the Day Night Level (DNL) which is based on the equivalent A-weighted sound pressure over a 24-hour period and has a 10 *dB* penalty applied between the hours of 10 p.m. and 7 a.m.

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 (2001) presented an improved exposure-response model based on the same dataset analyzed by Miedema and Vos. The statistical model used in this study (Groothuis-Oudshoorn and 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".

Recent studies have approached deriving exposure-response relationships from this dataset in a different manner. Fidell et al. (2011) proposed a new way to describe these noise annoyance datasets which assumes that annoyance is proportional to the effective loudness of cumulative noise exposure (i.e. sound pressure raised to the 0.3 power). It is further assumed that the relationship between the percentage of respondents expressing high annoyance and noise exposure follows:

$$\%HA = 100e^{-\frac{1}{x}}$$

Equation 9

where:

$$x = \left[10^{\frac{L_{dn}+K}{10}}\right]^{0.3}$$

Equation 10

where L_{dn} is the equivalent day-night level (DNL) and *K* is an arbitrary constant which determines the anchoring point of this transition function on the DNL axis.

This curve is fit to the pairwise percent highly annoyed and DNL data from which a value of *K* is determined. The choice of the point at which *K* is anchored to the DNL axis is arbitrary; Fidell (2011) selected the point at which 50% of respondents expressed high annoyance as an anchoring point. Fidell (2011) proposed that *K* had two components each expressed in terms of DNL (*dB*):

$$K = L_{CT} + 5.306$$ **Equation 11**

where L_{CT} is the 'community tolerance level' (*CTL*) and the 5.306 term is an artifact of the selection of 50% highly annoyed as an anchoring point for the transition function.

It is hypothesised that the L_{CT} term quantifies all factors not taken into account by the DNL noise exposure metric. For example, a difference in the *CTL* between two different survey areas of 10 *dB* would suggest that the area with the greater value of *CTL* is 10 *dB* more tolerant to environmental noise exposure. This method is therefore useful for quantifying differences in response between communities; however the ability to model data on the individual level is lost.

Schomer et al. (2012) have applied this method to data from nine different field studies into the community response to railway noise. Data from these studies were partitioned into sixteen 'communities' which were grouped into areas of high and low vibration based on information in the original reports of the studies. An average difference of around 12 *dB CTL* was found between communities with high vibration levels and those with low vibration levels. This is consistent with the findings of Öhrström and Skånberg (1996) and Ohrström (1997) (these findings are discussed further in section 2.5).

2.5 Community response to vibration

2.5.1 Perceptible groundborne vibration

The main source of literature concerned with the human response to vibration in residential environments derives from studies into annoyance caused by groundborne vibration induced by railways. In comparison to community response to noise, relatively little is known with regards to community response to vibration in part due to the limited number of field studies on the subject. Difficulties of comparison between studies also arise due to the different vibration assessment methods recommended via national standards in different countries (see section 2.3).

The earliest large scale field survey investigating the human response to vibration in residential environments was conducted by Woodroof and 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 were conducted. 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 road traffic induced vibration and airborne noise (Watts, 1984, 1987, 1990). Along with this questionnaire, measurements of airborne noise were conducted to quantify the noise exposure of each of the respondents. Figure 7 shows the relationship between airborne noise at the most exposed façade and annoyance due to noise and vibration. It can be seen from this figure that noise exposure at the most exposed façade of the respondent's property expressed as a 10th percentile (L_{10}) is reasonably well correlated with nuisance caused by vibration.

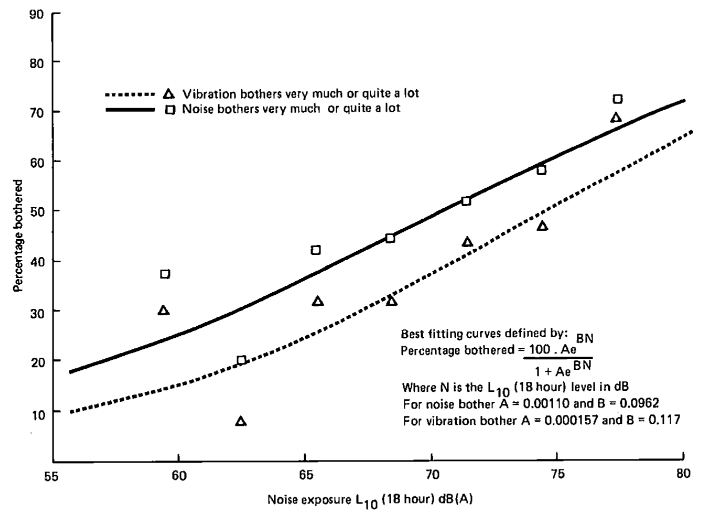


Figure 7 Relationship between airborne noise at the most exposed façade and noise and vibration annoyance [Source: Watts (1990)].

In a study conducted in Sweden (Öhrström and Skånberg, 1996; Öhrström, 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 exhibiting high vibration levels.

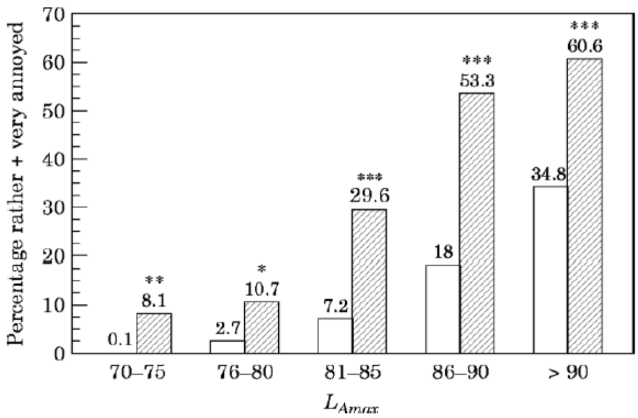


Figure 8 Percentage of respondents expressing high annoyance to noise in areas with weak (white bars) and strong (shaded bars) vibration (Source: Öhrström and Skånberg, 1996).

In a field study which aimed 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. However, it is not clear how noise and vibration were measured in this study. 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 (see section 2.2.7).

A large scale field study has been conducted in Norway (Klæboe et al., 2003a, 2003b; Turunen-Rise et al., 2003) with the aim of deriving an exposure-response relationship for the community response to vibration caused by road and railway traffic. 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 predictions 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 9). 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.

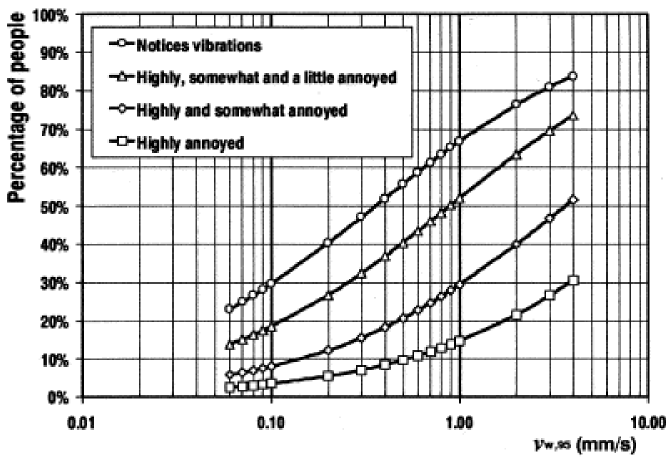


Figure 9 Exposure-response relationship for the cumulative percentage of people expressing different degrees of annoyance for a given vibration exposure (Source: Klæboe et al., 2003).

A social survey was carried out in Japan (Yano, 2005) to investigate the community response to the Sanyo Shinkansen high speed line in terms of annoyance due to noise and vibration. 724 questionnaires were conducted with residents living within 150 m of the Shinkansen railway line and 1612 questionnaires were conducted with residents living within 150 m of a conventional railway line. Measurements of vibration were conducted at 12.5, 25, 50, 75, 100, and 150 m from the centre of the railway line. These measurements were conducted at five sites along the Shinkansen line and six sites along the conventional railway lines. Distance attenuation relationships were determined from these measurements and the average maximum velocity level of the ten train events with greatest vibration magnitude (L_{Vmax}) were estimated for 358 respondents along the Shinkansen line and 422 respondents along the conventional railway lines. Noise exposure in terms of $L_{Aeq,24hr}$ was also estimated via a similar method of measurements and distance attenuation relationships. From these data, exposure-response relationships were determined for noise annoyance due to the two different types of railway. It was found that, at the same level of noise exposure, annoyance was greater for the Shinkansen line than for the conventional railway lines. It was hypothesised that higher than expected levels of annoyance due to noise from the Shinkansen compared to conventional railway lines were due to the higher levels of vibration generated by the high speed railway. Exposure-response relationships were determined for annoyance due to vibration from the two different types of railway (see Figure 10). As with noise annoyance, annoyance due to vibration was found to be higher for the Shinkansen line than the conventional railway lines for the same level of vibration exposure. It was however found that for the same level of noise exposure, levels of vibration were significantly higher for the Shinkansen line than the conventional lines. This finding led the authors to suggest a synergistic effect of vibration exposure on noise annoyance. It is however noted that attitudinal factor many play a significant role in the observed differences in annoyance responses for the different types of railway.

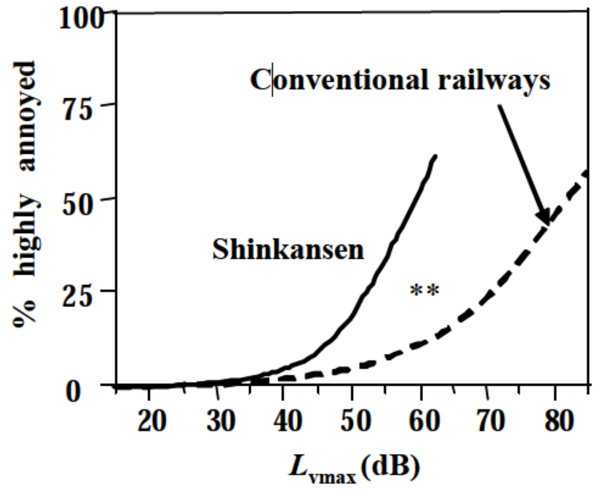


Figure 10 Exposure-response relationships for the percentage of respondents expressing high annoyance to vibration from the Shinkansen railway and conventional railways in Japan (Source: Yano, 2004).

In a study by the Transit Cooperative Research Program (Zapfe et al., 2009), a field survey was conducted 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 of annoyance as any other. Exposure-response relationships calculated using a logistic regression model were presented for groundborne vibration using the 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 exposure-response relationship presented in this study, 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.

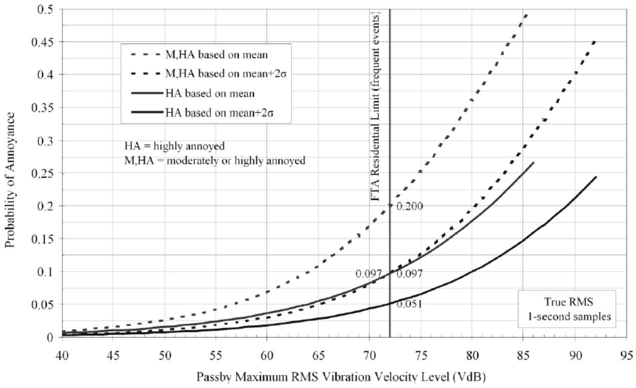


Figure 11 Exposure-response relationship for the percentage of respondents different degrees of annoyance to vibration from railways in North America (Source: Zapfe et. Al., 2009).

Within the project TVANE (Train Vibration and Noise Effects), a field survey was conducted in Sweden with the aim of investigating annoyance due to exposure to noise and vibration from railways in residential environments (summarised in Gidlöf-Gunnarsson et al., 2012). The main aims of this field study were to assess the how the relationship between noise exposure from railways and annoyance are influenced by the number of trains, the presence of groundborne vibration, and building situational factors such as orientation. Questionnaires were conducted with 1695 respondents living between 11 and 451 m from a railway line. These respondents were classified as living in one of three areas: areas with no vibration (N = 521), areas with vibration (N = 459), and areas with a high frequency of train passages (N = 715). Questionnaires collected, amongst other details, annoyance due to noise and vibration from the railway. Estimates of noise and vibration exposure were obtained for each respondent via measurement and prediction methods. Exposure-response relationships were derived for annoyance due to noise exposure for each of the three categories of respondents. For the same magnitude of noise exposure, a higher proportion of respondents expressing high annoyance was found in the areas categorised as having vibration than areas categorised as having no vibration. Exposure-response relationships were derived for annoyance due to vibration for respondents categorised as living in areas with vibration (see Figure 12).

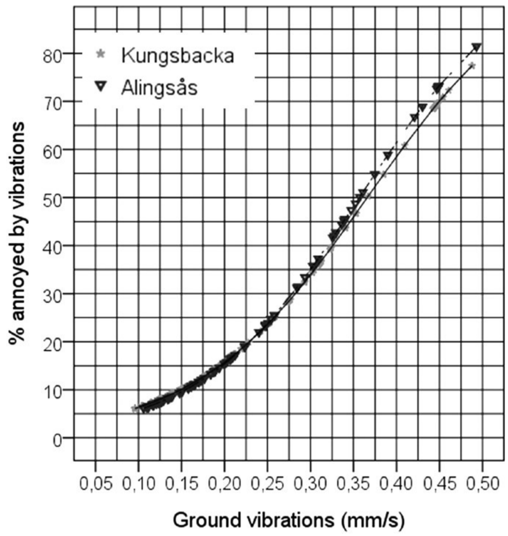


Figure 12 Exposure-response relationship for the percentage of respondents expressing annoyance to vibration from railway activities at two sites in Sweden (Source: Gidlöf-Gunnarsson et al., 2012).

2.5.2 *GROUNDBORNE 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 induced by London Underground train 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)*. Laboratory and field studies have been carried out to investigate human response to groundborne noise (Vadillo et al., 1996; Walker and Chan, 1996). It was concluded from a field study by 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 and 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.

2.5.3 VIBRATION INDUCED RATTLE

There have been a limited number of studies which have investigated the human response to vibration induced rattle. In two related field studies, Fidell et al. (1999, 2002) investigated the relationship between low-frequency aircraft noise and annoyance due to rattle and vibration suggesting that the underestimation of annoyance due to aircraft noise using existing exposure-response relationships may be due in part to vibration induced rattling of elements of residences such as window frames and household objects such as crockery. In this study, questionnaires were conducted with 495 residents living close to an airport runway in which they were asked about general noise annoyance and annoyance due to vibration induced rattle. One of the outcomes of this study was a relationship between annoyance due to vibration induced rattle and a measure of low frequency sound exposure. Although no concrete conclusions were drawn in this study, it was suggested that this relationship could complement the interpretation of the exposure-response relationships for aircraft noise.

2.6 THE CONCEPT AND MEASUREMENT OF ANNOYANCE

As highlighted in the previous section, response data in field studies into the community response to noise and vibration is generally recorded in terms of annoyance. Guski (1999) identifies annoyance as a broad concept associated with disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, nuisance, vexation, exasperation, discomfort, uneasiness, distress, and hate. The World Health Organisation (Fritschi et al., 2011) define health as a state of complete physical, mental, and social well being and it is currently their stance that noise annoyance should be considered as an environmental health burden.

The measurement of annoyance via socio-acoustical surveys is standardised in ISO/TS 15666:2003. The development of this standard was heavily influenced by the work of Team 6 of the International Commission on the Biological Effects of Noise (ICBEN) (Fields et al., 1997, 2001). This standard provides specifications on questions to be asked in surveys investigating the effects of noise, response scales, aspects of conducting socio-acoustical surveys, and recommendations on the reporting of results. A rationale for the wording of questions and the semantic labelling of scales is provided in an annex to the standard. No guidance is provided with regards to sampling procedures and analysis of data. It is recommended that two questions along with two rating scales are used in the measurement of noise annoyance. The first recommended question is posed as follows:

"Thinking about the last (12 months or so), when you are here at home, how much does noise from (noise source) bother, disturb or annoy you?"

and the response is recorded on a five-point semantic scale labelled {Not at all; Slightly; Moderately; Very; Extremely}.

The second recommended question is introduced as:

"*This uses a 0-to-10 opinion scale for how much (source) noise bothers, disturbs or annoys you when you are here at home. If you are not at all annoyed choose 0; if you are extremely annoyed choose 10; if you are somewhere in between, choose a number between 0 and 10.*"

and the following question is posed:

"Thinking about the last (12 months or so), what number from 0 to 10 best shows how much bothered, disturbed or annoyed by (source) noise?"

The response to this question is recorded on an eleven-point numerical scale labelled "Not at all" at the *0* end of the scale and "Extremely" at the *10* end of the scale.

The standard provides no recommendations as to the analysis of data collected using this method. However, through the history of field studies into the community response to environmental noise, expressing annoyance as a percentile based metric such as Percent Highly Annoyed (see section 2.4) has emerged as a de facto standard. This convention has been adopted in field studies investigating the community response to vibration (see section 2.5).

Currently, the only procedure available for the implementation of socio-vibrational surveys is the Nordtest Method NT ACOU 106 (2001). Similar to ISO/TS 15666:2003, it is recommended that annoyance responses be recorded on both semantic and numerical scales. It is recommended for annoyance responses recorded using the five-point semantic scale that the following question be asked:

"When you think about the last 12 months or so, how do you consider tremors or vibrations from (source) when indoors: highly annoying, moderately annoying, a little annoying, no annoying or do you not notice vibrations at all?"

An optional neutral filter question is provided in this method to determine if the respondent is able to notice vibration when indoors. If this filter question is used, those respondents able to feel vibration are asked the following:

"When you think about the last 12 months or so, do you consider these tremors or vibrations: highly annoying, moderately annoying, a little annoying, or not annoying?"

An optional question for the measurement of annoyance on an eleven-point numerical scale is provided as follows:

"When you think about the last 12 months or so when indoors, how would you rate your annoyance with tremors or vibrations from (source)? Pick a number from 0 to 10 where 0 denotes not noticeable and 10 denotes extremely annoyed."

Unlike ISO/TS 15666:2003, there is no rationale provided for the specific wording of these questions or the semantic labelling of the annoyance scales. It can be noted that the labelling of the highest category differs between the semantic ("*Highly annoying*") and numerical ("*Extremely annoying*") scales.

2.7 DISCUSSION

Despite the physiological complexity involved in the perception of vibration (see section 2.2.1), psychophysical laboratory investigations have gone some way towards characterising this phenomenon. From the laboratory studies detailed in section 2.2, it is evident that the perception of whole body vibration is dependent on frequency, magnitude, and duration. The results of some of these laboratory studies have informed the development of single figure descriptors and frequency weightings for the assessment of vibration exposure with regards to human response some of which have been adopted by national and international standards. There is however a lack of laboratory investigations into the perception of vibration from "*real world*" sources.

A review of national and international standards reveals three basic groups of vibration exposure descriptors recommended to describe human response: root-mean-squared energy equivalent values, maximum running root-mean-squared values, and the fourth power Vibration Dose Value. The use of the Vibration Dose Value as a vibration exposure descriptor is a contentious issue due to the relative complexity of its calculation and non-intuitive units ($m/s^{1.75}$). Although the use of the Vibration Dose Value is supported by laboratory findings, there is no field evidence supporting its applicability. There is a general agreement between standards regarding the use of frequency weightings although some differ in the use of acceleration or velocity. However as the W_b and W_k weightings, which are to be applied to acceleration signals, drop off at around 6 *dB/octave* above around 10 *Hz*, above this frequency these weightings approximate velocity. As with the single figure descriptors, the applicability of these frequency weightings under field conditions is unknown. Studies by Kaneko et al. (2005), Morioka and Griffin (2006b), Bellmann (2002), and Ahn (2008) have suggested the human response to vibration deviates from the frequency weightings recommended in current standards with increasing magnitude of vibration exposure. However, at the magnitudes of vibration expected in residential environments from environmental sources, laboratory evidence supports the use of the standard frequency weightings.

Recent studies into the community response to noise have advocated the use of an equivalent level noise exposure raised to the 0.3 power to approximate the psychophysical relation between the magnitude of sound pressure and subjective loudness (Fidell et al., 2011; Schomer et al., 2012). As discussed in section 2.2.2, laboratory studies have suggested that the growth constant for the subjective magnitude of vibration exposure fluctuates around unity. If this assumption were to be followed for modelling the community response to vibration, a growth function of unity suggests the use of a linear psychometric function.

In both socio-acoustic and socio-vibrational studies the relatively small amount of variance explained by the resulting exposure-response relationships has been acknowledged. It is often hypothesised that the predictive power of these exposure-response relationships can be improved through the investigation of non-acoustical factors (see, for example, Marquis-Favre and Premat, 2005; Marquis-Favre, 2005) and improvements in the metrics used to quantify exposure to the stimulus of interest (see, for example, Dittrich and Oberfeld, 2009; Kryter, 2007). In 1974, the Environmental Protection Agency (EPA) in the USA (Abatement and Control, 1974) proposed the use of a "normalised" noise exposure metric (termed Normalised DNL) which aimed to reduce the scatter in exposure-response relationships for noise annoyance. This normalised metric is calculated from a table of adjustment factors which impose penalties or bonuses expressed in decibels for non-acoustical factors and characteristics of the noise exposure. These factors include seasonal corrections, corrections for previous noise exposure, and corrections for noise exposures with impulsive or tonal characteristics. The use of the normalised DNL resulted in a reduction in the scatter around the exposure-response relationship. Schomer (2002) proposed an update to the EPA's adjustment factors which included not only non-acoustical factors but also additional factors relating to the quality of the noise such as rattle, tonal components, and different levels of impulsiveness. The improvement of the exposure-response relationship with the use of these adjustment factors raises the question of whether the variation in individual annoyance at the same noise exposure level is due to the inadequacy of a single figure energy equivalent noise metric to quantify objective features of noise exposure which are salient to human perception (i.e. temporal features, changes in frequency content).

Although laboratory studies have developed improved metrics for the prediction of annoyance due to environmental sources (see, for example, Alayrac et al., 2010; Fastl et al., 2003; Nilsson, 2007), they are difficult to validate and hence difficult to justify the use of. Data available from previous field studies into the community response to noise are generally only in terms a single figure descriptor of the noise exposure. As time history data is generally not retained in these studies it is impossible to validate new metrics.

Compared to the human response to environmental noise, there is a relative lack of field data relating to the human response to vibration in residential environments. The use of different vibration exposure descriptors in the field studies reported in the literature makes comparison of the results between these studies problematic. As the human response to vibration in residential environments emerges as a field of research, the shortcomings of research into the human response to noise in residential environments should be borne in mind. The use of attenuation laws and prediction models in the estimation of vibration exposure in field studies into the community response to vibration means there is not enough variance in the data to investigate new descriptors. If the applicability of vibration exposure metrics are to be assessed via socio-vibrational surveys, it is vital that measurements of vibration exposure are conducted in as many properties as practicable and that time histories of these measurements are retained.

2.8 Summary

This chapter has presented an overview of literature relating to the human response to whole body vibration. Laboratory studies into the perception of vibration have resulted in a number of psychophysical relationships describing the perception of vibration magnitude, frequency, and duration. Differences in results between these studies highlight the complexity of the perception of vibration. As well as objective features of the vibration stimuli, multimodal effects give rise to inter- and intra- subject differences; the perception of vibration can be affected by posture, auditory, and visual cues. It has been shown that, although a relatively large amount of work has been undertaken in laboratory studies there exists a lack of knowledge regarding the human response to vibration in residential environments. This is reflected by the significant differences in guidance and assessment methods which exist in national and international standards. A review of research into the human response to environmental noise reveals a wealth of approaches and techniques which can be utilised in the study of the human response to vibration.

CHAPTER 3

A FIELD SURVEY TO MEASURE RESPONSE AND EXPOSURE TO VIBRATION

3 A FIELD SURVEY TO MEASURE RESPONSE AND EXPOSURE TO VIBRATION

3.1 INTRODUCTION

As highlighted in the previous chapter, although much is known about the human response to noise exposure in residential environments, there is a need to further knowledge regarding the human response to environmental vibration. This is in part due to the need for relevant field data suitable for the derivation of exposure-response relationships. This chapter documents the planning and implementation of a large scale field survey to determine both exposure and response to vibration in residential environments. The main objective of the fieldwork detailed in this chapter was the development of a database of responses, primarily in terms of annoyance, due to environmental vibration along with measurements of vibration from which estimations of 24-hour internal vibration exposure could be made.

Response to vibration was measured via a questionnaire conducted face-to-face with residents in their own homes living within 150 *m* of either existing railway operations or the construction of a new light rail system. The development of the questionnaire, the sampling strategy, and the procedures for the selection of survey sites is detailed in section 3.2. Vibration data were recorded under the framework of a novel measurement methodology which encompassed an extensive campaign of external and internal vibration measurements. The details of the equipment and methodology employed in this measurement campaign are discussed in section 3.3.

3.2 Measurement of response

3.2.1 Development of questionnaire

The objective of the social science component of the fieldwork detailed in this chapter was to provide a robust sample of measurements of the human response to vibration induced by railway activities and railway construction in residential environments. To realise this objective, a questionnaire was designed by researchers working in the Salford Housing and Urban Studies Unit (SHUSU) (Condie et al., 2011). As discussed in section 2.6, response data in field studies into the community response to noise and vibration is generally measured in terms of annoyance with annoyance considered as a catchall concept for the negative evaluation of environmental conditions (Guski, 1999). Therefore, the primary response of interest which the questionnaire aimed to measure was self reported annoyance. Additionally, as situational and attitudinal factors have been shown to influence the human response to noise (Fields and Walker, 1982; Fields, 1993; Miedema and Vos, 1999), the questionnaire also measured a variety of other factors such as self-reported sensitivity to vibration and noise, factors related to concern and fear of the source, and satisfaction with the home and neighbourhood.

The questionnaire was based on a pilot questionnaire developed for Defra (2007), the Nordtest method for the development of socio-vibration surveys (NT ACOU 106-2001), best practice guidelines for the measurement of annoyance due to noise set out by Team 6 of the International Commission on the Biological Effects of Noise (ICBEN) (Fields et al., 2001), and guidance from ISO/TS 15666:2003. The questionnaire was also subject to a peer review process in which international experts were asked to review the questionnaire.

To avoid influencing response to questions on vibration and noise, the social survey questionnaire was presented as a neighbourhood satisfaction survey. If the questionnaire were presented as an investigation into annoyance due to vibration and noise, self selection could have resulted in responses skewed towards higher annoyance ratings (see, for example, NT ACOU 106-2001). As such, the opening questions of the survey focussed on the reasons for the respondent moving into the neighbourhood, neighbourhood satisfaction, and satisfaction with the home. Following this, questions regarding response to vibration and noise were asked. Source specific variations on these questions were developed for railway and construction vibration and noise.

Throughout the various field surveys conducted into the community response to noise exposure (see section 2.4), a variety of different response scales have been employed. The general design criteria, adapted from (Fields et al., 2001), for the annoyance response scales utilised in the questionnaire were as follows:

- Be clear and comprehensible for the respondent to provide a valid rating of annoyance.
- Allow exploration of any combined effect of vibration and noise on annoyance.
- Yield an interval-level measurement scale.
- Yield data suitable for analysing exposure-response relationships with objective vibration and noise measurements.
- Permit consistency throughout the questionnaire for ease of administration and comprehension for interviewers, respondents, policy makers, and report readers.

Based on the above criteria and following guidance from ICBEN (Fields et al., 2001) and ISO/TS 15666:2003, annoyance responses were measured on five-point semantic and eleven-point numerical scales. The questionnaire used for residents living close to a railway line is reproduced in full in Appendix IV.

To ensure consistency and comprehension when asking about vibration, any reference in the questionnaire to feeling vibration was always accompanied by the word "*shaking*". Similarly, any reference to hearing the effects of vibration was accompanied by the words "*rattle, vibrate, or shake*". These two different perceptual mechanisms were separated out in the questionnaire by asking respondents through which surfaces they have perceived vibration (see Figure 13) and which structures and objects they have heard or seen rattle, vibrate, or shake (see Figure 14). However, when asking respondents how bothered, annoyed, or disturbed they are by vibration, these two perceptual mechanisms are assessed simultaneously in a single question as a measure of overall annoyance (see Figure 15).

D2. When you have felt vibration, have you felt it:

	Yes	No
From the floor	☐	☐
When you have been sitting on a chair	☐	☐
When you have been lying on a bed	☐	☐
When you have touched any surfaces with your hands	☐	☐
From any other surfaces in this home	☐	☐

Figure 13 Question from social survey to determine through which surfaces a respondent has perceived vibration.

D6. Have you personally ever heard or seen any rattling, vibrating or shaking of:

	Yes	No
The windows	☐	☐
The doors	☐	☐
Any other part of this home	☐	☐
Crockery, like plates, or glasses in your cupboards	☐	☐
Any other objects in this home	☐	☐

Figure 14 Question from social survey to determine which objects and structures a respondent has seen or heard rattle, shake, or vibrate.

D9. Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by feeling vibration or shaking or hearing or seeing things rattle, vibrate or shake caused by **[insert source identified in D1 and D5]**? Would you say not at all, slightly, moderately, very or extremely?
[Show card 4]
[Repeat question for all sources identified at D1 and/or D5]
[For sources not noticed at D1 <u>and</u> D5, record as 'Don't notice']

Source	Don't notice	Not at all	Slightly	Moderately	Very	Extremely
Cars, lorries, buses or other road vehicles						
Aeroplanes						
Helicopters						
The railway, including passenger trains, freight trains, track maintenance or any other activity from the railway						
Underground trains (i.e. tube or metro)						
Trains in tunnels						
Construction activity, including building, demolition and road works						
Quarrying or mining						
Footsteps, slamming doors, domestic appliances inside this home						
Footsteps, slamming doors, domestic appliances in neighbouring homes						
Unidentified source/don't know						
Other things **[record below]**						

[If respondent is bothered, annoyed or disturbed, mark Section F (Yellow section) as a reminder to complete this section]

Figure 15 Question from social survey to measure annoyance due to vibration.

3.2.2 Site Identification, Sampling, and Implementation of Questionnaire

It is suggested in the Norwegian guidance document NT ACOU 106 that the primary objective in the selection of sites in socio-vibrational surveys is to achieve a sample of respondents exposed to a wide range of vibration magnitudes. Considering this, potential survey sites with a sufficient number of properties at a range of distances from the vibration source of interest were first identified using Google maps. For each identified site, a site reconnaissance was conducted to assess its suitability. Through the reconnaissance it was ensured that there were no potentially perceptible sources of vibration other than the source of interest and that the site was a safe area for the researchers conducting the questionnaires to work.

After the identification of suitable survey sites, a two-step sampling procedure was employed to engage residents to take part in the social survey. In the first step, researchers from the Salford Housing and Urban Studies Unit (SHUSU) engaged to conduct the questionnaires used door-to-door cold calling to attempt initial contact at each property in the identified survey areas. If the resident was not at home two additional attempts at contact were made on different dates and at different times of day. In the second step, one individual from each property where contact was successful was asked if they were willing to participate in a questionnaire. The tendency of this sampling procedure to under represent respondents from large households has been shown in previous studies to have little effect on resulting exposure-response relationships (Klæboe and Grue, 1999; Klæboe et al., 2003b). Using this procedure, contact was attempted 17923 times at 6366 properties. Of those properties, contact with a resident was successful in 3116 cases of which 1281 individuals agreed to participate in a questionnaire. This response rate of 41% is typical of this type of survey (see, for example, Gidlöf-Gunnarsson et al., 2012; Klæboe et al., 2003). 931 of the completed questionnaires were in areas with an active railway source and 350 of the completed questionnaires were in areas in proximity to the construction of a new light rail system.

Following the completion of a questionnaire, the respondent was asked if they were willing to allow a measurement of vibration to be conducted in their property at a later date. 87.9% of residents who took part in a questionnaire agreed to allow a measurement of vibration to be conducted. Details of those willing to allow a measurement were recorded and subsequently contacted during the vibration measurement campaign detailed in section 3.3.

3.2.3 DESCRIPTION OF SURVEY SAMPLE

As highlighted in the previous section, one of the primary objectives of the sampling strategy for the field survey detailed in this chapter was to ensure a sample of respondents exposed to a wide range of vibration magnitudes. As data regarding the magnitude of vibration at the identified sites was not available, distance from the source was considered as a proxy for vibration magnitude. Figure 16 and Figure 17 show the distribution of respondents as a function of distance from the source for railway and construction vibration. From these figures it can be seen that respondents are well distributed with respect to distance from the source up to around 100 *m*.

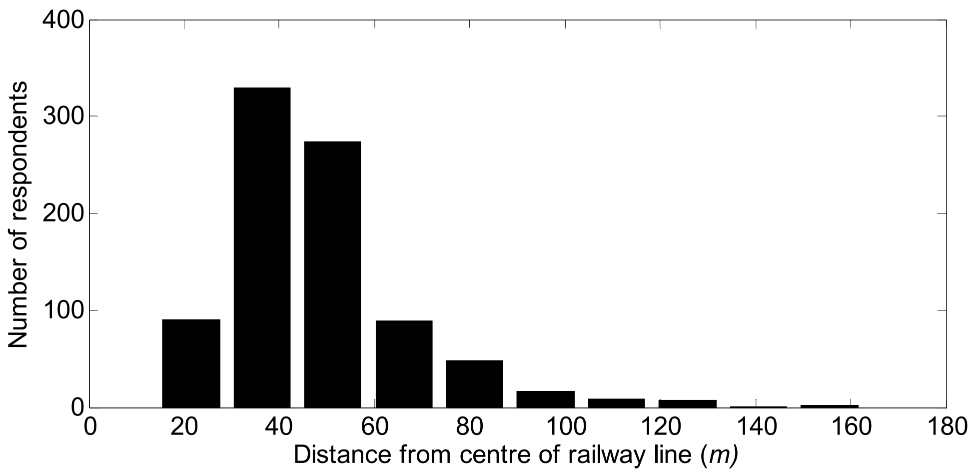


Figure 16 Distribution of respondents as a function of distance from the centre of the railway line (*N* = 932).

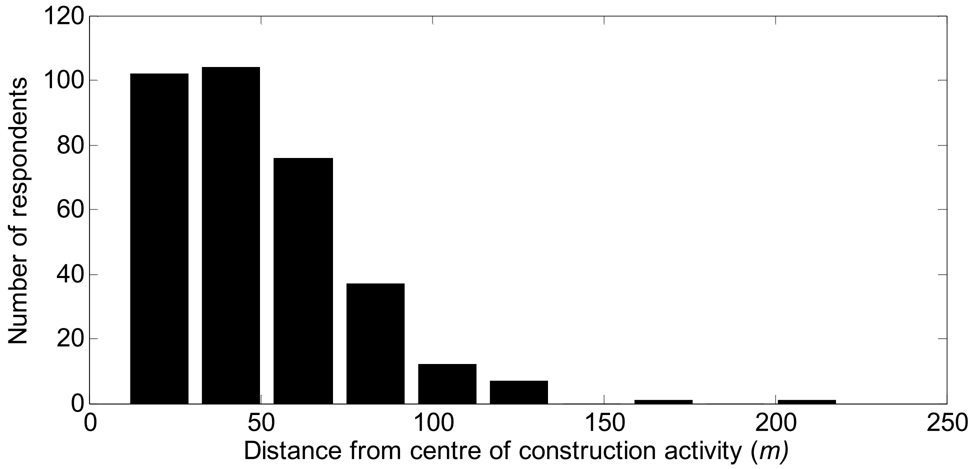


Figure 17 Distribution of respondents as a function of distance from the centre of construction activity (*N* = 350).

As discussed in section 2.4, the human response to environmental noise has been shown to be dependent on the noise source. For example, for the same level of noise exposure, aircraft noise has been shown to elicit a significantly higher annoyance response than railway noise. As there is no literature comparing annoyance responses due to vibration exposure from railway and construction sources, this suggests that initial analyses into the human response to vibration from railway and construction sources should be considered independently. In order to make a meaningful comparison between responses to different sources of vibration it should be ensured that the two samples are drawn from similar socio-demographic samples. Table 4 to Table 8 provide summaries of various socio-demographic factors of the two samples. It can be seen from these tables that the distributions of gender, age, employment status, ethnicity, and tenure between the samples for the different vibration sources are similar.

The 2011 UK census (Office for National Statistics, 2011) indicates that in England and Wales 49.2% of the population are male and 50.8% or the population are female. The figures presented in Table 4 therefore suggest that a greater proportion of the respondents in the current sample are female than the UK population as a whole. From the 2011 census, in England and Wales 16% of the population are aged 65 and over which suggests that respondents in this age bracket are over represented in the current sample. The majority of respondents describe themselves as being in employment, which is in line with figures from the census. However, there is an overrepresentation, particularly in the construction sample, of those describing themselves as being unemployed. In line with the census, the majority of respondents described themselves as being White British while the remainder were from a Black and Minority Ethnic background. The census reports that 64% of residents in England and Wales own their homes either outright or with a mortgage, 9% renting from the council, and 15% renting from a private landlord suggesting that those who own their home are overrepresented in the railway sample and those renting from the council are underrepresented in the construction sample. Although there are some differences between the demographics of current sample and that of England and Wales as a whole these figure suggest that the characteristics are broadly similar; it should however be highlighted that the goal of the sampling strategy was to provide a sample of respondents which were representative of those living close to railway and construction sites and not necessarily the UK as a whole. None of the socio-vibration surveys detailed in section 2.5.1 report sample characteristics therefore comparisons cannot be made between this sample and those collected in other surveys.

	Railway	**Construction**
Gender	N (%)	N (%)
Male	412 (44.2)	133 (37.9)
Female	511 (54.8)	216 (61.5)
Missing	9 (1.0)	2 (0.6)

Table 4 Overview of gender for railway and construction social survey datasets.

	Railway	Construction
Age	N (%)	N (%)
17-24	89 (9.5)	33 (9.4)
25-39	237 (25.4)	92 (26.2)
40-49	170 (18.2)	72 (20.5)
50-59	137 (14.7)	53 (15.1)
60-74	214 (23.0)	74 (21.1)
75-84	67 (7.2)	22 (6.3)
85+	15 (1.6)	4 (1.1)
Missing	3 (0.3)	1 (0.3)

Table 5 Overview of age for railway and construction social survey datasets.

	Railway	Construction
Employment Status	N (%)	N (%)
Employed	407 (43.7)	134 (38.2)
Self employed/Business owner	59 (6.3)	24 (6.8)
Student	48 (5.2)	11 (3.1)
Retired	265 (28.4)	90 (25.6)
Unemployed	60 (6.4)	41 (11.7)
Carer/homemaker	75 (8.0)	36 (10.3)
Volunteer	3 (.3)	1 (0.3)
Other/Missing	15 (1.7)	14 (3.0)

Table 6 Overview of employment status for railway and construction social survey datasets.

	Railway	Construction
Tenure	N (%)	N (%)
Own outright or with a mortgage	698 (74.9)	229 (65.0)
Part-rent and part-own with a mortgage	34 (3.6)	9 (2.6)
Rent from a private landlord/letting agency	91 (9.8)	53 (15.1)
Rent from a Housing Association or Council	99 (10.6)	5 (1.4)
Other/Missing	10 (1.2)	3 (0.9)

Table 7 Overview of tenure for railway and construction social survey datasets.

	Railway	Construction
Ethnicity	N (%)	N (%)
White British	774 (83.0)	274 (78.1)
White Irish	11 (1.2)	5 (1.4)
White Romany Gypsy	1 (0.1)	1 (0.3)
Other white background	11 (1.2)	13 (3.7)
Mixed B & W Caribbean	4 (0.4)	2 (0.6)
Mixed B & W African	2 (0.2)	1 (0.3)
Mixed White and Asian	5 (0.5)	6 (1.7)
Other mixed background	2 (0.2)	16 (4.6)
Asian - Indian	12 (1.3)	5 (1.4)
Asian - Pakistani	58 (6.2)	2 (0.6)
Asian - Bangladeshi	5 (0.8)	13 (3.7)
Other Asian background	10 (1.1)	7 (2.0)
Black Caribbean	5 (0.5)	13 (3.7)
Black African	10 (1.1)	7 (2.0)
Other Black background	4 (0.4)	1 (0.3)
Chinese	1 (0.1)	1 (0.3)
Other/Missing	15 (1.6)	4 (1.2)

Table 8 Overview of ethnicity for railway and construction social survey datasets.

3.3 MEASUREMENT OF EXPOSURE

For the assessment of the vibration exposure with respect to human response in residential environments, both BS 6472-1:2008 and the ANC guidelines (ANC, 2001) recommend that vibration is measured for a period of 24-hours in the centre of the floor of the room at which the magnitude of vibration is perceived to be greatest. As 1281 estimations of 24-hour vibration exposure were required, this approach was not practicable. As a consequence, a novel measurement approach was developed which encompassed elements of measurement and prediction. This section describes the measurement system used for the measurement of vibration in the field survey detailed in this chapter along with the different approaches developed for the measurement of vibration from railway and construction sources.

3.3.1 MEASUREMENT SYSTEM

The primary objective of the measurements described in this chapter was to obtain unweighted, band limited tri-axial acceleration time histories of groundborne vibration induced by environmental sources in residential environments. As the measured vibration data were to be assessed with regards to human response, a measurement system was needed with a low enough noise floor to faithfully measure vibration below the threshold of human perceptibility in the frequency range of interest (0.5 – 80 *Hz*). The volume of measurements required both externally and within residents' properties meant that a system was required which was durable and efficient to transport and set up.

From an assessment of commercially available measurement systems, it was found that Guralp 5-TD force-feedback strong-motion accelerometers met the required criteria to successfully implement the measurement methodologies described later in this chapter. A photograph of this measurement system is provided in Figure 18. The measurement system comprises a tri-axial force feedback accelerometer and a 24-bit digitiser in a self contained unit. The digitiser is able to be synchronised via GPS allowing phase locked measurements between multiple systems without the need for cabling. The physical construction of the instrument means it is relatively robust and able to withstand wet weather conditions.

Figure 18 Guralp 5-TD measurement system.

Figure 19 shows the vibration perception base curves from BS 6472-1:1992 compared to the theoretical noise floor and clip level of the Guralp 5-TD measurement system. It can be seen from this figure that that a theoretical dynamic range of around 127 *dB* is achievable by this system with a noise floor well below that of the quoted thresholds of human perceptibility.

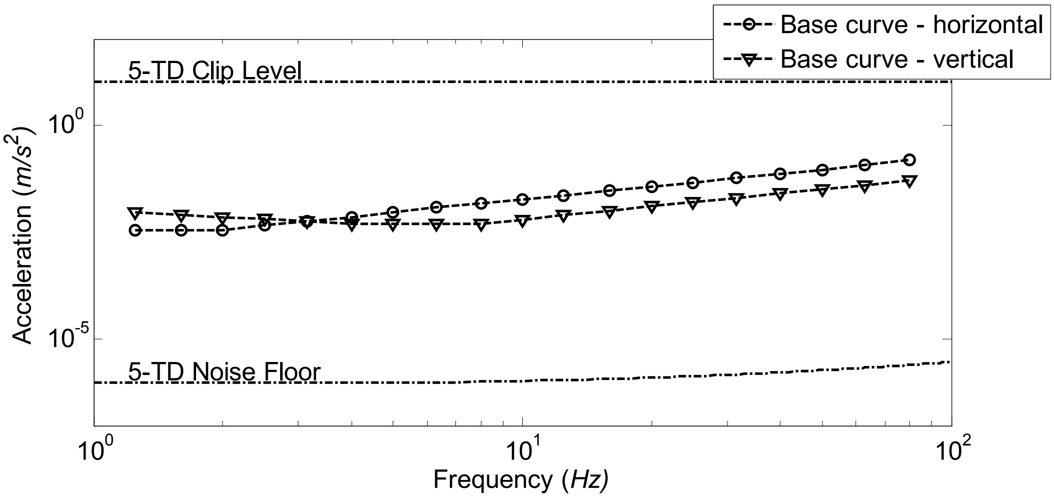


Figure 19 Theoretical noise floor and clip level of the Guralp 5-TD measurement system compared with the vibration perception base curves from BS 6472-1:1992.

3.3.2 MEASUREMENT OF VIBRATION FROM RAILWAY SOURCES

For the measurement of vibration from railway sources, long term vibration monitoring was conducted at external positions (labelled 'Control Position' in Figure 20) for a period of at least 24-hours. During the long term monitoring, short term 'snapshot' measurements, which were synchronized with the long term measurement, were conducted within the properties of residents who had completed a questionnaire. The short term measurements were generally around 30 minutes in duration, or a period which encompassed 5 to 10 train passes. For the internal 'snapshot' measurements, the measurement position was taken as close to the centre of the floor as possible of the room in which the respondent of the questionnaire stated that they could feel the strongest magnitude of vibration. For both the long term measurements and snapshot measurements, tri-axial acceleration time histories were recorded at a sampling frequency of 200 *Hz*.

The overall objective of this approach was to determine the transmissibility between the two measurement positions to enable the prediction of 24-hour vibration exposure at the internal measurement positions. The estimation of 24-hour internal vibration from these data is discussed further in Chapter 4. In total, 149 long term measurements were conducted along with 522 'snapshot' measurements.

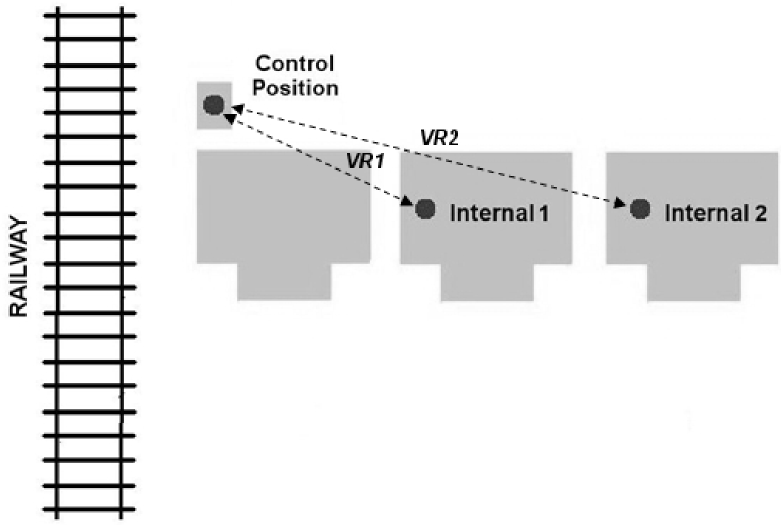


Figure 20 Schematic of measurement approach for railway sources

3.3.3 MEASUREMENT OF VIBRATION FROM CONSTRUCTION SOURCES

The measurement approach adopted for railway sources described in the previous section was found to be impracticable for the measurement of vibration induced by construction activity. This was mainly due to the unpredictable hours of operation and the transitory nature of the source. A paradox was encountered in which sites were required where residents had already been exposed to vibration induced by construction activities but, as the vibration exposure from the entire lifecycle of the construction activity needed to be monitored, construction work should not have commenced at the site. To overcome this, two sites were identified around the construction of a new light rail system at which the construction activities proceeded along the site in a linear fashion. This provided a situation where areas of the sites had already been exposed to the entire lifecycle of the construction activities and areas of the sites where construction was yet to commence. Therefore, the measurement approach for construction vibration required more emphasis on extrapolation and correction of measured levels from one location to estimate exposure in other locations (Sica et al., 2011).

Long term monitoring was conducted over a period of around 2 months to monitor the entire life-cycle of the construction activity (labelled 'Control Position' in Figure 21). At times of high activity (during piling operations, for example), a linear array of external measurements was conducted. The main objective of this measurement approach was the determination of ground attenuation laws for each measurement site to allow the propagation of the activity recorded at the long term monitoring position to any residence where a questionnaire had been completed.

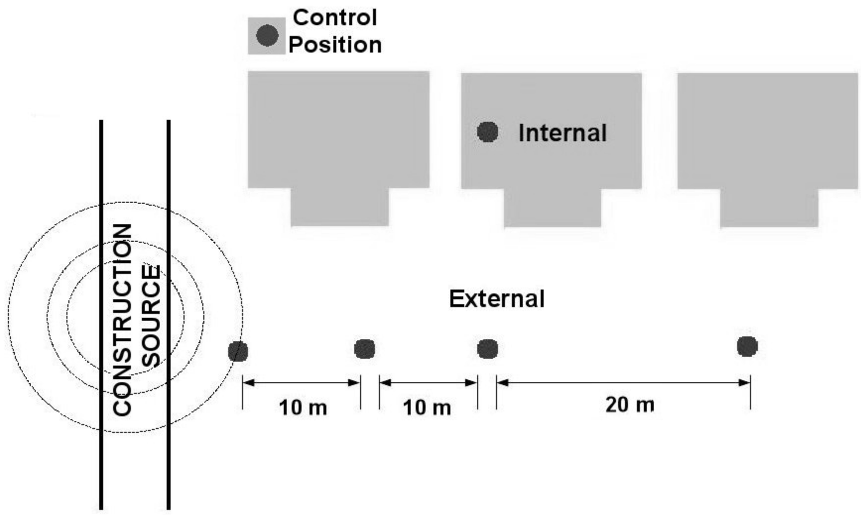


Figure 21 Schematic of measurement approach for construction sources.

3.4 SUMMARY

This chapter has detailed the design and implementation of a large scale field study to determine both response and exposure to vibration in residential environments. Response data were collected via a questionnaire which was conducted face to face with residents in their own homes. In total 1281 questionnaires were collected, 931 with residents living close to railway lines and 350 with residents living close to the construction of a new light rail system. For both sources of vibration a sample of respondents at different distances from the source was achieved suggesting the site selection and sampling strategy was successful. The socio-demographic characteristics of the samples for the two vibration sources were found to be similar suggesting that valid comparisons can be made between the responses to the different sources of vibration. Two novel measurement approaches were implemented to measure vibration from the two sources. The following chapter details how the vibration data gathered through the measurements described in this chapter were analysed to estimate 24-hour vibration exposure for as many residents who took part in a questionnaire as possible.

CHAPTER 4

ANALYSIS OF FIELD DATA

4 ANALYSIS OF FIELD DATA

4.1 INTRODUCTION

The previous chapter detailed the planning and implementation of a large scale field survey the main objective of which was to collect responses to vibration from railway and construction sources in residential environments in terms of annoyance and to conduct measurements of internal and external vibration from which estimates of internal vibration exposure could be calculated. In total, 1281 questionnaires were conducted face-to-face with residents in their own homes; 931 of the questionnaires were conducted with respondents living within 150 m of a railway line and 350 of the questionnaires were conducted with residents living within 150 m of the construction of a new light rail system. Around 4400 hours of continuous tri-axial acceleration time history data were recorded in a measurement programme designed to result in estimations of 24-hour vibration exposure for as many of the residents who had taken part in a questionnaire as possible.

This chapter details how the vibration data were analysed to predict 24-hour internal vibration exposures in the dwellings of residents who had participated in a questionnaire. An investigation into single figure descriptors of vibration exposure is provided and the relationship between these descriptors and annoyance responses collected via the questionnaire is explored. The main aim of this investigation is to determine if an ordinal relationship exists between self reported annoyance and vibration exposure in residential environments and, if such a relationship exists, which single figure descriptor of vibration exposure exhibits the greatest correlation with self reported annoyance.

4.2 ESTIMATION OF INTERNAL VIBRATION EXPOSURE

4.2.1 ESTIMATION OF RAILWAY INDUCED INTERNAL VIBRATION EXPOSURE

The field survey detailed in the previous chapter generated 149 24-hour external measurements and 523 short-term internal measurements of vibration. As discussed in section 3.3.2, the objective of this measurement methodology was to allow the determination of the transmissibility between the external and internal measurement positions and to apply this transmissibility to the vibration measured at the long term position to facilitate the estimation of 24-hour vibration exposure within the dwellings of residents who had participated in the social survey questionnaire. Briefly, this measurement methodology consisted of the following steps:

i. Long-term monitoring is conducted at an external position. Where possible, this position is located at a similar distance from the railway as dwellings in which an estimation of internal vibration exposure was required.
ii. Short-term "snapshot" measurements synchronised with the long term measurement in step i are taken in the respondent's property as close the point of entry of the human body as possible.
iii. The external-to-internal transmissibility (frequency dependent) from the measurement positions in step i and step ii is calculated.
iv. 24-hour vibration exposure inside the dwelling is estimated by applying the transmissibility calculated in step iii to the long-term measurement in step i.

All data recorded via this measurement methodology were stored as tri-axial acceleration time histories sampled at 200 *Hz*. As around 4400 hours of measured data were collected via this method, it was necessary to develop a trigger algorithm to automatically identify railway events in the data. An event in this context is defined as a period of measureable vibration induced by a single activity occurring on the railway such as the passage of a train. Examples of measured acceleration time histories of railway induced vibration events are illustrated in Figure 22.

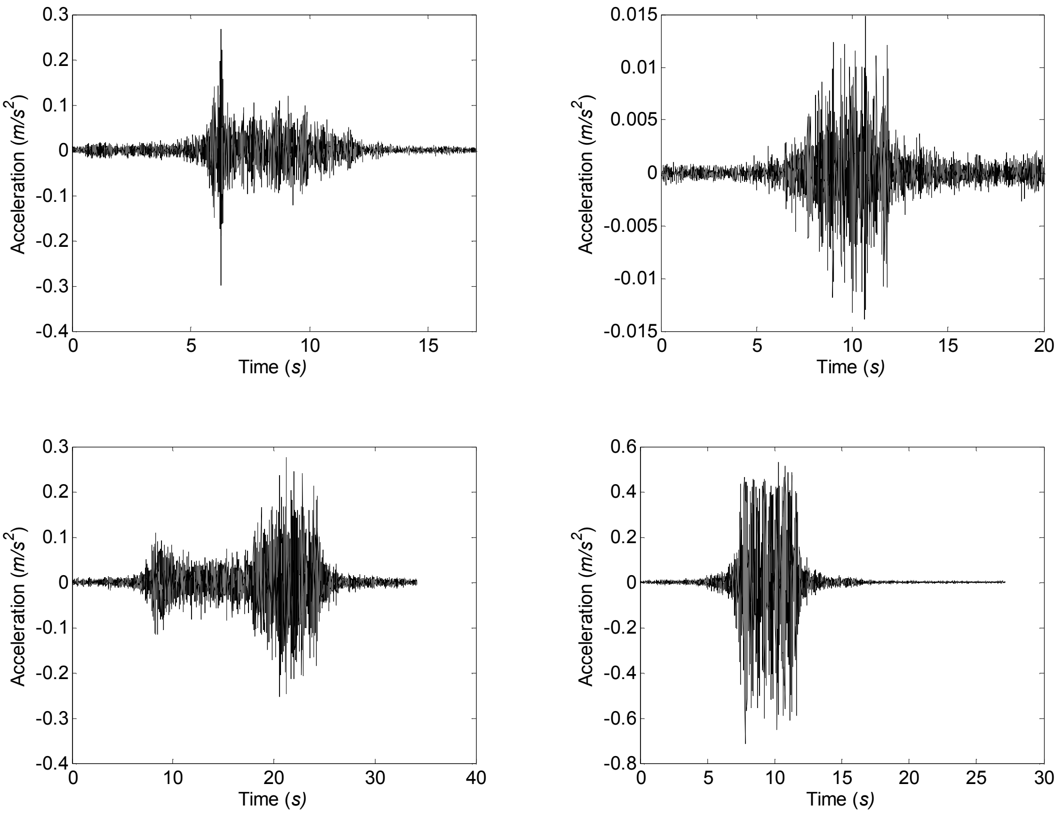


Figure 22 Examples of measured acceleration time histories of four railway events.

For each railway case study[4], vibration events were identified on the vertical axis of the data recorded at the long term external monitoring position (see Chapter 3 section 3.3.2) via a process based on a running short time average/long time average (STA/LTA) algorithm. The STA/LTA algorithm is a method of event identification commonly used in seismology to automatically identify periods of seismic activity (Havskov and Alguacil, 2004) and is

[4] A case study is defined as a completed social survey questionnaire along with a measurement of internal vibration

defined as the ratio between short-term and long-term running averages of time history data:

$$C_{trigger}(t) = \frac{\frac{1}{T_{STA}} \sum_{t-T_{STA}}^{t} \left|\ddot{x}(\tau)\right|^2}{\frac{1}{T_{LTA}} \sum_{t-T_{LTA}}^{t} \left|\ddot{x}(\tau)\right|^2}$$

Equation 12

Where $\ddot{x}$ is an acceleration time series, T_{STA} is the length of the short time window, and T_{LTA} is the length of the long time window.

The algorithm identifies an event when $C_{trigger}(t)$ exceeds a predetermined threshold. The determination of optimal values for T_{STA} and T_{LTA} is dependent on the type of events the algorithm is intended to detect and is somewhat a matter of trail and error. For the detection of railway events it has been found that the following parameter values are effective: T_{STA} = 1 *s*, T_{LTA} = 15 *s*, and a trigger threshold of 80%. Once an event has been identified by the algorithm, the period over which the event occurred is defined by the points at which the event is 10 *dB* below either side of the event maximum. Using the above T_{STA} and T_{LTA} parameters, the algorithm automatically rejects short transients such as single footfalls, however clusters of such transient signals are spuriously detected as an event. By assessing the crest factor of identified events, a proportion of these spurious events can be automatically rejected. Crest factor (x_{crest}) is defined as the ratio between the peak amplitude (x_{peak}) and RMS (x_{rms}) of a waveform:

$$x_{crest} = \frac{\left|x_{peak}\right|}{x_{rms}}$$

Equation 13

Short, highly impulsive signals will result in a high crest factor whereas waveforms with an amplitude envelope that evolves slowly with respect to time will exhibit a low crest factor. A vibration event due to train passage generally exhibits a crest factor of less than 10. By rejecting triggered events with a crest factor greater than 10 an improvement in the accuracy of the event identification algorithm can be achieved.

Figure 23 provides an illustration of how $C_{trigger}$ (black line) varies with respect to a measured acceleration time history (light grey line) over the duration of an internal snapshot measurement for one case study. In this case study, seven events have been identified by the algorithm. The inset plots in this figure show two of the identified time histories. It can be seen from this figure that the algorithm successfully identifies both low and high magnitude events. All events identified during an internal snapshot measurement can be verified as railway events by cross referencing the events identified by the triggering algorithm with the events logged on the measurement proforma by the operator conducting the measurement. As a final integrity check, each identified event was checked manually. Any spurious events or events overly contaminated with noise were excluded from further analysis, an example of such an event is shown in Figure 24.

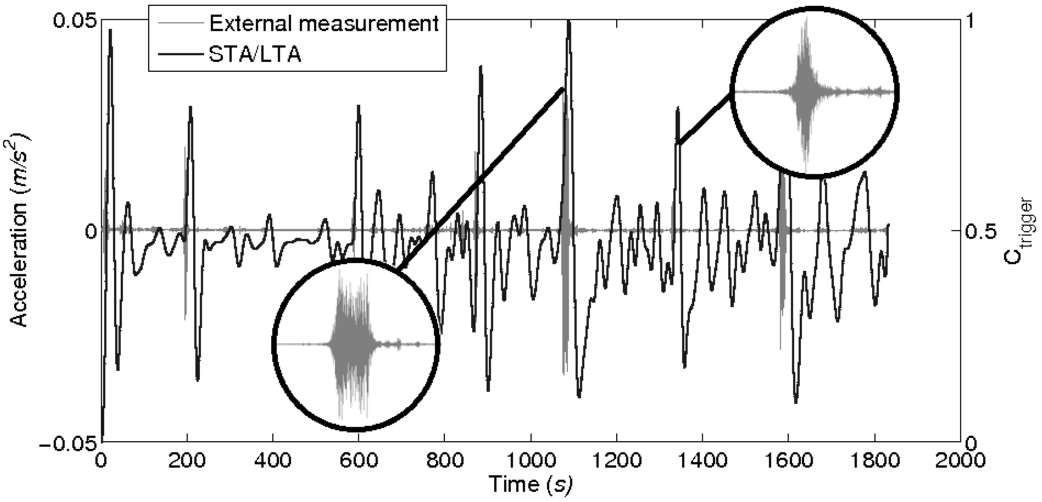


Figure 23 Example of how $C_{trigger}$ (black line) evolves over the course of a measured acceleration time history (light grey line). Inset plots show time histories of two identified railway events.

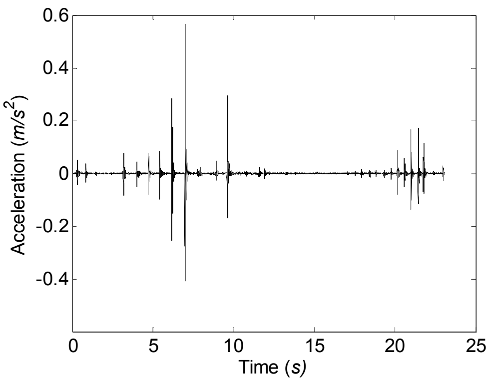


Figure 24 Example of a spurious event identified by the STA/LTA algorithm.

From the events identified from the synchronised internal and external measurement data, the transmissibility between each external measurement position and corresponding internal measurement position was determined. The acceleration time histories of events $[\ddot{x}(t)]$ were converted to the frequency domain by splitting the time record into Hanning windowed overlapping segments of duration T_{hann} and linearly averaging the magnitude Fourier spectra of these segments:

$$\ddot{X}(f,T_{hann}) = \int_0^T \ddot{x}(t,T_{hann}) \cdot w_{hann}(t,T_{hann}) \cdot e^{-j2\pi ft} dt$$ **Equation 14**

$$\ddot{X}(f) = \frac{2}{n_d T_{hann}} \sum_{i=1}^{n_d} \left| \ddot{X}(f,T_{hann}) \right|$$

where $\ddot{x}(t,T_{hann})$ is a windowed segment of the acceleration time history, $w_{hann}(t,T_{hann})$ is a Hanning window function, T_{hann} is the length of the segment, $\ddot{X}(f,T_{hann})$ is the Fourier transform of $\ddot{x}(t,T_{hann})$, and n_d is the number of windowed segments.

For an acceleration time history $\ddot{x}(t)$ of finite length, the choice of the segment length T_{hann} influences the random error associated with $\ddot{X}(f)$, the frequency resolution and lowest reliable frequency component of $\ddot{X}(f)$. If railway induced vibration is assumed to be a stationary random process, the normalised RMS random error associated with this analysis is inversely proportional to the square root of the number of averages n_d (Bendat and Piersol, 1971):

$$\varepsilon\left[\ddot{X}(f)\right] = \frac{1}{\sqrt{n_d}}$$ **Equation 15**

The number of averages is a function of the length of the time record $\ddot{x}(t)$, the length of the windowed segments T_{hann}, and the proportion of overlap in the windowed segments. From all events identified from the 24-hour external measurement data, the average duration of an event is 7 *s* (standard deviation 5 *s*, N = 14143) which equates to around 10 averages per event. On average, five synchronised internal and external events were available for each case study. If a 256 point segment length with an overlap of 128 points is used, according to Equation 15, this equates to a standard RMS error of around 13% or 1.1 *dB*. For a 256 point segment length, the lowest frequency at which the length of a full cycle is less than the window length is 0.78 *Hz*. Below this frequency, estimates of $\ddot{X}(f)$ will be highly unreliable. It will be shown in following sections that in the measured data the vibration energy in this frequency region would be imperceptible to human subjects. Therefore, in the frequency analyses reported in this chapter, a 256 point Hanning window is used with 50% overlap.

For each identified event for each case study, the transmissibility between the two measurement positions was determined as follows:

$$H_{event}(f) = \frac{\left|\ddot{X}_{\mathrm{int}}(f)\right|}{\left|\ddot{X}_{ext}(f)\right|}$$

Equation 16

where $\ddot{X}_{\mathrm{int}}(f)$ is the averaged magnitude Fourier spectrum of an internal event, $\ddot{X}_{ext}(f)$ is the averaged magnitude Fourier spectrum of an external event.

Due to the low coherence observed between the external and internal measurement positions the magnitude only transfer function *H* was used rather than cross-spectra transfer function methods such as *H1* and *H2*. The errors inherent in applying these different transfer function methods to this dataset have been explored by Sica et al. (2012a). In this study the transmissibility method was compared with cross-spectra transfer function methods in terms of the relative error associated with the estimation of 24-hour internal vibration. It was found that the magnitude only transfer function *H* resulted in a relative error of around 10%; the *H1* transfer function resulted in an underestimation of around

50% and the *H2* transfer function resulted in an overestimation of around 250%. These findings are mainly attributed to the relatively low coherence generally found between the external and internal measurement positions.

An average transmissibility was then calculated for each case study by linearly averaging the transmissibilities calculated for each individual event:

$$H_{ave}(f) = \frac{1}{n_e} \sum_{i=1}^{n_e} H_{event}(f)$$ **Equation 17**

Using this method, an external-to-internal transmissibility for each of the three measured orthogonal directions was calculated for 497 of the 523 case studies. Transmissibilities could not be calculated for the remaining 26 case studies due to either data corruption or excessive noise present on the data recorded at the internal measurement position.

In order to predict internal vibration exposure, the average transmissibility for a case study was interpolated to the length of each individual event identified in the 24-hour acceleration time history recorded at the external position. The interpolated averaged transmissibility was then applied to the complex Fourier spectrum of the event:

$$\ddot{X}_{pred}(f) = H_{ave}(f) \cdot \ddot{X}_{ext}(f)$$ **Equation 18**

Where $\left|\ddot{X}_{pred}(f)\right|$ is the predicted complex Fourier spectrum of an internal event, H_{ave} is the average interpolated velocity ratio calculated for a particular case study, and $\left|\ddot{X}_{ext}(f)\right|$ is the complex Fourier spectrum of an event measured at the external measurement position.

As the predicted spectrum $\ddot{X}_{pred}(f)$ takes on the phase of $\ddot{X}_{ext}(f)$, it can be inverse Fourier transformed to provide an estimation of the internal vibration exposure in the time domain. As the propagation of ground vibration is a dispersive phenomenon, phase errors will be introduced using this method. It is however necessary that a time domain estimate of internal vibration exposure be arrived at as many of the single figure descriptors of vibration exposure used for the evaluation of human response require time domain data for their calculation (see section 2.3.3). This process was conducted for every event identified during a 24-hour period at each external measurement position to build up an estimation of the 24-hour internal vibration exposure for each case study.

In cases where a snapshot measurement of internal vibration was either not conducted or unavailable due to data corruption, the internal vibration exposure was used from a similar type of property which was in the same measurement area and a similar distance from the vibration source. Using these methods, it was possible to estimate 24-hour internal vibration exposure in 752 of the 931 properties in which a resident had taken part in a social survey questionnaire. 497 of these estimations were based on the transmissibility method and 255 were based on estimations of internal vibration in a similar property type.

Figure 25, Figure 26, and Figure 27 provide comparisons between measured internal vibration events and predictions of said events using the method detailed above at different distances of separation between the internal and external measurement positions. The vibration events shown in these figures were not used in the calculation of the average transmissibilities. These figures suggest that there is good agreement between the measured and predicted events. To provide an indication of the uncertainties associated with calculating internal vibration exposure with respect to human response using this method, internal vertical vibration events were predicted for the 2831 events measured at the 523 internal measurement positions. Values of weighted RMS acceleration, VDV, and peak acceleration (see section 2.3.3) were determined for the measured and predicted internal events. These descriptors were calculated to provide indications of the total energy and the integrity of the recovered waveform of the predicted internal vibration events. The mean relative error between the measured and predicted internal events was 18% for RMS acceleration, 24% for VDV, and 29% for peak acceleration. If the events measured at the external measurement position were taken as being representative of internal vibration exposure (i.e. if the transmissibility between the internal and external position had not been determined), the mean relative error for weighted RMS acceleration, VDV, and peak acceleration would be 282%, 327%, and 324% respectively.

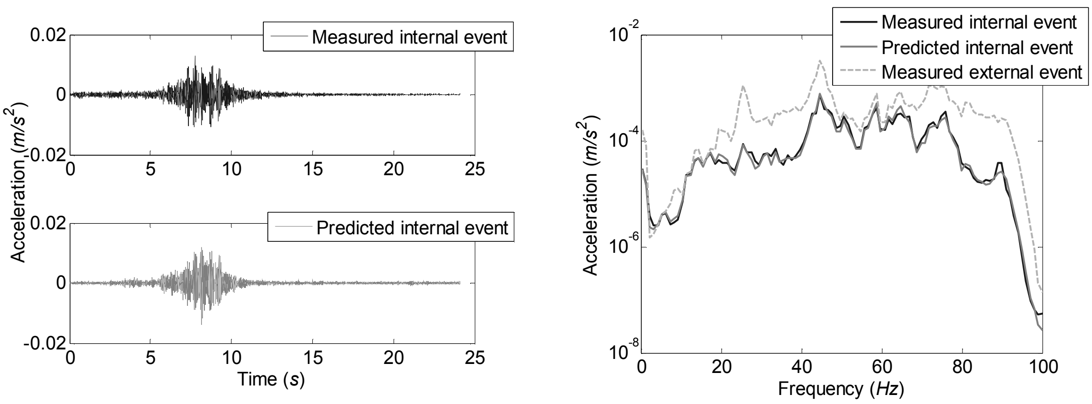


Figure 25 Measured and predicted internal vibration event, approximately 10 *m* separation between internal and external measurement position.

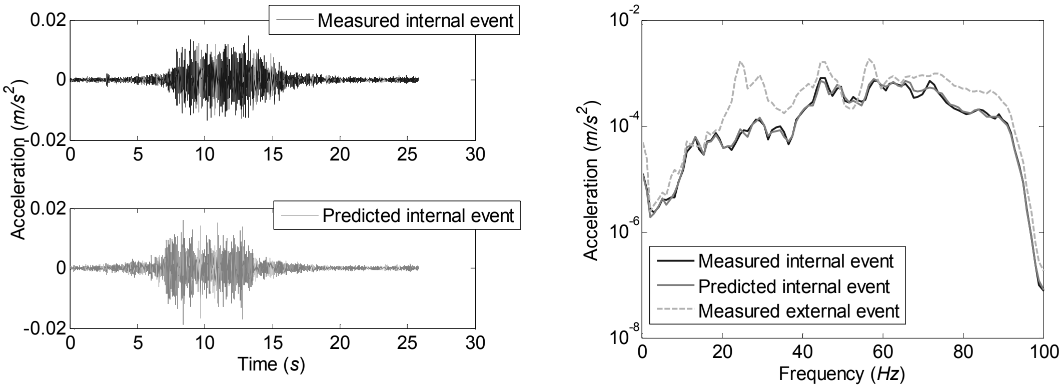


Figure 26 Measured and predicted internal vibration event, approximately 50 *m* separation between internal and external measurement position.

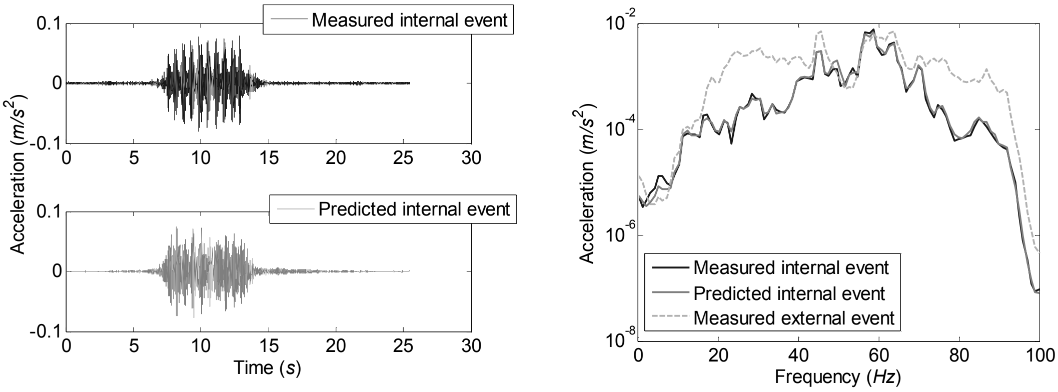


Figure 27 Measured and predicted internal vibration event, approximately 50 *m* separation between internal and external measurement position.

A comparison between 24-hour vibration exposures estimated at internal positions and the exposure calculated at the corresponding control position is provided in Figure 28. The scatter evident in this figure suggests that if only the external measurements had been conducted, internal vibration exposure would have been in some cases under- and some cases over- estimated.

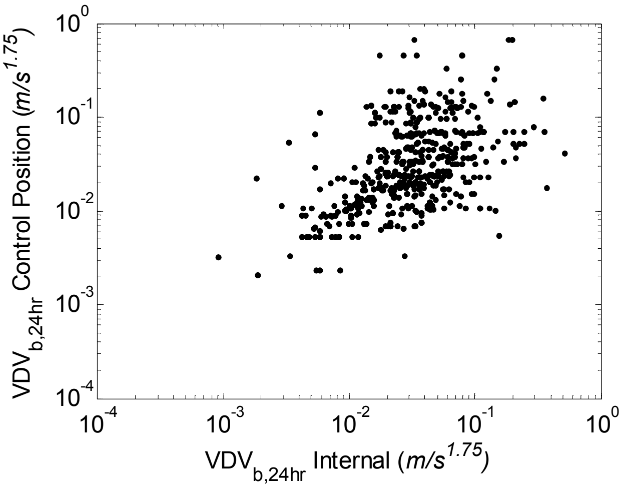


Figure 28 Comparison of 24-hour vibration exposure estimated at internal positions compared to 24-hour vibration exposure at corresponding control positions.

4.2.2 Estimation of construction induced internal vibration exposure

The methods by which vibration exposure were estimated for construction sources are detailed in Sica et al. (2012b). From the controlled array measurement described in section 3.3.3, semi-empirical relationships for ground attenuation were derived for each measurement site using the Bornitz equation (Woods, 1997):

EQUATION 19

$$A(d) = A_0 \left(\frac{d_0}{d} \right)^n e^{-\alpha(d - d_0)}$$

where *A* is the magnitude of acceleration to be predicted at distance *d*, A_0 is the measured magnitude of vibration at distance d_0, and *n* and α are the geometrical attenuation parameter and material damping parameter to be estimated respectively.

The parameter *n* requires an assumption as to the predominant wave type in the ground. As it is assumed that measurements were conducted outside of the near field of the source, Rayleigh waves are assumed to be the dominant wave type. For Rayleigh waves, *n* takes on a value of ½. The value of *a* is estimated by regressing the measured parameters of interest against distance.

Using the data measured in the controlled experiments described in section 3.3.3, estimates of α were determined for each measurement site. Values of α estimated in the 4 *Hz* to 64 *Hz* octave bands for the two measurement sites used in the study are provided in Table 9. According to (Woods, 1997), these values of α are what one might expect for "*competent soils*" which are described as sand, sandy clay, silty clay, gravel, silt, and weathered rock. According to the British Geological Survey, the superficial geology of the measurement sites is made up of clay, silt, sand, and gravel which suggests that the estimates of α are what might be expected for this type of soil.

	4 Hz	8 Hz	16 Hz	32 Hz	64 Hz
α Site I	0.0098	0.0254	0.0151	0.0676	0.1200
α Site II	0.0043	0.0156	0.0313	0.0527	0.0610

Table 9 Values of α estimated in the 4 *Hz* to 64 *Hz* octave bands for the two measurement sites.

The estimated ground attenuation relationships were then used to propagate the vibration exposure measured at the long term measurement position, A_0, to the distance of the respondent's properties from the vibration source. The unweighted peak acceleration measured at the long term measurement positions was 0.63 and 0.46. Attenuation relationships were determined for weighted and unweighted vertical RMS acceleration, vibration dose value, peak particle acceleration, and RMQ acceleration. Using this method, vibration exposure was estimated for 321 of the 350 respondents who had taken part in the social survey questionnaire.

4.3 Selection of vibration exposure descriptor

As highlighted in Chapter 2, there is currently no consensus as to which is the most appropriate single figure descriptor to quantify vibration exposure in terms of human response. One of the main considerations in the formulation of exposure-response relationships is the single figure descriptor of vibration exposure which will be used as the independent variable in the relationship. The two main considerations which go into the formulation of this descriptor are the method by which the measured vibration time history is represented as a single value and which, if any, frequency weighting (see section 2.3.3) is applied.

4.3.1 Single figure descriptors

The review of national and international standards and guidance documents provided in section 2.3.4 revealed three main types of vibration exposure descriptors which are advocated in these documents for the assessment of human response: energy equivalent RMS type descriptors, maximum running RMS values, and the Vibration Dose Value used in the United Kingdom. For energy equivalent type descriptors, the question also arises as to whether this descriptor is assessed only when vibration events are occurring or over the entire 24-hour evaluation period.

A variety of single figure descriptors of vibration exposure were calculated for the case studies in which estimations of internal acceleration time histories were derived (see section 4.2.1). The analyses presented in this section were limited to the case studies for railway sources of vibration. As vibration exposure for the construction vibration dataset was based upon predictions derived from attenuation curves, any correlation between these predictions and human response will be dominated by the distance from the source rather than objective features of the vibration exposure. This suggests that the dataset of construction vibration is unsuitable for the evaluation of different vibration exposure descriptors.

Table 10 provides a summary of the single figure descriptors calculated from the 497 estimates of 24-hour internal vibration from railway activities. These descriptors were calculated for each case study based on the estimated internal vibration of all train events during a 24-hour period. Additional to the descriptors presented in Table 10, 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentiles of the estimated 24-hour internal acceleration time histories were also calculated. Figure 29 shows an example of a distribution of an estimated internal acceleration time history of all train events identified during a 24-hour period along with how the various descriptors shown in Table 10 relate to this distribution. This figure indicates that the descriptors considered in this section cover the whole range of the distribution of internal vibration exposure from railway induced vibration.

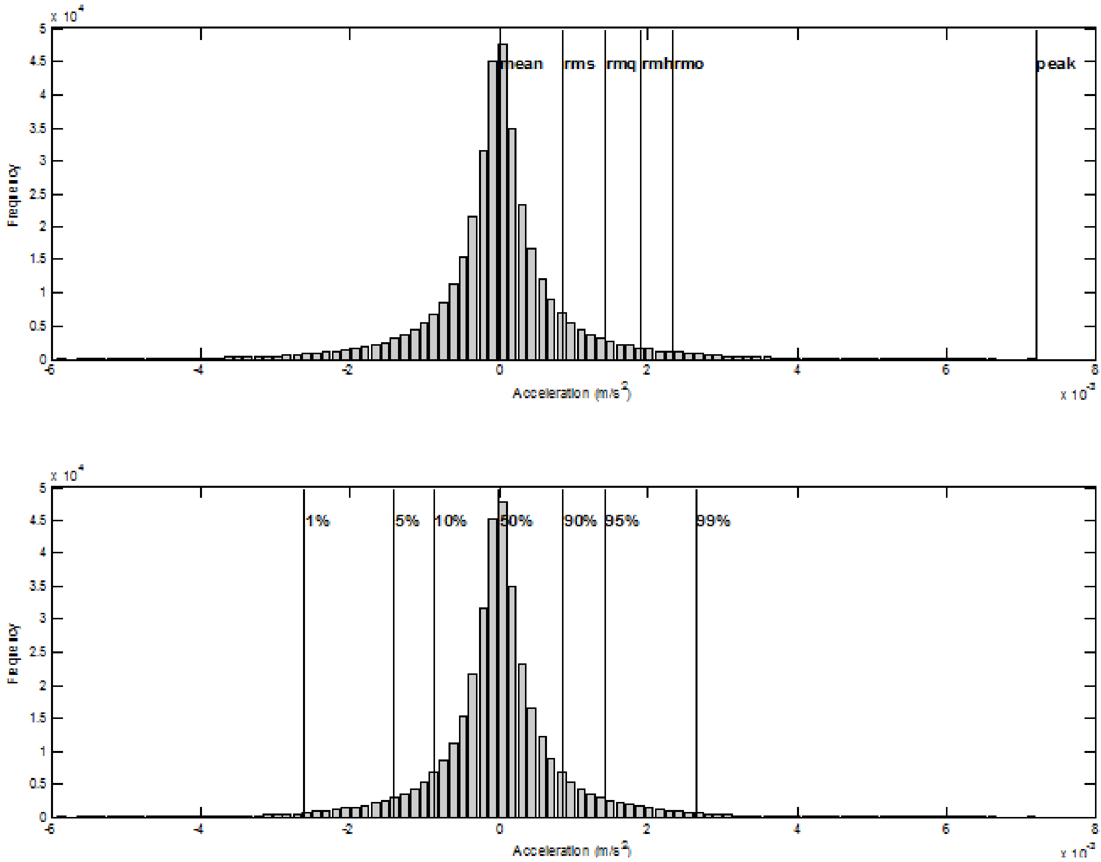


Figure 29 Distribution of acceleration time histories of all estimated internal railway events in a 24-hour period.

DESCRIPTOR	DESCRIPTOR TYPE	CALCULATION
ROOT MEAN SQUARE (M/S^2)	ENERGY AVERAGE	$\ddot{x}_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^2}$
ROOT MEAN QUAD (M/S^2)	ENERGY AVERAGE	$\ddot{x}_{rmq} = \sqrt[4]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$
ROOT MEAN HEX (M/S^2)	ENERGY AVERAGE	$\ddot{x}_{rmh} = \sqrt[6]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^6}$
ROOT MEAN OCT (M/S^2)	ENERGY AVERAGE	$\ddot{x}_{rmo} = \sqrt[8]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^8}$
VIBRATION DOSE VALUE ($M/S^{1.75}$)	CUMULATIVE DOSE	$\ddot{x}_{VDV} = \sqrt[4]{\frac{T}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$
MEAN (M/S^2)	STATISTICAL	$\overline{x} = \frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)$
STANDARD DEVIATION	STATISTICAL	$\sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\ddot{x}(n)-\overline{x})^2}$

DESCRIPTOR	DESCRIPTOR TYPE	CALCULATION
SKEWNESS	STATISTICAL	$S_k = \frac{1}{N \cdot \sigma^3} \sum_{n=1}^{N} (\ddot{x}(n) - \overline{x})^3$
KURTOSIS	STATISTICAL	$K_t = \frac{1}{N \cdot \sigma^4} \sum_{n=1}^{N} (\ddot{x}(n) - \overline{x})^4$
PEAK PARTICLE ACCELERATION (*M/S^2*)	MAXIMUM	MAXIMUM DEVIATION OF THE TIME SERIES FROM THE MEAN
L_{MAX} (*DB RE $1X10^{-6}$ M/S^2*)	RUNNING RMS	MAXIMUM 1 SECOND RUNNING AVERAGE *RMS* OVER AN EVENT
L_{EQ} (*DB RE $1X10^{-6}$ M/S^2*)	ENERGY AVERAGE	$L_{eq} = 20\log_{10}\left(\frac{\ddot{x}_{rms}}{1E-6}\right)$
L_E (*DB RE $1X10^{-6}$ M/S^2*)	ENERGY AVERAGE	$L_E = 20\log_{10}\left(\frac{\ddot{x}_{rms}}{1E-6}\right) + 10\log_{10}(T)$

Table 10 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.

To investigate the relationship between the different descriptors, a principal component analysis was carried out on a matrix of the calculated descriptors. Principal component analysis is a multivariate data analysis technique which can be used for the exploratory analysis of the relationships between a set of variables. Figure 30 shows the amount of variance explained by each of the computed principal components. It can be seen from this figure that more than 75% of the variance in the descriptor space is accounted for by the first principal component. Figure 31 shows the principal component coefficients for each of the calculated descriptors for the first two principal components. These coefficients indicate the weighting each descriptor has on the calculated principal components. 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. This result indicates that there is a high degree of correlation between the vibration exposure descriptors considered in this section.

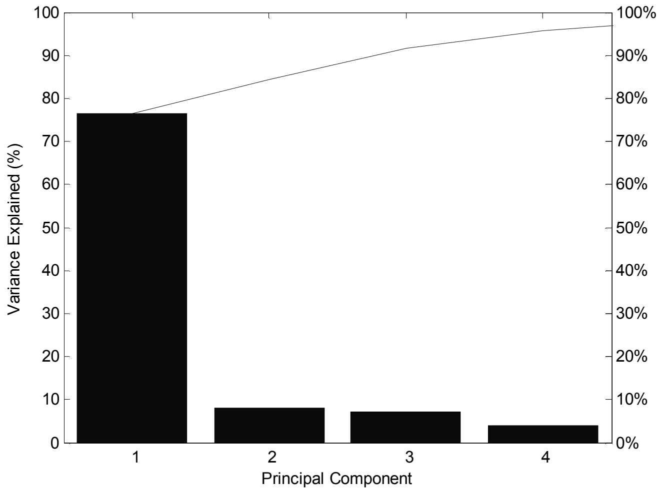


Figure 30 Scree plot showing the percentage of variance explained by each principal component.

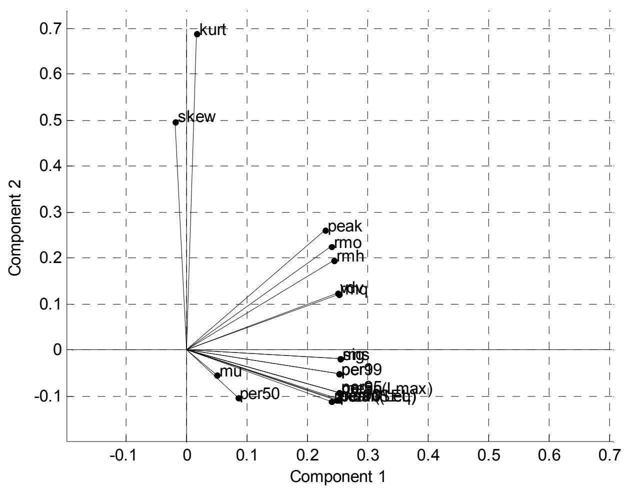


Figure 31 Principal component coefficients for each of the calculated vibration exposure descriptors.

This finding can be verified by examining the correlation between the different vibration exposure descriptors and self reported annoyance measured in the social survey questionnaire. These correlations were assessed using Spearman's rank correlation coefficient on both the 5-point semantic and 11-point numerical annoyance response scales. It can be seen from Table 11 that, excluding skewness, kurtosis, and mean, each of the vibration exposure descriptors considered exhibits a similar magnitude of correlation with self reported annoyance. Although the magnitude of correlation is low, each of the correlations presented in Table 11 are statistically significant to the 0.05 level and some to the 0.01 level. This coupling of low correlation and high statistical significance suggests that a marginal ordinal relationship exists between descriptors of unweighted vibration exposure and annoyance. The statistical significance of these relationships is an indication that a large enough sample size was achieved to detect these relationships. It should be noted that the Spearman's correlation coefficients presented in this section are only an indication of the presence of ordinal relationships between vibration exposure and annoyance on an individual level. As exposure-response relationships are generally derived using aggregated data (see section 2.4), the magnitude of these correlations do not necessarily reflect the statistical strength of the exposure-response relationships presented later in this thesis. These results suggest that, for the dataset of railway induced vibration under analysis, the single figure descriptors considered in this section are equally effective predictors of annoyance. These results are consistent with the findings of Zapfe et al. (2009).

Descriptor	**5-point scale**	**11-point scale**
ROOT MEAN SQUARE (*M/S^2*)	0.08*	0.09*
ROOT MEAN QUAD (*M/S^2*)	0.09*	0.08*
ROOT MEAN HEX (*M/S^2*)	0.10**	0.09*
ROOT MEAN OCT (*M/S^2*)	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 11 Spearman's correlation coefficient between different descriptors of 24-hour vibration exposure and self reported annoyance (N = 752). * p<0.05, ** p<0.01, -- not significant.

4.3.2 *FREQUENCY WEIGHTING AND DIRECTION OF EXCITATION*

As highlighted in Chapter 2, the human perception of whole body vibration is frequency dependent and this frequency dependency differs with the direction of excitation. Frequency weightings designed to account for this dependency are defined in a number of national and international standards. These frequency weightings are however not consistent across the available standards (see section 2.3.4). In order to assess the effectiveness of different frequency weightings, it should first be determined if there is sufficient range and variance in perceptible vibration exposures at different frequencies in the dataset under analysis. Figure 32 shows boxplots of the distribution of peak acceleration in each 1/3 octave band for 752 estimates of 24-hour internal vibration exposure in the vertical (left pane) and horizontal (right pane) directions. In these plots, the median value of peak acceleration in each 1/3 octave band is represented by a dot, the upper and lower quartile values by the extent of the thick lines, and outliers by circle markers. It can be seen from these figures that each 1/3 octave band exhibits a dynamic range in the order of 40 *dB*. These magnitudes are also compared to the perception threshold base curves provided in the (now superseded) 1992 version of BS 6472-1. The base curves presented in these figures are derived from laboratory studies and are intended to represent the magnitude of peak acceleration which will be just perceptible to 50 % of healthy human subjects. It can be seen from the left pane of Figure 32 that at frequencies above around 8 *Hz* the median peak vibration exposures in the vertical direction fall approximately on the perception base curve. For vibration exposure in the horizontal direction however, it can be seen that the median peak exposures are around an order of magnitude below the base curve.

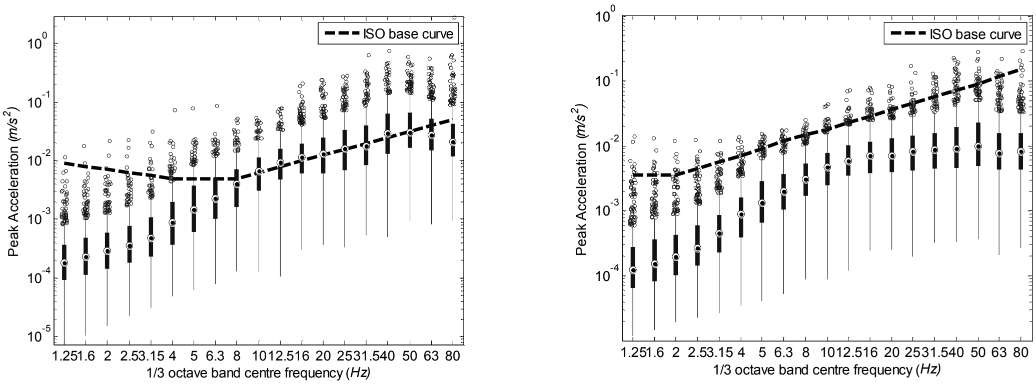


Figure 32 Boxplots illustrating the distribution of peak acceleration in 1/3 octave bands in the vertical (left pane) and horizontal (right pane) directions for 752 estimations of internal vibration exposure. Also shown are the vibration perception base curves from (the now superseded) BS 6472-1:1992.

There is some discrepancy between national standards regarding the direction of vibration to be assessed with regards to human response. BS6472-1:2008 suggests that if the magnitude of vibration is clearly dominant in one axis, only the direction with the highest magnitude need be considered. BS ISO 2631-1:1997 on the other hand suggests that vibration exposure be expressed as a vector sum of the weighted *RMS* acceleration measured in three orthogonal directions. In Figure 33, 24-hour vibration dose values in the vertical direction are compared with a vector sum of the vibration dose values calculated for the three measured directions. This figure indicates that the vibration in the vertical direction dominates the dataset and that including the horizontal components has almost no influence on the estimated 24-hour vibration exposure. Therefore, assuming a geo-centric coordinate system (see section 2.3.2) and considering that the horizontal vibration exposures shown in Figure 32 are an order of magnitude below the vibration perception base curve, vibration exposure in the remainder of this thesis will be considered only in the vertical direction. One of the main justifications of a geo-centric coordinate system is that the orientation of the subject is unknown. If an assumption regarding the orientation of the subject can be made, a recumbent position during the night for example, then a basi-centric coordinate system may be more appropriate and the horizontal components should be considered.

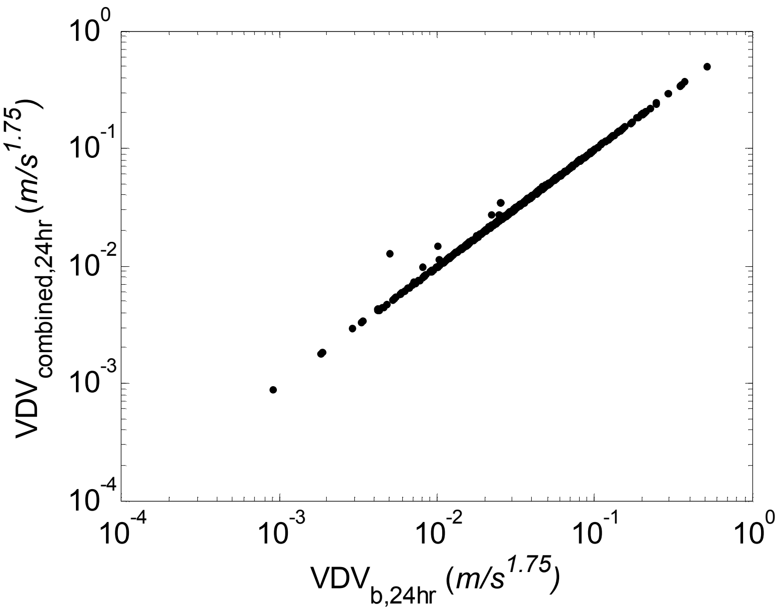


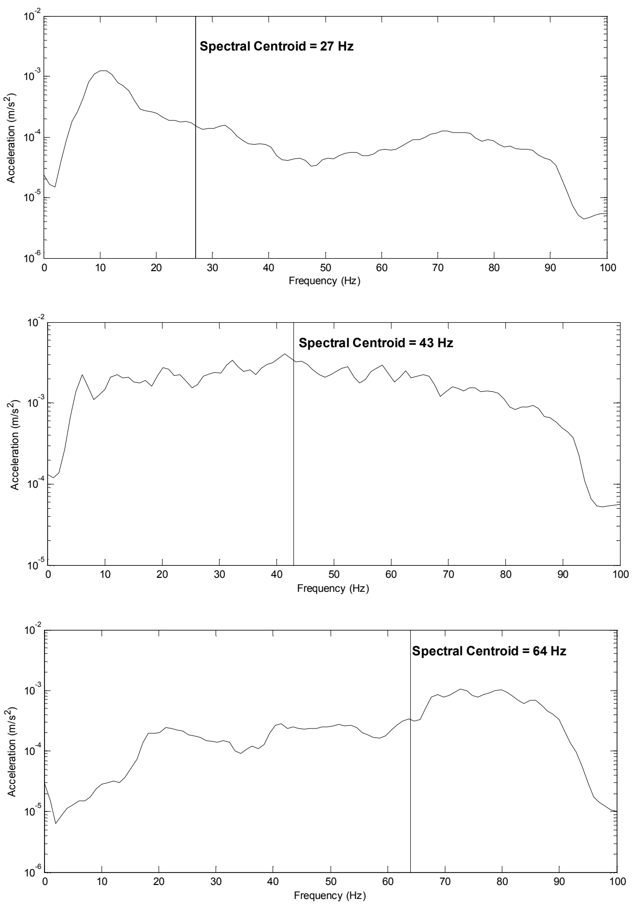
Figure 33 Comparison of vibration dose value of the vertical and combined components.

To determine the variability in the frequency content of vibration to which respondents were exposed, spectral centroid was calculated for the 497 estimations of internal vibration which were predicted via the transmissibility method detailed in section 4.2.1. Spectral centroid is a single figure measure of the distribution of spectral energy; higher values of spectral centroid indicate that energy is concentrated in the high frequency components of the spectrum and whereas lower values indicate energy is concentrated in the low frequency components of the spectrum. Spectral centroid is calculated using 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 20**

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 28 provides examples of magnitude the Fourier spectra of estimated 24-hour internal vibration with different values of spectral centroid.



a) b) c)

Figure 34 Magnitude Fourier spectrum of 24-hour internal vibration exhibiting spectral centroid values of a) 27 Hz, b) 43 Hz, and c) 64 Hz.

Figure 35 shows the distribution of spectral centroid values for the 497 estimations of 24-hour railway induced vibration in the vertical direction. The broad spread in spectral centroid values indicates that respondents were exposed to excitations with a range of different spectral content. This result, along with the wide dynamic range of vibration exposures in each 1/3 octave band, suggests that there may be sufficient variance in the frequency content of vibration exposures in the dataset to investigate and draw conclusions regarding the effectiveness of different frequency weightings with respect to human response.

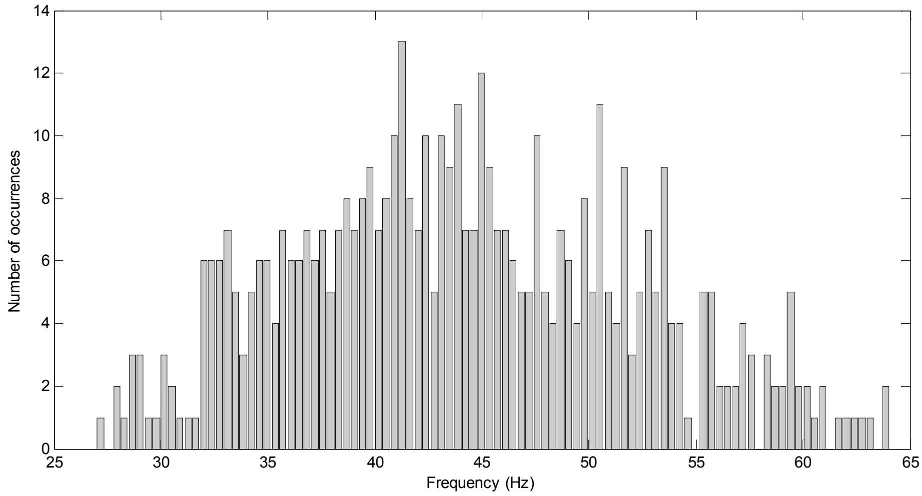


Figure 35 Distribution of spectral centroid for 497 estimations of internal vibration exposure in the vertical direction.

To investigate the effectiveness of the different frequency weightings recommended in different national and international standards, the Spearman's rank correlation coefficient was calculated between self reported annoyance and vibration exposure expressed in terms of *RMS* in the vertical and horizontal directions for acceleration, velocity, and using the appropriate frequency weightings defined in BS 6472-1:2008, BS ISO 2631-1:1997, and ISO 2631-2:2003 (see section 2.3.4).

These frequency weightings were realized by means of digital infinite impulse response (IIR) filters (Rimell and Mansfield, 2007), the coefficients of which are defined in BS 6841:1987 and BS EN ISO 8041:2005. To determine that the weighting filters were implemented correctly, the magnitude frequency responses of the filters were compared to the asymptotic approximations of the frequency weightings provided in the relevant standards. It can be seen from Figure 36 that the IIR implementation of the W_b weighting filter agrees well with the asymptotic approximation provided in BS 6472-1:2008. Similar results were observed for all the implemented weighting filters.

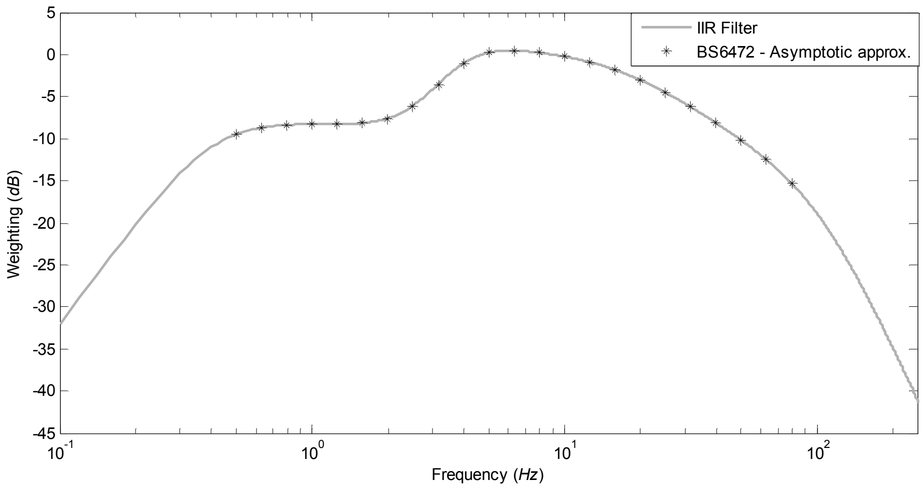


Figure 36 Magnitude frequency response of the IIR implementation of the W_b weighting filter compared with the asymptotic approximation presented in BS6472-1:2008.

As a number of the single figure descriptors defined in national and international standards are calculated from time domain data, it is important that the weighting filters do not introduce a significant amount of phase distortion. Figure 37 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 phase response is similar to the phase tolerances required by BS EN ISO 8041:2005.

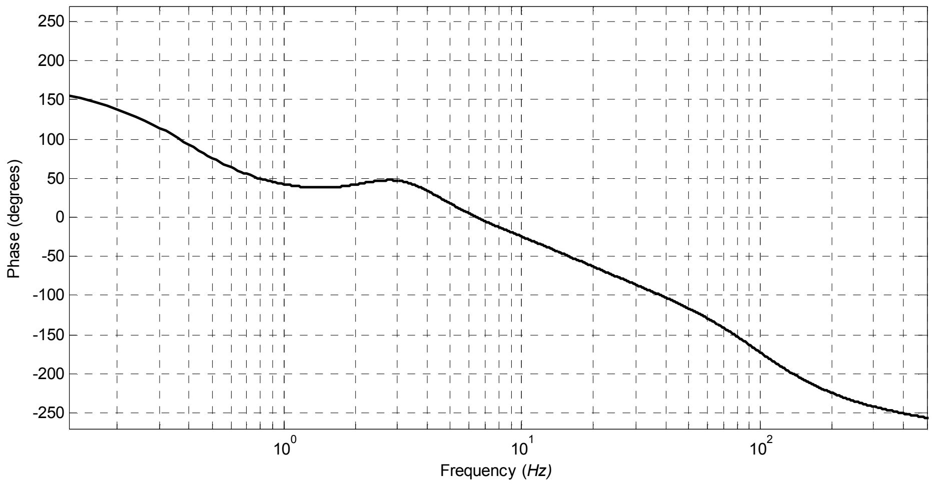


Figure 37 Phase response of the IIR implementation of the W_b weighting filter.

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

$$\dot{X}(f) = \frac{\ddot{X}(f)}{j\omega} \qquad \textbf{EQUATION 21}$$

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 12 presents the Spearman's rank correlation coefficients between annoyance ratings measured on the two response 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 the magnitude and significance of correlation can be achieved when the appropriate frequency weightings are applied. Similarly, expressing vibration exposure in terms of velocity results in a higher correlation than if the exposure is expressed in terms of unweighted acceleration; this result is expected as, for vibration in the vertical direction, the frequency weighting curves approximate velocity at frequencies above around 16 *Hz*.

	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 ***

Table 12 Spearman's correlation coefficient between frequency weighted *RMS* vibration exposure and self reported annoyance (N = 752). * p<0.05, ** p<0.01, *** p< 0.001.

4.3.3 OTHER FACTORS CONSIDERED

Additional to the single figure descriptors of vibration exposure detailed in the previous sections, a number of other factors were considered as correlates to self reported annoyance. The mean and maximum duration (*s*) of all train passes defined by their 10 *dB* down points in a 24-hour period were calculated for each case study. 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 (ϱ = -0.08, $p < 0.05$ for the five-point scale and ϱ = -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 10).

4.4 ASSESSMENT ACCORDING TO NATIONAL AND INTERNATIONAL STANDARDS

The results of the analyses detailed in section 4.3.1 demonstrated that, for the dataset of railway vibration under analysis, the form of the single figure descriptor of vibration exposure is largely unimportant. In Chapter 2 it was highlighted that due to the different methods of assessment of vibration exposure with respect to human response between different countries, the results of studies into the human response to vibration are difficult to compare. As none of the single figure descriptors considered emerged as a superior predictor of self reported annoyance, 24-hour internal vibration exposure was calculated following guidance from all major national and international standards. Table 13 provides a summary of the assessment methods provided in each of these standards along with the Spearman's correlation coefficient between each of the descriptors and annoyance measured on the 5-point semantic scale. Although a number of assessment methods recommend using a vector sum of vibration exposure measured in three orthogonal directions, the metrics detailed in this table are all based on vertical vibration due to the dominance of this component in the dataset under analysis (see section 4.3.2, Figure 33).

Descriptor	**Standard (Country)**	**Measured quantity**	**Frequency Weighting**	**Description**	**Correlation with annoyance**
RMS Passby	BS ISO 2631-1:1997 (International)	Acceleration (m/s^2)	W_k	Energy equivalent RMS acceleration over all train events	0.13***
RMS 24 hour	BS ISO 2631-1:1997 (International)	Acceleration (m/s^2)	W_k	Energy equivalent RMS acceleration over the entire 24-hour assessment period	0.16***

Descriptor	Standard (Country)	Measured quantity	Frequency Weighting	Description	Correlation with annoyance
RMS Passby	ISO 2631-2:2003 (International)	Acceleration (m/s^2)	W_m	Energy equivalent RMS acceleration over all train events	0.14***
RMS 24 hour	ISO 2631-2:2003 (International)	Acceleration (m/s^2)	W_m	Energy equivalent RMS acceleration over the entire 24-hour assessment period	0.17***
Maximum Transient Vibration Value (MTVV)	BS ISO 2631-1:1997 (International)	Acceleration (m/s^2)	W_k	Maximum 1 second running RMS value in a 24-hour period	0.14***
Maximum Transient Vibration Value (MTVV)	BS ISO 2631-1:1997 (International)	Acceleration (m/s^2)	W_m	Maximum 1 second running RMS value in a 24-hour period	0.15***
Vibration Dose Value	BS ISO 2631-1:1997 (International)	Acceleration (m/s^2)	W_k	Fourth root of the fourth power integration over 24-hours	0.14***
Vibration Dose Value	ISO 2631-2:2003 (International)	Acceleration (m/s^2)	W_m	Fourth root of the fourth power integration over 24-hours	0.14***
KB_{FMax}	DIN 4150-2:1999 (Germany)	Velocity	KB	Maximum 0.125 second running RMS in a 24-hour period	0.16***

Descriptor	**Standard (Country)**	**Measured quantity**	**Frequency Weighting**	**Description**	**Correlation with annoyance**
KB_{FTm}	DIN 4150-2:1999 (Germany)	Velocity	KB	Average of maximum 0.125 second running RMS in each 30 second period over 24-hours	0.12**
V_{max}	SBR Richtlijn – Deel B:2002 (Netherlands)	Velocity (mm/s)	KB	Maximum 0.125 second running RMS in a 24-hour period	0.16***
V_{per}	SBR Richtlijn – Deel B:2002 (Netherlands)	Velocity (mm/s)	KB	Average of maximum 0.125 second running RMS in each 30 second period over 24-hours	0.12**
$v_{w,95}$	NS 8176:2005 (Norway)	Velocity (mm/s)	W_m	Statistical maximum	0.13***
$a_{w,95}$	NS 8176:2005 (Norway)	Acceleration (m/s^2)	W_m	Statistical maximum	0.14***
L_{aw}	SS 460 48 61:1992, UNI 9641:1990 , Real Decreto 1367/2007 (Sweden, Italy, Spain respectively)	Acceleration (m/s^2)	W_m	Maximum 1 second running RMS in a 24-hour period	0.15***
L_{vw}	SS 460 48 61:1992 (Sweden)	Velocity (mm/s)	W_m	Maximum 1 second running RMS in a 24-hour period	0.15***
L_v	Japanese Vibration Regulation Law	Acceleration (m/s^2)	W_k	Maximum 0.63 second running RMS in a 24-hour period	0.14***

Descriptor	Standard (Country)	Measured quantity	Frequency Weighting	Description	Correlation with annoyance
V_{dB}	FTA guidelines (USA)	Velocity (µinch/s)	None	Maximum 1 second running RMS in a 24-hour period	0.15***
Vibration Dose Value	BS 6472-1:2008 (United Kingdom)	Acceleration (m/s^2)	W_b	Fourth root of the fourth power integration over 24-hours	0.13***
Vibration Dose Value	BS 6472-1:1992 (Superseded) (United Kingdom)	Acceleration (m/s^2)	W_g	Fourth root of the fourth power integration over 24-hours	0.16***
RMS 24 hour	BS 6472-1:1992 (Superseded) (United Kingdom)	Acceleration (m/s^2)	W_g	Energy equivalent RMS acceleration over the entire 24-hour assessment period	0.16***
RMS Passby	BS 6472-1:1992 (Superseded) (United Kingdom)	Acceleration (m/s^2)	W_g	Energy equivalent RMS acceleration over all train events	0.14***

Table 13 Spearman's rank correlation between annoyance and vibration exposure assessed according to a variety of national and international standards (N=752) ** p<0.01, *** p< 0.001

4.5 SUMMARY

This chapter has detailed how single figure estimates of 24-hour internal vibration exposure were calculated from the vibration data collected via the field survey detailed in Chapter 3. An investigation into the most appropriate single figure descriptor of vibration exposure with respect to human response revealed that, for the railway dataset under analysis, none of the evaluated descriptors could be identified as the superior predictor of annoyance. Use of appropriate frequency weightings was found to lead to an improvement in correlation between vibration exposure and self-reported annoyance. The following chapter details the formulation of exposure-response relationships from the social survey and vibration exposure data. Considering the similar degree of correlation between self reported annoyance and vibration exposure expressed according to different assessment methods and the general difficulty in comparing results between social surveys into the human response to vibration in residential environments, relationships will be presented in the next chapter according to all available national and international guidance.

CHAPTER 5

DETERMINATION OF EXPOSURE-RESPONSE RELATIONSHIPS

5 DETERMINATION OF EXPOSURE-RESPONSE RELATIONSHIPS

5.1 INTRODUCTION

The previous chapter detailed how 24-hour internal vibration exposure was estimated for the respondents to the social survey questionnaire along with an investigation into single figure descriptors for vibration exposure with respect to human response. Due to the high degree of correlation between the vibration exposure descriptors considered compared to the strength of correlation between each of the descriptors and self reported annoyance, none of the descriptors could be shown to be the statistically superior predictor of annoyance. Owing to this, it was concluded that exposure-response relationships be derived for all available vibration exposure descriptors in national and international standards and guidance. In this chapter statistical methods for deriving exposure-response relationships are discussed and relationships are derived for perception, annoyance, and vibration induced rattle. Differences in response to railway and construction vibration are discussed along with the scientific robustness and the relevance to policy of the derived relationships. Finally, the findings presented in this chapter are compared to various national vibration limits.

5.2 STATISTICAL METHODS FOR THE FORMULATION OF EXPOSURE-RESPONSE RELATIONSHIPS

A major consideration associated with the formulation of exposure-response relationships is 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 (Agresti, 1990; Long, 1997; Weisberg, 2005). 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 and 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 (Miedema and 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., 2003b; Zapfe et al., 2009), namely logistic regression and ordinal logit models.

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.

5.2.1 BINARY PROBIT MODEL

Figure 38 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:

$$y_i = \mathbf{x_i}\boldsymbol{\beta} + \varepsilon$$ **Equation 22**

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 38.

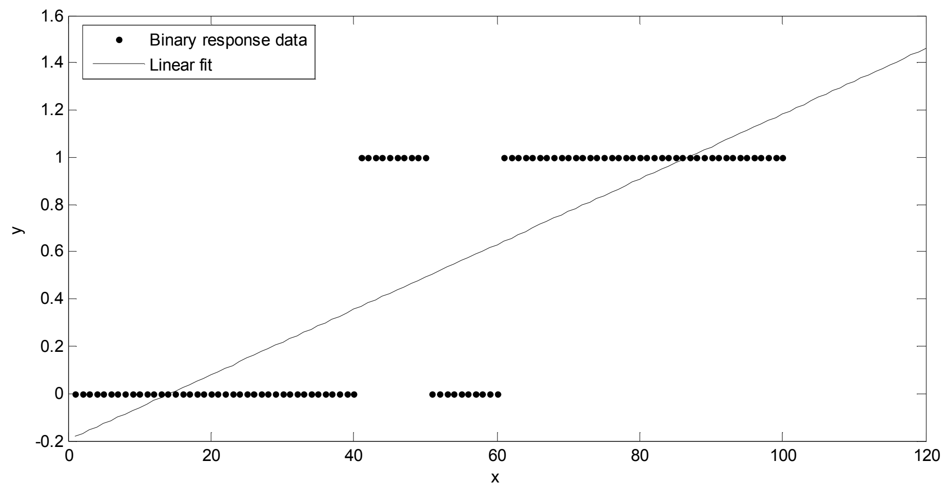


Figure 38 Ordinary least squares regression of a continuous independent variable on a binary dependent variable.

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 $y_i = 1$:

$$\begin{aligned} E\left(y_i \middle| \mathbf{x_i}\right) &= \Pr\left(y_i = 1 \middle| \mathbf{x_i}\right) \\ &= \mathbf{x_i}\boldsymbol{\beta} \end{aligned}$$ **Equation 23**

As can be seen from Figure 38, 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:

$$y_i^* = \mathbf{x_i}\boldsymbol{\beta} + \varepsilon$$ **Equation 24**

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

$$y_i = \begin{cases} 1 & \text{if } y_i^* > \tau \\ 0 & \text{if } y_i^* \le \tau \end{cases}$$ **Equation 25**

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

If it is assumed that xβ is Gaussian normally distributed and therefore symmetrical, 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 26**

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

$$\Pr\left(y=1\middle|\mathbf{x}\right)=\Phi(\mathbf{x\beta})$$ **Equation 27**

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:

$$L\left(\boldsymbol{\beta}\middle|\mathbf{y},\mathbf{X}\right)=\prod_{y=1}\Phi(\mathbf{x\beta})\prod_{y=0}\left[1-\Phi(\mathbf{x\beta})\right]$$ **Equation 28**

Figure 39 shows the application of the binary probit model to the data shown in Figure 38. It can be seen that, unlike the case of ordinary least squares regression, this model is bound between zero and one.

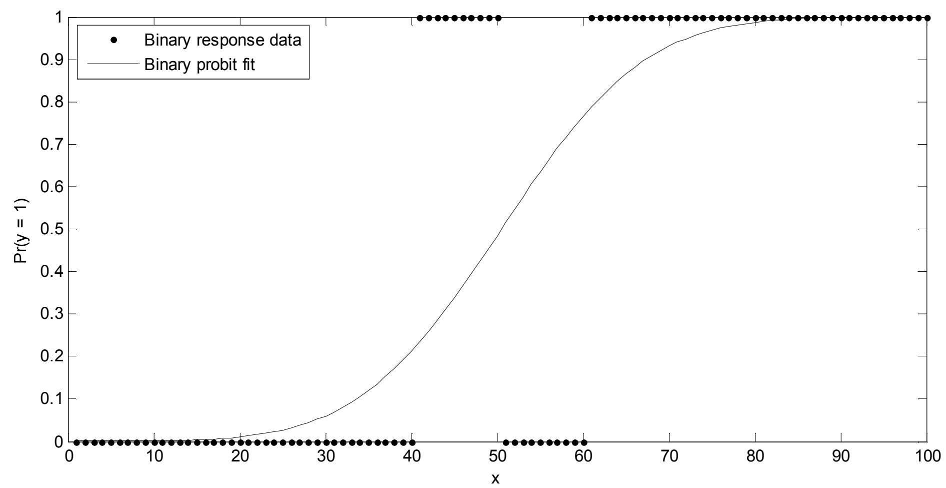


Figure 39 Binary probit regression of a continuous independent variable on a binary dependent variable.

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

5.2.2 *Grouped regression model*

In this section, an ordinal probit model with fixed thresholds is presented which is adapted from (Groothuis-Oudshoorn and 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:

$$\tau_j = 100j / m \qquad \textbf{Equation 29}$$

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 chapter, 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*.

$$A_i^* = \mathbf{X_i \beta} + \varepsilon \qquad \textbf{Equation 30}$$

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 31

It is common practice to express annoyance as the proportion of people who respond above a certain annoyance level *C* (Miedema and 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 (*x*) responds with an annoyance level above a cutoff *C* [$p_C(x)$] can be expressed as:

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

Equation 32

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

$$p_C(x) = (1 - \Phi\left[\frac{C - \mathbf{X\beta}}{\sigma}\right])$$

Equation 33

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

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 34**

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 thresholds of annoyance can be expressed.

The 95% upper and lower confidence limits of this model at a given exposure level *x* are given as:

$$C_{LU} = \mathbf{x}^{\mathbf{T}}\mathbf{b} \pm Z\sqrt{(\mathbf{x}^{\mathbf{T}}\boldsymbol{\Sigma}_b\mathbf{x})}$$ **Equation 35**

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 $p_C(x)$ can then be expressed as:

$$1 - \Phi\left(\frac{C - C_{L,U}}{\sigma}\right)$$ **Equation 36**

5.2.3 GOODNESS-OF-FIT AND TESTS OF SIGNIFICANCE

Unlike ordinary least squares regression, there is no generally 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 37). 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 37**

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 chapter, 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 37). $L_{intercept}$ is considered to be analogous to the total sum of squares (denominator in Equation 37).

$$R^2_{pseudo} = 1 - \frac{\ln(L_{full})}{\ln(L_{\text{intercept}})}$$ **Equation 38**

As can be seen from Equation 38, for models based on the same data, McFadden's pseudo-R^2 would be higher for the model with the greater likelihood.

5.3 FUNCTIONAL FORM OF THE VIBRATION EXPOSURE DESCRIPTOR

The exposure-response relationships presented in subsequent sections in this chapter were assessed 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 found to result in a significant increase in the likelihood of the model. This result is consistent with the findings of Klæboe et al. (2003). Unless otherwise stated, the relationships presented in the rest of this chapter have been calculated using the exposure descriptor in logarithmic form.

5.4 PERCEPTION MODELS FOR RAILWAY AND CONSTRUCTION VIBRATION

In the social survey questionnaire, before respondents were asked about annoyance due to vibration they were first asked to indicate whether they were able to feel vibration from a variety of sources (see section 3.2). The response to this question was of a binary outcome, either "Yes" or "No". A binary probit model was calculated with the response to this question as the dependent variable and vibration exposure expressed as W_b weighted Vibration Dose Value as the independent variable. The resulting model is a curve which describes the proportion of respondents able to feel vibration for a given vibration exposure. Figure 40 shows the results of this model for vibration due to railway and construction activities. This figure suggests that a similar proportion of respondents reported being able to feel vibration at a similar magnitude of Vibration Dose Value for both railway and construction sources. As the question of whether a stimulus is perceived or not will result in less intra-subject variability than measures of response such as annoyance, this result provides confidence that responses to the two different sources of vibration can be compared.

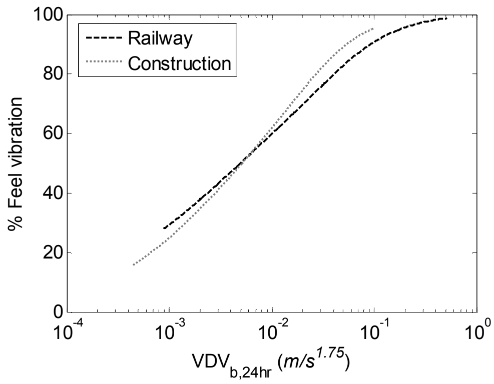


Figure 40 Proportion of respondents reporting feeling vibration for a given vibration exposure from railway sources (N = 752) and construction sources (N = 321).

A number of national and international standards provide indicative values for perception thresholds in terms of weighted peak acceleration. Figure 41 shows the curve for the percentage of respondents able to feel railway induced vibration in its 95% confidence intervals compared with the five perceptual categories provided in German guidance document VDI 2057. A similar absolute perception threshold of a weighted peak acceleration of 0.015 m/s^2 is stated in BS ISO 2631-1:1997. Although an explicit definition of the category labels shown in Figure 41 is not provided, the percentage of respondents reporting being able to feel vibration seems reasonable compared to the category labels. That the vibration exposure spans the full range of categories presented in these guidance documents suggests that the field methodology presented in Chapter 3 was successful in generating a sample with a sufficient range of vibration exposures for both railway and construction sources.

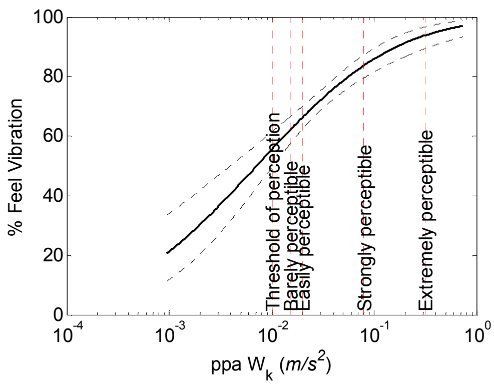


Figure 41 Proportion of respondents reporting feeling vibration for a given vibration exposure from railway sources (N = 752) compared with the different degrees of perception reported in VDI 2057.

Respondents stating that they were able to feel vibration were also routed to a set of questions which asked through which surfaces in their home they were able to perceive vibration. Figure 42 shows the proportion of respondents able to feel vibration through different surfaces for railway induced (left pane) and construction induced (right pane) vibration. It can be seen from this figure that for both sources, the majority of respondents are able to perceive vibration through the floor, followed by furniture such as the chair or bed, with the smallest proportion of respondent able to perceive vibration through other surfaces though the hands. Perception of vibration through furniture suggests whole body vibration as the whole body is supported by the vibrating surface whereas feeling vibration through the hands suggests vibrotactile perception through the skin. From the discussion of the physiological mechanisms of vibration perception presented in Chapter 2 section 2.2.1, it is clear that there are differences in the sensitivity with respect to frequency between whole body and vibrotactile vibration perception. As current frequency weightings are based upon perception thresholds for whole body vibration, these findings suggest that considering vibrotactile perception alongside whole body vibration may be useful in the understanding of the human response to vibration from the two sources considered in this thesis.

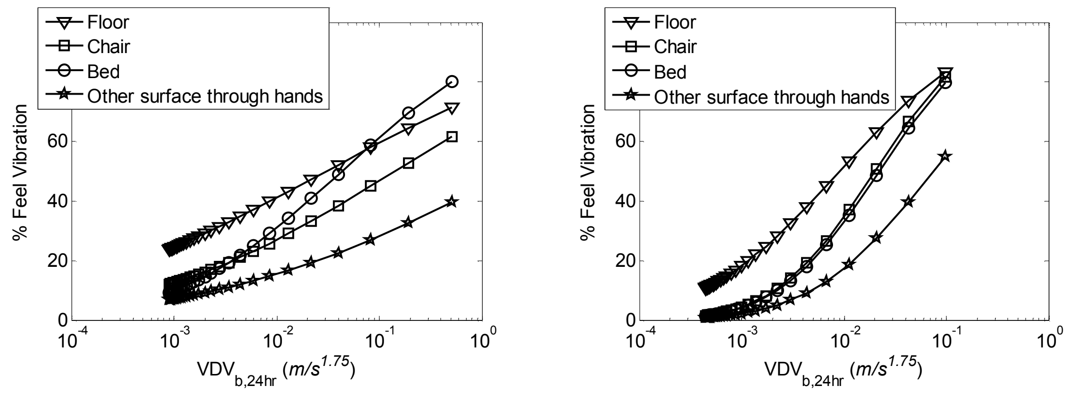


Figure 42 Breakdown of the pathways of vibration perception for railway induced (left pane, N = 752) and construction induced (right pane, N = 321).

5.5 EXPOSURE-RESPONSE RELATIONSHIPS FOR RAILWAY VIBRATION

An investigation into single figure vibration exposure descriptors presented in the previous chapter revealed that all of the descriptors considered described a similar amount of variance in the annoyance response data. It was therefore concluded that none of the currently advocated vibration exposure descriptors would be a better predictor of annoyance due to railway vibration than any other. Due to the different assessment methods and lack of international consensus regarding the most appropriate vibration exposure descriptor, comparison between studies conducted in different countries into the human response to vibration is problematic. Therefore, in this section exposure-response relationships are presented for annoyance due to railway vibration in terms of all available national and international guidance both historic and current (see Chapter 4 section 4.4).

All relationships are presented in terms of the vertical component due to its dominance over the horizontal components (see Chapter 4 section 4.3.2). For each of the exposure-response relationships for annoyance presented in this chapter, three thresholds of annoyance are reported which describe the proportion of subjects reporting annoyance in the upper 28% of the response scale (percent highly annoyed), the upper 50% of the response scale (percent annoyed), and upper 72% of the response scale (percent slightly annoyed). These thresholds are the same as those reported by Miedema and Oudshoorn (2001) for the exposure-response relationships for environmental noise. All respondents stating that they are unable to feel vibration have been recoded to the lowest annoyance category and all of the relationships presented in this section have been derived using the 5-point semantic annoyance response scale (see Chapter 3 section 3.2). The models presented in this section were derived using the grouped regression model detailed in section 5.2.2. Parameters, covariance matrices, and polynomial approximation for the exposure-response relationships in this section are provided in Appendix I.

5.5.1 BS6472-1:1992 (United Kingdom)

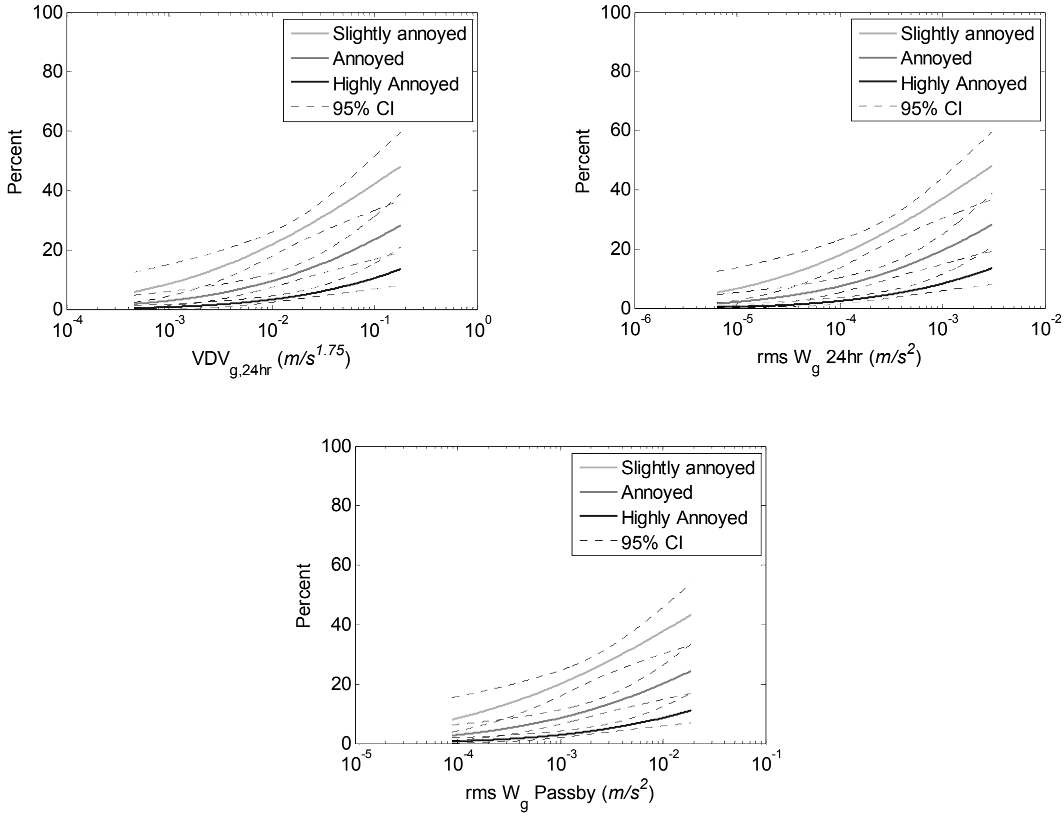


Figure 43 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from BS 6472-1:1992. N = 752, R^2_{pseudo} = 0.02 except relationship for RMS W_g Passby where R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.2 BS ISO 2631-1:1997

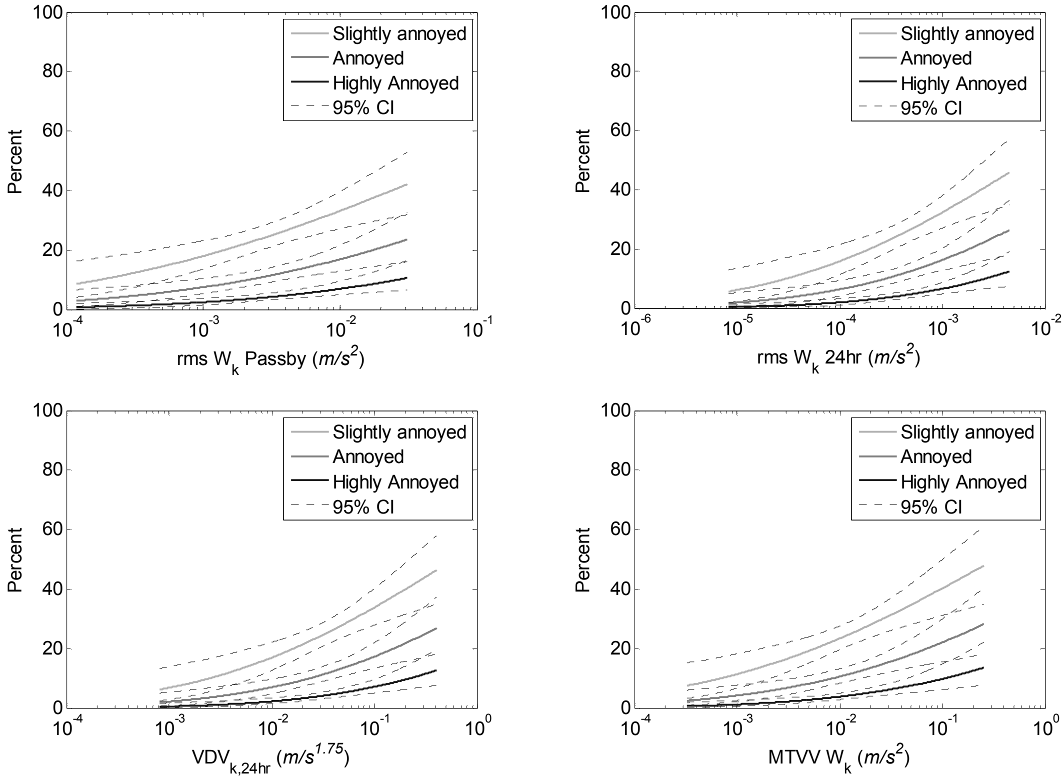


Figure 44 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from BS ISO 2631-1:1997. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.3 BS ISO 2631-2:2003

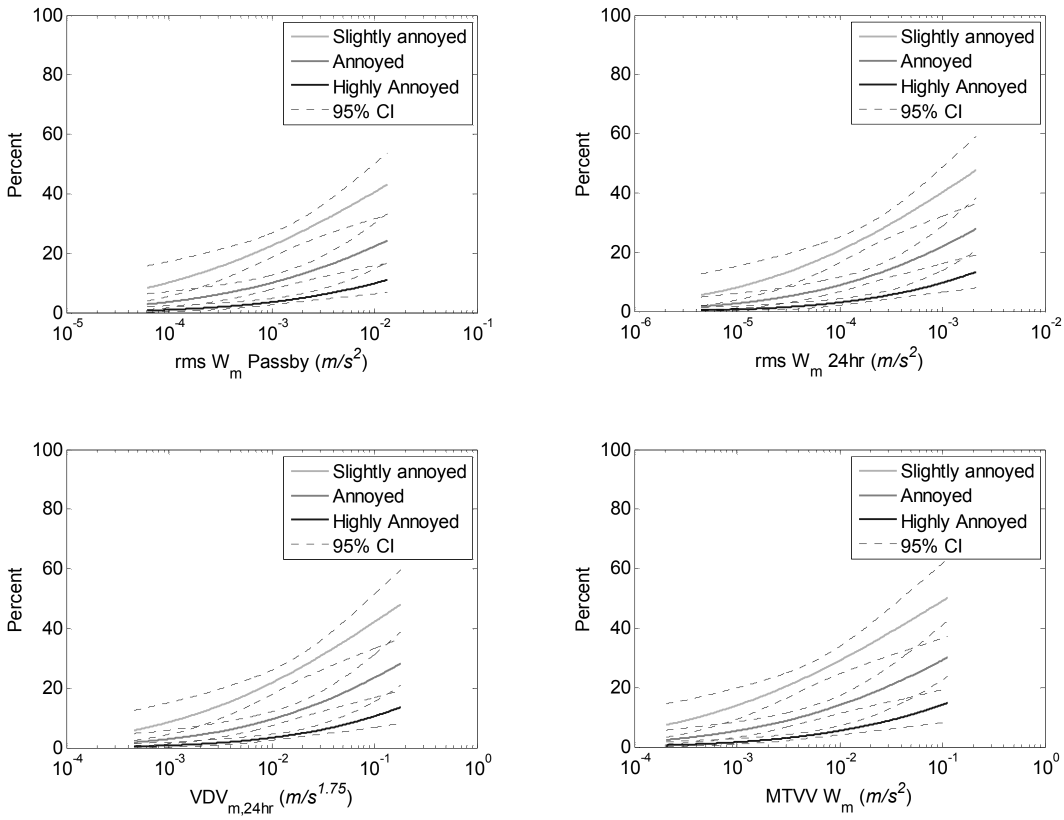


Figure 45 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from BS ISO 2631-2:2003. N = 752, R^2_{pseudo} = 0.01 except relationships for RMS W_m 24hr and $VDV_{m,24hr}$ where R^2_{pseudo} = 0.02, all curves significant to the 0.001% level.

5.5.4 BS 6472-1:2008(UNITED KINGDOM)

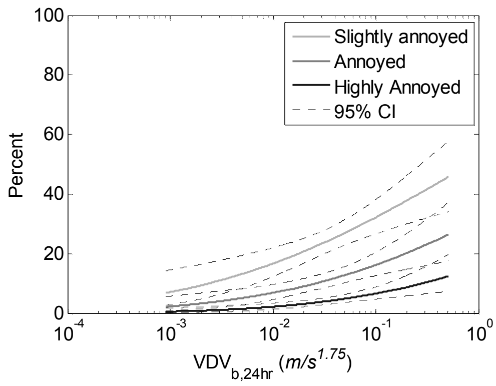


Figure 46 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from BS 6472-1:2008. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.5 DIN 4150-2:1999 (GERMANY)

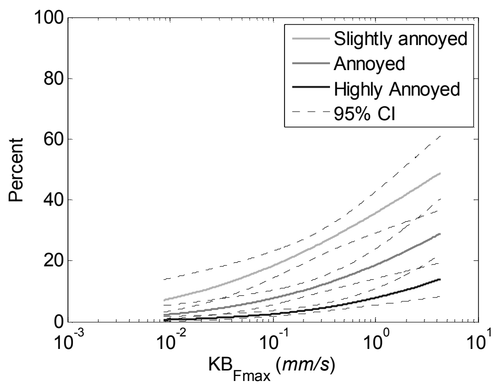


Figure 47 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from DIN 4150-2:1999. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.6 SBR Richtlijn – Deel B (2002)

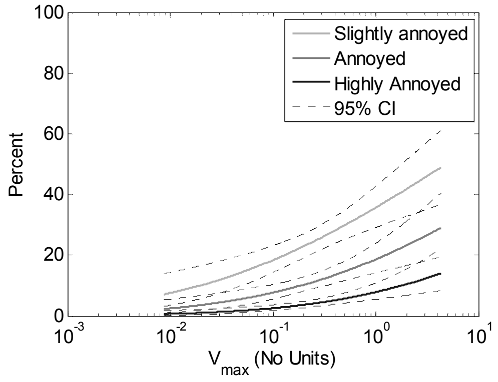


Figure 48 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from SBR Richtlijn – Deel B:2002. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.7 NS 8176:2005 (Norway)

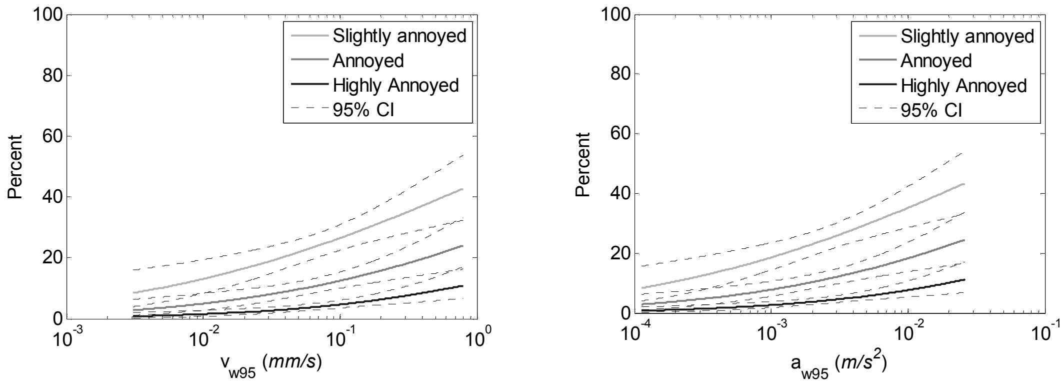


Figure 49 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from NS 8176:2005. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.8 UNI 9641:1990 (ITALY) AND REAL DECRETO 1367/2007 (SPAIN)

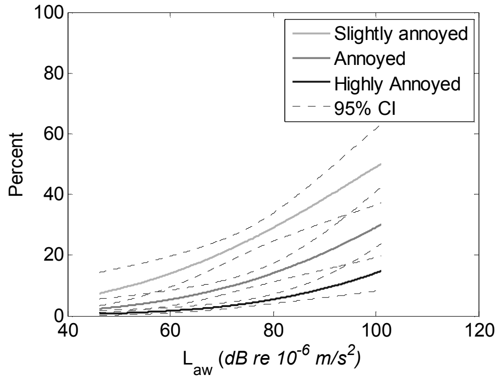


Figure 50 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from UNI 9641:1990 and Real Decreto 1367/2007. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.9 SS 460 48 61:1992 (SWEDEN)

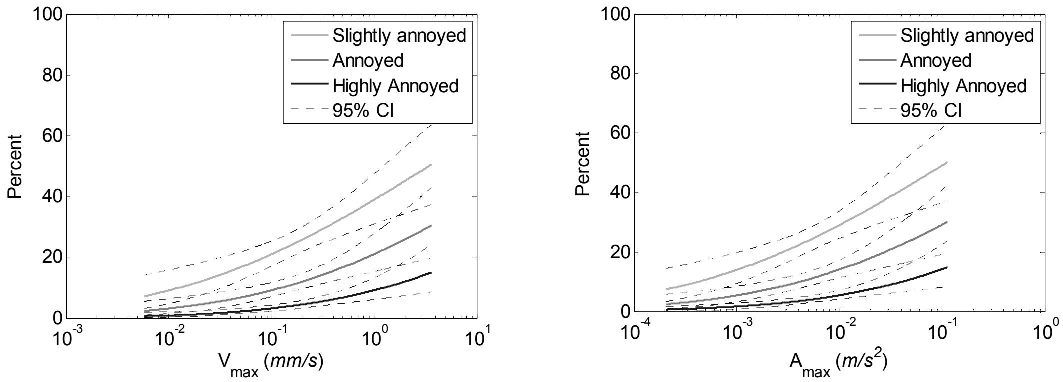


Figure 51 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from SS 460 48 61:1992. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.10 Japanese Vibration Regulation Law

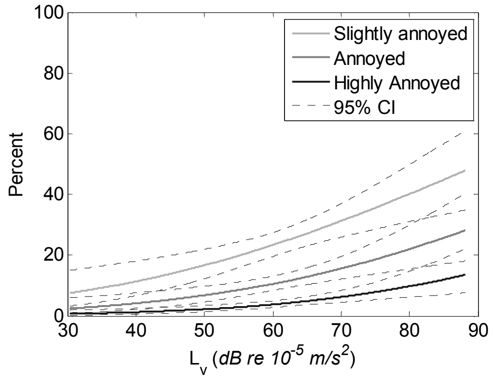


Figure 52 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following guidance from Japanese Vibration Regulation Law. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.5.11 FTA Guidelines (USA)

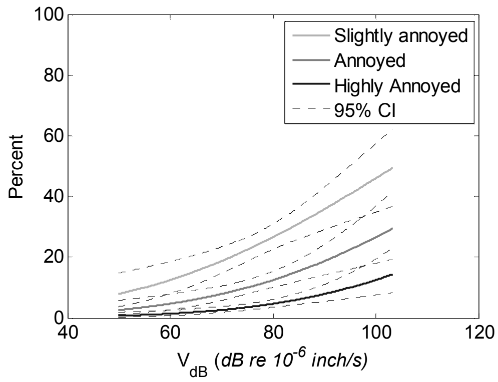


Figure 53 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from railway activities. Vibration exposure assessed following FTA guidelines. N = 752, R^2_{pseudo} = 0.01, all curves significant to the 0.001% level.

5.6 EXPOSURE-RESPONSE RELATIONSHIPS FOR CONSTRUCTION VIBRATION

Figure 54, Figure 55, and Figure 56 present exposure response relationships for construction induced vibration expressed in terms of W_b weighted VDV, W_b weighted RMS acceleration, and peak particle velocity. As with the exposure-response relationships for railway induced vibration presented in the previous section, three thresholds of annoyance are reported which describe the proportion of subjects reporting annoyance in the upper 28% of the response scale (percent highly annoyed), the upper 50% of the response scale (percent annoyed), and upper 72% of the response scale (percent slightly annoyed). Respondents stating that they could not feel vibration have been recoded to the lowest annoyance category and all of the relationships are calculated using the five-point semantic annoyance response scale.

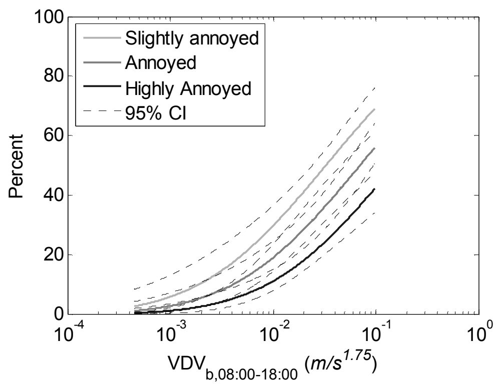


Figure 54 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from construction activities. Vibration exposure assessed following guidance from BS 6472-1:2008. N = 321, R^2_{pseudo} = 0.11, all curves significant to the 0.001% level.

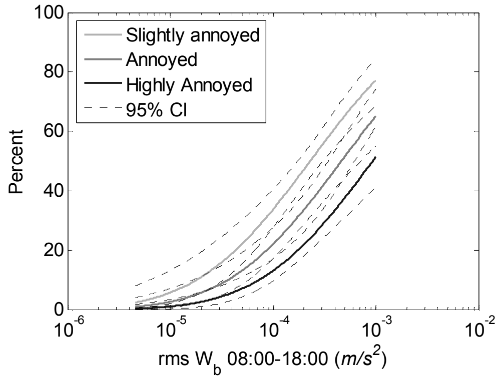


Figure 55 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from construction activities. Vibration exposure assessed following guidance from BS ISO 2631-1:1997. N = 321, R^2_{pseudo} = 0.11, all curves significant to the 0.001% level.

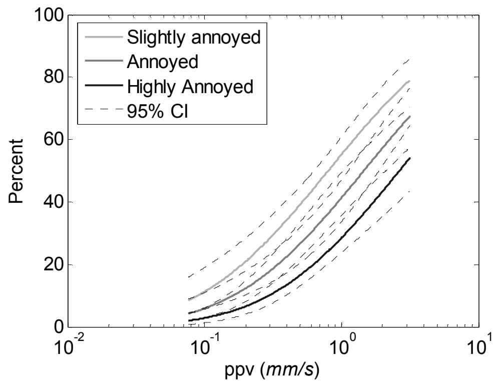


Figure 56 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure from construction activities. Vibration exposure assessed following guidance from BS 5228-2:2009. N = 321, R^2_{pseudo} = 0.11, all curves significant to the 0.001% level.

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

5.7.1 EFFECT OF OUTLIERS

To investigate the sensitivity of the calculated models to outliers, the exposure-response relationship for railway induced vibration in terms of Vibration Dose Value presented in section 5.5.4 was recalculated using only the data in the 5 to 95 percentile range of the vibration exposure. Figure 57 provides a comparison between the exposure-response relationship calculated with the full dataset and the relationship calculated with the subset of data. It can be seen from this figure that the full model and the subset model show good agreement with the subset model falling within the confidence intervals of the full model. This result indicates that the exposure-response relationships presented in this chapter were not significantly influenced by outliers.

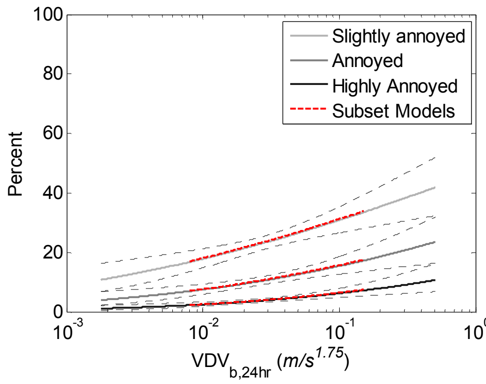


Figure 57 Exposure-response relationship for annoyance caused by railway induced vibration recalculated on a subset of responses.

5.7.2 EFFECT OF SITE

To investigate the influence of potential differences between measurement sites, the exposure-response relationship was calculated with data from each site removed sequentially. A site in this context was defined crudely as all responses collected in a single town or city. Figure 58 shows the exposure-response relationship describing the percentage of respondents expressing high annoyance (%HA) calculated using the full dataset (solid line) compared with the relationships calculated with data from different sites omitted. The agreement shown in this figure between the relationship calculated from the full dataset and the subset relationships indicates that none of the sites as defined in this section had a significant influence on the exposure-response relationships presented in this chapter.

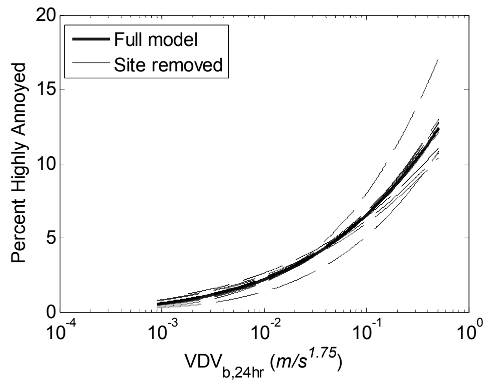


Figure 58 Comparison between an exposure-response relationship calculated using a full dataset and exposure-response relationships calculated with data from different measurement sites omitted.

5.7.3 *EFFECT OF RESPONSE SCALES*

To investigate potential differences in the way respondents utilised the different annoyance response scales used in the social survey questionnaire (see Chapter 3 section 3.2), exposure-response relationships were calculated using both the 5-point semantic and 11-point numerical response scales. Figure 59 provides a comparison between the relationships calculated using the two different response scales. It can be seen from this figure that both the semantic and numerical annoyance response scales result in nearly identical exposure-response relationships.

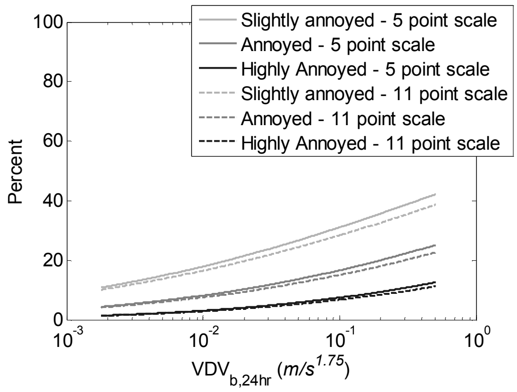


Figure 59 Exposure-response relationship for annoyance due to railway induced vibration calculated using the 5-point semantic and 11-point numerical response scales.

5.7.4 PERCEPTION CRITERIA MODEL

In the analysis of the vibration data collected via the field survey conducted by Woodroof and Griffin (1987) (see section 2.5.1), railway induced vibration events were excluded from analysis if the peak magnitude of the event was below 0.01 m/s^2. This value was chosen to exclude events with magnitudes which fell below the median vibration perception threshold for vertical whole body vibration. Figure 60 shows the exposure-response relationship for railway vibration in terms of $VDV_{b,24hr}$ only including events with a peak magnitude exceeding 0.01 m/s^2. Comparing this relationship to that presented in Figure 46, it can be seen that the use of a perceptibility criteria for the analysis of vibration exposure has little effect on the resulting exposure-response relationship other than a reduction in the dynamic range of the relationship.

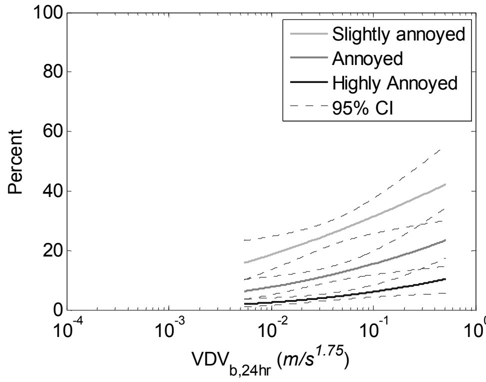


Figure 60 Exposure-response relationship for railway induced vibration. Vibration exposure calculated only considering events with peak magnitude greater than 0.01 m/s^2.

5.8 Response to combined noise and vibration

As discussed in section 2.2.7, laboratory studies have found that annoyance responses to vibration are modified by noise exposure. An exposure-response model was calculated for annoyance caused by vibration exposure ($VDV_{b,24hr}$ $m/s^{1.75}$) and noise exposure (L_{DEN} dB) as independent variables. Noise exposure was calculated for each respondent using the calculation of railway noise procedure (Koziel et al., 2011). The improvement in likelihood when noise exposure was included as an independent variable in the model was found to be significant ($p < 0.05$).

Figure 61 shows the proportion of respondents reporting high annoyance due to vibration as a function of vibration and noise exposure. It can be seen from this figure that annoyance due to vibration increases with both noise and vibration exposure. This result suggests that noise exposure has an influence on annoyance due to vibration although it can be seen that vibration exposure has the greatest influence in the relationship.

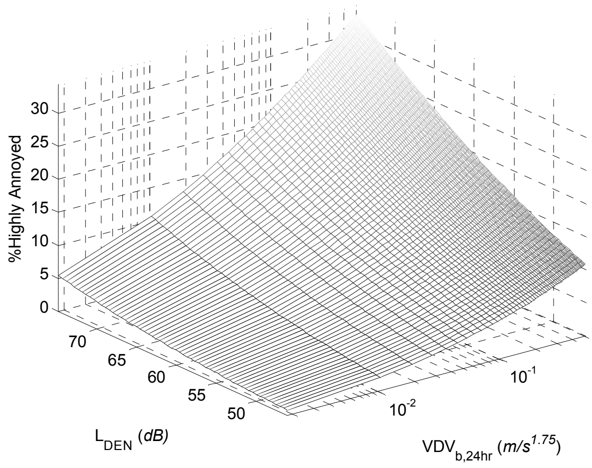


Figure 61 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance due to vibration as a function of vibration and noise exposure.

5.9 COMPARISON BETWEEN RAILWAY AND CONSTRUCTION VIBRATION

5.9.1 MIXED SOURCE MODEL

Research into environmental noise has shown that different noise sources (namely road, railway, and aircraft) elicit different annoyance responses for the same level of noise exposure and it is generally accepted that separate exposure-response relationships are required for each noise source (Miedema and Oudshoorn, 2001). However, the results of a socio-vibration survey conducted in Norway (Klæboe et al., 2003b) have suggested that a single exposure response relationship is adequate to describe the human response to vibration from both railway and road traffic sources. To investigate the influence of the vibration source in the present study on self reported annoyance due to vibration exposure, data collected for the railway and construction vibration sources were pooled and a dummy variable was created for 'source type'. An exposure-response relationship was calculated using the 5-point semantic annoyance scale as the dependent variable and vibration exposure ($VDV_{b,24hr}$ m/s$^{1.75}$) and the 'source type' dummy variable as independent variables. The inclusion of the 'source type' dummy variable in the model resulted in a significant improvement in the likelihood of the model (p < 0.001). This result suggests that for construction and railway sources, separate exposure-response relationships are required for the two different sources.

5.9.2 DIFFERENCES IN RESPONSE TO RAILWAY AND CONSTRUCTION SOURCES

It is clear from the results presented in sections 5.5 and 5.6 that for the same magnitude of vibration exposure, railway induced vibration and construction induced vibration elicit significantly different responses. It can be seen in the relationships for both sources that the proportion of respondents expressing high annoyance starts at zero at similar magnitudes of vibration exposure and increases monotonically with increasing vibration exposure. However, annoyance increases much more rapidly with increasing vibration exposure from construction activities than it does for vibration from railway activities. These results are in line with previous research into community response to environmental noise where it has been found that significantly different responses can be observed for exposure to noise from railway, road, and aircraft sources (Miedema & Oudshroon, 2001).

It was shown in Figure 40 that for the same magnitude of vibration exposure, a similar proportion of respondents reported feeling vibration for both railway and construction sources. That the same magnitude of vibration exposure can result in the same proportion of respondents able to feel vibration but a difference in the annoyance response between the two different sources suggests that the differences observed in the annoyance response could potentially be attributed to both differences in the characteristics of the vibration generated by the different sources other than the magnitude and also non-vibrational and non-acoustical factors (Marquis-Favre and Premat, 2005; Marquis-Favre, 2005).

Secondary effects of vibration such as rattle could potentially play a role in explaining the differences in response to the two sources. Figure 62 shows the proportion of respondents reporting hearing or seeing objects and structures rattle as a function of weighted vibration dose value for railway and construction sources. This figure shows that above around 1 mm/s$^{1.75}$ a significantly higher proportion of respondents report noticing rattle from construction vibration than for railway vibration. The difference in response between the two sources grows with increasing vibration exposure. This finding is in line with previous research which has suggested that vibration induced rattle influences annoyance responses to aircraft noise (Fidell et al., 2002; Schomer, 1987).

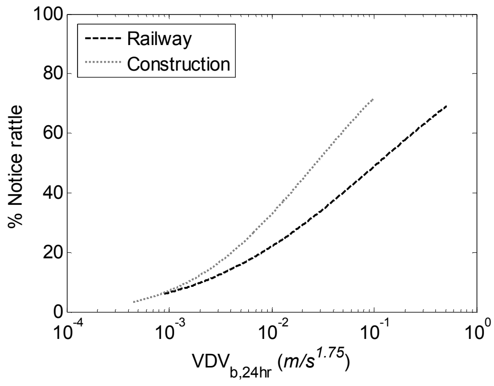


Figure 62 Proportion of respondents reporting hearing or seeing objects and structures rattle for a given vibration exposure from railway sources (N = 752) and construction sources (N = 321).

5.10 COMPARISON WITH EXISTING CRITERIA

5.10.1 BS 6472-1:2008 AND ANC GUIDELINES

BS 6472-1:2008 suggests the probability of adverse comment for five categories of vibration exposure (see Table 14). 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 6472-1:2008 but the categories for night-time exposure are expressed as single figure values (these values are shown in brackets in Table 14). As it is not stated what is meant by "adverse comment", it is difficult to assess the suitability of this guidance. Table 15 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 14 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.

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 15 Percentage of respondents expressing high annoyance for vibration exposure in the limits provided in Table 14. (* - outside range of measured exposures).

For railway noise exposure, PPG24 recommends a 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".

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

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

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 (Miedema and 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. It is also apparent from the results presented in Table 15, 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.

5.10.2 NORWEGIAN SOCIO-VIBRATION STUDY

Based on the exposure-response relationships derived from the Norwegian socio-vibration study (Klæboe et al., 2003b), guidance was provided for classification of dwellings based on four categories of statistical maximum weighted velocity and acceleration (Turunen-Rise et al., 2003). This guidance is summarised in Table 2. Class C, which corresponds to 7 – 8% of people highly annoyed, was suggested as the minimum vibration requirement for new residential buildings. Figure 49 shows the exposure-response relationships for the railway dataset under analysis expressed in terms of $v_{w,95}$ and $a_{w,95}$ respectively. Comparing this relationship to the guidance provided in Table 2, 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 49, 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 vw,95 (mm/s)	0.1	0.15	0.3	0.6
Statistical maximum value for weighted acceleration aw,95 (mm/s2)	3.6	5.4	11	21

Table 16 Guidance classification of dwellings with the upper limits for the statistical maximum value for weighted velocity $v_{w,95}$ or acceleration $a_{w,95}$ [Source: Turunen-Rise et al. (2003)]

5.10.3 BS 5228-2:2009

BS5228-2:2009 provides guidance on the effect of vibration from construction activities in residential environments (see Table 3). This guidance is provided in terms of peak particle velocity (*ppv*). The exposure-response relationship for annoyance due to construction vibration in terms of *ppv* is shown in Figure 56. Table 18 shows the percentage of respondents expressing high annoyance based on this relationship 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 17 Guidance of effects of construction vibration levels as stated in BS5228-2:2009.

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

5.10.4 FTA GUIDELINES

The FTA guidelines used in the USA have a current vibration limit in residential environments of 72 *VdB*. From Figure 53, this relates to around 3% of the population expressing high annoyance. This is slightly lower than the 5-10% highly annoyed predicted by the exposure-response relationships produced in North America by Zapfe et al. (2009). It should be noted that the statistical methods employed by Zapfe et al. (2009) differ from those used to produce the relationships presented in this chapter with the former using the upper 40% of the annoyance response scale to define high annoyance and the latter using the upper 28%. It is therefore expected that the percentage of respondents highly annoyed in Figure 53 is slightly lower than that reported by Zapfe et al. (2009).

5.11 DISCUSSION

The exposure-response relationships presented in this chapter represent the first of their kind for vibration based upon extensive measurement and the first relationships for construction induced vibration. However, if these relationships are to be used as practical tools for the assessment of the human response to vibration in residential environments, some thought needs to be given as to their validity. In a study by Berry & Flindell (2009), a framework is provided for the assessment of the scientific robustness and relevance with respect to policy of exposure-response relationships for the human response to noise exposure where it is suggested that the main criteria are:

i. The relevance, statistical representativeness, and measurement accuracy of the [exposure], or input variables, measured in the research study.
ii. The relevance, statistical representativeness and measurement accuracy of the response, or outcome, variables in the research study.

iii. The range of applicability to other types of noise exposure and/or environment not included in the research study.

iv. The range of applicability to other types of adverse health effects not included in the research study.

v. The statistical strength of the observed [exposure]-response relationship in relation to known and/or estimated statistical uncertainty and in relation to the statistical power of the research study as designed.

vi. The relative absence of potential confounding variables that could have been equally or more responsible for the observed [exposure]-response relationships.

vii. The scientific plausibility of the observed [exposure]-response relationship considered in terms of known or theoretical biological mechanisms.

In this section, the findings presented in this chapter are considered with respect to these criteria.

5.11.1 Exposure and response variables

As discussed in section 2.2, the perception of vibration is facilitated through complex physiological mechanisms and is dependent upon, among other factors, the magnitude, frequency, duration, and temporal characteristics of the vibratory stimulus. As applies to many of the relationships presented in this chapter, by expressing vibration exposure as an average or accumulated single figure value over a 24-hour period, objective features of vibration exposure salient to perception may not be characterised. As there is no physiological evidence that annoyance due to noise or vibration is accumulated over time, expressing vibration exposure with respect to human response as an equivalent energy or cumulative value somewhat undermines the scientific validity of the relationships presented in this chapter. However, as these measures are utilised in national and international standards for the assessment of vibration with regards to human response as well as being the basis for the quantification of vibration limits in a number of nations it is useful from a policy and administrative viewpoint to present these relationships as such.

The difference between the observed annoyance response between railway and construction induced vibration (see sections 5.5 and 5.6) considering the similar response with regards to absolute perception (see section 5.4) suggests that further research is needed into the single figure descriptor used as the dependent variable in the relationships. Situational and attitudinal response variables which modify the exposure-response relationship should also be explored.

The single figure vibration descriptors throughout this thesis have been expressed in terms of exposure rather than dose and as such the resulting relationships have been referred to throughout as *exposure*-response rather than the often used *dose*-response. “Exposure” and “dose” are often used interchangeably however there is an important distinction to be made between these two terms. Vibration dose relates to the total amount of vibration energy absorbed by a subject’s body over a given time period whereas vibration exposure relates to the total amount of vibration energy measured at a single point over a given time period. If the subject were to remain in the position at which the vibration was measured over the entire measurement period then the subject’s vibration exposure would be equal to their vibration dose. However, this is clearly not the case as people do not remain in a fixed position in their house for 24-hours a day. Considering this and also that the measurement methodology was designed to represent the “worst case scenario” (see section 3.3), it is likely that the vibration exposure used in the calculation of the exposure-response relationships in this chapter are an overestimation of each respondent’s true vibration dose. However, as it is not the aim of the relationships presented in this chapter to predict individual response and knowledge of the amount of time a given person spends in their home is generally not available, in the case of these relationships vibration exposure is the more appropriate measure.

5.11.2 *Applicability to other sources of vibration and adverse effect*

As is the case for environmental noise, it appears from the relationships derived for railway and construction vibration that separate exposure-response relationships may be required for different sources of vibration. However, as was discussed in sections 5.9.2 and 5.11.1 it may be the case that these differences are partly attributable to inadequacies of currently recommended single figure vibration exposure descriptors to account for salient perceptual features of the vibration exposure and also attitudinal and situational factors. An important distinction between the two sources is that the railway is a *steady state* source whereas the construction source represents an abrupt change in vibration exposure. There is evidence that for a step change in noise exposure, the increase in annoyance is greater than that which would be predicted by an exposure-response relationship derived under steady state conditions (Brown and van Kamp, 2009a, 2009b). This may provide further explanation as to the differences in response to the different sources. This effect is however impossible to investigate using the current data set and would require a longitudinal survey to be conducted.

5.11.3 *Statistical strength*

In field studies into the human response to environmental noise, noise exposure has been found to account for between 4 – 20% of the variance in annoyance on the individual level (see, for example, Brink and Wunderli, 2010; Fields, 1993; Job, 1988). The Spearman's correlation coefficients between standardised vibration exposure descriptors and annoyance presented in Chapter 4 section 4.4 shows that the highest correlation for railway induced vibration is 0.16 and 0.42 for construction induced vibration. If these values were to be converted to R^2 values on the individual level, this would equate to 3% explained variance for railway induced vibration and 18% explained variance for construction induced vibration; these values are therefore in line with what might be expected in field studies into the community response to noise. The confidence intervals in the relationships presented in sections 5.5 and 5.6 are relatively narrow and are within a range which is comparable to other studies into the human response to vibration (see, for example, Klæboe et al., 2003; Zapfe et al., 2009) and noise (see, for example, Miedema and Oudshoorn, 2001) from transportation sources. This suggest that, although it appears that there is room for improvement in the exposure-response relationships, the statistical strength of the relationships presented in this chapter are in line with what one may expect to achieve from this type of study.

5.11.4 CONFOUNDING VARIABLES

As was shown in section 3.2.3, the socio-demographic characteristics of the samples of respondents for the two sources of vibration considered in this thesis are similar suggesting that comparisons between the resulting relationships are valid. Careful planning of the survey site selection detailed in chapter 3.2.2 ensured that there were no sources of environmental vibration other than the source of interest. Of those respondents living in close proximity to a railway, 71.4% of those interviewed reported noticing vibration from railway activities, 7.5% from road vehicles, 5.6% from neighbouring homes, and 4% from aeroplanes and helicopters. Of those respondents living in close proximity to construction activities, 67.1% of those interviewed reported noticing vibration from construction sources, 34.3% from road vehicles, 3.4% from neighbouring homes, and 2% and 4% from aeroplanes and helicopters respectively.

The results presented in section 5.8 suggest that airborne noise exposure has an influence on the annoyance response to vibration. Therefore, noise exposure could be considered as a confounding variable in the analyses presented in this chapter. However, for the sources considered in this thesis, perceptible vibration is in most cases accompanied by airborne noise. This suggests that future research in this area should consider combined exposure to vibration and noise.

5.11.5 *Scientific plausibility and causality*

The statistical significance of the exposure-relationships presented in this chapter is not necessarily proof of a causal relationship between vibration exposure and annoyance due to vibration. At present, little is known regarding the physiological and psychological mechanisms which result in annoyance due to vibration and as such no definite claim can be made regarding the causality of the observed relationships. However, the findings presented in this chapter do suggest that, although not yet fully understood, a relationship does exist between vibration exposure and annoyance in residential environments and that this relationship can be described by curves indicating the proportion of the population expected to express annoyance above a given threshold for a given vibration exposure.

5.12 Summary

This chapter has detailed the formulation of exposure-response relationships for the human response to vibration in residential environments. Relationships have been presented for vibration exposure assessed according to a number of different national and international standards. Due to differences in response between the two vibration sources considered in this thesis, separate exposure-response relationships for annoyance have been derived for railway and construction sources of vibration. Narrow confidence intervals, the statistical significance of the relationships, and a sensitivity analysis suggest that these relationships are statistically robust. However, differences in response to the different vibration sources and the relatively low explained variance in the relationships suggest that improvements can be made to the relationships through investigation into new vibration exposure descriptors. As highlighted in section 5.11.5, little is known regarding the physiological and psychological mechanisms which result in annoyance due to vibration. Therefore, single figure descriptors based upon perceptual models would also improve the scientific plausibility of the exposure-response relationship. The following chapter details a pilot test designed to investigate the feasibility of using the method of paired comparisons and multidimensional scaling to investigate the perception of vibration from railway activities.

CHAPTER 6

CONSIDERING THE PERCEPTION OF VIBRATION AS A MULTIDIMENSIONAL PHENOMENON

6 CONSIDERING THE PERCEPTION OF VIBRATION AS A MULTIDIMENSIONAL PHENOMENON

6.1 INTRODUCTION

In the previous chapter, exposure-response relationships were derived for the human response to railway and construction induced vibration in residential environments. In the derived relationships, vibration exposure was expressed in terms single figure descriptors advocated in various national and international standards and guidance. Although the derived relationships were statistically significant and exhibited relatively narrow confidence intervals, it was noted that a large proportion of the variance in the response is unaccounted for and that significant differences in response can be observed for vibration from different sources. The differences and scatter in the response could be due to both non-acoustical factors and the inadequacy of the single figure descriptors to characterise the features of the vibration exposure which are salient to human perception.

In acoustics, in particular the fields of psychoacoustics and sound quality, it is widely accepted that the perception of sound is a multidimensional phenomenon. Multidimensionality in this context refers to the overall perception of a sound being made up of a number of perceptual dimensions which relate to separate objective features of the sound. In areas such as the perception of musical timbre and product sound quality, much research has been conducted to determine the perceptual dimensions which underlie the perception of a given set of sounds. In the case of product sound quality, these perceptual dimensions have been used to develop models which can be used to predict the perceived quality of a product based on objective acoustic features of the product sound. If a similar approach can be taken towards the perception of vibration from environmental sources, it may be possible to develop models to predict perceived annoyance based upon objective features of a measured vibration signal.

As highlighted in Chapter 2, much of the previous research into the perception of whole body vibration has been in the form of ranking or magnitude estimation tasks conducted in a laboratory setting using artificial signals such as pure sine excitation as stimuli. Although research of this sort provides a valuable insight into psychophysical aspects of vibration perception such as perception thresholds and subjective magnitude, these subjective test methodologies impose limitations on the researcher; namely, the perceptual dimension or dimensions of interest must be determined *a priori* (Torgerson, 1952). If the underlying perceptual dimensions of a certain stimulus type are unknown, then it is possible that psychologically relevant dimensions will be unaccounted for in models and metrics used to describe the human response to the stimulus.

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 chapter is to determine if the perception of whole body vibration is multidimensional in nature and if so, can these perceptual dimensions be represented by a non-metric representation of a group of objects in a low-dimensional Euclidean space. The second aim of the work presented in this chapter is to determine if these perceptual dimensions can be related to annoyance responses.

6.2 Similarity, psychological distance, and multidimensional scaling

Much of the work detailed in this chapter is underpinned by the concepts of psychological similarity and distance which are widely employed in the field of cognitive psychology. In Coombs' theory of data (Coombs, 1960, 1964), it is proposed that if a subject is presented with a pair of stimuli and asked to make a judgement, such as the perceived similarity of the objects in the pair, the resulting judgement is a proximity relation; that is to say, the quantification of similarity represents a "distance" in a psychological space between the two objects. If judgements of similarity are made upon all possible pairings of a group of stimuli, the resulting proximity relations relate to points in a latent high dimensional psychological space which describes the response of the subject to the group of stimuli. To understand how a group of stimuli are perceived, is therefore of interest to understand the underlying structure and psychologically relevant dimensions of this perceptual space.

Multidimensional scaling (MDS) is an exploratory multivariate data analysis technique which, when combined with paired comparison tests of similarity, allows the investigation of the underlying perceptual dimensions of a group of stimuli. The main aim of multidimensional scaling is to determine a configuration of a group of objects in an R-dimensional multidimensional space to provide a visual representation of pairwise distances or (dis)similarities between objects in the group. The 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 63).

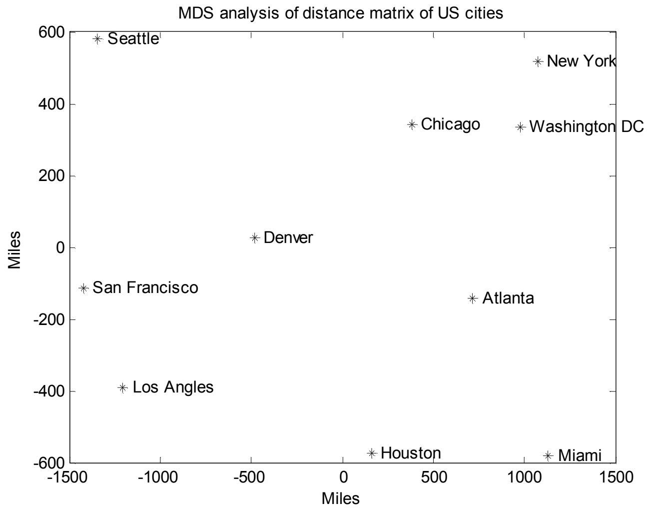


Figure 63 Results of MDS analysis on pairwise distances between US cities.

If a test has been conducted in which subjects were presented with every possible pairing (*i, j*) of *n* objects and asked to judge how dissimilar ($\delta_{i,j}$) they perceive the pair of objects to be, a matrix of pairwise dissimilarities can be formed $\{\delta_{i,j}\}$. This dissimilarity matrix $\{\delta_{i,j}\}$ can then be subjected to MDS analysis which aims to find the best representation of the *n* objects in a Euclidean[7] space of a user defined number of dimensions (*R*) with a large distance ($d_{i,j}$) between objects in the MDS configuration representing a large judged dissimilarity ($\delta_{i,j}$) and *vice versa*. By studying the configuration of points in this multidimensional configuration it is possible to identify the perceptual attributes which underlie the group of objects, each of the *R* dimensions being orthogonal and therefore representative of a salient perceptual attribute underlying the group of *n* objects.

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.,

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[7] The configuration does not necessarily have to be Euclidean and there are a variety of different distance metrics which can be used. However, for the work presented in this chapter it is assumed the the resulting configuration is Euclidean.

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 determined 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 discovered 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, it is often the aim to relate the revealed perceptual dimensions to some judgment of product sound quality to build a model for the prediction of perceived sound quality based on objective acoustical features of the sound emitted by the product in question.

6.3 Levels of data for MDS

There are numerous different MDS models and selecting which model is appropriate 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 annoyance on a group of sounds would be classified as *one-way* data whereas a matrix describing pairwise annoyance 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 annoyance 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 ($\delta_{i,j,s}$) 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 (i and j) from a number of subjects (s).

6.4 METRIC AND NON-METRIC SCALING

The general procedure for MDS is to find a configuration of points in low dimensional Euclidean space where distances between points ($d_{i,j}$) are approximately equal to $f(\delta_{i,j})$ where f is a parametric monotonic function and $\delta_{i,j}$ are measured pairwise distances. This is commonly achieved by fitting the matrix of distances $\{d_{i,j}\}$ by least squares or eigendecomposition to $\{f(\delta_{i,j})\}$. For example, a configuration may be sought which minimises the loss function given in Equation 39 where the parameters of the function f are to be estimated (Cox and Cox, 2001).

$$\sqrt{\frac{\sum_{i,j}(d_{i,j}-f(\delta_{i,j}))^2}{\sum_{i,j}{d_{i,j}}^2}}$$

Equation 39

where $d_{i,j}$ are the reproduced distances, and $\delta_{i,j}$ are measured dissimilarities.

The form of the function f is largely dependent on the measurement level of the input data $\{\delta_{i,j}\}$. If the data to be analysed by MDS are on the interval or ratio scale, metric multidimensional scaling can be used. For metric multidimensional scaling, a constraint on the function f is imposed such that f must be continuous and monotonic. If the data to be analysed are on the ordinal scale, non-metric multidimensional scaling may be a more appropriate model. In non-metric MDS, a relaxation on the constraints imposed on the function *f* is introduced such that *f* may be a non-parametric monotonic function. 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 (Borg and Groenen, 2005; Cox and Cox, 2001; Coxon and Davies, 1982).

6.5 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 inter-subject variability is lost. Carroll & Chang (1970) proposed a multidimensional scaling algorithm in which inter-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 et al. (1985).

Some basic features of INDSCAL analysis are illustrated in Figure 64 [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 64 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 judgements 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 40**

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 41**

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

Private spaces for subjects 1 and 2 are shown in Figure 64. 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.

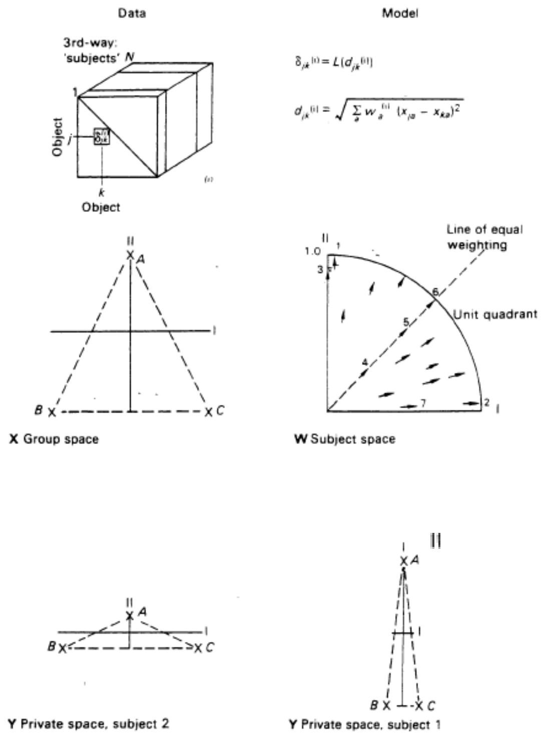

Figure 64 Illustration of some basic features of the INDSCAL model [taken from Coxon et al. (1985)].

6.6 MULTIDIMENSIONAL PERCEPTION OF VIBRATION

As discussed in section 6.2, the aim of multidimensional scaling analysis in studies of perception is generally to gain an understanding of the salient perceptual dimension upon which a group of stimuli are judged. This technique is therefore particularly useful in studies where neither the nature nor the number of salient perceptual dimensions is known. In the perception of vibration, previous studies have generally focussed on the investigation of relatively objective perceptual dimensions such as perceptual magnitude and just noticeable differences (see Chapter 2 section 2.2). Therefore, little is known regarding the nature of the psychologically relevant dimensions which determine the perception of vibration. As such, there is little psychological validity concerning the single figure descriptors used to quantify vibration exposure with regards to human response.

Considering this, it is hypothesised that the perception of vibration from railway activities can be described by a small number of perceptual dimensions and that these dimensions can be related to objective features of the vibration stimuli. It is further hypothesised that, if an understanding can be gained of the perceptual structure of a set of complex vibration stimuli, models can be developed which relate the salient perceptual dimensions to some measure of response, namely annoyance.

To summarise the concepts explored thus far in this chapter, Figure 65 illustrates the basic principals of multidimensional scaling analysis in the context of vibration perception. In this figure the subject is exposed to four different railway vibration events in all possible pairs. The subject is asked to rate the degree of similarity between the pairs of vibration events on a continuous scale ranging between 0 and 1. It is assumed that there exists a latent perceptual structure which allows the subject to make comparisons between the vibration stimuli, that this structure consists of a number of perceptual dimensions, and that the subject's similarity ratings represent a comparison between stimuli based upon this psychological structure. The similarity matrix resulting from these judgements is then submitted to multidimensional scaling analysis which attempts to create a mapping of the stimuli in a low-dimensional space. It is then assumed that each of the dimensions in the multidimensional scaling configuration relate to a dimension in the psychological structure which the subject uses to make comparisons between the stimuli. By finding objective features of the vibration stimuli which correlate to these dimensions, an understanding can be gained as to how objective features of vibration influence perception.

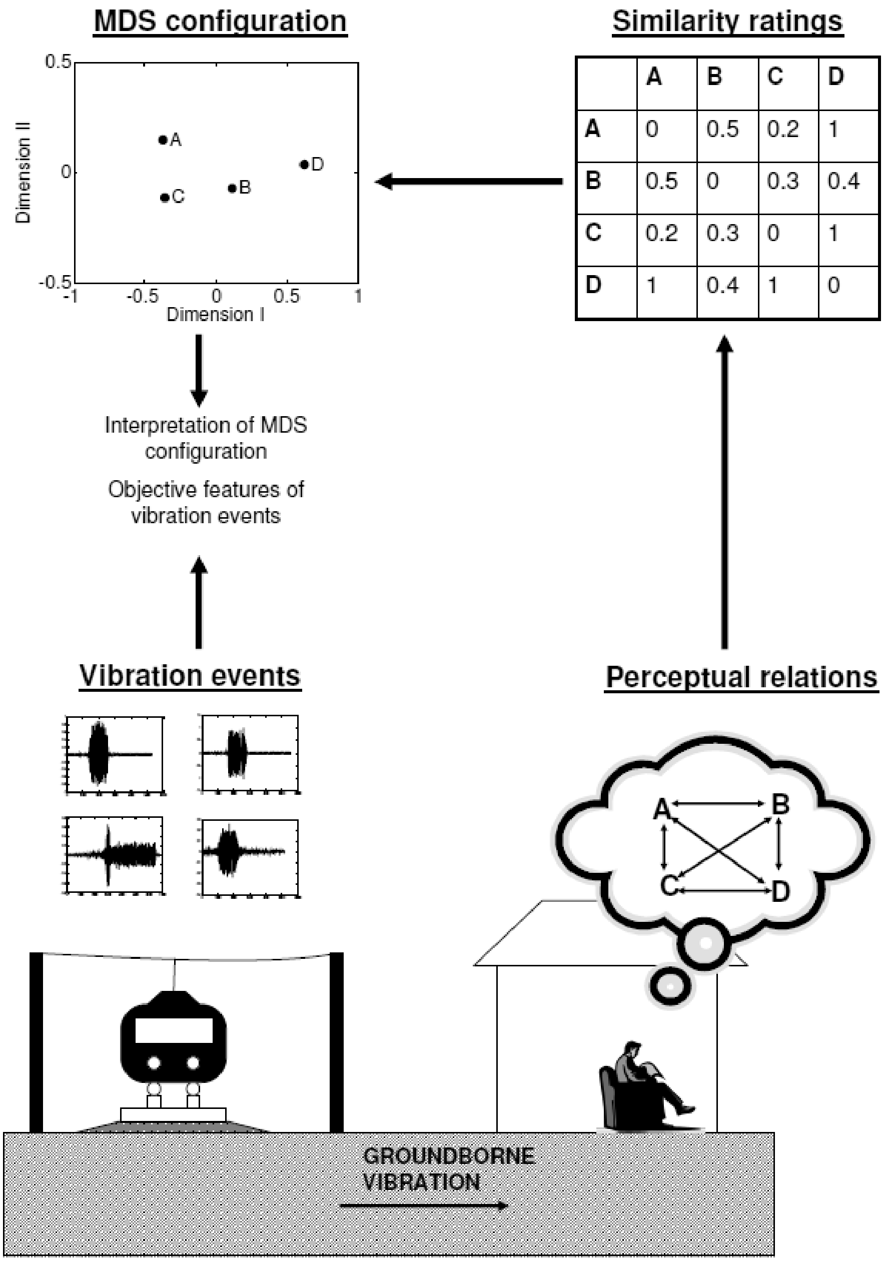

Figure 65 Illustration of the basic principles of multidimensional scaling

The remainder of this chapter details a pilot test conducted to determine the feasibility of using the methods of paired comparisons and multidimensional scaling for the investigation of the perception of and response to vibration from railway activities. The suitability of using these methods is assessed via the following criteria:

- The test procedure is simple and readily understood by subjects.

- Data collected via the test is suitable for multi-dimensional scaling analysis.
- The axes revealed through the multidimensional scaling analysis relate to a perceptual continuum and not a simple grouping of objects.
- The axes revealed through the multidimensional scaling analysis can be related to self reported annoyance

6.7 PILOT TEST METHODOLOGY

6.7.1 TEST SETUP

The test setup used to reproduce vibration in the pilot test detailed in this chapter 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 test setup was calibrated by measuring the frequency response function measured between the voltage into the amplifier and the acceleration measured at the seat of the chair. This frequency response 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 and Porat, 1984). Figure 66 shows the magnitude Fourier spectra of acceleration measured at the seat of the chair for a white noise input with and without this frequency response 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.

The Buttkicker tactile transducer was however found to be highly non-linear and to generate a high degree of harmonic distortion. This behaviour has been observed in previous studies (C. Abercrombie & Braasch 2010). Because of this distortion and non-linearity, it was found to be almost impossible to control the excitations produced by the test setup in terms of frequency content meaning that the pilot test described in this chapter was limited in terms of the stimuli which could be reliably reproduced by the test setup.

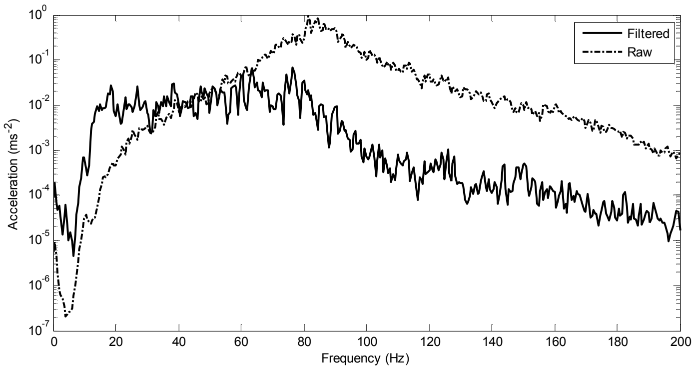

Figure 66 Response of test rig measured at the seat for a white noise input before and after calibration.

6.7.2 GENERATION OF STIMULI

Twelve vibration stimuli were synthesized by combining signals with three types of frequency content, two time windows (see Figure 67), and two different durations (3 seconds and 5 seconds). The three types of frequency content were achieved via the addition of 10 *Hz* and 13 *Hz* sinusoids, the addition of a 16 *Hz* and 19 *Hz* sinusoids, and pink noise. The different frequency contents were generated through the addition of sinusoids rather than shaping noise signals due to the harmonic distortion produced by the tactile transducer. It was found that most shaped noise signals input to the system resulted in a vibration output which was flat with frequency. Table 19 shows how the twelve stimuli were synthesized from these three attributes. The resulting time histories of the stimuli are shown in Figure 68.

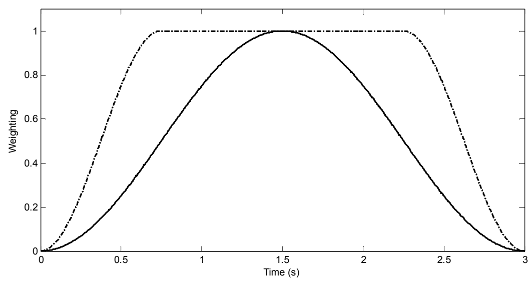

Figure 67 The Hanning (solid line) and flat top (dashed line) time windows used to generate the vibration stimuli for the pilot test.

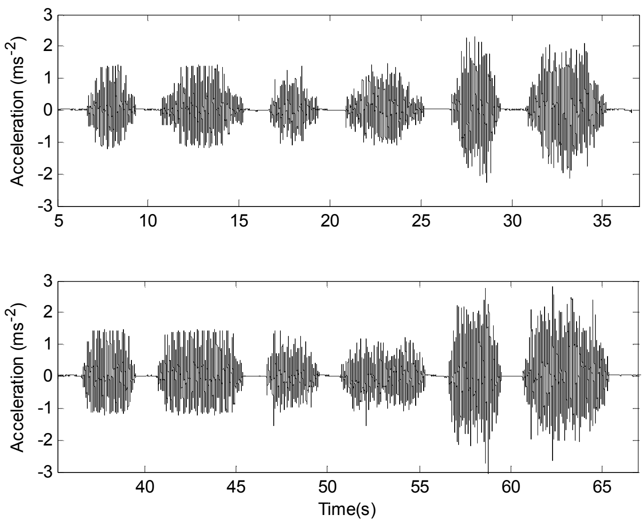

Figure 68 Acceleration time histories of the twelve vibration stimuli used in the pilot test.

Stimulus	Frequency content	Window	Duration
1	10 Hz + 13 Hz	Hanning	3 sec
2	10 Hz + 13 Hz	Hanning	5 sec
3	16 Hz + 19 Hz	Hanning	3 sec
4	16 Hz + 19 Hz	Hanning	5 sec
5	Pink noise	Hanning	3 sec
6	Pink noise	Hanning	5 sec
7	10 Hz + 13 Hz	Flat top	3 sec
8	10 Hz + 13 Hz	Flat top	5 sec
9	16 Hz + 19 Hz	Flat top	3 sec

Stimulus	Frequency content	Window	Duration
10	16 Hz + 19 Hz	Flat top	5 sec
11	Pink noise	Flat top	3 sec
12	Pink noise	Flat top	5 sec

Table 19 Characteristics of the twelve vibration stimuli used in the subjective test.

6.7.3 TEST PROCEDURE

Eleven subjects participated in paired comparison tests of similarity and annoyance using the twelve vibration stimuli generated in section 6.7.2. 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 familiarise themselves with the group of stimuli on which they would be making judgments. To allow subjects to familiarise themselves with the test interface, five trial paired comparison judgments were performed prior to the main test. Figure 69 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).

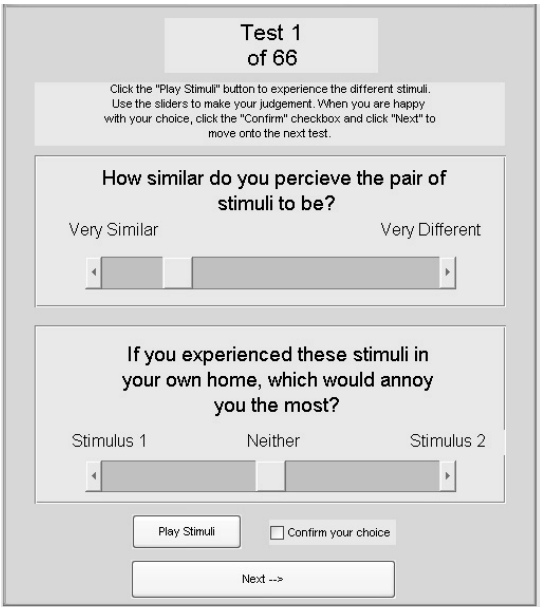

Figure 69 Graphical interface developed for pilot subjective test.

When the "*Play Stimuli*" button was clicked, subjects were presented with a pair of vibration stimuli separated by 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) which ensures the greatest separation of pairs with a common stimulus. The next pair of vibration signals could be assessed by clicking the "*Next*" button. Each test took around 40 minutes in total.

6.8 RESULTS AND DISCUSSION

6.8.1 PERCEPTUAL SPACE

The goodness-of-fit of an MDS solution can be assessed by examining the *stress* of the configuration. A lower stress value for an 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 an 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 70 shows stress for non-metric MDS configurations calculated in 2 to 8 dimensions from the data collected in the perceptual tests. 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 and Groenen, 2005). Therefore for the purpose of this study, a four dimensional INDSCAL configuration will be analysed.

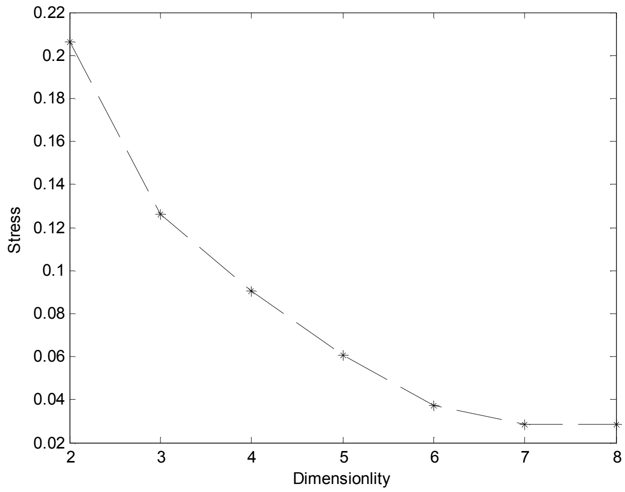

Figure 70 Relationship between stress and the number of calculated dimensions.

Figure 71, Figure 72, and Figure 73 show the group and subject spaces of an INDSCAL 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 fairly evenly distributed across each of the dimensions suggesting that subjects were rating dissimilarities based on a perceptual continuum and not simply categorizing the stimuli. The angle between a subject's vector and a given dimension in the subject space relates to the relative importance the subject places on that 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.

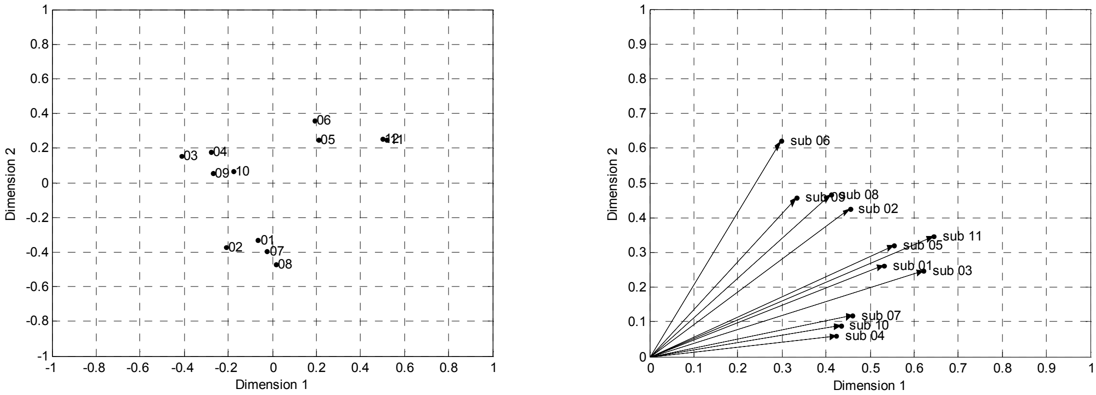

Figure 71 Dimension 1 and Dimension 2 INDSCAL solution. Left pane: Group space. Right pane: Subject space.

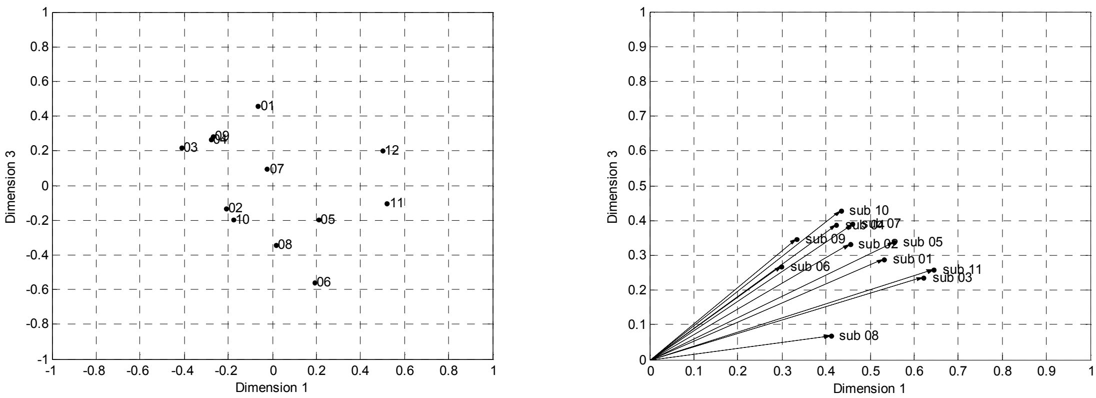

Figure 72 Dimension 1 and Dimension 3 INDSCAL solution. Left pane: Group space. Right pane: Subject space.

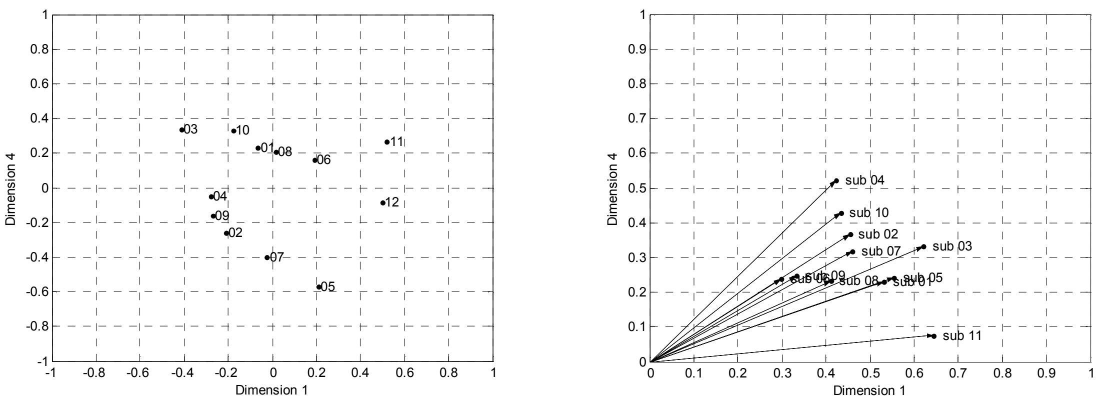

Figure 73 Dimension 1 and Dimension 4 INDSCAL solution. Left pane: Group space. Right pane: Subject space.

6.8.2 SINGLE FIGURE ANNOYANCE 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 42**

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

Calculation of single figure annoyance scores using this method assumes that the perceived annoyance scores are based on an interval level psychological scale. This method has been utilised in the estimation of single figure merit scores in sound quality tests (Parizet et al., 2005). There are however other widely used models for the estimation of single figure scores from paired comparison data such as the Thurstone's law of categorical judgement (Case V) (Thurstone, 1927) or the Bradley-Terry-Luce (Bradley and Terry, 1952; Luce, 1959) model. To assess if P_{ji} is well represented by the single figure annoyance scores A, P_{ji} was estimated by the following relationship:

$$\tilde{P}_{i,j} = A_i - A_j$$ **Equation 43**

The RV coefficient, which can be interpreted as the multivariate form of the Pearson's correlation coefficient, between the matrices $P_{i,j}$ and $\tilde{P}_{i,j}$ is 0.93 suggesting that, although some information is lost, P_{ji} is well represented by the single figure annoyance scores A.

Figure 74 shows the single figure annoyance scores calculated using this method 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 the annoyance ratings were fairly consistent between subjects.

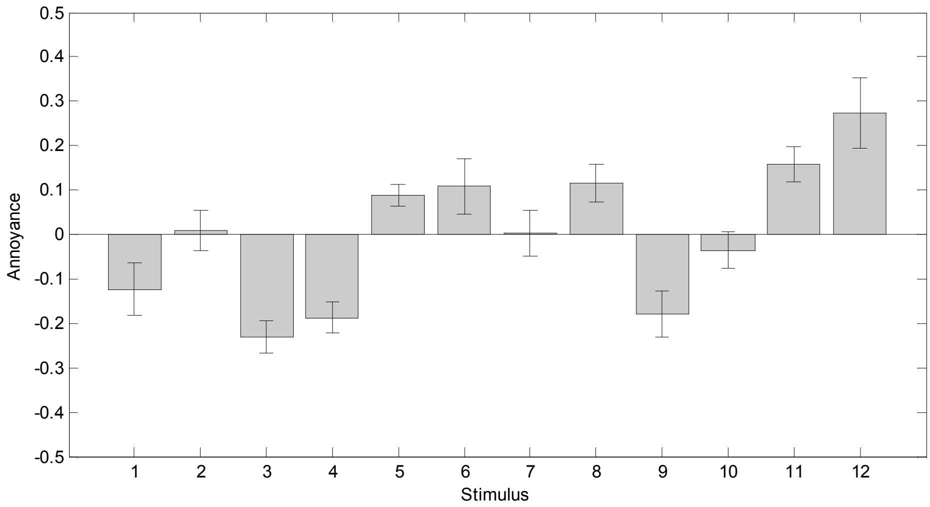

Figure 74 Single figure annoyance scores shown in their 95% confidence intervals (*N* = 11).

6.8.3 *INTRA-SUBJECT CONSISTENCY*

The consistency of a subject's responses in a paired comparison test 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 75 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 75 (Parizet, 2002). These results suggest that, apart from arguably subject 5, subjects were relatively consistent in rating perceived annoyance due to whole body vibration suggesting that the subjective test was a relatively simple task for the subjects to complete. Considering the relative acuity of vibration perception compared with the perception of sound, it is encouraging that these figures are similar to those obtained from studies into the perception of sound.

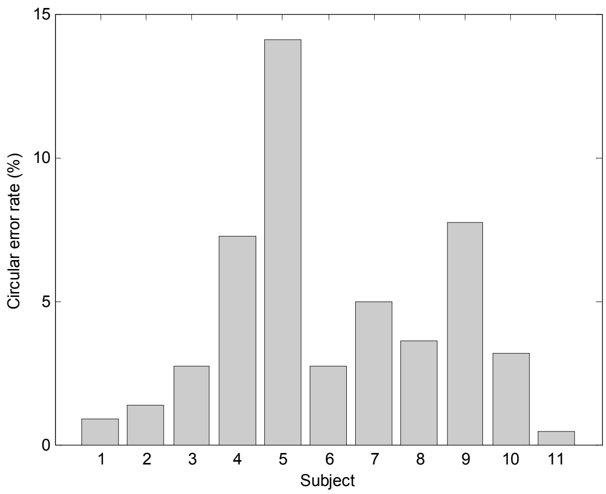

Figure 75 Circular error rate for each subject in the pilot laboratory test.

6.8.4 RELATIVE ANNOYANCE MODEL

From the results of the MDS analysis presented in section 6.8.1 and the single figure annoyance scores presented in section 6.8.2, multiple regression was used to investigate the relationship between the perceptual dimensions and perceived annoyance. 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:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\beta} \qquad \textbf{Equation 44}$$

where **Y** is a vector of responses, **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:

$$RSS(\boldsymbol{\beta}) = \sum (y_i - \mathbf{x_i}^{\mathbf{T}}\boldsymbol{\beta})^2 \qquad \textbf{Equation 45}$$

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 described by the equation below:

$$A = 0 + 0.45D_1 - 0.10D_2 - 0.15D_3 - 0.03D_4 \qquad \textbf{Equation 46}$$

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 76 shows the relationship between the single figure annoyance scores measured through the subjective test and the single figure annoyance scores predicted using Equation

46. It can be seen from this figure that there is a good agreement (R^2=0.92, p < 0.001) between the measured and predicted single figure annoyance scores. This figure represents the key result of the pilot test as it confirms the hypothesis that dimensions of psychological similarity can be related to overall annoyance. The implication that the perception of vibration can be described by a small number of orthogonal perceptual dimensions suggests that objective features of the vibration stimuli can be found which relate to these perceptual dimensions. These findings suggest 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 stimuli can be formulated.

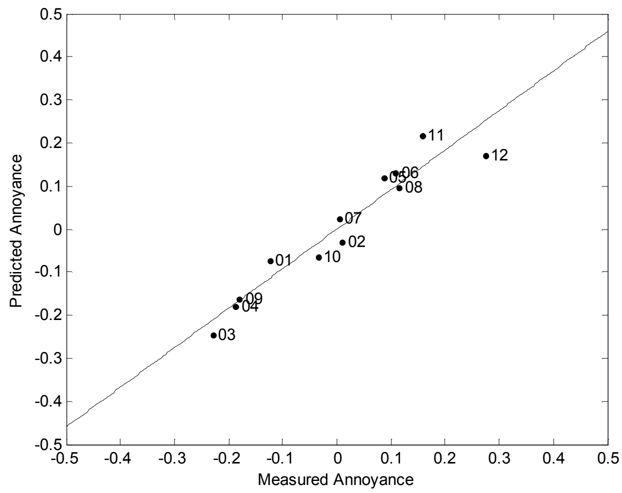

Figure 76 Measured and predicted single figure annoyance scores. (N = 11) (*R^2*=0.92, *p*<0.001).

6.9 Summary

This chapter has presented the results of a pilot 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 and a multidimensional scaling analysis was conducted using these data. 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. The low circular error rates observed in the paired comparison of annoyance tests suggest that subjects did not have difficultly in completing the subjective test. 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 chapter 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 chapter.

CHAPTER 7

MULTIDIMENSIONAL SCALING ANALYSIS OF COMPLEX VIBRATION STIMULI

7 MULTIDIMENSIONAL SCALING ANALYSIS OF COMPLEX VIBRATION STIMULI

7.1 INTRODUCTION

In the previous chapter a pilot test was conducted to determine the feasibility of using the methods of paired comparisons and multidimensional scaling for the study of the perception of whole body vibration. The test was conducted using twelve synthesised stimuli reproduced using a commercially available tactile transducer. The results of the pilot test indicated that the perception of the group of stimuli could be described by three or four perceptual dimensions and that these perceptual dimensions could be related to self reported annoyance through multiple linear regression. This chapter describes the development, implementation, and analysis of a full scale paired comparison test programme the design of which addresses shortcomings identified in the pilot test detailed in the previous chapter.

7.2 DESIGN OF TEST RIG

7.2.1 SHAKER AND FRAME

In the pilot test detailed in Chapter 6, the test setup was highlighted as a major shortcoming due to distortion and nonlinearities inherent in the tactile transducer used to excite vibration in the test setup. To overcome this issue, a new test rig was built which was designed to be capable of the faithful and repeatable reproduction of measured vibration signals. Figure 77 shows a sketch of the initial design of the vibration test rig. The rig consists of an electrodynamic shaker coupled to a frame consisting of a table supported on springs and linear guides with a chair with a cushioned seated rigidly fixed to the table. As the seat of the chair is cushioned, some uncertainty is introduced in the vibration exposure experienced by subjects of different masses due to the compression of the cushion.

The shaker used in this setup was a Derritron VP-85 powered by a 6000 Watt TW6000 amplifier. As the manufacturer stated maximum static load of the shaker is 35 kg, the spring supports were included in the test rig to ensure that the shaker was not loaded with the full mass of a test subject. The linear guides were included in the design to constrain the movement of the shaker table to the vertical direction. The photographs in Figure 78 show the shaker and frame assembly installed in the laboratory.

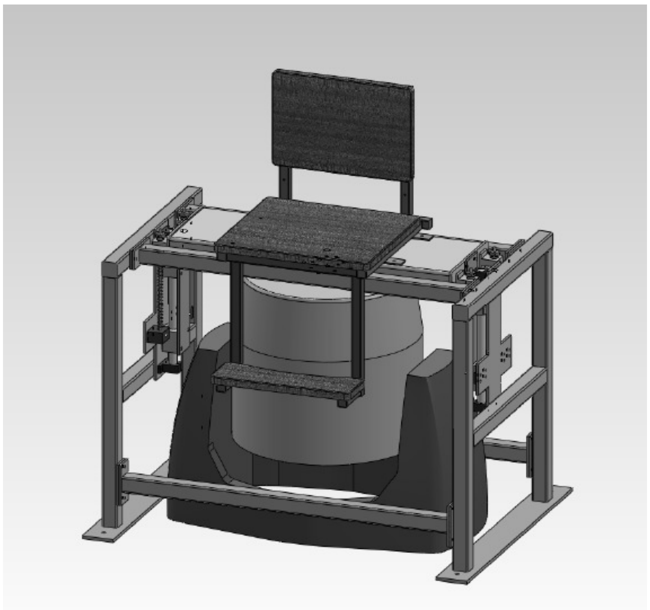

Figure 77 Sketch showing initial design of test rig.

Figure 78 Photographs of the shaker system installed in the lab.

7.2.2 RESPONSE OF TEST RIG

To investigate the response of the test rig, a number of measurements were conducted using piezoelectric accelerometers mounted to the table of the shaker rig in the positions indicated in Figure 79. All of the results presented in this section were measured using a B&K PULSE acquisition system with a window length of 800 samples and 800 FFT lines. All of the frequency response functions shown in this section were calculated using the H1 method (Randall, 1987).

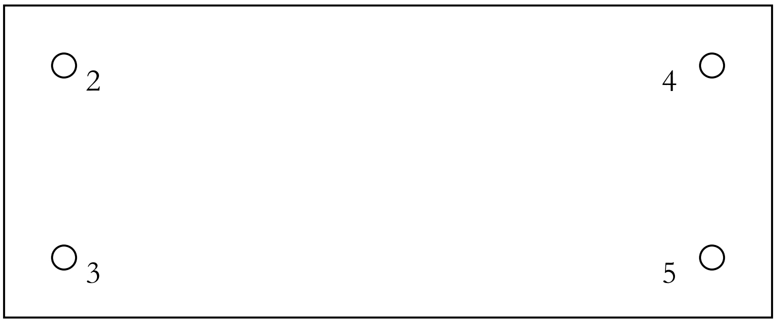

Figure 79 Plan view of the positions of accelerometers on the table of the shaker rig

Figure 80 shows the magnitude Fourier spectrum of the background vibration in the vertical direction on the shaker table with the shaker system switch on but in an idle state. The dashed line in this figure shows the vertical vibration perception base curve from BS 6471-1:1992. It can be seen from this figure that, according to the perception base curve, the background vibration on the shaker table is well below the threshold of perceptibility.

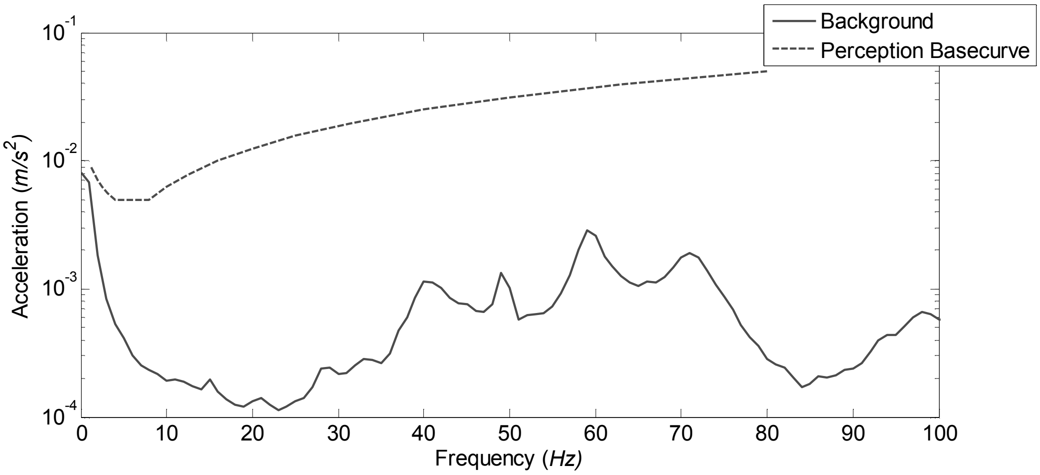

Figure 80 Background vibration in the vertical direction on the shaker table compared to the vibration perception base curve in the vertical direction.

Figure 81 shows the frequency response function between the voltage input to the amplifier and the four measurement positions on the table of the test rig. The excitation for this frequency response function measurement was broadband noise and the measurement was conducted with an 81 kg person seated on the test rig. It can be seen from the top pane of this figure that, apart from in the 40 Hz to 60 Hz region the magnitude frequency response function exhibits a broadly linear trend and below around 60 Hz there is good agreement between the four measurement positions. From the bottom pane of Figure 81, it can be seen that the system has a relatively flat phase response.

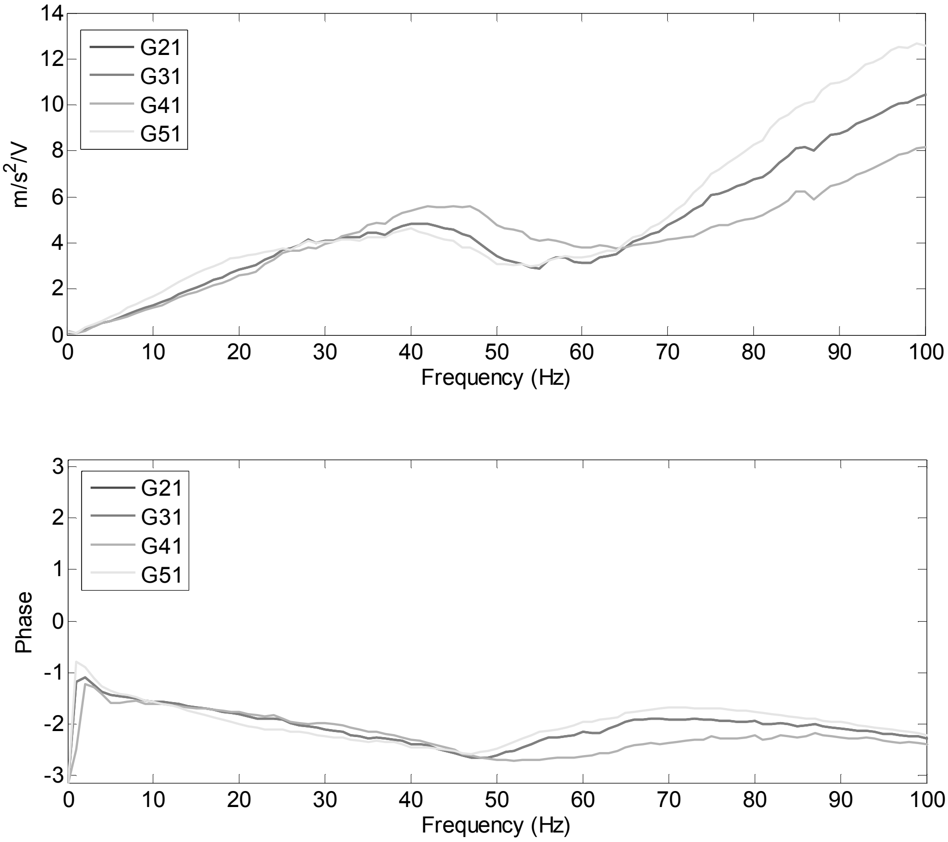

Figure 81 Magnitude (top pane) and phase (bottom pane) of frequency response function of the amplifier and shaker system. Gx1 is the frequency response function between the voltage input to the system and the acceleration at the xth measurement position in Figure 79.

Figure 82 shows the frequency response function between the four measurement positions indicated in Figure 79. This measurement was conducted using a white noise excitation with an 81 kg person seated on the test rig. The magnitude of the frequency response function is shown in the top pane of this figure and the phase is shown in the bottom pane. It can be seen from the top pane of this figure that the magnitude of the frequency response function between the positions differs from unity by around +/- 0.25 in the frequency range 0 – 100 Hz. This suggests that the whole shaker table is moving broadly in phase with minimal rocking.

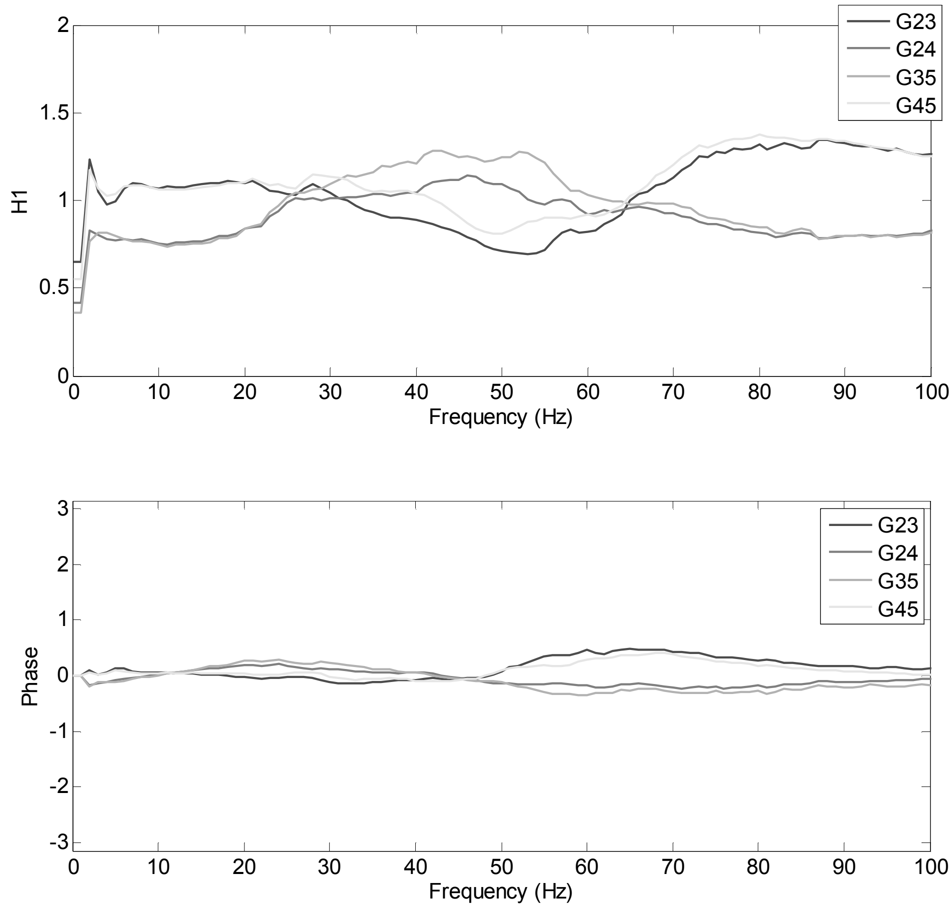

Figure 82 Magnitude (top pane) and phase (bottom pane) of the frequency response function between the different measurement positions in Figure 79. Gxy is the frequency response function between the xth and the yth position in Figure 79.

The inverse of the linear trend shown in the magnitude frequency response function of the shaker system in the top pane of Figure 81 was applied to a measurement of train vibration and this signal was input to the shaker system. Figure 83 shows the acceleration measured on the table of the shaker system with and without this compensation applied compared with the original measured signal. It can be seen that with the application of this compensation a good agreement between the original measured train vibration and the vibration reproduced by the shaker system can be achieved. Figure 84 shows the time history of the original signal and the acceleration reproduced by the shaker system. It can be seen from this figure that a reasonable approximation of the measured signal in time can also be achieved. Similar results were observed for a number of measured railway vibration signals.

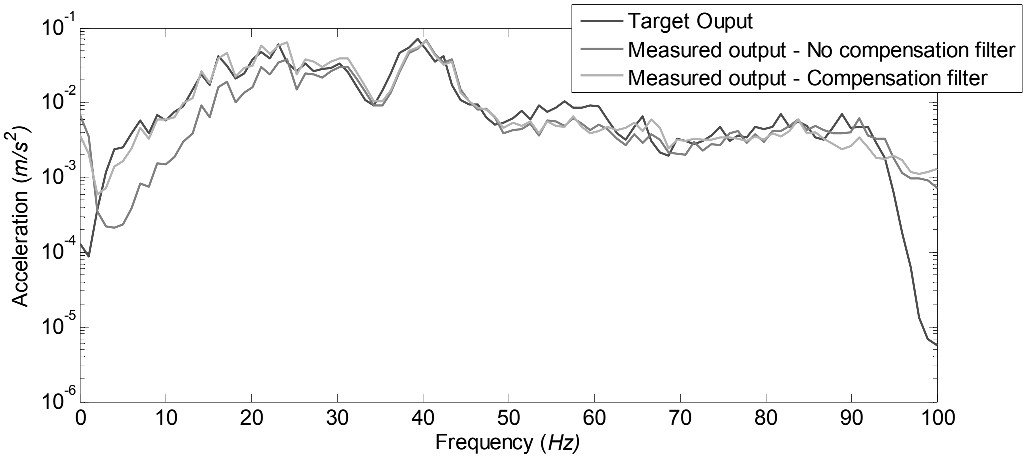

Figure 83 Magnitude Fourier spectrum of a train event measured on the shaker table with and without compensation filter.

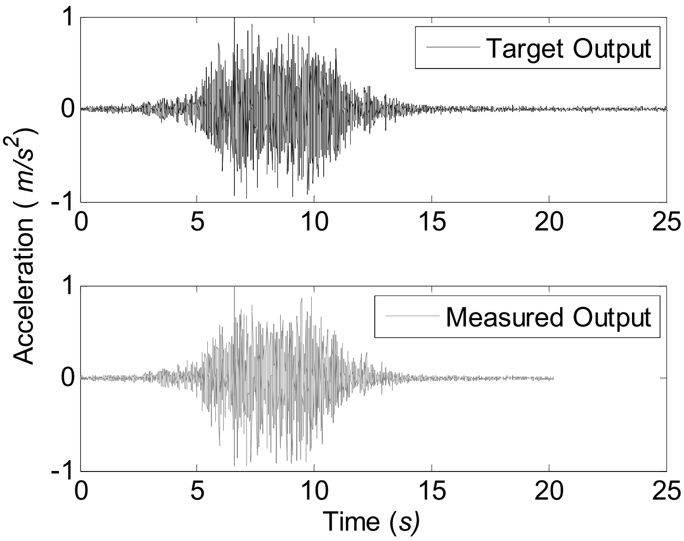

Figure 84 Time history of acceleration measured on the shaker table compared to the target acceleration.

7.2.3 Safety and Ethical Considerations

BS 7085:1989 states that in laboratory tests, human subjects should not be exposed to whole body vibration which exceeds a W_b weighted Vibration Dose Value (VDV) of 15 m/s$^{1.75}$. To ensure that this level can not be exceeded due to a power surge or signal generation fault, the amplifier which drives the shaker is fitted with a current limiter. Throughout the subjective tests described in this chapter it was ensured that the current limiter was set to its most sensitive setting. To determine the maximum W_b weighted VDV which the shaker system is capable of with the current limiter at this setting, a high amplitude transient signal was input to the shaker system. Figure 85 shows the W_b weighted acceleration measured on the table of the test rig when the system shuts down due to a high amplitude input. The W_b weighted VDV of this excitation is 1.33 m/s$^{1.75}$ which is significantly below the upper limit suggested in BS 7085:1989.

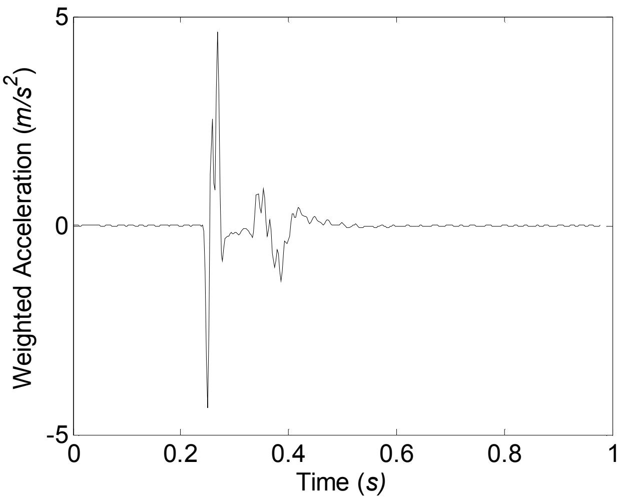

Figure 85 Weighted acceleration measured on the shaker table during amplifier shutdown due to a high amplitude transient.

In addition to ensuring that subjects were not exposed to harmful levels of vibration, prior to the tests it was ensured that subjects did not suffer from, nor had suffered in the past, any medical condition which would prevent them from taking part in a test which involved exposure to whole body vibration. This was checked via a consent form which was signed by each subject prior to the test. The consent form is reproduced in Appendix II.

The subjective testing presented in this chapter was approved by the University of Salford's ethical committee.

7.3 SELECTION OF STIMULI

From the field work described in Chapter 3, over 64,500 recorded train signals were available as potential stimuli for the subjective test described in this chapter. A method of stimulus reduction was therefore required to generate a representative set of stimuli to be used in the subjective tests described in this chapter. As an initial step, any of the available train signals with a W_b weighted peak magnitude less than 0.015 m/s^2 was excluded as a potential test stimulus. This step was taken as, according to ISO 2331 – 1:1997, this magnitude is the median vibration perception threshold for healthy human subjects. Although the applicability of this perception threshold to vibration under field conditions has been questioned both in this thesis and other publications, this appeared to be the logical first step in the reduction of the stimulus set. Following this initial step, 14,143 train signals remained as potential stimuli.

For the remaining signals, a number of objective descriptors describing frequency, energy, and temporal characteristics of each train signal were calculated. The descriptors of energy calculated were RMS acceleration and the VDV both of which are defined in Chapter 4 section 4.3.1. Spectral centroid, which is defined in Chapter 4 section 4.3.2, was calculated as a descriptor of the frequency content of each train signal. To describe temporal aspects of the train signals the crest factor (see Chapter 4 section 4.3.1), kurtosis (see Chapter 4 section 4.3.1), duration defined by the 3 dB and 10 dB down points of the signal envelope, and the modulation depth and modulation frequency were calculated.

The modulation depth was defined as the average difference between the maxima and minima of the signal envelope expressed in decibels. Modulation frequency was defined as one over the average period between the maxima of the signal envelope (T_f). These parameters were evaluated in the portion of the signal between the 10 dB up and down points. Modulation depth and modulation frequency are illustrated in Figure 86 which shows the envelope of a train vibration signal compared with its acceleration time history.

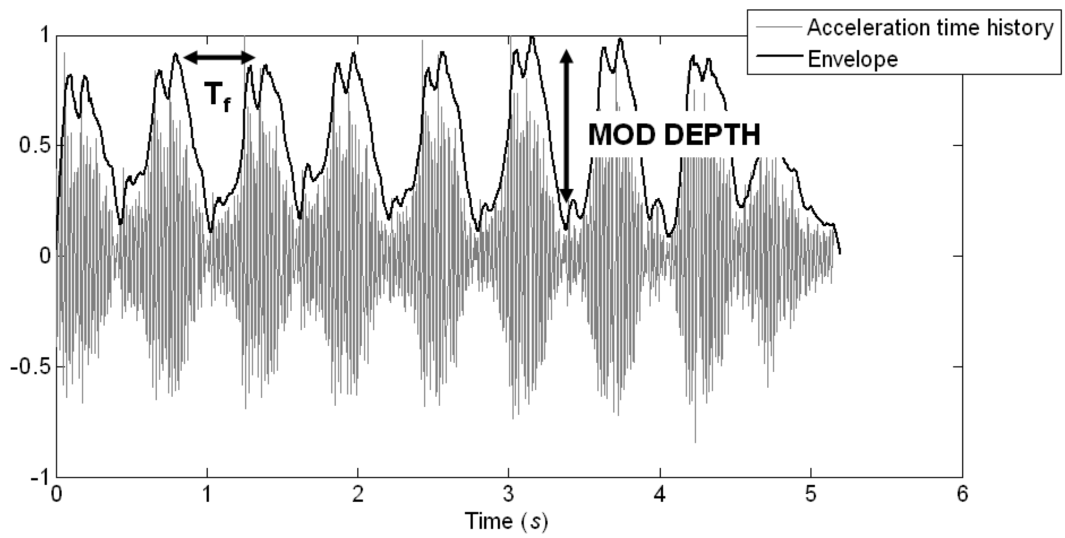

Figure 86 Illustration of the modulation depth and modulation frequency of a train signal.

A principal component analysis was then conducted on a matrix of these descriptors. Figure 87 shows a scree plot of the percentage of variance explained by each of the recovered principal components. Although there is no obvious 'elbow' in the scree plot, a four dimensional solution was examined as this dimensionality accounts for almost 80% of the explained variance in the descriptor space. Figure 88, Figure 89, and Figure 90 show the positions of each of the 14,143 train signals on the first four principal component along which the weighting of each of the calculated descriptors has on the component. The results presented in these figures suggest that the first principal component is related to the length of the signal, the second component is related to the energy of the signal, the third component is related to envelope modulation, and the fourth component is related to frequency content.

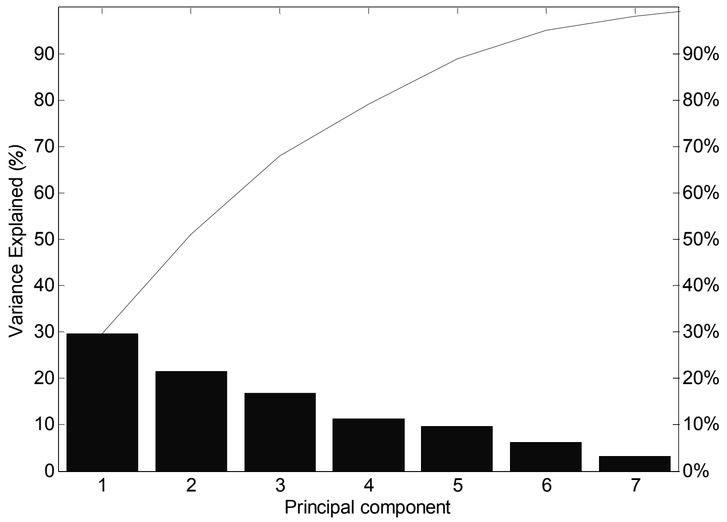

Figure 87 Scree plot of the percentage of the percentage of variance explained by each of the recovered principal components.

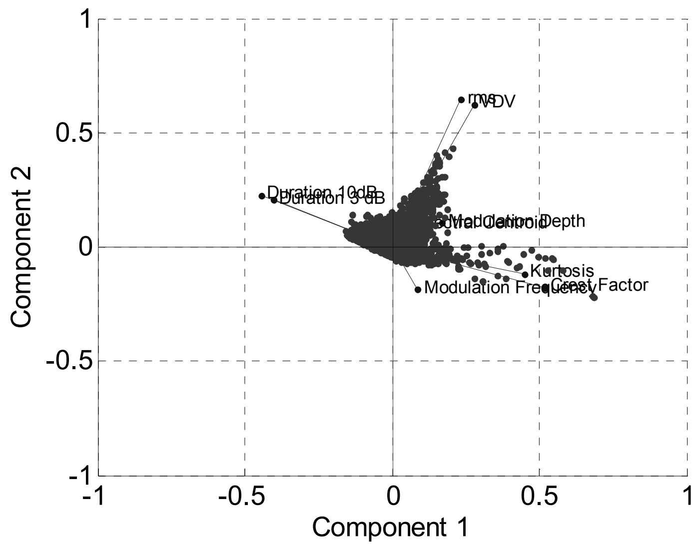

Figure 88 Position of the 14,143 considered train signals on the first and second principal components along with the weighting each metric has on the component.

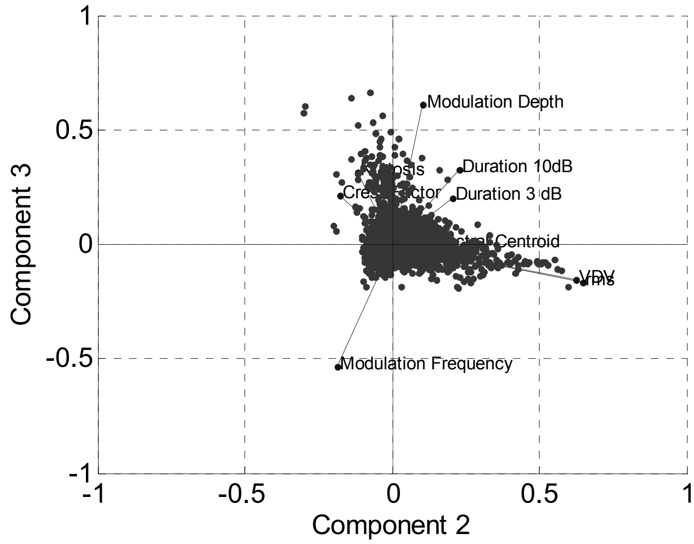

Figure 89 Position of the 14,143 considered train signals on the second and third principal components along with the weighting each metric has on the component.

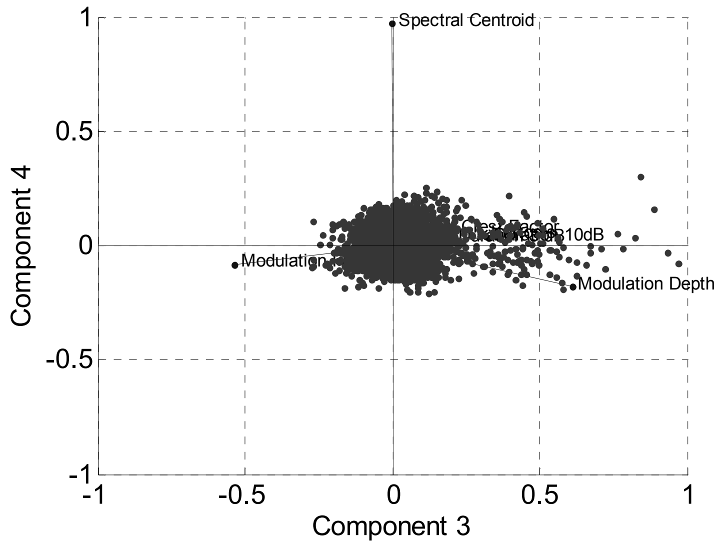

Figure 90 Position of the 14,143 considered train signals on the third and fourth principal components along with the weighting each metric has on the component.

To select the final stimulus set for the subjective test, each of the four recovered principal components was divided into four equal areas and a single train signal was randomly selected from each area. Upon investigation of the generated stimulus set, it was discovered that a number of the signals at the extreme of the first principal component were spurious events such as footfalls. By rejecting these signals, a final stimulus set of fourteen train signals was arrived at. The acceleration time histories of the set of fourteen test stimuli used in the subjective test described in this chapter are presented in Figure 91.

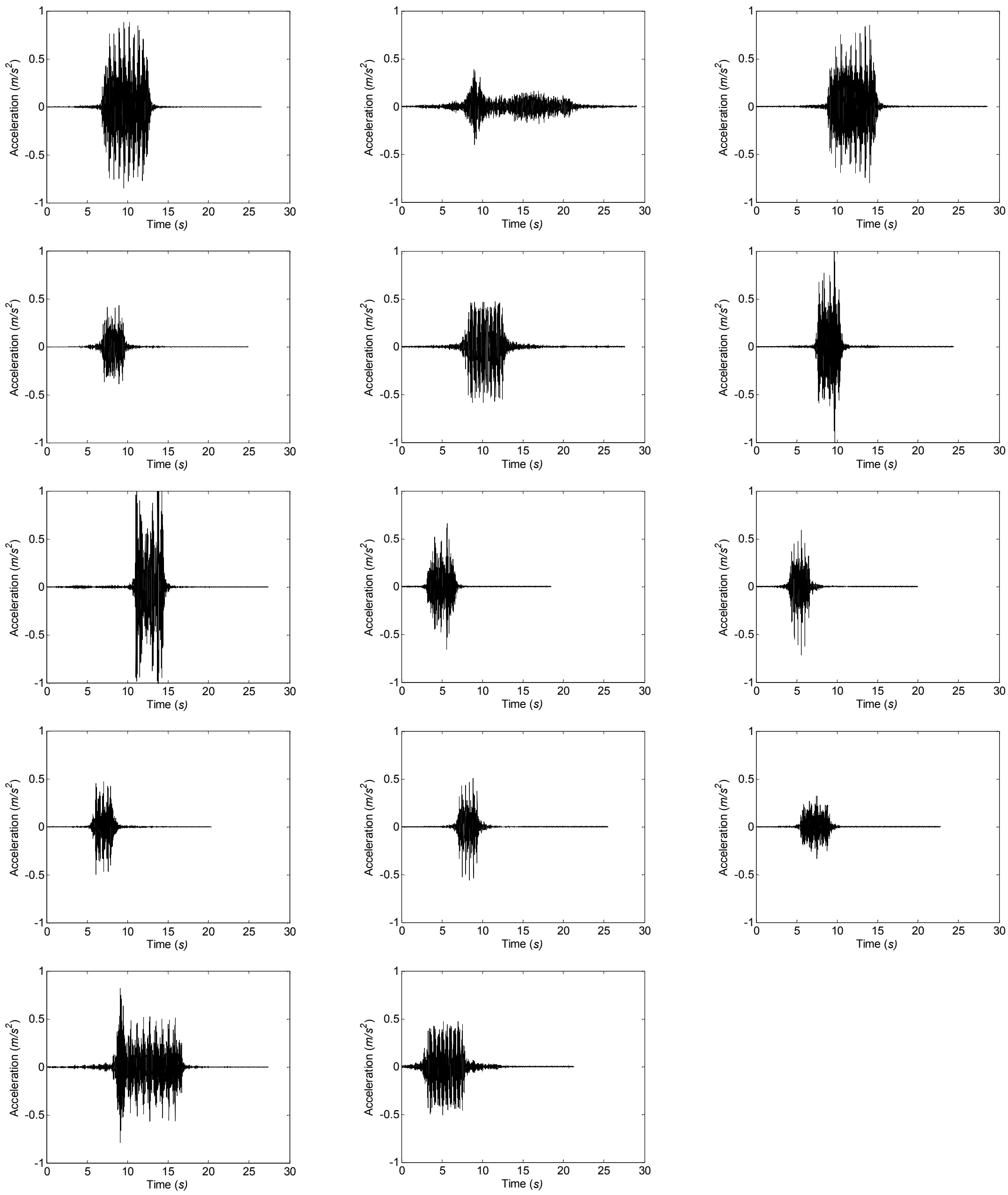

Figure 91 Acceleration time histories of the fourteen train signals used as stimuli in the subjective test.

7.4 TEST DESIGN

7.4.1 ORDER OF STIMULI

One disadvantage of the paired comparison test methodology is the prohibitive test length inherent in studies with either a large number of stimuli or stimuli of long duration. In a full paired comparison test design, the subject is required to make a judgement upon $\frac{N(N-1)}{2}$ pairs of stimuli where N is the number of stimuli under investigation. If it is assumed that it takes a subject 5 seconds to make a judgement upon a pair of stimuli of duration t (s) with a 1 second gap between the pair, then the duration of the total test in seconds is:

$$T = \frac{N(N-1)}{2} \cdot (t+6)$$ **Equation 47**

As illustrated in Figure 92, by increasing either the duration or number of stimuli the total test time quickly becomes unfeasible.

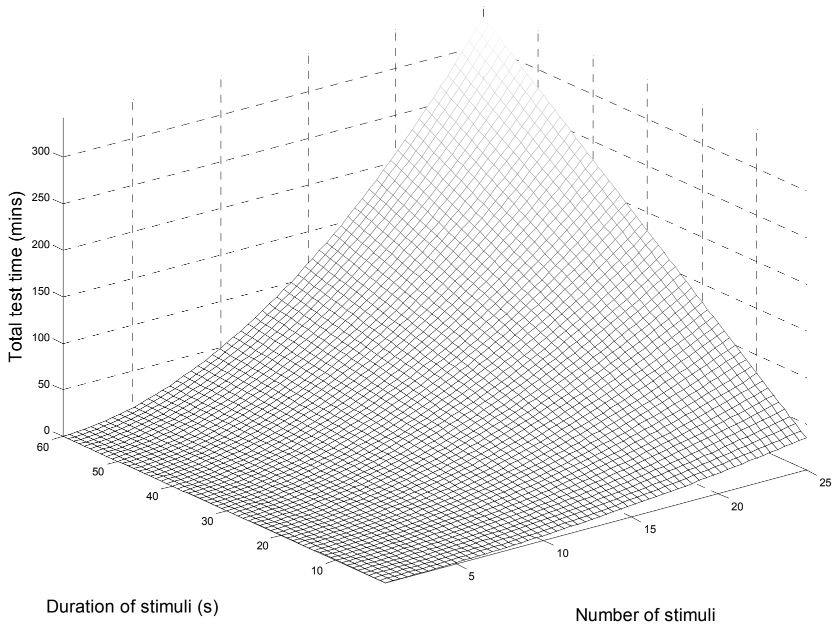

Figure 92 Estimated duration of a full paired comparison test for different numbers and duration of stimuli

It was therefore decided that for the paired comparison tests described in this chapter, an incomplete test design would be utilised to reduce the length of the perceptual test. It has been shown by Spence and Domoney (1974) that many of the pairs tested in a complete paired comparison design[8] lead to essentially redundant data. Spence and Domoney investigated data redundancy in paired comparison tests by conducting Monte-Carlo simulations to determine the influence of incomplete paired comparison data upon non-metric scaling configurations (see section 6.4). From a complete matrix of paired comparison data, pairs were omitted via four different methods; random designs, overlapping clique designs, and two cyclic designs. For the random designs, 1/3 and 2/3 of the dataset were omitted at random. For the overlapping clique designs, overlapping sub-matrices consisting of 1/3 and 2/3 of the full dataset were used. For the cyclic designs, two types of incomplete cyclic designs consisting of 1/3 and 2/3 of the full dataset were investigated. It was found that incomplete cyclic designs resulted in the most accurate reconstruction of the MDS solution and that a reasonable solution could be achieved even when 2/3 of the data was omitted.

Incomplete cyclic designs (ICDs) are a systematic method for omitting pairs in a paired comparison test design. The use of an ICD ensures that each object appears an equal number of times in the paired comparison test. A method for generating ICDs, adapted from David (1963), is outlined below:

1. The test consists of N objects labelled 0, 1, 2, … , $N-1$
2. Cyclic sets can be built from these objects such that:

[8] A complete paired comparison design refers to a test in which every possible pair of stimuli is tested

$\{s\}$: $(0, s)$ $(1, s + 1)\ldots(N - 1, s + N - 1)$ where all elements are modulo N. Each of these sets contains a pair of objects to be presented to the subject.

For example, if $N = 8$

{3}: (0,3) (1,4) … (4,7)

3. A number of cyclic sets can then be combined to increase the number of pairs in the design.

   For example, the design {1,3} would consist of the sets {1}+{3}

ICDs can be visualised by means of a ring of objects representing the group of stimuli to be tested along with connections between the objects representing which pairs are included in the paired comparison test (Burton, 2003). Figure 93 shows examples of a number of ICDs designed using the method outlined above. By randomising the positions of the objects in the ring, different designs can be achieved.

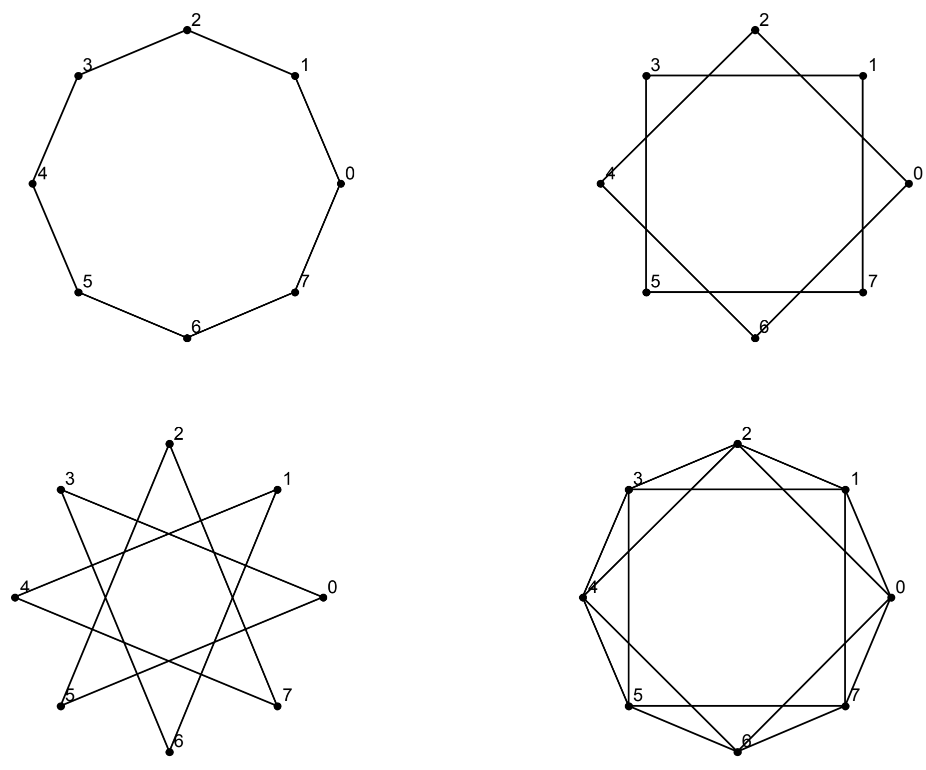

Figure 93 Examples of ICDs for designs (clockwise from top left) {1}, {2}, {3}, {1,2}

Using the method outlined above, a {1,3,5,9} incomplete cyclic design was generated for each subject taking part in the paired comparison tests described in this chapter. Removing any duplicate pairs, the incomplete cyclic designs resulted in test series with between 42 and 56 pairs for each subject. For 14 stimuli a full paired comparison test would require each subject to judge 91 pairs of stimuli, therefore the incomplete test designs used in this chapter resulted in perceptual test between 46% and 62% of the length which would have been required if using a full paired comparison design.

7.4.2 SUBJECT TRAINING

Twenty-one subjects participated in the subjective tests described in this section. Prior to the start of the subjective test, subjects were provided with written (see Appendix III) and verbal instructions of their task. Following this, they were asked to sit comfortably on the chair of the test rig with their feet supported by a stationary footrest. Once sat in a comfortable position, the subject was asked to maintain their posture as far as possible throughout the test. Subjects were then given the opportunity to familiarise themselves with the main paired comparison test interface (see following section) via five trial pairs of vibration stimuli. Once the subject had familiarised themselves with the paired comparison test interface, they were given the opportunity to feel each of the fourteen vibration stimuli used in the test via the interface shown in Figure 94.

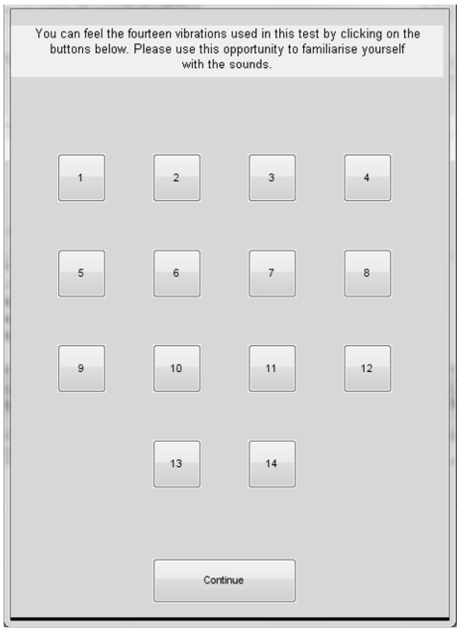

Figure 94 Graphical interface used in the training session of the paired comparison tests.

7.4.3 PAIRED COMPARISON OF SIMILARITY AND ANNOYANCE

The test interface developed for the paired comparison tests is shown in Figure 95. Via this interface, subjects were presented with pairs of vibration stimuli separated by 1 *s* and ordered according to an incomplete cyclic design (see section 7.4.1). The start of each stimulus was marked via a 0.5 *s* beep generated by a loudspeaker. Subjects were asked to make two judgements upon each pair of vibration stimuli:

1) *Which of the trains would bother, disturb, or annoy you most if you felt them in your home?*
2) *How similar do you perceive the pair of vibrations to be?*

The responses to both of these questions were recorded via continuous sliders and coded -0.5 to 0.5 for question 1) and 0 to 1 for question 2). For each paired comparison trial, the sliders were initialised to the positions shown in Figure 95. Subjects were allowed to feel each pair of vibration stimuli as many times as they wished, they were however encouraged during the training period of the test to make their judgements based as far as possible upon their initial reactions.

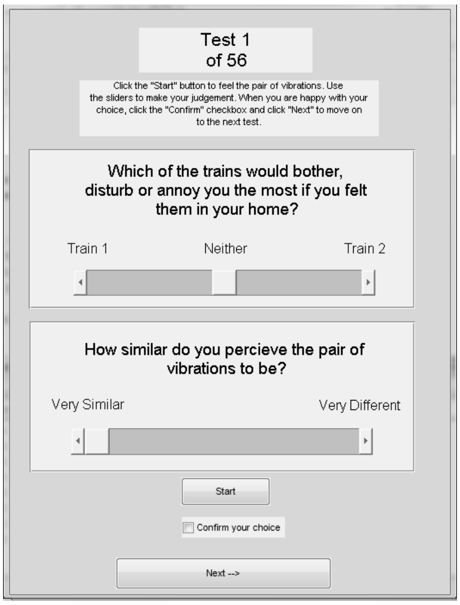

Figure 95 Graphical interface used in the paired comparison tests.

7.4.4 CATEGORY RATING OF ANNOYANCE

It was highlighted in Chapter 6 section 6.8.2 that paired comparison tests of annoyance result in single figure annoyance ratings which are on an arbitrary scale and relative to the set of stimuli upon which they were judged. To measure annoyance on an absolute scale and to allow the results of the subjective tests detailed in this chapter to be comparable to the annoyance responses collected via the field work detailed in Chapter 3, subjects were exposed to each of the vibration stimuli individually and asked to indicate on a five-point semantic scale how bothered, disturbed or annoyed they would be if they were to feel this vibration in their home. This section of the test took place immediately after the paired comparison judgements detailed in the previous section. The interface for this phase of the subjective test is shown in Figure 96.

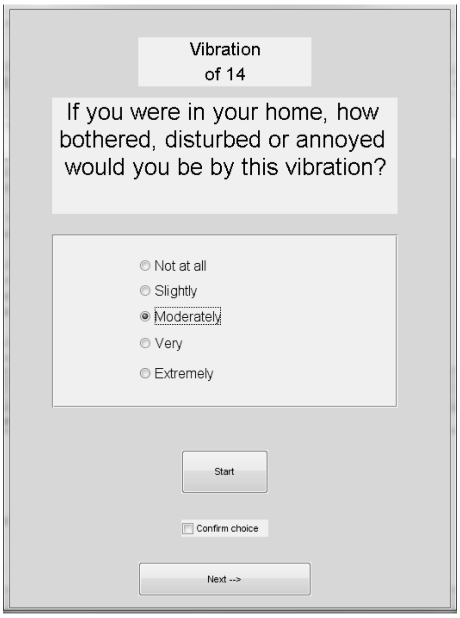

Figure 96 Graphical interface used for the category rating of annoyance tests.

7.5 RESULTS

7.5.1 MULTIDIMENSIONAL SCALING OF DISSIMILARITY

In the pilot test detailed in Chapter 6, the analysis of the dissimilarity data measured in the paired comparison tests were analysed using the INDSCAL multidimensional scaling algorithm. This MDS routine has the advantage of representing the inter-subject differences in the calculated solution. However, this and similar MDS algorithms which preserve inter-subject differences are sensitive to missing values (Giguère, 2006) which are inherent in data collected using incomplete paired comparison designs. It was therefore necessary to generate a single average dissimilarity matrix from the data measured in the incomplete paired comparison tests detailed in section 7.4.3.

From the incomplete cyclic designs generated for each subject, an inclusion matrix Q_S was calculated for each subject whereby:

$$q_{s,i,j} = \begin{cases} 1 \text{ if dissimilarity } \delta_{s,i,j} \text{ is included in test} \\ 0 \text{ otherwise} \end{cases}$$ **Equation 48**

Where $q_{s,i,j}$ is the element in the inclusion matrix Q_S for subject *s* and the comparison between stimulus *i* and *j* and $\delta_{s,i,j}$ is a judged dissimilarity.

Partial dissimilarity matrices $\tilde{D}_S$ were then created for each subject *s* where:

$$\tilde{D}_S = \begin{cases} \delta_{s,i,j} \text{ if } \mathrm{q}_{s,i,j} = 1 \\ 0 \text{ otherwise} \end{cases}$$ **Equation 49**

A single aggregated dissimilarity matrix $\bar{D}$ was then calculated by summing each of the partial dissimilarity matrices over the subject group and dividing by the inclusion matrices summed over the subject group:

$$\bar{D} = \frac{\sum_{s=1}^{S} \tilde{D}_s}{\sum_{s=1}^{S} Q_s}$$ **Equation 50**

Non-metric multidimensional scaling solutions were calculated for the aggregated dissimilarity matrix $\bar{D}$ in one to eight dimensions. Figure 97 illustrates the relationship between stress and the number of dimensions for these solutions. As discussed in Chapter 6 section 6.8.1, stress is a measure of the goodness of fit of the multidimensional scaling solution to the original pairwise dissimilarities. Lower values of stress indicate a better fit between the multidimensional scaling configuration and the judged dissimilarities. As the stress is for a non-metric solution, the stress being close to zero for the eight dimensional solution implies that a nearly perfect monotonic relationship has been found between the fitted distances and measured dissimilarities but not necessarily that the dissimilarities have been perfectly reproduced in this configuration (Kruskal, J., 1964). The case where a permissible ordinal transformation has been found but the relationship between the fitted distances and the original dissimilarity data is poor is known as a degenerate solution. Such degenerate solutions can be expected in non-metric multidimensional scaling when the dimensionality is high compared to the number of stimuli (Borg, 2005). Although there is no obvious 'elbow' in this relationship, a four dimensional solution was taken as a starting point for the analyses presented in this chapter.

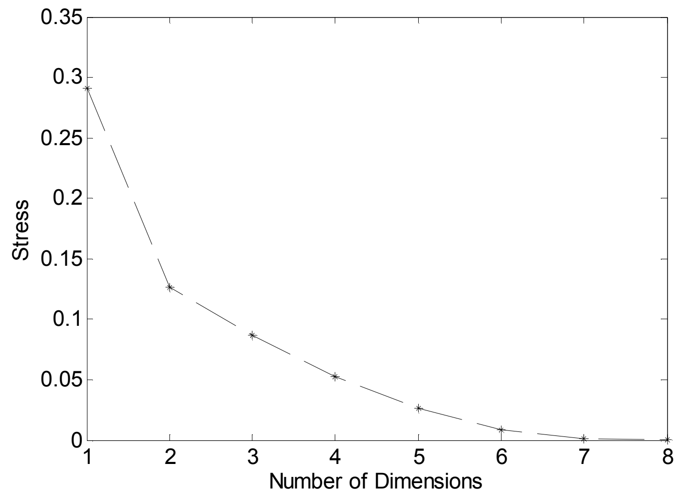

Figure 97 Scree plot showing stress as a function of number of dimensions.

Figure 98 shows the four dimensional multidimensional scaling solution for the paired comparison of dissimilarity tests. The fourteen points in the configurations shown in this figure represent the fourteen train vibration stimuli used in the paired comparison tests with large distances between points in the configurations representing large judged dissimilarities. As with the results of the pilot test presented in Chapter 6, it can be seen from this figure that the positions of the stimulus points are well distributed across each of the perceptual dimensions suggesting that subjects made their judgements based upon perceptual continua and did not simply categorise the stimuli.

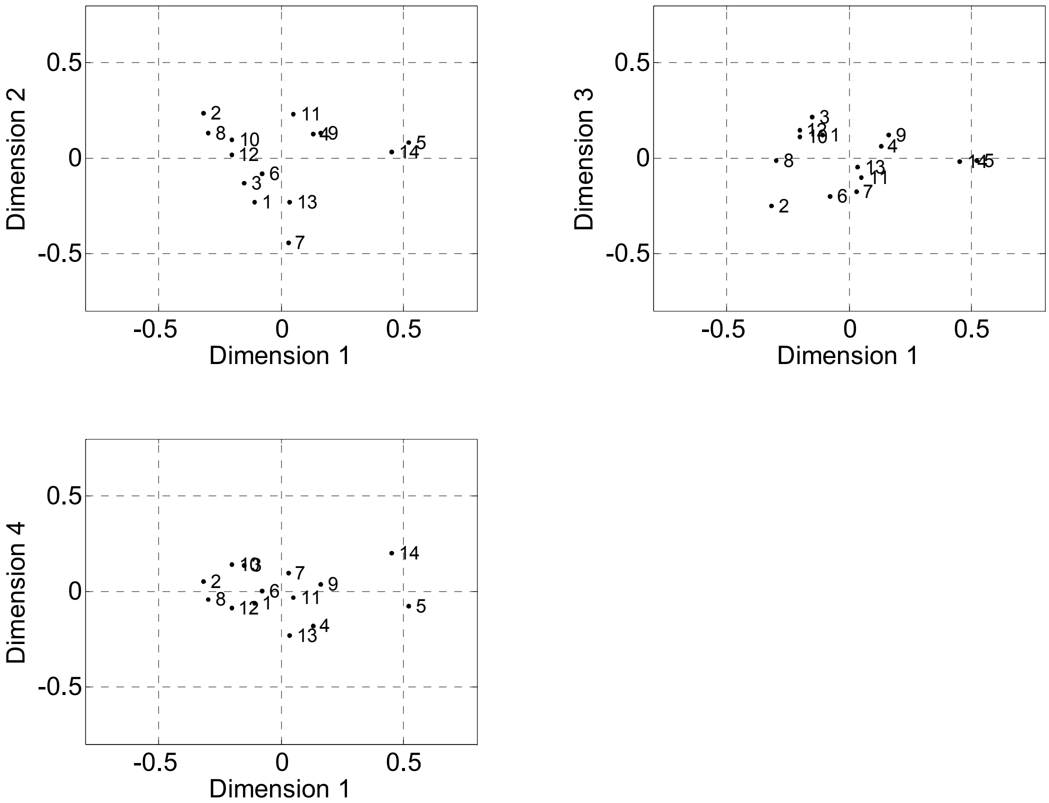

Figure 98 Four dimensional non-metric multidimensional scaling configuration calculated form the main paired comparison tests of dissimilarity.

7.5.2 SINGLE FIGURE PERCEIVED ANNOYANCE RATINGS

From the paired comparison of annoyance data, Perceived Annoyance Ratings were calculated for each subject using the following method:

$$A_{i,s} = \frac{1}{N_i} \sum_{j \neq i} P_{j,i,s}$$ **Equation 51**

where $A_{i,s}$ is the Perceived Annoyance Rating for subject s stimulus i, N_i is the number of times stimulus i appeared in the subjective test for subject s and P_{ji} is the paired comparison annoyance rating for stimuli i and j.

Figure 99 shows the Perceived Annoyance Ratings for the fourteen stimuli used in the paired comparison tests linearly averaged across the twenty-one subjects presented in their 95% confidence intervals. The narrow confidence intervals shown in this figure highlight the high inter-subject consistency which can be achieved using the method of paired comparisons. Although the annoyance ratings presented in this section appear to be relatively consistent, previous studies into the perception of sound and vibration have found intra-subject differences from which groupings of subjects can be formed based on their subjective assessments (see, for example, Parizet et al., 2004). It must be pointed out that, with a sample of twenty-one subjects and an incomplete paired comparison test design, any information on intra-subject differences may have been lost due to the relatively small sample size.

As was discussed in Chapter 6 section 6.8.2, it should again be noted that the Perceived Annoyance Ratings presented in this section are on a relative scale with an arbitrary reference point. It is clear from Figure 99, for example, that stimulus five has a greater Perceived Annoyance Rating than stimulus two. What is not clear, however, is how the stimuli would be judged on an absolute scale of annoyance. Although there is variation in the Perceived Annoyance Ratings presented in this figure, it is conceivable that all of the stimuli could be judged in the "Not at all annoying" category on the five-point semantic annoyance scale used in the social survey questionnaire described in Chapter 3. This issue is explored in greater detail in section 7.7.2.

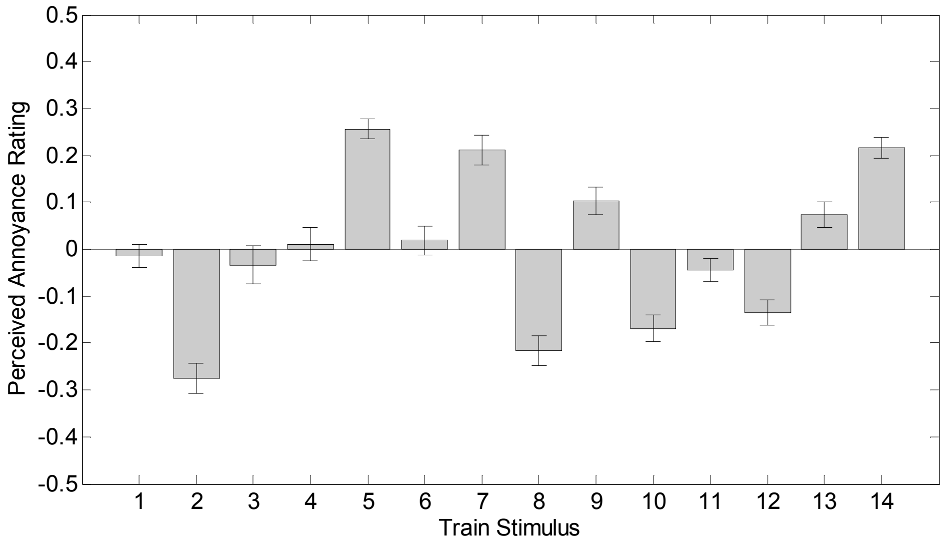

Figure 99 Perceived Annoyance Ratings for the 14 train stimuli. Values shown in their 95% confidence intervals.

7.5.3 INTRA-SUBJECT CONSISTENCY

As discussed in Chapter 6 section 6.8.3, intra-subject consistency in paired comparison tests can be assessed using circular error rates. A circular error is defined as occurring when a subject makes an inconsistent judgement on a triad of stimuli. For example, an inconsistency would occur if a subject were to judge stimulus A is more annoying than stimulus B, stimulus B as more annoying than stimulus C, and stimulus C as more annoying than stimulus A. Figure 100 shows the circular error rates for each of the twenty-one subjects who took part in the paired comparison tests detailed in this chapter. It can be seen from this figure that the majority of subjects were consistent in their judgements with nine subjects making no inconsistent judgements. This may be attributed to the use of an incomplete paired comparison test design as there are fewer triads of stimuli formed than in a full paired comparison test and therefore fewer opportunities for subjects to make inconsistent judgements. This suggests that, in an incomplete paired comparison test, the circular error rate may underestimate intra-subject inconsistency. Therefore, subjects exhibiting circular error rates greater than 10% were omitted from further analysis. It should be noted that this decision was made after an initial investigation into objective correlates to the perceptual dimensions calculated using data from all subjects was found to be problematic.

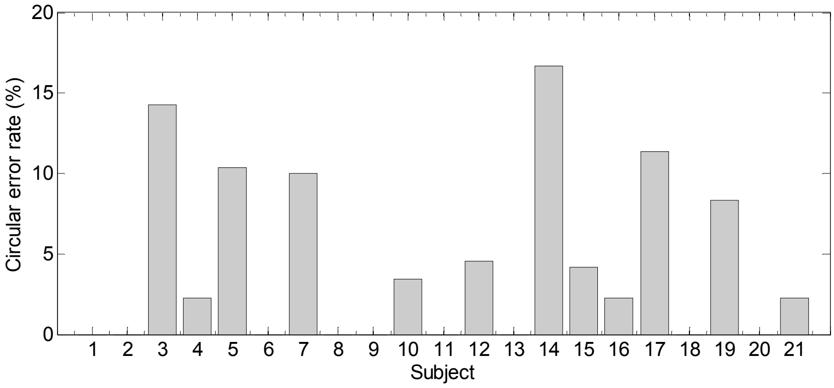

Figure 100 Circular error rate for each of the twenty-one subjects.

Figure 101 shows the four dimensional non-metric multidimensional scaling solution calculated after the omission of subjects 3, 14, and 17. Any further reference in this chapter to the multidimensional scaling configuration or perceptual space refers to that presented in Figure 101 and not Figure 98.

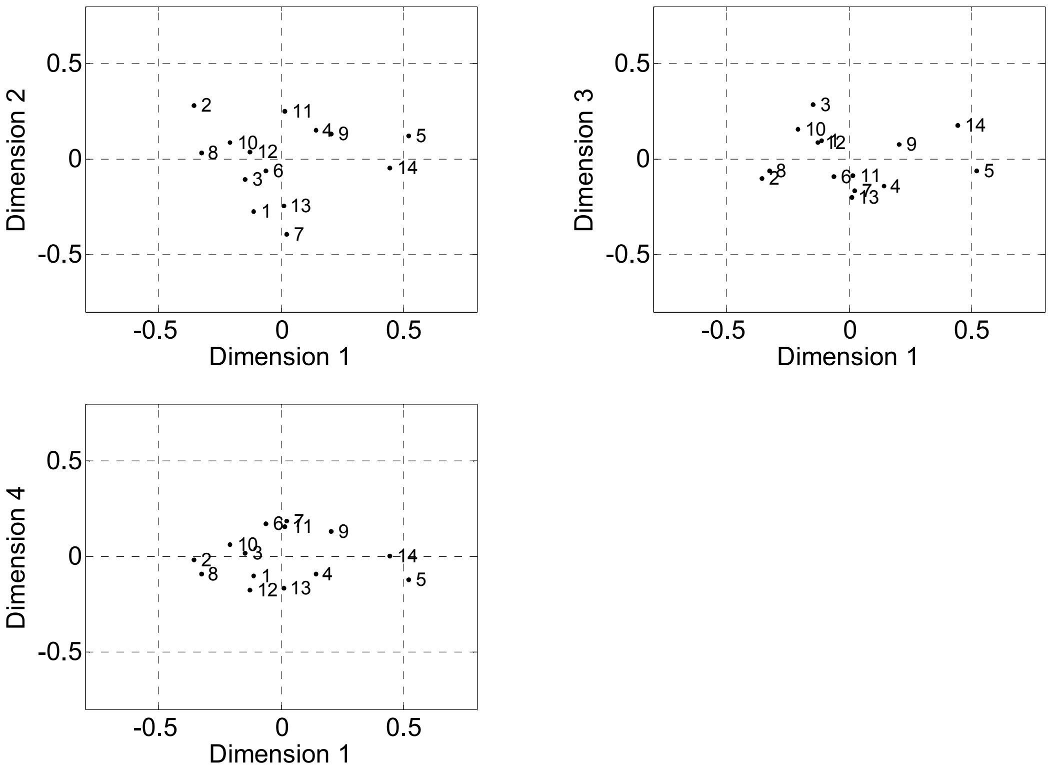

Figure 101 Four dimensional non-metric multidimensional scaling configuration calculated form the main paired comparison tests of dissimilarity. Subjects with circular error rates greater than 10% removed from analysis.

7.5.4 CATEGORICAL ANNOYANCE RATINGS

The stacked bar chart presented in Figure 102 shows the proportion of subjects rating each of the train vibration stimuli in a given annoyance category in the categorical annoyance test described in section 7.4.4. The bars in this figure have been rank ordered according to the Perceived Annoyance Ratings calculated in section 7.5.2. In this figure a general trend can be observed with train stimuli exhibiting higher Perceived Annoyance Ratings being rated with higher categorical annoyance responses. Compared to the confidence intervals of the Perceived Annoyance Ratings shown in Figure 99, there is however large spread of different category ratings for each stimulus.

These results illustrate the advantage of paired comparison tests in terms of inter-subject variability. In a paired comparison test, there is always a reference stimulus meaning inter-subject judgements are fairly consistent. However, when making a judgement on a single stimulus on an absolute scale, the reference is likely the subject's own experience. As experience and perception varies greatly from subject to subject, so do their responses in this type of test. If this sort of spread in annoyance ratings is observed in controlled laboratory tests, the spread observed in the annoyance data collected via the field work described in Chapter 3 is perhaps unsurprising.

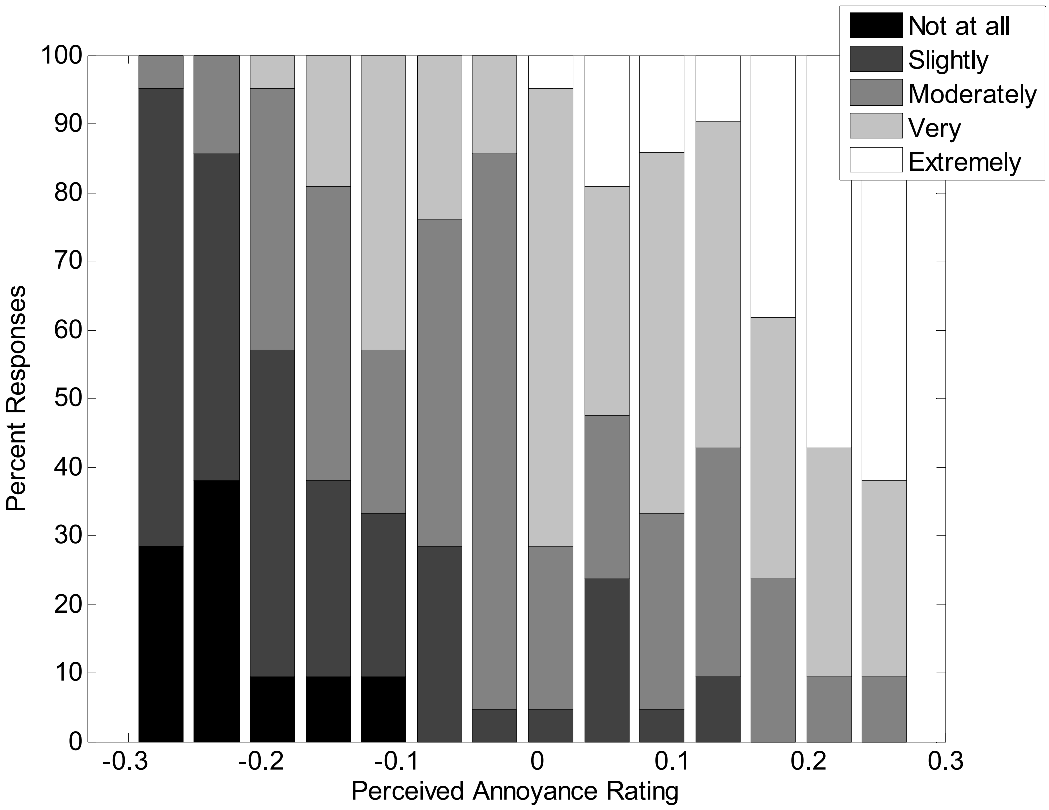

Figure 102 Stacked bar chart showing the proportion of subjects attributing each train stimulus to a categorical annoyance category.

7.6 Interpretation of the perceptual space

7.6.1 Objective correlates

A number of objective descriptors were calculated for each of the vibration signals as potential correlates to the perceptual dimensions revealed the multidimensional scaling analysis of the paired comparison of similarity data. These descriptors were calculated from measurements of acceleration made at the interface between an 81 kg subject and the seat cushion. As was noted in section 7.2.1, due to the compression of the seat cushion for subjects of different masses, there is some uncertainty in the vibration exposure for different subjects. As measures of the energy of the stimuli, VDV, RMS acceleration, peak acceleration, root mean quad (RMQ) acceleration, root mean hex (RMH) acceleration, and root mean oct (RMO) acceleration were calculated. Maximum exponentially weighted running RMS values were also determined with time constants of 1 *s* and 0.125 *s*. These descriptors were also calculated with the application of the W_b frequency weighting advocated in BS 6472-1:2008. In addition to these descriptors of vibration energy, the 50^{th}, 75^{th}, 90^{th}, and 95^{th} percentile of the acceleration time histories were determined. Temporal features of the stimuli were characterised through the calculation of the crest factor, the ratio between the 95^{th} and 50^{th} percentile, modulation depth, modulation frequency, and duration, rise time, and decay time defined by the 10 dB and 3 dB down points of the signal envelope. Statistical characteristics of the acceleration time histories were described through skewness and kurtosis. Spectral centroid and the dominant frequency of the power spectral density (f_{max}) of the stimuli were calculated to characterise the frequency content of the stimuli. As these descriptors cover temporal, frequency, energy, and statistical characteristics of the stimulus set, it is assumed that the stimulus set is sufficiently characterised so as to give an indication of the nature of each of the perceptual dimensions calculated through the multidimensional scaling analysis.

Table 20 to Table 24 present Pearson's correlation coefficients between these descriptors and the four perceptual dimensions calculated through the multidimensional scaling analysis. The significant correlations presented in these tables are discussed in further detail in the following four sections.

	VDV	RMS	VDV W_b	RMS W_b	Peak	Crest Factor
Dimension I	--	--	0.65*	0.62*	--	--
Dimension II	-0.70**	-0.74**	-0.57*	-0.60*	--	--
Dimension III	--	--	--	--	--	-0.58*
Dimension IV	--	--	--	--	--	--

Table 20 Pearson's correlation coefficients between the four perceptual dimensions and objective vibration metrics. -- not significant, * p < 0.05, ** p < 0.01.

	Running RMS (Fast)	Running RMS (Slow)	Running RMS W_b (Fast)	Running RMS W_b (Slow)	RMQ	RMH
Dimension I	--	--	0.56*	0.65*	--	--
Dimension II	-0.71**	-0.78**	-0.56*	-0.59*	-0.62*	-0.58*
Dimension III	--	--	--	--	--	--
Dimension IV	--	--	--	--	--	--

Table 21 Pearson's correlation coefficients between the four perceptual dimensions and objective vibration descriptors. -- not significant, * p < 0.05, ** p < 0.01.

	RMO	RMQ W_b	RMH W_b	RMO W_b	Mod. Depth	Mod. Freq
Dimension I	--	0.64*	0.60*	0.56*	--	--
Dimension II	-0.56*	--	--	--	--	--
Dimension III	--	--	--	--	--	--
Dimension IV	--	--	--	--	0.79**	-0.57*

Table 22 Pearson's correlation coefficients between the four perceptual dimensions and objective vibration descriptors. -- not significant, * p < 0.05, ** p < 0.01.

	Duration 10 dB	Duration 3 dB	Skewness	Kurtosis	Spectral Centroid	f_{max}	50th percentile
Dimension I	--	--	--	--	--	-0.53*	--
Dimension II	--	--	--	--	--	--	--
Dimension III	0.60*	--	--	--	--	--	--
Dimension IV	--	--	--	--	--	--	--

Table 23 Pearson's correlation coefficients between the four perceptual dimensions and objective vibration descriptors. -- not significant, * p < 0.05, ** p < 0.01.

	75th percentile	90th percentile	95th percentile	95th/50th percentile	Rise time	Decay time
Dimension I	--	--	--	--	--	--
Dimension II	-0.80**	-0.83**	-0.80**	-0.63*	-0.56*	--
Dimension III	--	--	--	--	--	--
Dimension IV	--	--	--	--	--	--

Table 24 Pearson's correlation coefficients between the four perceptual dimensions and objective vibration descriptors. -- not significant, * p < 0.05, ** p < 0.01.

7.6.2 DIMENSION I

The correlations presented in Table 20 to Table 24 suggest that the first perceptual dimension revealed through the multidimensional scaling analysis is related to the W_b weighted VDV, and the W_b weighted RMS, RMQ, RMH, and RMO energy averages of the vibration stimuli. It can be seen from the presented correlation coefficients that the use of the higher power energy average descriptors such as the RMQ, RMH, and RMO does not result in significantly higher correlations with this perceptual dimension over the more conventional RMS averaging. Figure 103 shows the relationship between the positions of the stimuli on the first perceptual dimension and W_b weighted VDV and W_b weighted RMS acceleration. Although there is some scatter apparent, this figure gives confidence that there is a relationship between the first perceptual dimension and these two objective descriptors.

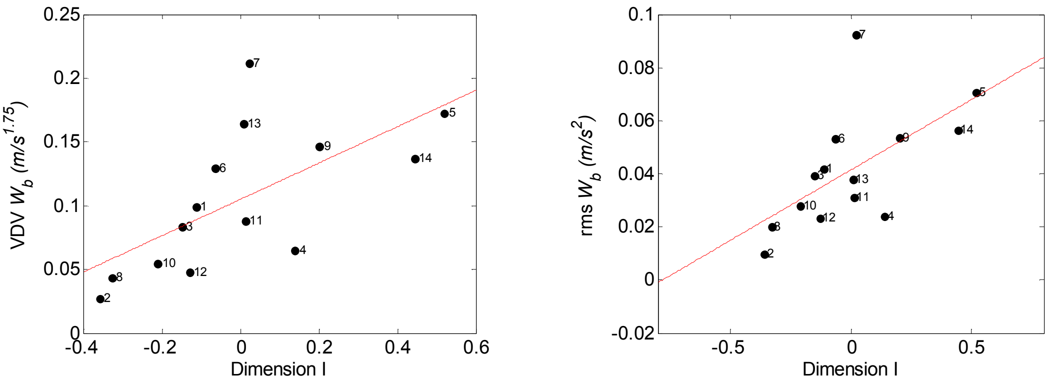

Figure 103 Relationship between the first perceptual dimension and W_b weighted VDV (left pane) and W_b weighted RMS acceleration.

From the correlations presented in Table 20 to Table 24 it is interesting to observe that the weighted RMS and VDV descriptors exhibit a stronger correlation to the first perceptual dimension than their unweighted counterparts. This, along with the moderate correlation between this perceptual dimension and f_{max}, suggests that the frequency content of the vibration exposure has a role in the interpretation of the first perceptual dimension. To further investigate this perceptual dimension, each of the stimuli were filtered into octave bands of centre frequency 4 *Hz*, 8 *Hz*, 16 *Hz*, 32 *Hz*, and 64 *Hz*. Peak acceleration, RMS acceleration, and VDV were then determined for each octave band. Figure 104 shows the Pearson's correlation coefficient between the first perceptual dimension and these three descriptors in each octave band. It can be seen from this figure that there is a strong correlation between the first perceptual dimension and each of the calculated descriptors in the 4 *Hz*, 8 *Hz*, and 16 *Hz* octave bands, the p-value of the correlations in each of these bands is less than 0.001.

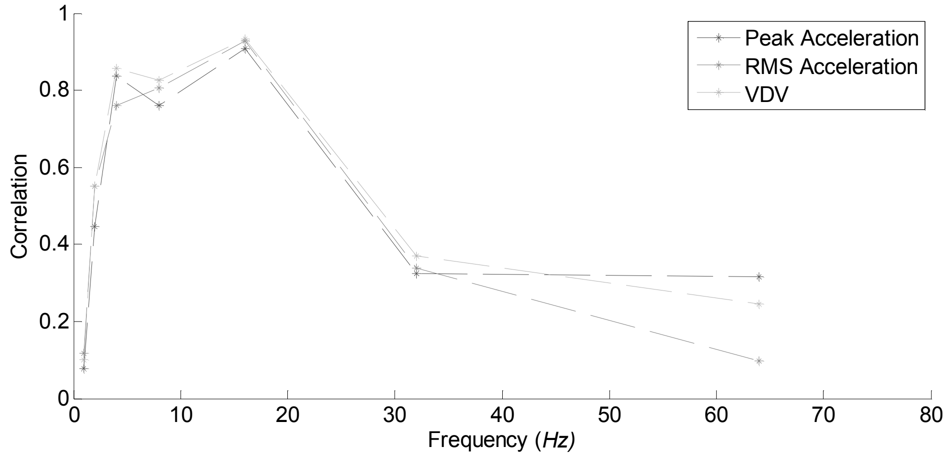

Figure 104 Pearson's correlations coefficient between the first perceptual dimension and peak acceleration, RMS acceleration, and VDV in the 4 Hz, 8 Hz, 16 Hz, 32 Hz, and 64 Hz octave bands.

To illustrate the relationships suggested by the correlation coefficients shown in Figure 104, scatter plots of the positions of each of the stimuli on the first perceptual dimension and RMS acceleration in the 4 *Hz*, 8 *Hz*, and 16 *Hz* octave bands are presented in Figure 105. These figures confirm the relationships suggested by the correlation coefficients presented in Figure 104.

The trend in the correlations shown in Figure 104 with respect to frequency is similar to that of the apparent mass[9] of the seated human body to vertical vibration [see Figure 106 (Fairley and Griffin, 1989)] suggesting that the first perceptual dimension relates to vibration magnitude in the range of frequencies related to whole body vibration. This trend also shows similarities with vertical vibration perception thresholds for the seated position and the W_b and W_k weighting curves (see Chapter2 section 2.3.3).

[9] Apparent mass is the ratio between the force at the interface between the seat and the subject and the acceleration measured at the interface between the seat and the subject.

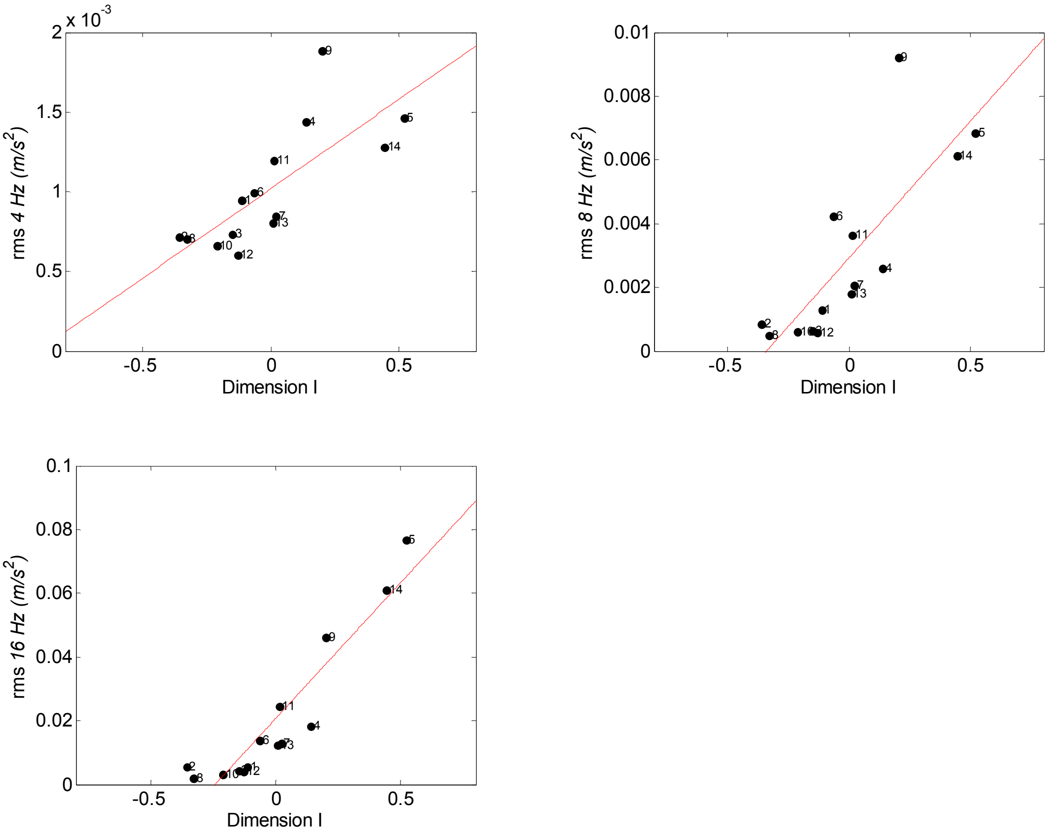

Figure 105 Relationship between the first perceptual dimension and RMS acceleration in the 4 Hz, 8 Hz, and 16 Hz octave bands.

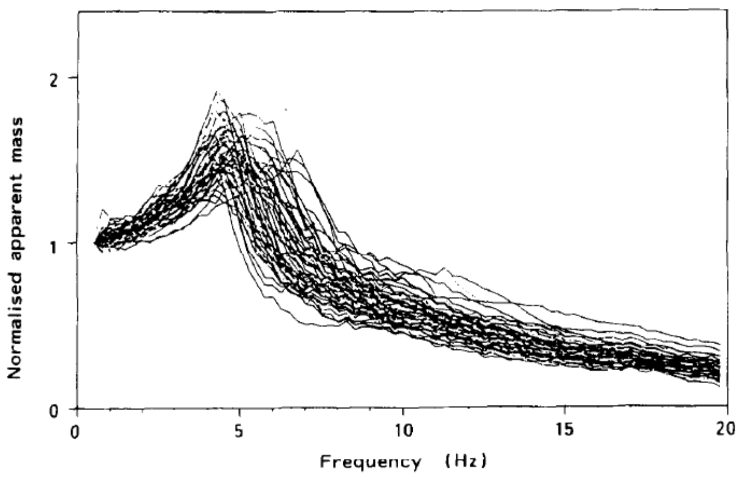

Figure 106 Normalised apparent mass of 60 subjects [source (Fairley and Griffin, 1989)]

7.6.3 DIMENSION II

The correlations presented in Table 20 to Table 24 suggest that the second perceptual dimension revealed through the multidimensional scaling analysis is related to the unweighted VDV and the unweighted RMS, RMQ, RMH, and RMO energy averages of the vibration stimuli. Less significant correlations are also observed between this perceptual dimension and the W_b weighted VDV and RMS acceleration descriptors. Figure 107 shows the relationship between the positions of the stimuli on the second perceptual dimension and the unweighted VDV (left pane) and the unweighted RMS acceleration (right pane).

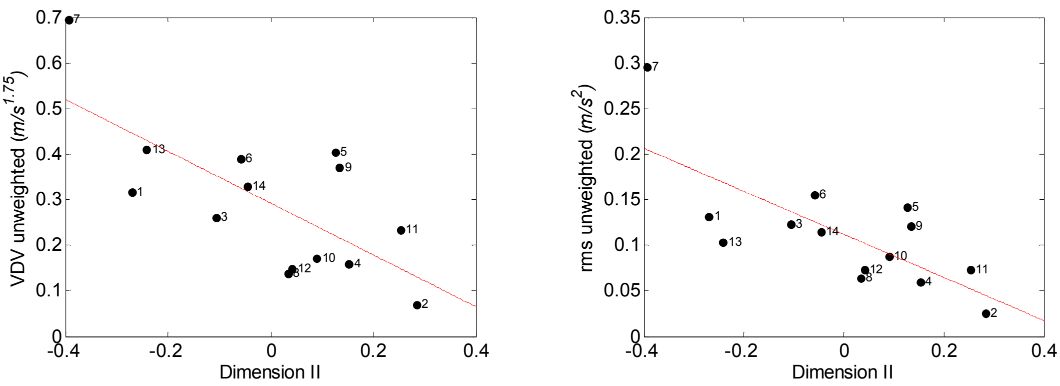

Figure 107 Relationship between the second perceptual dimension and unweighted VDV (left pane) and unweighted RMS acceleration (right pane).

It can also be seen from Table 24 that the second perceptual dimension also shows a strong correlation with the 75th, 90th, and 95th percentiles of the acceleration time histories. Figure 108 shows the relationships between the second perceptual dimension and these descriptors. It should be noted that these three descriptors are highly correlated with each other (Pearson's correlation coefficients ranging between 0.91 and 0.99) making it impossible to judge which may be the more appropriate objective descriptor of the second perceptual dimension.

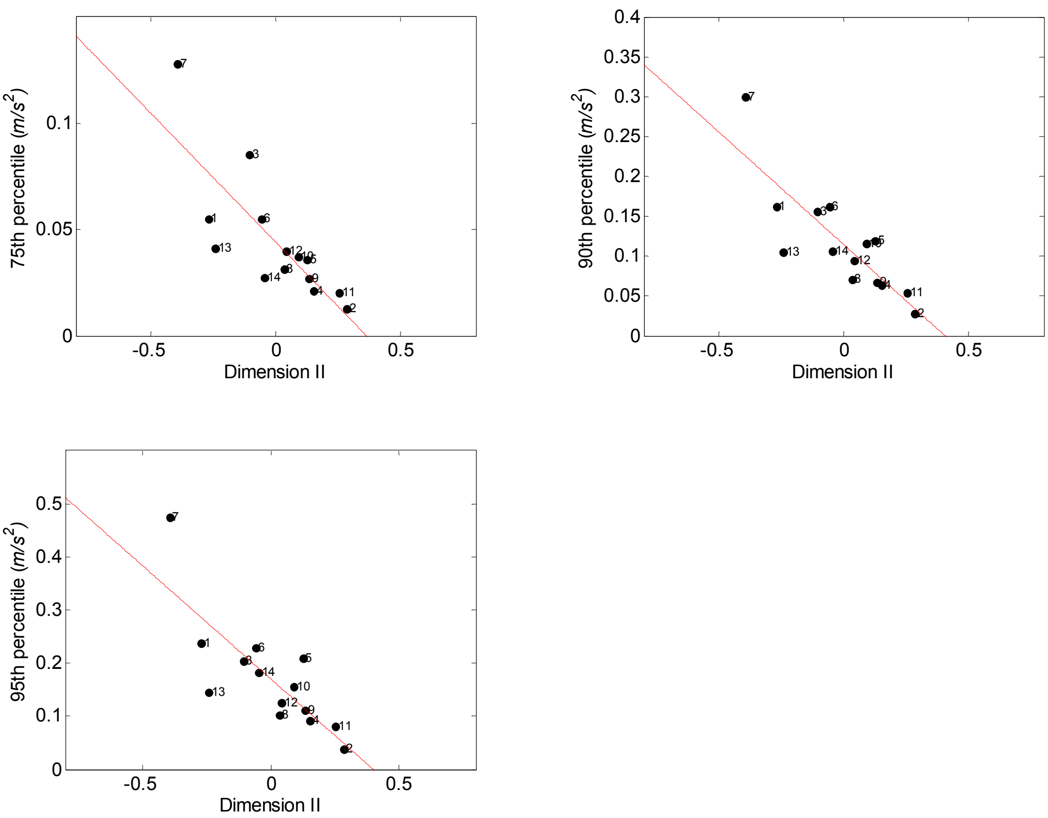

Figure 108 Relationship between the second perceptual dimension and (clockwise from top left) the 75th, 90th, and 95th percentiles of the acceleration time histories.

As with the first perceptual dimension, that the second perceptual dimension shows a greater degree of correlation with the unweighted VDV and RMS acceleration descriptors over their W_b weighted counterparts suggests that the frequency content of the vibration exposure has an influence upon this perceptual dimension. Figure 109 shows the Pearson's correlation coefficients between the second perceptual dimension and peak acceleration, RMS acceleration, and VDV in the 4 *Hz*, 8 *Hz*, 16 *Hz*, 32 *Hz*, and 64 *Hz* octave bands. For ease of comparison with Figure 104, the absolute values of the correlation coefficients are shown. It can be seen from this figure that the second perceptual dimension is significantly correlated with the three descriptors in the 32 *Hz* and 64 *Hz* octave bands.

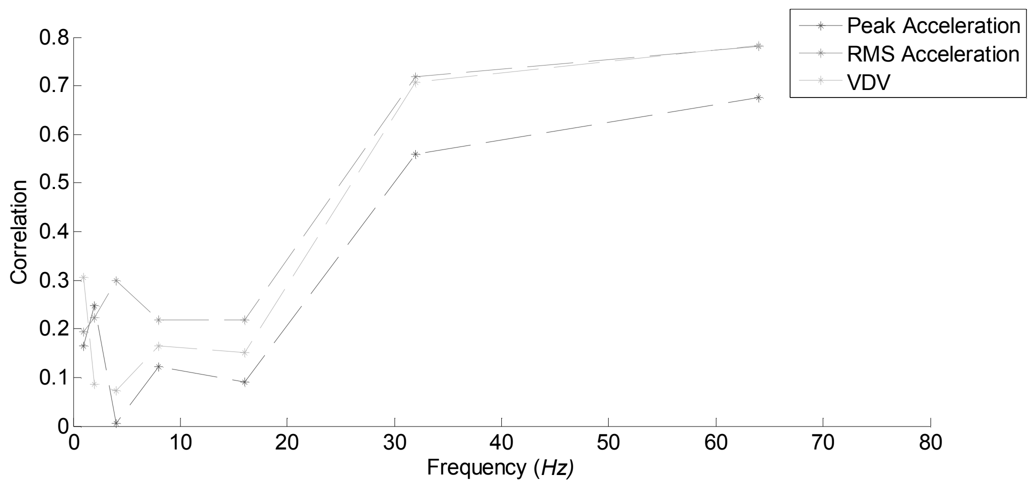

Figure 109 Pearson's correlations coefficient (absolute values) between the second perceptual dimension and peak acceleration, RMS acceleration, and VDV in the 4 *Hz*, 8 *Hz*, 16 *Hz*, 32 *Hz*, and 64 *Hz* octave bands.

To illustrate the relationships suggested by the correlation coefficients suggested in Figure 109, scatter plots of the positions of the stimuli on the second perceptual dimension and RMS acceleration in the 32 *Hz* and 64 *Hz* octave bands are presented in Figure 110. These figures confirm the relationships suggested by the correlation coefficients presented in Figure 109.

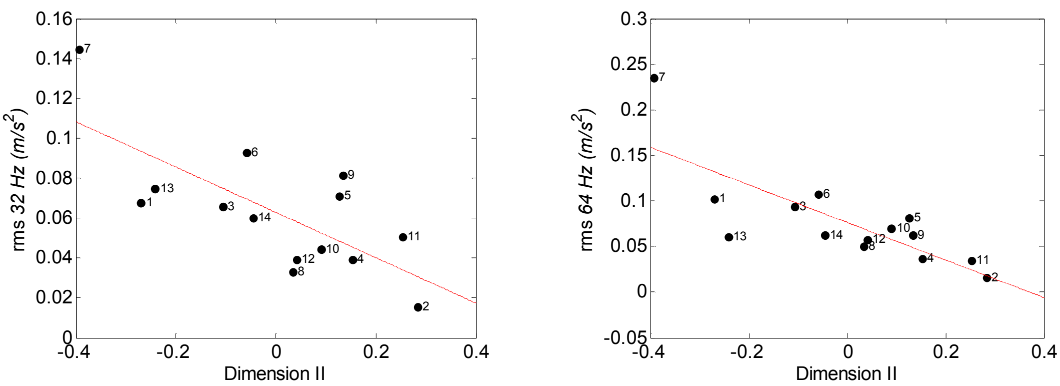

Figure 110 Relationship between the second perceptual dimension and RMS acceleration in the 32 *Hz*, and 64 *Hz* octave bands.

The range of frequencies in which a significant correlation was found with the second perceptual dimension shown in Figure 109 is in the range generally associated with vibrotactile perception through the Pacinian and Meissner's corpuscle mechanoreceptors (see, for example, Gandhi et al., 2011; Kandel et al., 2000). The thresholds of detection of vibration for Pacinian and Meissner's corpuscles are shown in Figure 111. This result along with the findings for the first perceptual dimension suggests that whole body vibration and vibrotactile vibration may be perceived independently.

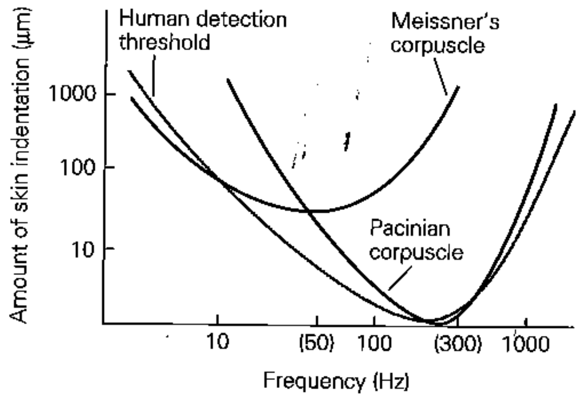

Figure 111 Thresholds of detection of vibration from the Pacinian corpuscle and Meissner's corpuscle mechanoreceptors (Source: Kandel et al., 2000)

To confirm the independence of these two frequency regions in the stimulus set, Table 23 shows a matrix of Pearson's correlation coefficients between RMS acceleration in the 4 *Hz*, 8 *Hz*, 16 *Hz*, 32 *Hz*, and 64 *Hz* octave bands. It can be seen from this table that there is high correlation between RMS acceleration within the octaves bands significantly correlated with the first and second perceptual dimensions respectively. There is however no correlation between RMS acceleration in the octave bands between these two groups. This provides further confidence that subjects perceive these two frequency regions separately in the group of stimuli used in this test.

	4 Hz	**8 Hz**	**16 Hz**	**32 Hz**	**64 Hz**
4 Hz	1.00	0.91	0.77	--	--
8 Hz	0.91	1.00	0.87	--	--
16 Hz	0.77	0.87	1.00	--	--
32 Hz	--	--	--	1.00	0.90
64 Hz	--	--	--	0.90	1.00

Table 25 Pearson's correlation coefficients between RMS acceleration in the 4 Hz, 8 Hz, 16 Hz, 32 Hz, and 64 Hz octave bands (-- not significant, otherwise p < 0.001 for all coefficients).

7.6.4 DIMENSION III

The correlations presented in Table 20 to Table 24 suggest that the third perceptual dimension revealed through the multidimensional scaling analysis is related to the crest factor and the duration of the stimuli defined by the 10 dB down points. Figure 112 presents scatter plots showing the relationship between the third perceptual dimension and these two descriptors. Although the correlation between this dimension and these descriptors are significant at the 0.05 level, it can be seen from this figure that there is quite a large amount of scatter in these relationships.

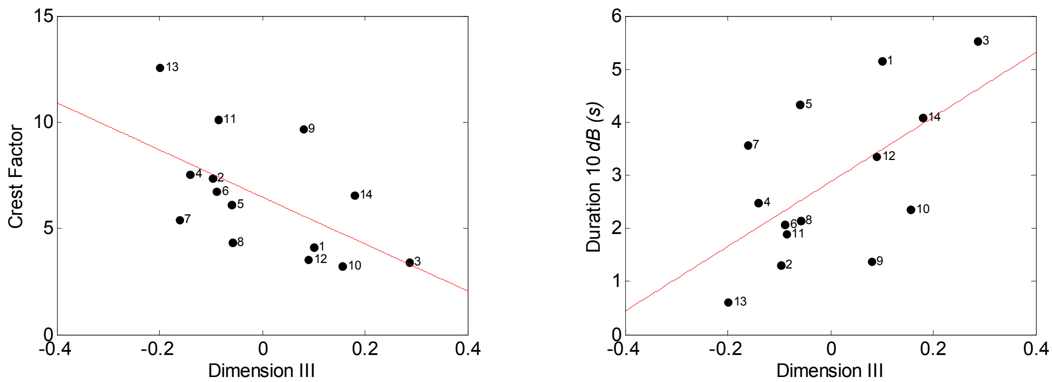

Figure 112 Relationship between the third perceptual dimension and crest factor (left pane) and duration defined by the 10 dB down points.

As the objective correlates to the first two perceptual dimensions were shown to be frequency dependent, these two descriptors were evaluated in octave bands. The Pearson's correlation coefficients between this perceptual dimension and these two descriptors calculated in octave bands are shown in Figure 113. From this figure, it can be seen that a slight improvement in the correlation with this perceptual dimension can be achieved by expressing these descriptors in octave bands, particularly for the duration of the vibration exposure in the 8 *Hz* octave band.

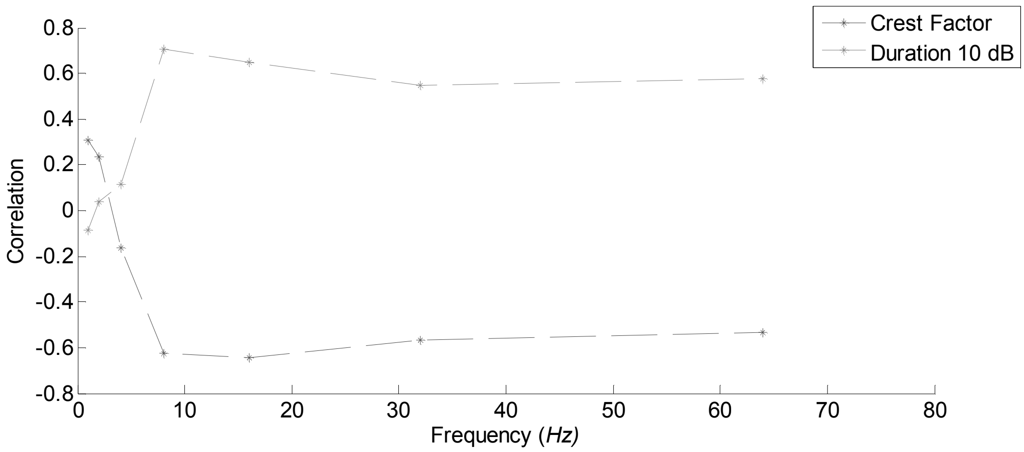

Figure 113 Pearson's correlations coefficient between the third perceptual dimension and crest factor and duration defined by 10 dB down points in the 4 Hz, 8 Hz, 16 Hz, 32 Hz, and 64 Hz octave bands.

7.6.5 DIMENSION IV

The correlations presented in Table 20 to Table 24 suggest that the fourth perceptual dimension revealed through the multidimensional scaling analysis is related to modulation depth and modulation frequency. The relationships between the fourth perceptual dimension and these descriptors are shown in Figure 114. The modulation depth and the modulation frequency are significantly correlated ($r = -0.7$, $p < 0.01$) making it difficult to assess which of these descriptors is most appropriate to describe the fourth perceptual dimension. However, from the right pane of Figure 114 it appears that the relationship between the fourth perceptual dimension and the modulation frequency is strongly influenced by the outlier stimulus 13.

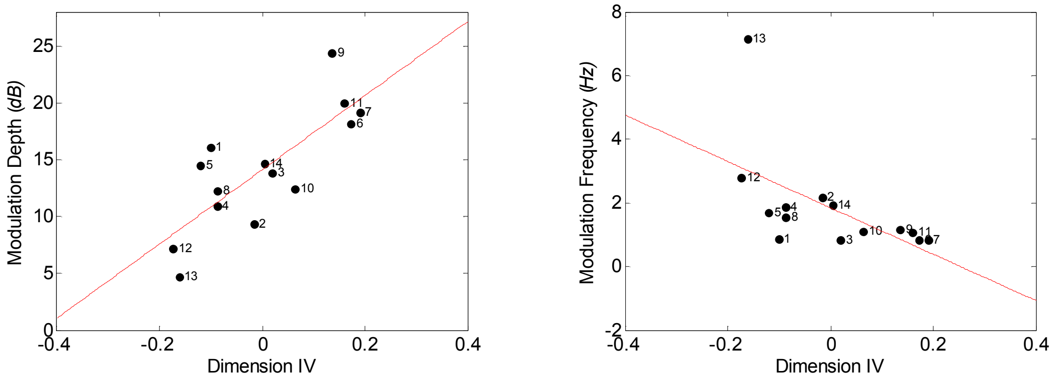

Figure 114 Relationship between the fourth perceptual dimension and modulation depth (left pane) and modulation frequency (right pane).

7.7 MODELS OF PERCEIVED ANNOYANCE

7.7.1 RELATIVE ANNOYANCE MODELS

To investigate the relationship between the perceptual dimensions revealed through the multidimensional scaling analysis and the Perceived Annoyance Ratings calculated from the paired comparison of annoyance tests, a multiple linear regression was conducted (see Chapter 6 section 6.8.4) with the Perceived Annoyance Ratings as the dependent variable and the position of the stimuli on the four perceptual dimensions as independent variables. The result of this regression is described in Equation 52.

$$A = 0 + 0.60D_1 - 0.34D_2 - 0.10D_3 + 0.23D_4$$ **Equation 52**

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

Apart from the intercept coefficient, which is zero, all of the coefficients in the model presented in Equation 52 are statistically significant; the coefficients for dimensions I, II, and IV are significant to the 0.001 level and the coefficient for dimension III is significant to the 0.05 level. This result suggests that each of the four recovered perceptual dimensions has some influence upon the Perceived Annoyance Ratings. As each of the dimensions in Equation 52 are unitless with similar mean and variance, the coefficients in this equation can be directly interpreted as the relative weightings each of the dimensions has upon the Perceived Annoyance Ratings. Interpreting Equation 52 in this manner suggests that the first dimension has the greatest influence on perceived annoyance, followed by the second then fourth dimension with the third dimension having the least influence.

Figure 115 shows a comparison between the Perceived Annoyance Ratings measured through the perceptual testing and the Perceived Annoyance Ratings predicted using Equation 52. The adjusted R^2 value for this model is 0.98, $p < 0.001$.

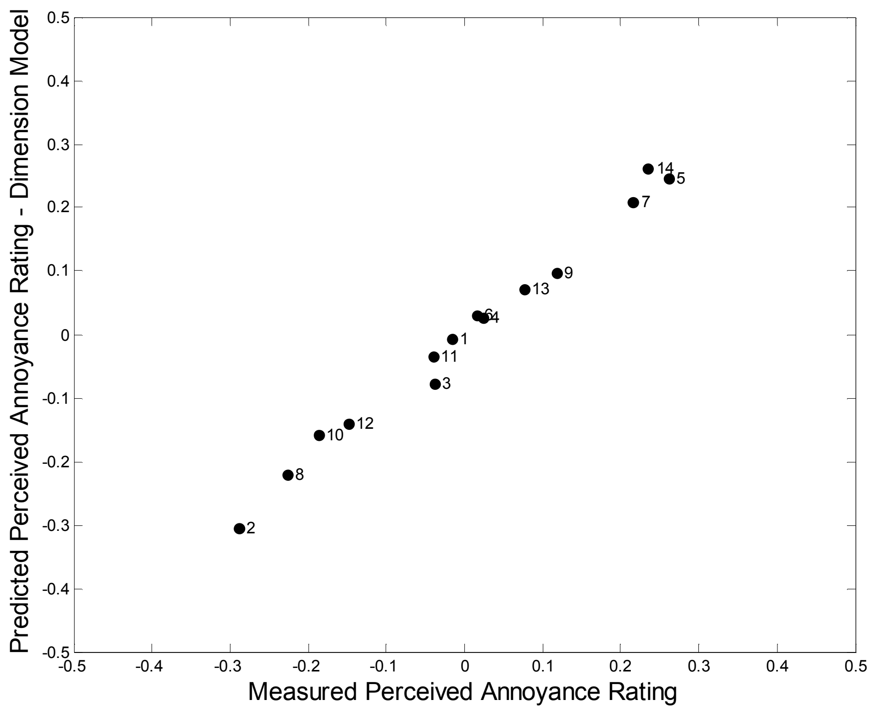

Figure 115 Comparison between measured Perceived Annoyance Ratings and those predicted using the model in Equation 52.

In section 7.6, a number of potential objective correlates were found for each of the perceptual dimensions revealed through the multidimensional scaling analysis. Multiple linear regression models were calculated with every possible combination of the objective descriptors found as significant correlates to each of the perceptual dimensions. The adjusted R^2 values for the calculated models were found to range between 0.72 and 0.92. The model exhibiting the highest value of adjusted R^2 included the RMS acceleration in the 16 *Hz* and 32 *Hz* octave bands, the duration defined by the 10 dB down points, and the modulation frequency. The results of this regression are described by Equation 53.

$$A = -0.40 + 4.57\ddot{X}_{RMS,16Hz} + 3.18\ddot{X}_{RMS,32Hz} + 0.02T_{10dB} + 0.02f_{\mathrm{mod}}$$ **Equation 53**

where A is the predicted single figure Perceived Annoyance Rating, $\ddot{X}_{RMS,16Hz}$ and $\ddot{X}_{RMS,32Hz}$ are the RMS acceleration of each train event in the 16 *Hz* and 32 *Hz* octave band respectively, T_{10dB} is the duration of each train event defined by its 10 dB down points, and f_{mod} is the modulation frequency of the envelope of each train event. The coefficients for the $\ddot{X}_{RMS,16Hz}$ and $\ddot{X}_{RMS,32Hz}$ terms are significant to the 0.001 level, the coefficient for the f_{mod} term is significant to the 0.05 level, and the coefficient for the T_{10dB} term failed to reach significance with a p-value of 0.06.

Figure 116 shows a comparison between the Perceived Annoyance Ratings measured through the perceptual testing and the Perceived Annoyance Ratings predicted using Equation 53. The adjusted R^2 value for this model is 0.92, $p < 0.001$.

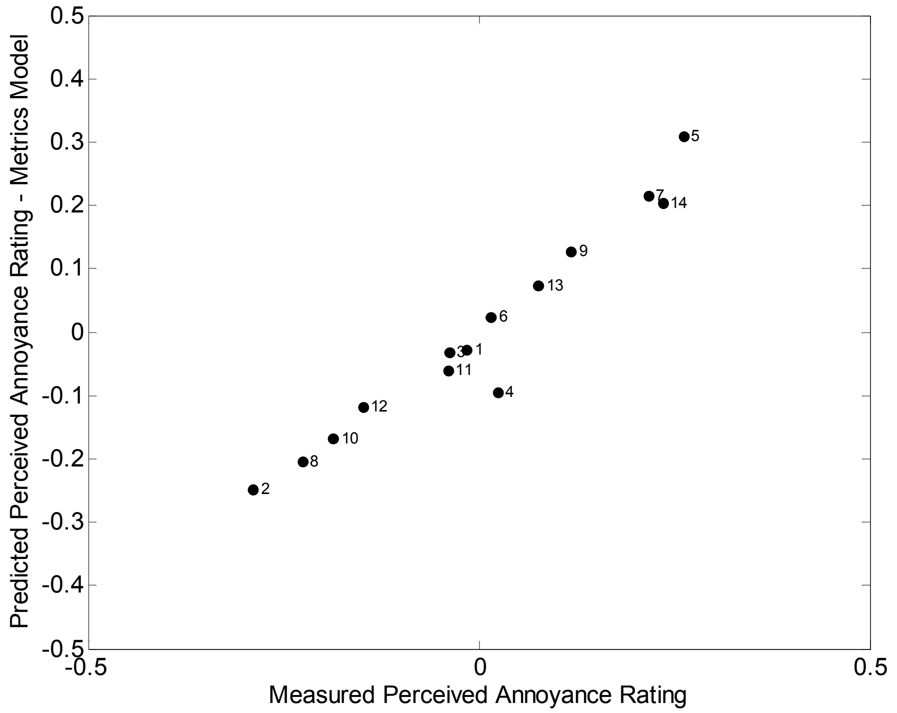

Figure 116 Comparison between measured Perceived Annoyance Ratings and those predicted using the model in Equation 53.

To explore trade-off between reducing the number of predictor variables in the model described by Equation 53 and the amount of variance explained by the model, a stepwise regression was conducted the results of which are presented in Table 26. The criterion for the inclusion of a predictor variable in the model is that the estimated β coefficient must have a p-value of less than 0.05. It can be seen from Table 26 that the stepwise regression results in a model containing only the $\ddot{X}_{RMS,16Hz}$ and $\ddot{X}_{RMS,32Hz}$ terms, the resulting adjusted R^2 for this model is 0.88 confirming that the reduced model describes a similar amount of variance as the full model.

In the model relating the positions of the stimuli on the four perceptual dimensions to the Perceived Annoyance Ratings (see Equation 52), it can be noted that each of the coefficients in the model reached statistical significance. This suggests that further work is needed to find objective correlates for the third and fourth perceptual dimensions.

Variable	Coefficient	Include in model	p-value
$\ddot{X}_{RMS,16Hz}$	4.68	IN	<0.0001
$\ddot{X}_{RMS,32Hz}$	3.22	IN	<0.0001
T_{10dB}	0.01	OUT	0.40
f_{mod}	0.01	OUT	0.16

Table 26 Stepwise regression results.

If a regression model were derived using only the weighted VDV as the independent variable, the standard descriptor used in the United Kingdom for evaluating annoyance due to vibration, the adjusted R^2 value for the resulting model would be 0.79. This suggests that the Perceived Annoyance Rating model in Equation 53 accounts for 13% more variance in the annoyance ratings than a model using only the weighted VDV. Figure 117 provides a comparison between the Perceived Annoyance Ratings predicted by the model in Equation 53 and a model with W_b weighted VDV as the only independent variable. It can be seen from this figure that, particularly at higher magnitudes of Perceived Annoyance Ratings, there is greater scatter in the predicted Perceived Annoyance Ratings using the VDV only model.

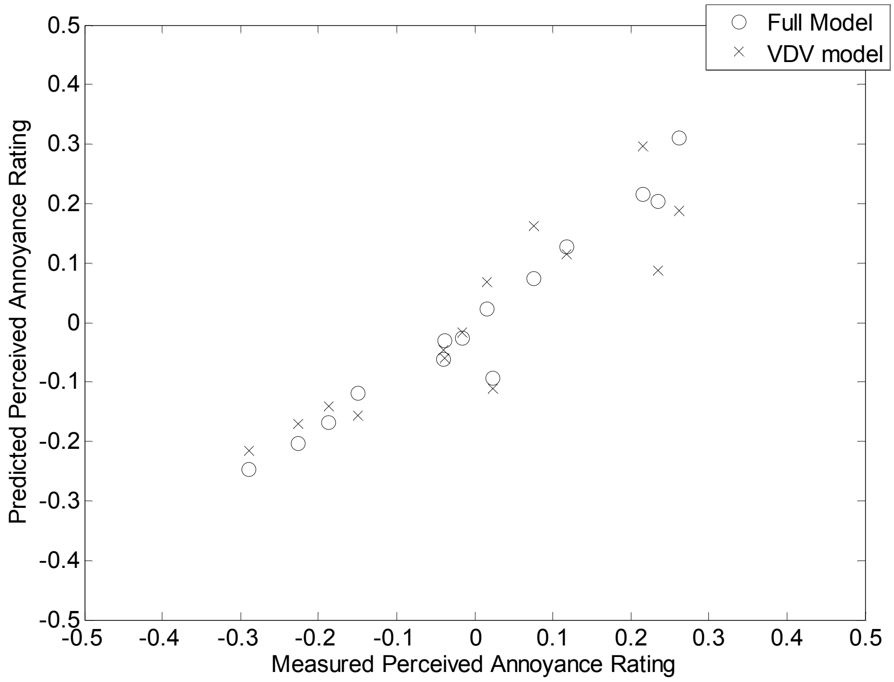

Figure 117 Comparison between measured Perceived Annoyance Ratings and those predicted using the model in Equation 53 and a model with weighted VDV as the only independent variable.

7.7.2 CATEGORICAL ANNOYANCE MODEL

As discussed in section 7.5.2, the Perceived Annoyance Ratings calculated from the paired comparison of annoyance tests are relative to the group of stimuli on which they were judged and are on an arbitrary scale. That is to say, although a greater Perceived Annoyance Rating implies greater annoyance, it is unknown what the absolute rating of that annoyance is. From the categorical annoyance ratings presented in section 7.5.4, a single categorical annoyance rating for each train stimulus was calculated by taking the mode of the annoyance ratings for each stimulus. The mode of the categorical annoyance ratings for each train stimulus are shown in Figure 118 with the category labels coded as {1 = Not At All; 2 = Slightly; 3 = Moderately; 4 = Very; 5 = Extremely}.

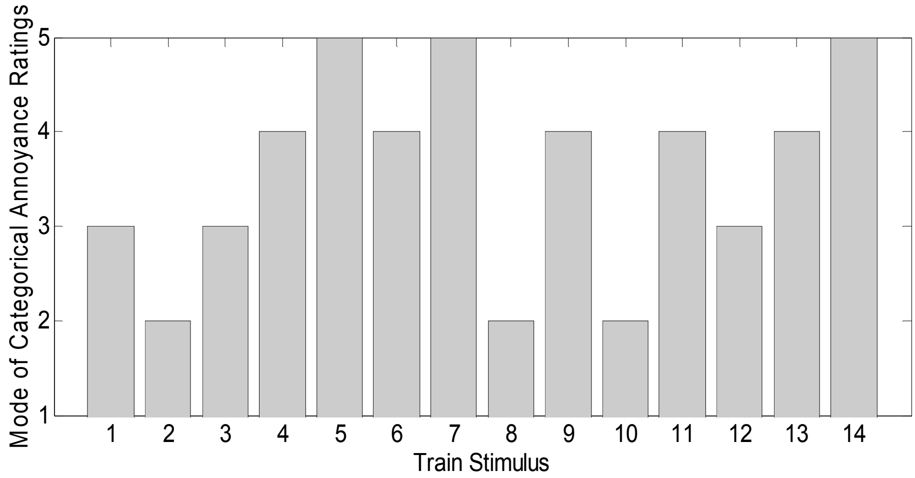

Figure 118 Mode of the categorical annoyance ratings for each train stimulus.

Figure 119 shows the relationship between the Perceived Annoyance Ratings and the categorical annoyance ratings. The Spearman's correlation coefficient between these two variables is 0.93 ($p < 0.0001$).

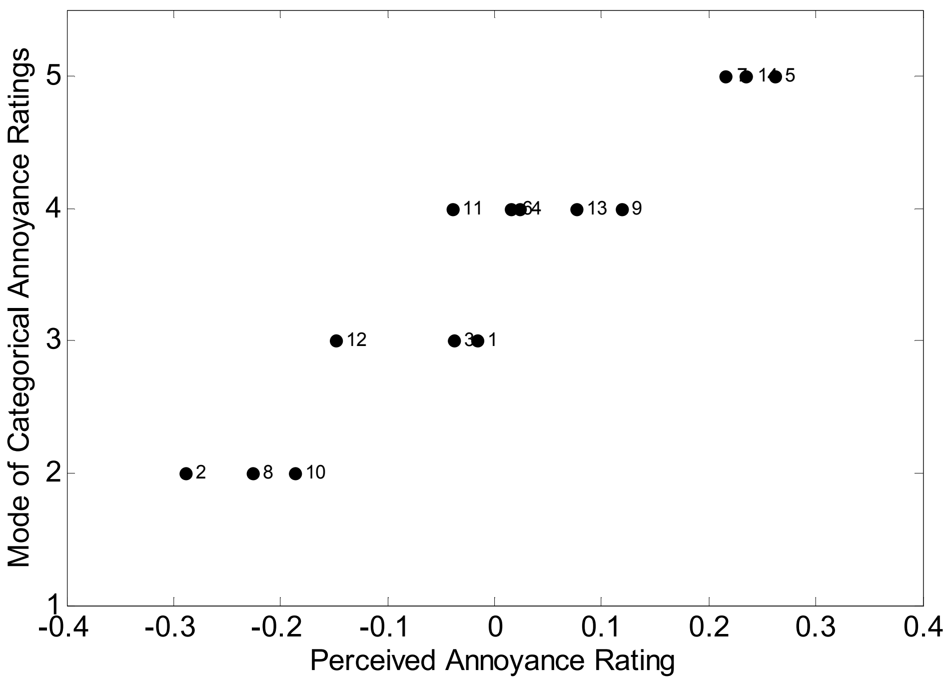

Figure 119 Relationship between Perceived Annoyance Ratings and categorical annoyance ratings.

As discussed in Chapter 5 section 5.2, the categorical nature of the absolute annoyance ratings mean that models cannot be derived using linear regression techniques. To determine the relationship between the continuous, relative Perceived Annoyance Ratings and the categorical ratings of annoyance, an ordinal logistic regression model was calculated with the Perceived Annoyance Ratings as the independent variable and the mode of the categorical annoyance ratings for each vibration stimuli as the dependent variable.

If Y is a categorical variable with k ordered categories ($k = 1$ to j), ordinal logistic regression models the probability p_{ij} that Y_i falls into the jth category or higher (see Equation 54).

$$\ln\left(\frac{p_{ij}}{1-p_{ij}}\right) = a_j + \sum aX_i$$

Equation 54

The coefficients of this model were estimated via maximum likelihood the outcome of which is shown in Figure 120. The curves in this figure indicate the probability of a train with a given Perceived Annoyance Rating being rated in a certain annoyance category. The relatively equal widths between the points at which these curves intersect suggest that the assumption of equal category widths in the model used to derive the exposure-response relationships in Chapter 5 was valid.

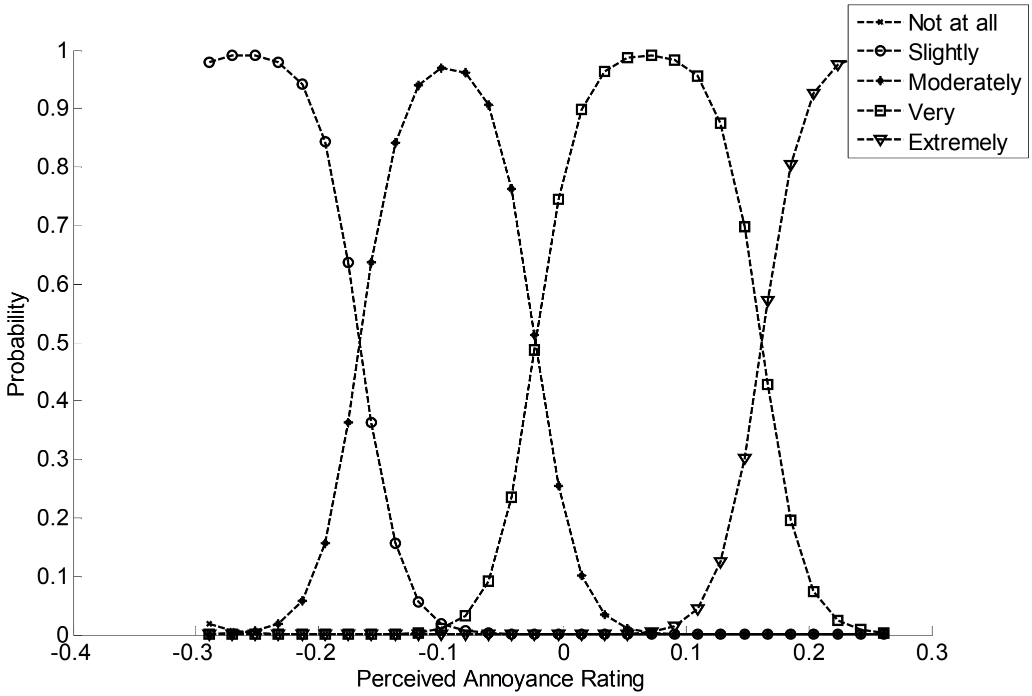

Figure 120 Probability of a railway vibration event with a given Perceived Annoyance Rating being rated in a certain annoyance category on a five-point semantic scale.

7.8 Validation of Perceived Annoyance Rating model

As a validation of the relative Perceived Annoyance Rating model presented in section 7.7.1, the model described in Equation 53 was used to predict the single figure annoyance ratings measured in the pilot test (see Chapter 6 section 6.8.2). Figure 121 shows a comparison between the annoyance ratings measured in the pilot test and the ratings predicted using the model in Equation 53. The Pearson's correlation coefficient between the measured and predicted annoyance ratings shown in this figure is 0.91 ($p < 0.0001$). As the Perceived Annoyance Ratings are a relative measure of annoyance and are therefore arbitrary and dependent upon the set of stimuli on which they were judged, the absolute values of the annoyance ratings shown in this figure differ. The predicted annoyance values are higher than the measured because the stimuli used in the pilot test were of much higher magnitude that those used in the tests described in this chapter. It can however be seen that there is good agreement in the trend of the measured and predicted values suggesting that the model was successfully able to predict the relative perceived annoyance ratings.

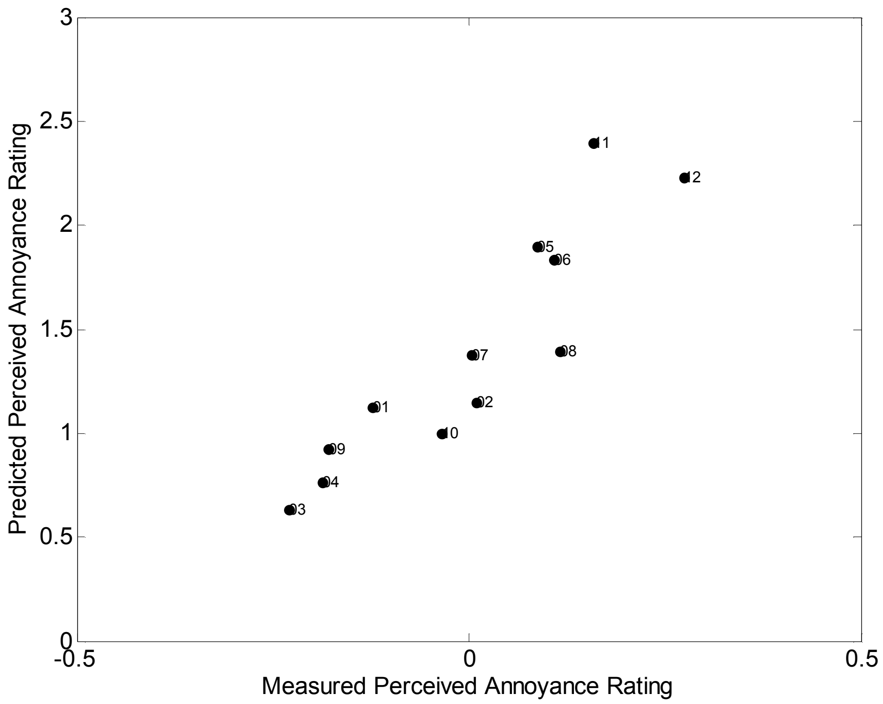

Figure 121 Comparison between Perceived Annoyance Ratings measured in the pilot test and those predicted using the model in Equation 53.

The annoyance ratings from the pilot test were also predicted using a model in which the only independent variable is the weighted VDV. Figure 122 shows a comparison between the predicted annoyance ratings using the full model and predicted annoyance ratings using the weighted VDV only model. This figure suggests that both the full model and the VDV only model result in good predictions of the Perceived Annoyance Ratings measured in the pilot test resulting in Pearson's correlations coefficients between the predicted and measured Perceived Annoyance Ratings of 0.91 and 0.92 respectively (each of these values are significant to the 0.0001 level). This result is contrary to the findings of the main test where the full model was found to explain around 12% more of the variance in measured Perceived Annoyance Ratings than the VDV only model. This difference may be due in part to the stimulus set used in the pilot test where differences in the frequency content of the stimuli was difficult to achieve due to limitations of the equipment and envelope characteristics of each of the stimuli were similar.

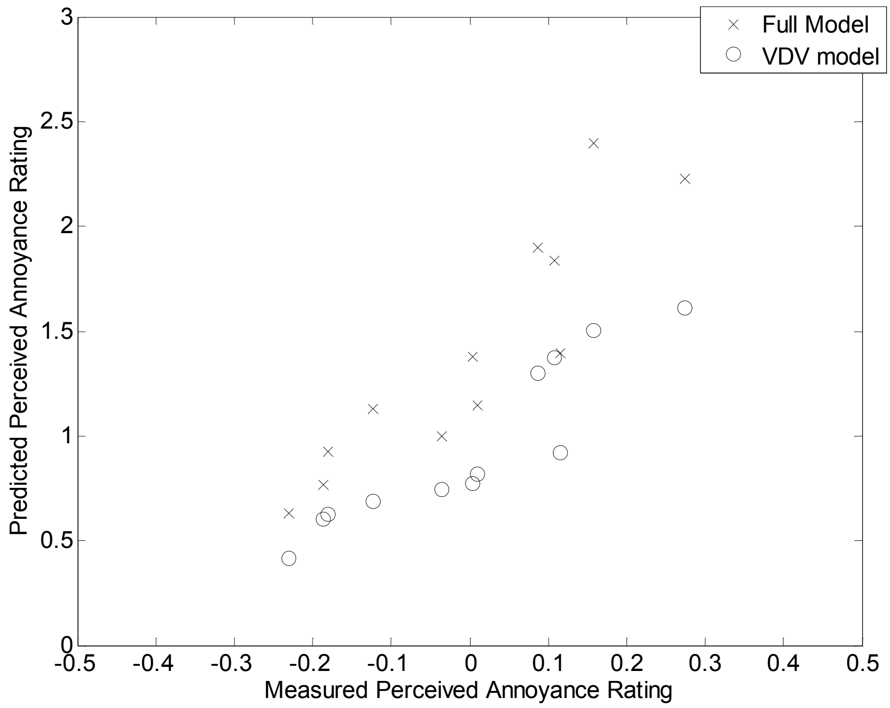

Figure 122 Comparison between Perceived Annoyance Ratings measured in the pilot test and those predicted using the model in Equation 53 and a model with weighted VDV as the only independent variable.

7.9 Summary

This chapter has presented the design, implementation, and results of a paired comparison test to investigate the perception of groundborne vibration from railways. Paired comparison tests of similarity and annoyance were conducted using fourteen measured railway vibration signals selected so as to be representative of the range of railway vibration in residential environments in the United Kingdom. A multidimensional scaling analysis of the data gathered through the paired comparison tests of similarity has revealed four perceptual dimensions salient to the perception of the group of railway vibration stimuli used in the perceptual tests described in this chapter. A number of objective descriptors of the vibration stimuli were found as correlates to these perceptual dimensions.

Single figure Perceived Annoyance Ratings were calculated for each of the railway vibration stimuli and the objective descriptors revealed through the multidimensional scaling analysis were related to these annoyance ratings via a multiple linear regression model. This model was validated via prediction of the single figure annoyance ratings measured in the pilot test detailed in Chapter 6. Absolute category ratings of annoyance were related the relative Perceived Annoyance Ratings via an ordinal logistic regression model describing the probability of a vibration stimulus being rated in a given annoyance category on a five-point semantic annoyance scale for a given perceived annoyance rating.

CHAPTER 8

SUMMARY, CONCLUSIONS, AND FURTHER WORK

8 SUMMARY, CONCLUSIONS, AND FURTHER WORK

8.1 SUMMARY AND CONCLUSIONS

With proposed increases in both freight and passenger railway in the United Kingdom and the European Union and the building of new high speed lines, there has been an increase in interest in recent years in the human response to vibration in residential environments. This interest is mirrored in the recent EU funding of two large projects investigating the human response to railway vibration, RIVAS and Cargovibes, and the recently concluded Defra funded project in the United Kingdom "NANR209: Human response to vibration in residential environments". This thesis has drawn upon data collected through the latter project and new laboratory studies with the overall objective of investigating the human response to groundborne vibration on a community and individual level.

To investigate the human response to groundborne vibration on a community level, a large scale field survey was conducted to determine both response and exposure to vibration from existing railway operations and the construction of a new light rail system. In this survey, response to vibration was measured via questionnaires conducted face-to-face with residents in their own homes. In total 1281 questionnaires were conducted, 931 with residents living within around 150 *m* of an existing railway line and 350 residents living within around 150 *m* of the construction of a new light rail system. Due to the large uncertainties associated with the prediction and estimation of groundborne vibration, an extensive programme of measurement was conducted to determine estimations of 24-hour internal vibration exposure for as many of the residents who had taken part in the social survey questionnaire as possible. For residents living close to an existing railway line, the measurement approach consisted of 24-hour measurements at external positions along with synchronised short term measurements within resident's properties. The objective of this measurement approach was to allow the determination of the transmissibility between the external and internal measurement positions and to apply this transmissibility to the vibration measured at the 24-hour position to facilitate the estimation of 24-hour vibration exposure within the dwellings of residents who had participated in the social survey questionnaire. For residents living close to the construction of a new light rail system, the measurement approach consisted of long term monitoring over a period of around two months complemented by controlled experiments to determine attenuation laws for the prediction of long term vibration exposure at different distances from the source.

The data gathered for the estimation of vibration exposure for residents living close to an existing railway line was utilised in an investigation which aimed to determine the most appropriate single figure descriptor of vibration exposure with respect to human response. A variety of single figure descriptors of vibration exposure were calculated from these data and assessed by investigating the Spearman's correlation coefficient with the annoyance data collected through the social survey questionnaire. It was found that, due to the high degree of correlation between the different descriptors, none of the methods of expressing 24-hour vibration exposure as a single value could be identified as a superior predictor of annoyance. Application of appropriate frequency weightings were found to lead to an improvement in correlation between the single figure descriptors and annoyance compared to their unweighted counterparts. Considering these findings in light of the difficulty in comparing results between studies into the human response to vibration in residential environments due to the use of different vibration exposure descriptors, it was deemed prudent to calculate exposure-response relationships in terms of as many of the common vibration exposure descriptors advocated in national and international standards as possible.

Using the grouped regression model developed for the calculation of the internationally accepted exposure-response relationships for environmental noise (Groothuis-Oudshoorn and Miedema, 2006), exposure-response relationships were derived for variety of different vibration exposure descriptors for both railway and construction sources of vibration. The resulting relationships were found to be statistically significant and to exhibit relatively narrow confidence intervals. These exposure-response relationships represent the first of the kind for railway induced vibration in the United Kingdom and the first of their kind of construction induced vibration in the world. From these relationships it was found that, for the same magnitude of vibration exposure, construction induced vibration elicited a greater annoyance response than railway induced vibration suggesting that separate exposure-response relationships are needed for different vibration sources. This finding is inline with research into the human response to environmental noise which has found that different exposure-response relationships are needed for different noise sources.

The differences in the observed response to vibration from different sources and the relatively low amount of variance explained in the annoyance response by the different measures of vibration exposure suggest an inadequacy in the single figure descriptors used to describe vibration exposure. The descriptors used to derive the exposure-response relationships were all based on equivalent energy values, maximum values, or cumulative doses. The lack of physiological or psychological evidence regarding the validity of the use of these descriptors in models of human response prompted a pilot laboratory study to investigate the salient perceptual dimensions for the perception of railway induced groundborne vibration. The aim of the pilot study was to determine the feasibility of using the methods of paired comparisons and multidimensional scaling to investigate the perception of railway induced groundborne vibration. Paired comparison tests of similarity and annoyance were conducted using synthesised signals of railway vibration.

Multidimensional scaling analysis of the paired comparison data suggested that the perception of railway induced groundborne vibration could be characterised by three or four perceptual dimensions and that, through multiple linear regression models, these dimensions could be related to perceived annoyance.

Prompted by the findings of the pilot study, a full scale programme of subjective tests was conducted using a set of measured railway vibration as stimuli. The stimuli set was selected to be representative of the range of railway induced vibration in the United Kingdom. An improved test rig was designed and built which was capable of faithfully reproducing measured vibration signals. Multidimensional scaling analysis of the data gathered through these subjective tests revealed four perceptual dimensions salient to the perception of railway induced groundborne vibration. The first and second perceptual dimensions were found to be related to vibration energy in the 4 *Hz* to 16 *Hz* and 32 *Hz* to 64 *Hz* frequency ranges respectively. The third perceptual dimension was found to be related to both the crest factor and the duration of the vibration exposure defined by its 10 dB down points. The fourth perceptual dimension was found to be related to the modulation frequency and the modulation depth of the envelope of the vibration signal.

Single figure Perceived Annoyance Ratings were calculated for each of the stimuli used in the subjective testing. The objective descriptors revealed through the multidimensional scaling analysis were related to these annoyance ratings via a multiple linear regression model which was found to describe 92% of the variance in the measured Perceived Annoyance Ratings. This model was used to predict annoyance ratings measured for the set of vibration stimuli used in the pilot test. The Pearson's correlation coefficient between the annoyance ratings measured in the pilot test and the annoyance ratings predicted by the model was 0.91.

Subjects were also asked to rate their perceived annoyance on a five-point semantic scale for each of the vibration stimuli used in the main programme of subjective tests. These absolute ratings of annoyance were related the relative Perceived Annoyance Ratings calculated from the paired comparison data via an ordinal logistic regression model. This model describes the probability of a railway vibration stimulus being rated in a given annoyance category on a five-point semantic scale for a given Perceived Annoyance Rating.

The work presented in this thesis represents the first study which has derived exposure-response relationships for annoyance due to railway and construction induced vibration in the United Kingdom. The laboratory studies conducted in this work provide an insight into the perceptual features of vibration which contribute to annoyance due to groundborne vibration in residential environments. The results of this work strongly suggest that the perception of whole body vibration is multidimensional and it is hoped that further research into the perception this phenomenon will allow for better prediction and control of annoyance due to by groundborne vibration in residential environments.

8.2 FURTHER WORK

8.2.1 RELATIONSHIP BETWEEN LABORATORY FINDINGS AND FIELD DATA

Further work is needed to relate the findings of the laboratory study detailed in Chapter 7 to the finings of the field work detailed in Chapter 3, Chapter 4, and Chapter 5. As the model of Perceived Annoyance Ratings developed in Chapter 7 predicts annoyance ratings for individual train vibration events, it is currently unclear how the Perceived Annoyance Ratings relate to long term annoyance due to vibration in residential environments. One approach to this problem in future work may be to apply the individual perceptual dimensions revealed through the laboratory work to the field data. For example, Figure 123 shows the Spearman's correlation coefficient between 24-hour internal vibration exposure expressed in octave bands and annoyance. It can be seen that this figure displays a similar trend to the relationship between the first perceptual dimension and vibration exposure expressed in octave bands shown in Chapter 7 section 7.6.2. That the correlation between the magnitude of vibration exposure in the 8 Hz octave band and annoyance is greater than that found for any of the descriptors of vibration exposure explored in Chapter 4 suggests that an improvement in the exposure-response relationship may be achieved in light of the findings of the laboratory study detailed in Chapter 7.

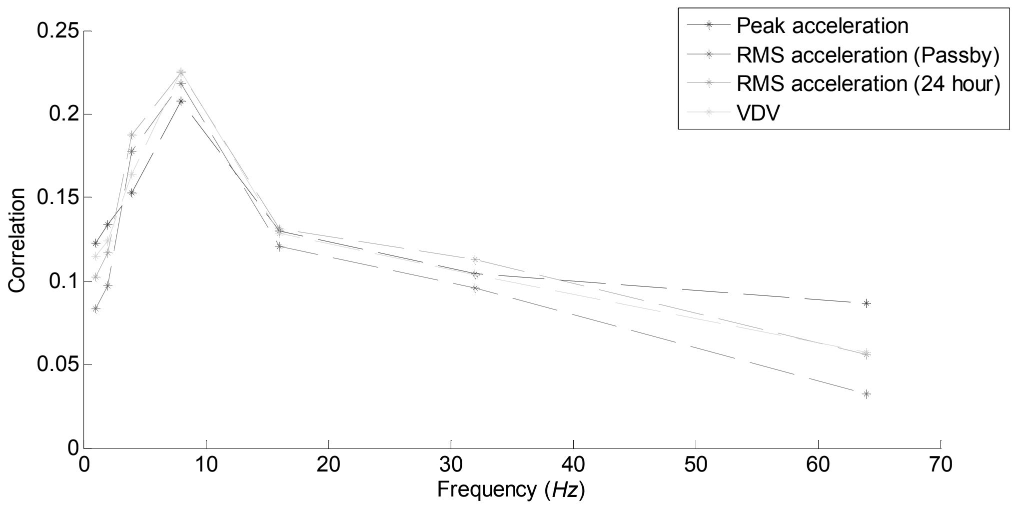

Figure 123 Spearman's correlation between 24-hour vibration exposure in octave bands and self reported annoyance (N = 752)

8.2.2 ADDITIONAL DATA FOR CATEGORY ANNOYANCE RATINGS

In Chapter 7, an ordinal logistic regression model was derived describing the probability of a railway vibration event of a given Perceived Annoyance Rating being categorised in a given category on a five-point semantic annoyance scale. The dependent variable upon which this model was derived was the mode of the judgements of categorical annoyance for each of the vibration stimuli used in the subjective tests detailed in Chapter 7. It can be seen from Figure 102 that there is a large amount of scatter in the absolute judgements of annoyance for each of the vibration stimuli. This finding suggests that confidence in this model could be improved with further subjective testing of the categorical annoyance ratings.

8.2.3 INVESTIGATION INTO A PSYCHOLOGICALLY RELEVANT SET OF DESCRIPTORS

In Chapter 5, it was highlighted that the vocabulary at our disposal for the description of the perception of vibration is much less that that available for the description of the perception of sound. The results of the perceptual tests in Chapter 7 however revealed that there are at least four perceptual dimensions salient in the perception of groundborne vibration induced by railway activities. This finding suggests that fundamental research is required to determine a set of descriptors to relate objective features of vibration to perception, similar to the work conducted by Fastl & Zwicker (2007) in the field of psychoacoustics. This work could take the form of a sorting task and semantic labelling to determine a psychologically relevant vocabulary for the investigation of the perception of vibration.

8.2.4 RELATING PARAMETRIC MODELS OF RAILWAY INDUCED VIBRATION TO PERCEPTUAL DIMENSIONS

To determine the physical parameters of the generation of railway induced vibration which influence annoyance, perceptual testing could be conducted using vibration stimuli generated from a parametric dynamic model of railway vibration. By investigating the relationship between the perceptual features determined in the multidimensional scaling analysis and the parameters of the dynamic model used to develop the stimuli for the perceptual tests, the annoyance ratings determined through the perceptual tests could be mapped onto the parameter space of the model. The minima of the resulting annoyance function could then be located and the corresponding combinations of parameter values identified. This would allow a cost-benefit analysis of mitigation measures enabling changes in design of the track and train to be related directly to changes in perceived annoyance.

8.2.5 Further investigation of the perception of construction induced vibration

As vibration exposure for the exposure-response relationships derived for construction sources presented in Chapter 5 of this thesis were based on attenuation models, it is not possible to investigate the relationship between different vibration exposure descriptors and annoyance for this source. Further laboratory or field studies into the human response to this source of vibration could go some way towards explaining the difference in response observed between the construction and railway sources of vibration. Investigating the response to the two sources out of context in a laboratory study would provide an indication as to whether the differences in response observed in the field was dominated by objective features of the vibration from the different sources or by non-acoustical factors.

8.2.6 Multimodal models

In Chapter 5 section 5.8, a model was presented indicating an additive model of annoyance due to vibration based on both vibration and noise exposure. In this model noise exposure was expressed as L_{DEN}. Previous laboratory studies into the combined effects of vibration and noise (see Chapter 2 section 2.2.7), with the exception of Parizet et al. (2004), have considered noise and vibration exposure as equivalent energy or dose values. If a multimodal multidimensional approach to the perception of combined noise and vibration stimuli from railways were taken, perceptual models could be developed taking into account objective and psychoacoustical features of both the noise and vibration stimuli.

8.2.7 Longitudinal studies into change effects

The difference in response observed between vibration from railway and construction sources may be partly attributable to railway induced vibration being a steady state exposure and construction induced vibration representing a step change in exposure. Brown & van Kamp (2009a, 2009b) have suggested that for a change in noise exposure, annoyance responses may be underestimated using exposure-response relationships derived under steady state conditions. The differences in response between railway induced vibration and construction induced vibration suggest that this may also be the case for the human response to vibration. With the proposed increase of both passenger and freight traffic on existing lines and the construction of new lines, an understanding is needed of how a step change in exposure to both noise and vibration influences human response. Such studies are however time consuming and expensive. At the very least, it should be made explicitly clear that results derived under steady state conditions should not be used to predict a change in exposure.

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REFERENCES

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ANSI S2.71-1983 (R2006) Guide to the Evaluation of Human Exposure to Vibration in Building

BS ISO 2631-1:1997 Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration -- Part 1: General requirements

BS ISO 5228-2:2009 Code of practice for noise and vibration control on construction and open sites – Part 2: Vibration

BS 6472-1:2008 Guide to evaluation of human exposure to vibration in buildings. Vibration sources other than blasting

BS 6841:1987 Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock

BS EN ISO 8041:2005 Human response to vibration – Measuring instrumentation

DIN 4150-2:1999 Structural vibration - Human exposure to vibration in buildings

Federal Transit Administration (2006) – Transit noise and vibration impact assessment

ISO/TS 15666:2003 Acoustics—assessment of noise annoyance by means of social and socio-acoustic surveys

ISO 2631-2:2003 Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration - Part 2: Vibration in buildings (1 Hz to 80 Hz)

NS8176:2005 Vibration and Shock - Measurement of Vibration in Buildings from Landbased Transport and Guidance to Evaluation of its Effect on Human Beings

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UNI 9641:1990 Misura delle vibrazioni negli edifici e criteri di valutazione del disturbo

APPENDIX I

MODEL COEFFICIENTS

APPENDIX I: MODEL COEFFICIENTS

NOTE: The exposure-response relationships in this section were calculated from data derived under steady state conditions and should therefore not be used to predict annoyance following a significant change in vibration conditions.

The exposure-response relationships should not be used to predict response at magnitudes of vibration outside the ranges presented in the figures in Chapter 5.

The following table provides the model coefficients for the exposure-response relationships presented in Chapter 5 section 5.5 and section 5.6. In these tables, β_0, β_1, and σ are the coefficients for the following parametric form of the exposure-response relationships:

$$p = (1 - \Phi\left[\frac{C - \beta_0 + \beta_1 10\log_{10}(x)}{\sigma}\right]) * 100$$ for all descriptors expressed in absolute units

and,

$$p = (1 - \Phi\left[\frac{C - \beta_0 + \beta_1 x}{\sigma}\right]) * 100$$ for all descriptors expressed in decibels.

where C is the threshold of annoyance which the resulting exposure-response curve is to describe and Φ is the cumulative normal (i.e. zero mean and unit variance) distribution function, and *x* is vibration exposure. By varying C in this equation, exposure-response curves for any threshold of annoyance can be calculated.

For example, to calculate the percent highly annoyed, for a W_b weighted Vibration Dose Value of 0.1, C should be set to 72 if percent highly annoyed is defined as the proportion of respondents expressing annoyance in the upper 28 % of the annoyance response scale.

$$\%\text{HA} = (1-\Phi\left[\frac{72-29.61+2.13*10\log_{10}(0.1)}{41.00}\right])*100$$

Third order polynomial approximations to the exposure-response relationships for each of the descriptors are provided for three values of C along with upper and lower 95% confidence intervals. The X coefficients in these polynomial approximations are normalised, so vibration exposures must be scaled accordingly before using these equations.

RAILWAY INDUCED VIBRATION

Descriptor	**β₀**	**β₁**	**σ**	**Polynomial approximations**
$VDV_{g,24hr}$	43.95	2.44	41.79	$\%LA = -0.137X^3 + 1.944X^2 + 12.347X + 21.073$ $CU_{LA} = +0.599X^3 + 3.612X^2 + 11.713X + 25.626$ $CL_{LA} = -0.935X^3 + 0.723X^2 + 12.333X + 17.096$ $\%A = +0.139X^3 + 1.909X^2 + 7.049X + 9.167$ $CU_A = +0.846X^3 + 3.298X^2 + 7.227X + 11.761$ $CL_A = -0.439X^3 + 0.942X^2 + 6.494X + 7.067$ $\%HA = +0.211X^3 + 1.224X^2 + 3.046X + 3.149$ $CU_{HA} = +0.730X^3 + 2.178X^2 + 3.337X + 4.236$ $CL_{HA} = -0.127X^3 + 0.608X^2 + 2.608X + 2.320$ Where: $X = \frac{10\log_{10}(Descriptor) + 20.37}{4.34}$

Descriptor	β_0	β_1	σ	Polynomial approximations
$RMS_{g,Passby}$	87.37	2.44	41.73	$\%LA = -0.141X^3 + 2.187X^2 + 12.777X + 20.265$ $CU_{LA} = +0.787X^3 + 3.840X^2 + 11.562X + 25.021$ $CL_{LA} = -1.097X^3 + 1.041X^2 + 13.082X + 16.201$ $\%A = +0.173X^3 + 2.099X^2 + 7.181X + 8.696$ $CU_{A} = +1.010X^3 + 3.483X^2 + 7.034X + 11.347$ $CL_{A} = -0.488X^3 + 1.149X^2 + 6.769X + 6.610$ $\%HA = +0.247X^3 + 1.327X^2 + 3.051X + 2.937$ $CU_{HA} = +0.838X^3 + 2.288X^2 + 3.186X + 4.019$ $CL_{HA} = -0.130X^3 + 0.703X^2 + 2.675X + 2.140$ Where: $X = \frac{10\log_{10}(Descriptor) + 38.53}{7.74}$
$RMS_{g,24hr}$	59.08	2.21	41.92	$\%LA = -0.087X^3 + 1.369X^2 + 10.479X + 21.750$ $CU_{LA} = +0.532X^3 + 3.004X^2 + 9.761X + 26.262$ $CL_{LA} = -0.766X^3 + 0.191X^2 + 10.650X + 17.752$ $\%A = +0.079X^3 + 1.362X^2 + 6.066X + 9.586$ $CU_{A} = +0.663X^3 + 2.620X^2 + 6.095X + 12.223$ $CL_{A} = -0.404X^3 + 0.524X^2 + 5.690X + 7.416$ $\%HA = +0.126X^3 + 0.875X^2 + 2.664X + 3.352$ $CU_{HA} = +0.536X^3 + 1.673X^2 + 2.865X + 4.502$ $CL_{HA} = -0.144X^3 + 0.383X^2 + 2.319X + 2.464$ Where: $X = \frac{10\log_{10}(Descriptor) + 28.84}{6.75}$

Descriptor	β_0	β_1	σ	Polynomial approximations
$VDV_{b,24hr}$	29.64	2.12	42.00	$\%LA = -0.114X^3 + 1.725X^2 + 11.600X + 21.136$ $CU_{LA} = +0.654X^3 + 3.624X^2 + 10.832X + 25.740$ $CL_{LA} = -0.955X^3 + 0.364X^2 + 11.699X + 17.110$ $\%A = +0.116X^3 + 1.693X^2 + 6.651X + 9.246$ $CU_{A} = +0.854X^3 + 3.213X^2 + 6.716X + 11.883$ $CL_{A} = -0.484X^3 + 0.678X^2 + 6.173X + 7.106$ $\%HA = +0.176X^3 + 1.085X^2 + 2.895X + 3.205$ $CU_{HA} = +0.712X^3 + 2.089X^2 + 3.124X + 4.322$ $CL_{HA} = -0.165X^3 + 0.467X^2 + 2.491X + 2.351$ Where: $X = \frac{10\log_{10}(Descriptor) + 16.70}{7.96}$
$RMS_{k,Passby}$	49.41	1.99	42.42	$\%LA = -0.071X^3 + 1.160X^2 + 9.711X + 22.071$ $CU_{LA} = +0.542X^3 + 2.901X^2 + 8.857X + 26.669$ $CL_{LA} = -0.748X^3 - 0.078X^2 + 10.010X + 17.988$ $\%A = +0.060X^3 + 1.165X^2 + 5.697X + 9.880$ $CU_{A} = +0.635X^3 + 2.471X^2 + 5.605X + 12.612$ $CL_{A} = -0.419X^3 + 0.323X^2 + 5.417X + 7.624$ $\%HA = +0.099X^3 + 0.759X^2 + 2.553X + 3.532$ $CU_{HA} = +0.500X^3 + 1.566X^2 + 2.689X + 4.756$ $CL_{HA} = -0.165X^3 + 0.280X^2 + 2.249X + 2.585$ Where: $X = \frac{10\log_{10}(Descriptor) + 27.19}{6.98}$

Descriptor	β_0	β_1	σ	Polynomial approximations
$RMS_{k,24hr}$	76.79	2.27	41.84	$\%LA = -0.111X^3 + 1.982X^2 + 11.953X + 19.926$ $CU_{LA} = +0.829X^3 + 3.644X^2 + 10.532X + 24.702$ $CL_{LA} = -1.065X^3 + 0.870X^2 + 12.424X + 15.853$ $\%A = +0.152X^3 + 1.874X^2 + 6.687X + 8.530$ $CU_{A} = +0.974X^3 + 3.206X^2 + 6.375X + 11.192$ $CL_{A} = -0.490X^3 + 0.993X^2 + 6.394X + 6.442$ $\%HA = +0.210X^3 + 1.170X^2 + 2.833X + 2.881$ $CU_{HA} = +0.769X^3 + 2.060X^2 + 2.881X + 3.974$ $CL_{HA} = -0.143X^3 + 0.609X^2 + 2.516X + 2.080$ Where: $X = \frac{10\log_{10}(Descriptor) + 37.12}{7.90}$
$VDV_{k,24hr}$	32.93	2.26	41.91	$\%LA = -0.114X^3 + 1.831X^2 + 11.771X + 20.662$ $CU_{LA} = +0.671X^3 + 3.553X^2 + 10.900X + 25.252$ $CL_{LA} = -0.950X^3 + 0.609X^2 + 11.929X + 16.673$ $\%A = +0.130X^3 + 1.771X^2 + 6.682X + 8.958$ $CU_{A} = +0.860X^3 + 3.158X^2 + 6.688X + 11.559$ $CL_{A} = -0.458X^3 + 0.834X^2 + 6.239X + 6.864$ $\%HA = +0.190X^3 + 1.122X^2 + 2.876X + 3.071$ $CU_{HA} = +0.708X^3 + 2.047X^2 + 3.074X + 4.160$ $CL_{HA} = -0.142X^3 + 0.540X^2 + 2.493X + 2.247$ Where: $X = \frac{10\log_{10}(Descriptor) + 17.40}{7.66}$

Descriptor	β_0	β_1	σ	Polynomial approximations
$MTVV_k$	37.13	1.99	42.06	$\%LA = -0.137X^3 + 1.536X^2 + 11.813X + 23.364$ $CU_{LA} = +0.376X^3 + 3.724X^2 + 12.050X + 27.976$ $CL_{LA} = -0.809X^3 - 0.160X^2 + 11.214X + 19.228$ $\%A = +0.083X^3 + 1.624X^2 + 7.050X + 10.566$ $CU_A = +0.710X^3 + 3.443X^2 + 7.791X + 13.331$ $CL_A = -0.459X^3 + 0.374X^2 + 6.152X + 8.249$ $\%HA = +0.159X^3 + 1.095X^2 + 3.198X + 3.800$ $CU_{HA} = +0.685X^3 + 2.334X^2 + 3.794X + 5.027$ $CL_{HA} = -0.178X^3 + 0.343X^2 + 2.579X + 2.824$ Where: $X = \frac{10\log_{10}(Descriptor) + 20.00}{8.16}$
$RMS_{m,Passby}$	61.10	2.16	41.95	$\%LA = -0.083X^3 + 1.318X^2 + 10.300X + 21.831$ $CU_{LA} = +0.532X^3 + 2.981X^2 + 9.561X + 26.350$ $CL_{LA} = -0.761X^3 + 0.122X^2 + 10.494X + 17.824$ $\%A = +0.075X^3 + 1.313X^2 + 5.973X + 9.640$ $CU_A = +0.655X^3 + 2.584X^2 + 5.981X + 12.288$ $CL_A = -0.407X^3 + 0.473X^2 + 5.616X + 7.458$ $\%HA = +0.119X^3 + 0.845X^2 + 2.630X + 3.379$ $CU_{HA} = +0.526X^3 + 1.644X^2 + 2.818X + 4.538$ $CL_{HA} = -0.149X^3 + 0.356X^2 + 2.293X + 2.483$ Where: $X = \frac{10\log_{10}(Descriptor) + 30.41}{6.78}$

Descriptor	β_0	β_1	σ	Polynomial approximations
$RMS_{m,24hr}$	89.49	2.40	41.76	$\%LA = -0.137X^3 + 2.120X^2 + 12.613X + 20.373$ $CU_{LA} = +0.793X^3 + 3.811X^2 + 11.355X + 25.145$ $CL_{LA} = -1.098X^3 + 0.955X^2 + 12.958X + 16.290$ $\%A = +0.164X^3 + 2.040X^2 + 7.107X + 8.764$ $CU_{A} = +1.003X^3 + 3.440X^2 + 6.926X + 11.433$ $CL_{A} = -0.499X^3 + 1.089X^2 + 6.719X + 6.661$ $\%HA = +0.236X^3 + 1.291X^2 + 3.029X + 2.970$ $CU_{HA} = +0.827X^3 + 2.255X^2 + 3.148X + 4.065$ $CL_{HA} = -0.140X^3 + 0.672X^2 + 2.661X + 2.162$ Where: $X = \frac{10\log_{10}(Descriptor) + 40.10}{7.77}$
$VDV_{m,24hr}$	43.95	2.44	41.79	$\%LA = -0.137X^3 + 1.944X^2 + 12.347X + 21.073$ $CU_{LA} = +0.599X^3 + 3.612X^2 + 11.713X + 25.626$ $CL_{LA} = -0.935X^3 + 0.723X^2 + 12.333X + 17.096$ $\%A = +0.139X^3 + 1.909X^2 + 7.049X + 9.167$ $CU_{A} = +0.846X^3 + 3.298X^2 + 7.227X + 11.761$ $CL_{A} = -0.439X^3 + 0.942X^2 + 6.494X + 7.067$ $\%HA = +0.211X^3 + 1.224X^2 + 3.046X + 3.149$ $CU_{HA} = +0.730X^3 + 2.178X^2 + 3.337X + 4.236$ $CL_{HA} = -0.127X^3 + 0.608X^2 + 2.608X + 2.320$ Where: $X = \frac{10\log_{10}(Descriptor) + 20.34}{7.34}$

Descriptor	β_0	β_1	σ	Polynomial approximations
$MTVV_m$	47.78	2.17	41.94	$\%LA = -0.164X^3 + 1.606X^2 + 12.436X + 24.122$ $CU_{LA} = +0.256X^3 + 3.693X^2 + 13.013X + 28.742$ $CL_{LA} = -0.760X^3 - 0.068X^2 + 11.572X + 19.957$ $\%A = +0.083X^3 + 1.746X^2 + 7.505X + 10.995$ $CU_A = +0.655X^3 + 3.543X^2 + 8.509X + 13.803$ $CL_A = -0.428X^3 + 0.468X^2 + 6.426X + 8.631$ $\%HA = +0.175X^3 + 1.200X^2 + 3.438X + 3.983$ $CU_{HA} = +0.687X^3 + 2.466X^2 + 4.187X + 5.242$ $CL_{HA} = -0.159X^3 + 0.407X^2 + 2.722X + 2.975$ Where: $X = \frac{10\log_{10}(Descriptor) + 22.77}{7.74}$
KB_{Fmax}	12.52	2.24	41.90	$\%LA = -0.156X^3 + 1.724X^2 + 12.410X + 22.995$ $CU_{LA} = +0.359X^3 + 3.591X^2 + 12.597X + 27.524$ $CL_{LA} = -0.801X^3 + 0.258X^2 + 11.841X + 18.947$ $\%A = +0.101X^3 + 1.805X^2 + 7.344X + 10.312$ $CU_A = +0.702X^3 + 3.396X^2 + 8.061X + 13.002$ $CL_A = -0.418X^3 + 0.671X^2 + 6.460X + 8.069$ $\%HA = +0.187X^3 + 1.209X^2 + 3.296X + 3.667$ $CU_{HA} = +0.685X^3 + 2.321X^2 + 3.877X + 4.847$ $CL_{HA} = -0.140X^3 + 0.498X^2 + 2.688X + 2.735$ Where: $X = \frac{10\log_{10}(Descriptor) + 6.94}{7.65}$

Descriptor	β_0	β_1	σ	Polynomial approximations
V_{max}	12.52	2.24	41.90	$\%LA = -0.156X^3 + 1.724X^2 + 12.410X + 22.995$ $CU_{LA} = +0.359X^3 + 3.591X^2 + 12.597X + 27.524$ $CL_{LA} = -0.801X^3 + 0.258X^2 + 11.841X + 18.947$ $\%A = +0.101X^3 + 1.805X^2 + 7.344X + 10.312$ $CU_A = +0.702X^3 + 3.396X^2 + 8.061X + 13.002$ $CL_A = -0.418X^3 + 0.671X^2 + 6.460X + 8.069$ $\%HA = +0.187X^3 + 1.209X^2 + 3.296X + 3.667$ $CU_{HA} = +0.685X^3 + 2.321X^2 + 3.877X + 4.847$ $CL_{HA} = -0.140X^3 + 0.498X^2 + 2.688X + 2.735$ Where: $X = \frac{10\log_{10}(Descriptor) + 6.94}{7.65}$
v_{w95}	22.40	2.08	42.00	$\%LA = -0.078X^3 + 1.254X^2 + 10.056X + 21.893$ $CU_{LA} = +0.498X^3 + 2.980X^2 + 9.499X + 26.367$ $CL_{LA} = -0.722X^3 - 0.003X^2 + 10.128X + 17.912$ $\%A = +0.069X^3 + 1.252X^2 + 5.843X + 9.687$ $CU_A = +0.627X^3 + 2.568X^2 + 5.953X + 12.315$ $CL_A = -0.396X^3 + 0.381X^2 + 5.431X + 7.510$ $\%HA = +0.110X^3 + 0.806X^2 + 2.579X + 3.405$ $CU_{HA} = +0.508X^3 + 1.628X^2 + 2.813X + 4.560$ $CL_{HA} = -0.149X^3 + 0.308X^2 + 2.222X + 2.506$ Where: $X = \frac{10\log_{10}(Descriptor) + 12.98}{6.89}$

Descriptor	β_0	β_1	σ	Polynomial approximations
a_{w95}	55.11	2.16	41.95	$\%LA = -0.084X^3 + 1.278X^2 + 10.242X + 22.128$ $CU_{LA} = +0.486X^3 + 2.944X^2 + 9.672X + 26.611$ $CL_{LA} = -0.721X^3 + 0.059X^2 + 10.325X + 18.134$ $\%A = +0.070X^3 + 1.286X^2 + 5.970X + 9.812$ $CU_{A} = +0.621X^3 + 2.566X^2 + 6.080X + 12.454$ $CL_{A} = -0.392X^3 + 0.432X^2 + 5.558X + 7.621$ $\%HA = +0.114X^3 + 0.832X^2 + 2.642X + 3.455$ $CU_{HA} = +0.508X^3 + 1.639X^2 + 2.880X + 4.619$ $CL_{HA} = -0.145X^3 + 0.337X^2 + 2.281X + 2.548$ Where: $X = \frac{10\log_{10}(Descriptor) + 27.54}{6.71}$
L_{aw}	-82.11	1.08	41.94	$\%LA = -0.164X^3 + 1.606X^2 + 12.435X + 24.121$ $CU_{LA} = +0.218X^3 + 3.672X^2 + 13.169X + 28.711$ $CL_{LA} = -0.724X^3 - 0.068X^2 + 11.453X + 19.980$ $\%A = +0.083X^3 + 1.746X^2 + 7.505X + 10.995$ $CU_{A} = +0.629X^3 + 3.535X^2 + 8.609X + 13.786$ $CL_{A} = -0.408X^3 + 0.466X^2 + 6.363X + 8.640$ $\%HA = +0.175X^3 + 1.200X^2 + 3.438X + 3.982$ $CU_{HA} = +0.673X^3 + 2.465X^2 + 4.237X + 5.235$ $CL_{HA} = -0.151X^3 + 0.405X^2 + 2.696X + 2.977$ Where: $X = \frac{Descriptor - 74.46}{15.47}$

Descriptor	β_0	β_1	σ	Polynomial approximations
V_{max}	15.77	2.17	41.94	$\%LA = -0.174X^3 + 1.675X^2 + 12.700X + 24.070$ $CU_{LA} = +0.229X^3 + 3.766X^2 + 13.411X + 28.699$ $CL_{LA} = -0.762X^3 - 0.017X^2 + 11.720X + 19.901$ $\%A = +0.088X^3 + 1.820X^2 + 7.659X + 10.964$ $CU_{A} = +0.659X^3 + 3.646X^2 + 8.768X + 13.774$ $CL_{A} = -0.424X^3 + 0.513X^2 + 6.501X + 8.600$ $\%HA = +0.186X^3 + 1.252X^2 + 3.506X + 3.967$ $CU_{HA} = +0.708X^3 + 2.554X^2 + 4.313X + 5.224$ $CL_{HA} = -0.154X^3 + 0.433X^2 + 2.751X + 2.962$ Where: $X = \frac{10\log_{10}(Descriptor) + 7.99}{7.88}$
A_{max}	47.78	2.17	41.94	$\%LA = -0.164X^3 + 1.606X^2 + 12.436X + 24.122$ $CU_{LA} = +0.256X^3 + 3.693X^2 + 13.013X + 28.742$ $CL_{LA} = -0.760X^3 - 0.068X^2 + 11.572X + 19.957$ $\%A = +0.083X^3 + 1.746X^2 + 7.505X + 10.995$ $CU_{A} = +0.655X^3 + 3.543X^2 + 8.509X + 13.803$ $CL_{A} = -0.428X^3 + 0.468X^2 + 6.426X + 8.631$ $\%HA = +0.175X^3 + 1.200X^2 + 3.438X + 3.983$ $CU_{HA} = +0.687X^3 + 2.466X^2 + 4.187X + 5.242$ $CL_{HA} = -0.159X^3 + 0.407X^2 + 2.722X + 2.975$ Where: $X = \frac{10\log_{10}(Descriptor) + 22.77}{7.74}$

Appendix I: Model coefficients for railway induced vibration

Descriptor	β_0	β_1	σ	Polynomial approximations
V_{dB}	-82.07	1.04	41.95	$\%LA = -0.138X^3 + 1.440X^2 + 11.725X + 24.122$ $CU_{LA} = +0.224X^3 + 3.458X^2 + 12.403X + 28.668$ $CL_{LA} = -0.659X^3 - 0.183X^2 + 10.819X + 20.008$ $\%A = +0.071X^3 + 1.561X^2 + 7.076X + 10.997$ $CU_{A} = +0.578X^3 + 3.267X^2 + 8.098X + 13.770$ $CL_{A} = -0.382X^3 + 0.353X^2 + 6.017X + 8.650$ $\%HA = +0.148X^3 + 1.067X^2 + 3.242X + 3.987$ $CU_{HA} = +0.601X^3 + 2.242X^2 + 3.985X + 5.241$ $CL_{HA} = -0.147X^3 + 0.336X^2 + 2.550X + 2.980$ Where: $X = \frac{Descriptor - 77.22}{15.14}$

CONSTRUCTION INDUCED VIBRATION

Descriptor	**β_0**	**β_1**	**σ**	**Polynomial fit**
$VDV_{b,08:00\text{-}18:00}$	126.24	6.62	63.60	$\%LA = -0.809X^3 + 4.290X^2 + 21.567X + 23.728$ $CU_{LA} = +0.150X^3 + 3.891X^2 + 19.399X + 31.042$ $CL_{LA} = -1.507X^3 + 4.847X^2 + 21.731X + 17.792$ $\%A = -0.024X^3 + 4.922X^2 + 15.950X + 14.483$ $CU_A = +0.736X^3 + 4.850X^2 + 15.378X + 19.938$ $CL_A = -0.508X^3 + 4.927X^2 + 15.092X + 10.385$ $\%HA = +0.558X^3 + 4.587X^2 + 10.468X + 7.971$ $CU_{HA} = +1.177X^3 + 4.892X^2 + 10.756X + 11.567$ $CL_{HA} = +0.169X^3 + 4.177X^2 + 9.358X + 5.466$ Where: $X = \frac{10\log_{10}(Descriptor) + 21.81}{6.77}$
$RMS_{b,08:00\text{-}18:00}$	291.29	7.24	62.22	$\%LA = -1.416X^3 + 4.558X^2 + 25.749X + 27.198$ $CU_{LA} = -0.309X^3 + 4.242X^2 + 23.311X + 34.556$ $CL_{LA} = -2.311X^3 + 5.014X^2 + 26.091X + 21.113$ $\%A = -0.364X^3 + 5.755X^2 + 19.672X + 16.962$ $CU_A = +0.544X^3 + 5.847X^2 + 19.096X + 22.559$ $CL_A = -1.026X^3 + 5.547X^2 + 18.739X + 12.678$ $\%HA = +0.528X^3 + 5.726X^2 + 13.287X + 9.508$ $CU_{HA} = +1.323X^3 + 6.326X^2 + 13.731X + 13.239$ $CL_{HA} = -0.049X^3 + 4.990X^2 + 11.987X + 6.857$ Where: $X = \frac{10\log_{10}(Descriptor) + 41.72}{6.77}$

Descriptor	β_0	β_1	σ	Polynomial fit
ppv	36.12	8.46	62.82	$\%LA = -1.236X^3 + 1.734X^2 + 24.024X + 38.773$ $CU_{LA} = -0.831X^3 + 2.277X^2 + 22.851X + 44.935$ $CL_{LA} = -1.824X^3 + 1.361X^2 + 24.366X + 32.967$ $\%A = -0.742X^3 + 3.346X^2 + 20.504X + 26.373$ $CU_{A} = -0.309X^3 + 4.016X^2 + 20.694X + 31.691$ $CL_{A} = -1.270X^3 + 2.735X^2 + 19.628X + 21.652$ $\%HA = -0.127X^3 + 4.073X^2 + 15.513X + 16.349$ $CU_{HA} = +0.348X^3 + 5.001X^2 + 16.572X + 20.391$ $CL_{HA} = -0.618X^3 + 3.187X^2 + 14.055X + 12.961$ Where: $X = \frac{10\log_{10}(Descriptor) + 3.1}{4.69}$

APPENDIX II

CONSENT FORM

APPENDIX II: CONSENT FORM

Prof. Andy Moorhouse
School of Computing Science and Engineering

The University of Salford
Newton Building
Salford, Greater Manchester
M5 4WT. United Kingdom

T +44(0)161 295 5490
F +44(0)161 295 4442
a.t.moorhouse@salford.ac.uk

Participant Identification Number for this trial:

CONSENT FORM

Title of Project: **Human response to vibration in residential environments**

Name of Researcher: ________________________________

Please tick box and sign.

1. I confirm that I have read and understand the information sheet dated 20th December 2012 (NANR209/ information sheet/ 1) for the above study. I have had the opportunity to consider the information, ask questions and have had these answered satisfactorily. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. ☐

3. I understand that some things I say to the researcher may be quoted anonymously in project reports. I give permission for anonymous quotes to be used. ☐

4. I do not suffer from, nor have suffered in the past, any medical condition which would prevent me from taking part in an experiment which involves exposure to whole body vibration (including, but not limited to, back or neck problems, cardiovascular disorders, diseases of the ears or eyes, retinal detachment). ☐

5. I agree to take part in the above study. ☐

________________	________________	________________
Name of Participant	Date	Signature
Name of Person taking consent	Date	Signature

When completed, 1 for participant; 1 for researcher file

NANR209/consent form/1 23rd January 2012

APPENDIX III

INFORMATION SHEET

APPENDIX III: INFORMATION SHEET

Prof. Andy Moorhouse
School of Computing Science and Engineering

The University of Salford
Newton Building
Salford, Greater Manchester
M5 4WT. United Kingdom

T +44(0)161 295 5490
a.t.moorhouse@salford.ac.uk

Human response to vibration in residential environments
Information Sheet for participants

You are invited to take part in a research study. Before you decide whether or not you wish to take part it is important for you to understand why the study is being done and what it will involve if you agree to take part. Please read the following information carefully. Ask the researcher if there is anything you don't understand or if you would like more information.

What is the purpose of the study?

Some people can feel vibration in their homes, for example if they live near a railway or construction site. For some, this can be annoying. The study is designed to help us find out more about why vibration in the home can cause annoyance. The results will be helpful in planning construction sites, railways and other activities so as to minimise unnecessary annoyance caused by vibration.

Who is funding the study?

The study is funded by the Department for Environment, Food and Rural Affairs (Defra). Defra is responsible for the environment in the UK which includes possible disturbance by noise and vibration. Further funding is provided by the Engineering and Physical Research Council (EPSRC) which supports the researcher for completing a PhD.

What will happen to me if I take part?

You will be asked to sit in a chair which is part of a test setup capable of producing low level vibrations. The level of these vibrations is similar to what you would feel if your home was situated close to a railway line. You will then feel a vibration event lasting a few seconds. After a short pause there will be another vibration event. You will be asked to mark on a scale whether the first or second event was more annoying. This pattern will be repeated a number of times during the session which will last about 30 minutes.

Is there any risk?

There is no risk of harm. In this study we are interested in the annoyance caused by vibration in the home and the levels of vibration are low. You would experience much higher levels of vibration on a car, train or plane journey, or when walking or jogging.

Confidentiality – who will have access to the data ?

All the data will be held securely and will be treated confidentially. The arrangements for data storage and security comply with the terms of the Data Protection Act. If it helps to clarify the results of the study we may quote some phrases that you say when talking to the researcher. Any quotes will be anonymous – nobody will know you have taken part in the study. If you decide to withdraw from the study for any reason or at any time, any data already collected will be deleted and any paper copies destroyed.

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What will happen to the study results?
In any material published from this study, all participants will be anonymous. The results of this study will be published in the researcher's PhD thesis during 2012.

You can decide to change your mind and withdraw from the study at any time without having to give a reason for withdrawing.

The researcher conducting the test will be able to answer your questions
(Researcher's name)
……………………
……………………

APPENDIX IV

SOCIAL SURVEY QUESTIONNAIRE

Social Survey Questionnaire

Introduction

My name is [   ] and I work for the University of Salford [show badge]. We are conducting a neighbourhood satisfaction survey on behalf of the Department for the Environment, Food and Rural Affairs and would really like to get your views. It should take no more than 25 minutes. Is that okay?

Before I start, can I just ask how long you have been living in this home?

[If the answer is less than 9 months, say: "Unfortunately we need to talk to people who have been here for more than 9 months. Thank you for your time."]

[If the respondent answers that they do not have the time, ask: "Is there a better time for you?" If this is not possible ask: "Do you have a few minutes for me to just ask some brief questions?" If yes, complete the non-response sheet.]

Throughout the questionnaire we want to know your personal views and opinions rather than the opinions of other people you might live with. I will be writing down your answers but the information will be completely anonymous.

If there are any questions you don't want to answer, just let me know and if you're not happy, I'll move on to the next question

Full Address: ____

____

Postcode: ____

Telephone **[record at end]**: ____________________________________

Date of Interview: ____

Start time: ___________ End time: ___________

Complete after survey has been administered

I declare that this is a true record of an interview for this survey.

Interviewer name: ______________________
Signature: ______________________
Case study number: ______________________
Site Name/Number: ______________________
Proximity to Source: ______________________

SECTION A: Dwelling Information

This section is to be completed by the interviewer (not with respondent).

A1. In which of the following is the property situated?

Centre of a large city ☐
Suburbs/Outskirts of a large city ☐
Large town or small city ☐
Small town ☐
Village ☐
Countryside ☐
Other ☐
[If 'Other' record below]

____

A2a. What type of dwelling is the property?

Detached	☐	**[Go to A3]**
Semi-detached	☐	**[Go to A3]**
Terraced	☐	**[Go to A3]**
End terrace	☐	**[Go to A3]**
Maisonette	☐	**[Go to A3]**
Apartment/Flat	☐	**[Go to A2b]**
Bedsit	☐	**[Go to A2b]**
Mobile home/Caravan	☐	**[Go to A5]**
Other **[record below]**	☐	**[Go to A3]**

____

A2b. Is the property:

Purpose built ☐
Conversion ☐

[Go to A4]

A3. If the property is detached, semi-detached, terraced (including end terrace) or maisonette, how many storeys does it have?
[Record number] ____________

A4. If the property is an apartment, flat, bedsit or maisonette.

(a) On which floor is the entrance to the property?

[i.e. entrance to individual property, not the building in which it is located]

[Record floor number] ________________

[G = ground floor, B = below ground]

How many floors are there in the whole building? ________________

(b) Does the living space include the top floor of the building (i.e. directly below the roof or loft space)?

Yes ☐

No ☐

A5. In what type of residential area is the property located?

Residential/housing estate only (i.e. no commercial/industrial buildings) ☐

Residential/housing estate with some commercial buildings (shops, offices etc.) ☐

Residential/housing estate with some industrial facilities (factories) nearby ☐

Primarily a commercial area with some residential (e.g. city centres) ☐

Primarily an industrial area with some residential ☐

Mixed residential/countryside ☐

Mostly countryside ☐

Other **[record below]** ☐

____

SECTION B: Neighbourhood Satisfaction

This first set of questions is about this neighbourhood and how satisfied you are with it. We will talk about satisfaction with this home later on in the survey.

B1. To begin with we'd like to know what first attracted you to live in this neighbourhood. Was it because you:

	Yes	No
Were born in this neighbourhood	☐	☐
Liked the neighbourhood	☐	☐
Wanted to be nearer family/friends	☐	☐
Wanted to be nearer to work	☐	☐
Wanted to be nearer your own community	☐	☐
Did not have a choice	☐	☐
Were there any other reasons?	☐	☐

[If 'yes' to other reasons, ask: "What were the other reasons?" and record below]

____

____

[If respondent answers that they did not have a choice, route to B2; if not, route to B3]

B2. Do you mind telling me why you did not have a choice?
[Record below]

____

____

B3. When did you move into this neighbourhood?

Month__________________ Year____________

[If respondent only states the year, ask: "Do you remember what month it was?"]

B4. Looking at this card **[show card 1]**, overall, how satisfied or dissatisfied are you personally with living in this neighbourhood? Would you say that you are very satisfied, satisfied, neither satisfied nor dissatisfied, dissatisfied or very dissatisfied?

Very satisfied ☐
Satisfied ☐
Neither satisfied nor dissatisfied ☐
Dissatisfied ☐
Very dissatisfied ☐

B5. In giving this rating, are there particular aspects of this neighbourhood that you are thinking of? **[Record below]**

____
____
____

Code if respondent mentions

N ☐
V ☐

B6. Looking at this card **[show card 2]**, how would you personally rate this neighbourhood on **[insert neighbourhood characteristic]**? Would you say that it is very good, good, neither good nor poor, poor or very poor?

Aspect	**Very good**	**Good**	**Neither good nor poor**	**Poor**	**Very poor**	**Don't know**
Standard of schools						
Childcare facilities						
Public transport						
Closeness to shops						
Standard of health care services						
Upkeep of roads						
Parking facilities						
Leisure facilities						
How peaceful it is						
How quiet it is						
Standard of the parks and other open spaces						
Closeness to place of worship						
Reputation of neighbourhood						
Appearance of buildings						

B7. Is there anything else that you personally particularly like about this neighbourhood?

[Record below]

[Prompt: "Why do you like this?"]

Code if respondent mentions

N ☐

V ☐

B8. Is there anything else that you personally particularly dislike about this neighbourhood?

[Record below]

[Prompt: "Why do you dislike this?"]

Code if respondent mentions

N ☐

V ☐

SECTION C: Satisfaction with Home

The next set of questions is about how satisfied you are with this home, where we are now, rather than this neighbourhood as a whole.

C1. Can you tell me why you first moved to this home here?
[Record below]

____
____
____

Code if respondent mentions
N ☐
V ☐

C2. Looking at this card **[show card 1]**, overall, how satisfied or dissatisfied are you personally with living in this home? Would you say that you are very satisfied, satisfied, neither satisfied nor dissatisfied, dissatisfied or very dissatisfied?

Very satisfied ☐
Satisfied ☐
Neither satisfied nor dissatisfied ☐
Dissatisfied ☐
Very dissatisfied ☐

C3. In giving this rating, are there any particular things that you are thinking about?
[Record below]

____
____
____

Code if respondent mentions
N ☐
V ☐

C4. Is there anything else that you personally particularly like about living in this home?

[Record below]

[Prompt: "Why do you like this?"]

____

____

____

Code if respondent mentions	
N	☐
V	☐

C5. Is there anything else that you personally particularly dislike about living in this home?

[Record below]

[Prompt: "Why do you dislike this?"]

____

____

____

Code if respondent mentions	
N	☐
V	☐

C6. Can I just check again, when did you move into this home?

Month__________ Year_____________

[If respondent only states the year, ask: "Do you remember what month it was?"]

C7. Do you want to move home?

Yes	☐	**[Go to C8]**
No	☐	**[Go to C9]**
Don't know	☐	**[Go to C9]**

C8. Why do you want to move?

[Record below]

____

____

Code if respondent mentions	
N	☐
V	☐

C9. Looking at this list **[show card 3]**, which best describes your current situation with this home?

Do you or your family:

Own outright or with a mortgage	☐
Part-rent and part-own with a mortgage	☐
Rent from a private landlord/letting agency	☐
Rent from a Housing Association or Council	☐
Other	☐

[If stating 'other' ask: "Can you tell me what that is?"]

[Record below]

____

C10. What kind of windows do you have here? Is it:

	None	Some	All
Single glazing	☐	☐	☐
Double glazing	☐	☐	☐
Secondary glazing	☐	☐	☐
Triple glazing	☐	☐	☐
Other	☐	☐	☐

[If stating 'other' ask: "Can you tell me what kind they are?"]

[Record below]

____

C11. [If property is a house or ground floor flat] Do you have a cellar or basement?

Yes ☐
No ☐

[If yes ask]	Yes	No
Is it used as a living space?	☐	☐
Is it used as a working space?	☐	☐
Is it used for storage?	☐	☐

C12. From any room in this home, can you see:

	Yes	No
A motorway or any motorway traffic	☐	☐
A dual carriageway road or traffic on one	☐	☐
A residential or estate road or traffic on one	☐	☐
A town or city road or traffic on one	☐	☐
A country lane or traffic on one	☐	☐
Any other type of road	☐	☐

[If yes to 'any other type of road' ask: "Can you tell me what type it is?"]

[Record below]

____

A railway track or any type of passing train	☐	☐
Construction activity	☐	☐

SECTION D: Vibration Questions

One of the things that we are interested in in this questionnaire is the impact of vibration and noise from sources both outside and inside this home. The next set of questions is about any vibration or shaking you personally experience whilst in this home. This includes vibration that you think may be caused by noise, but I will ask about the noise itself later on.

D1. Thinking about the last 12 months or so, when indoors at home, have you felt any vibration or shaking anywhere that you think was caused by:

	Yes	No
Cars, lorries, buses and other road vehicles	☐	☐
Aeroplanes	☐	☐
Helicopters	☐	☐
The railway, including passenger trains, freight trains, track maintenance or any other activity from the railway	☐	☐
Underground trains like the tube or metro	☐	☐
Trains in tunnels	☐	☐
Construction activity, including building, demolition and road works	☐	☐
Quarrying or mining	☐	☐
Footsteps, slamming doors, domestic appliances inside this home	☐	☐
Footsteps, slamming doors, domestic appliances in neighbouring homes	☐	☐
An unidentified source	☐	☐
Any other source	☐	☐

[If yes to 'any other source' ask: "Can you tell me what the source is?"]

[Record below]

____

[If the respondent has answered 'yes' to any above, route to D2; if not, route to D5]

D2. When you have felt vibration, have you felt it:

	Yes	No
From the floor	☐	☐
When you have been sitting on a chair	☐	☐
When you have been lying on a bed	☐	☐
When you have touched any surfaces with your hands	☐	☐
From any other surfaces in this home	☐	☐

[If yes to 'any other surfaces' ask: "Where else have you felt it?"]

[Record below]

____

D3. Can you tell me where in this home you have felt the vibration or shaking, starting with where you have felt it the most?

[Record room and floor below. If unsure, ask: "On which floor is that?" after the response]

	Room	Floor
1.	______________________	_______
2.	______________________	_______
3.	______________________	_______
4.	______________________	_______

D4. Has feeling vibration or shaking of the floor, chair, bed or other surfaces bothered, annoyed or disturbed you personally when you have been:

	Yes	No
Watching the television	☐	☐
Listening to the radio or music	☐	☐
Talking to someone in person or on the telephone	☐	☐
Reading or doing any other quiet activities	☐	☐
Writing, drawing, painting or doing any other activity requiring a steady surface	☐	☐
Resting	☐	☐
Sleeping	☐	☐
Using any rooms in this home	☐	☐
Doing anything else	☐	☐

[If yes to 'doing anything else' ask: "Can you tell me what that was?"]
[Record below]

____

We'd now like to find out if you have heard or seen anything rattle, vibrate or shake in this home over the last 12 months or so.

D5. Thinking about the last 12 months or so, when indoors at home, have you heard or seen things rattle, vibrate or shake that you think was caused by:

	Yes	No
Cars, lorries, buses and other road vehicles	☐	☐
Aeroplanes	☐	☐
Helicopters	☐	☐
The railway, including passenger trains, freight trains, track maintenance or any other activity from the railway	☐	☐
Underground trains like the tube or metro	☐	☐
Trains in tunnels	☐	☐
Construction activity, including building, demolition and road works	☐	☐
Quarrying or mining	☐	☐
Footsteps, slamming doors, domestic appliances inside this home	☐	☐
Footsteps, slamming doors, domestic appliances in neighbouring homes	☐	☐
An unidentified source	☐	☐
Any other source	☐	☐

[If yes to 'any other source' ask: "Can you tell me what the source is?"]
[Record below]

____

[If the respondent has answered 'no' to all above, route to D9]

D6. Have you personally ever heard or seen any rattling, vibrating or shaking of:

	Yes	No
The windows	☐	☐
The doors	☐	☐
Any other part of this home	☐	☐
Crockery, like plates, or glasses in your cupboards	☐	☐
Any other objects in this home	☐	☐

[If yes to 'any other part of this home' or 'any other objects in this home' ask: "What other things have you heard or seen rattle, vibrate or shake in this home?"]
[Record below]

____

____

D7. Can you tell me where in this home you have heard or seen things rattle, vibrate or shake, starting with where you have heard or seen it the most?

[Record room and floor below. If unsure ask: "On which floor is that?" after the response]

	Room	Floor
1.	__________________________	________
2.	__________________________	________
3.	__________________________	________
4.	__________________________	________

D8. Has hearing or seeing things rattle, vibrate or shake bothered, annoyed or disturbed you when you have been:

	Yes	No
Watching the television	☐	☐
Listening to the radio or music	☐	☐
Talking to someone in person or on the telephone	☐	☐
Reading or doing any other quiet activities	☐	☐
Writing, drawing, painting or doing any other activity requiring a steady surface	☐	☐
Resting	☐	☐
Sleeping	☐	☐
Using any rooms in this home	☐	☐
Doing anything else	☐	☐

[If yes to 'doing anything else' ask: "Can you tell me what that was?"]

[Record below]

____

[If the respondent has not identified that they feel vibration or hear or see any effects of it, go to E1]

D9. Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by feeling vibration or shaking or hearing or seeing things rattle, vibrate or shake caused by **[insert source identified in D1 and D5]**? Would you say not at all, slightly, moderately, very or extremely?

[Show card 4]

[Repeat question for all sources identified at D1 and/or D5]

[For sources not noticed at D1 and D5, record as 'Don't notice']

Source		Don't notice		Not at all	Slightly	Moderately	Very	Extremely
Cars, lorries, buses or other road vehicles								
Aeroplanes								
Helicopters								
The railway, including passenger trains, freight trains, track maintenance or any other activity from the railway								
Underground trains (i.e. tube or metro)								
Trains in tunnels								
Construction activity, including building, demolition and road works								
Quarrying or mining								
Footsteps, slamming doors, domestic appliances inside this home								
Footsteps, slamming doors, domestic appliances in neighbouring homes								
Unidentified source/don't know								
Other things **[record below]**								
______________________								
______________________								

[If respondent is bothered, annoyed or disturbed, mark Section F (Yellow section) as a reminder to complete this section]

Next is a 0–10 opinion scale for how bothered, annoyed or disturbed you were when you felt or feel vibration here at home **[show card 5]**. If you are not at all annoyed choose 0, if you are extremely annoyed choose 10; if you are somewhere in between, choose a number between 1 and 10.

D10. Thinking about the last 12 months or so, when indoors at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by feeling vibration or shaking or hearing or seeing things rattle, vibrate or shake caused by **[insert source identified at D1 and/or D5]**?

[Repeat question for all sources identified at D1 and/or D5]

[For sources not noticed at D1 and D5, record as 'Don't notice']

Source	**Don't notice**	**Not at all**										**Extremely**
Cars, lorries, buses or other road vehicles		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Aeroplanes		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Helicopters		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
The railway, including passenger trains, freight trains, track maintenance or any other activity from the railway		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Trains in tunnels		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Underground trains (i.e. tube or metro)		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Construction activity, including building, demolition and road works		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Quarrying or mining		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Footsteps, slamming doors, domestic appliances inside this home		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Footsteps, slamming doors, domestic appliances from neighbouring homes		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Unidentified source/don't know		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Other things **[record below]**												
______________________________		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
______________________________		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
______________________________		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

D11. In the future, do you think the level of vibration you experience whilst indoors at home will get worse, get better or remain the same?

Worse ☐ Better ☐ Same ☐

D12. Can I ask why you think that?

[Record below]

____

____

____

D13. We would like to know if you are concerned that the vibration may damage this home or your possessions inside it in any way. **[Show card 4]**

Are you not at all concerned, slightly concerned, moderately concerned, very concerned or extremely concerned?

No - Not at all	☐	**[Go to D15]**
Yes - Slightly	☐	**[Go to D14]**
Yes - Moderately	☐	**[Go to D14]**
Yes - Very	☐	**[Go to D14]**
Yes - Extremely	☐	**[Go to D14]**

D14. Are you concerned about damage to:

	Yes	No
The way this home looks	☐	☐
The structure of this home	☐	☐
Your possessions inside this home	☐	☐
The value of this home	☐	☐
Anything else	☐	☐

[If 'yes' to 'Anything else' ask: "What other things?"]

[Record below]

____

____

____

D15. How sensitive would you say you are personally to vibration in general? Would you say you are not at all sensitive, slightly sensitive, moderately sensitive, very sensitive or extremely sensitive?

[Show card 4]

Not at all	☐
Slightly	☐
Moderately	☐
Very	☐
Extremely	☐

D16. Looking at this scale **[show card 6]** and given all that you have said, over the last 12 months or so, how acceptable have you found the level of vibration you have experienced in this home. Would you say it has been very acceptable, acceptable, neither acceptable nor unacceptable, unacceptable or very unacceptable?

Very acceptable	☐
Acceptable	☐
Neither acceptable nor unacceptable	☐
Unacceptable	☐
Very unacceptable	☐

SECTION E: Noise Questions

Moving on from any vibration or shaking you may experience when in this home, the following set of questions is about noise you may hear whilst inside this home. We have already talked about the noise of things rattling or shaking in this home which might be caused by vibration, so now we just want to know about the actual noise from the sources. For example, when we say the noise of cars, lorries and other road vehicles, we don't want to know about the noise of the windows shaking when they pass, but the noise of things like the engines, brakes, doors slamming and things like that. Is that okay?

E1. Thinking about the last 12 months or so, when indoors at home, have you heard any noise that you think was caused by:

	Yes	No
Cars, lorries, buses and other road vehicles	☐	☐
Aeroplanes	☐	☐
Helicopters	☐	☐
The railway, including passenger trains, freight trains, train horns, track maintenance, any noise from nearby stations, people or vehicles going to or from the stations or any other activity from the railway	☐	☐
Underground trains (i.e. tube or metro)	☐	☐
Trains in tunnels	☐	☐
Construction activity, including building, demolition and road works	☐	☐
Quarrying or mining	☐	☐
Footsteps, slamming doors, domestic appliances inside this home	☐	☐
Footsteps, slamming doors, domestic appliances in neighbouring homes	☐	☐
An unidentified source	☐	☐
Any other source	☐	☐

[If yes to 'any other source' ask: "Can you tell me what the source is?"]

[Record below]

____

[If respondent states 'no' to all above, route to source-specific vibration sections if relevant, or to Section Y if not]

E2. Has hearing noise from these sources bothered, annoyed or disturbed you when you have been:

	Yes	No
Watching the television	☐	☐
Listening to the radio or music	☐	☐
Talking to someone in person or on the telephone	☐	☐
Reading or with any other quiet activities	☐	☐
Writing, drawing, painting or any doing any other activity requiring a steady surface	☐	☐
Resting	☐	☐
Sleeping	☐	☐
Using any rooms in your house	☐	☐
Opening any windows in your house	☐	☐
Doing anything else	☐	☐

[If yes to 'doing anything else' ask: "Can you tell me what that was?"]

[Record below]

____

E3. Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by hearing noise caused by **[insert source identified in E1]**? Would you say not at all, slightly, moderately, very or extremely?

[Show card 4]

[Repeat question for all sources identified in E1]

Source	**Don't notice**	**Not at all**	**Slightly**	**Moderately**	**Very**	**Extremely**
Cars, lorries, buses or other road vehicles						
Aeroplanes						
Helicopters						
The railway, including passenger trains, freight trains, train horns, track maintenance, any noise from nearby stations, people or vehicles going to or from the stations or any other activity from the railway						
Trains in tunnels						
Underground trains (i.e. tube or metro)						
Construction activity, including building, demolition and road works						
Quarrying or mining						
Footsteps, slamming doors, domestic appliances inside this home						
Footsteps, slamming doors, domestic appliances in neighbouring homes						
Unidentified source/don't know						
Other things **[record below]**						

[If respondent is bothered, annoyed or disturbed, mark Section G (Blue section) as a reminder to complete this section]

Next is the 0–10 opinion scale for how bothered, annoyed or disturbed you have been when you have heard noise here at home **[show card 5]**. If you are not at all annoyed choose 0, if you are extremely annoyed choose 10; if you are somewhere in between choose a number between 1 and 10.

E4. Thinking about the last 12 months or so, when indoors at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by hearing noise caused by **[insert source identified at E1]**?

[Repeat question for all sources identified at E1]
[For sources not noticed at E1, record as 'Don't notice']

Source	Don't notice	Not at all										Extremely
Cars, lorries, buses or other road vehicles		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Aeroplanes		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Helicopters		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
The railway, including passenger trains, freight trains, train horns, track maintenance, any noise from nearby stations, people or vehicles going to or from the stations or any other activity from the railway		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Trains in tunnels		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Underground trains (i.e. tube or metro)		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Construction activity, including building, demolition and road works		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Quarrying or mining		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Footsteps, slamming doors, domestic appliances inside this home		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Footsteps, slamming doors, domestic appliances from neighbouring homes		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Unidentified source/don't know		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Other things **[record below]**												
______________________		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
______________________		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
______________________		**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

E5. How sensitive would you say you are personally to noise in general? Would you say you are not at all sensitive, slightly sensitive, moderately sensitive, very sensitive or extremely sensitive?
[Show card 4]

Not at all ☐
Slightly ☐
Moderately ☐
Very ☐
Extremely ☐

E6. Looking at this scale **[show card 6]** and given all that you have said, over the last 12 months or so, how acceptable have you found the level of noise you have experienced in this home. Would you say very it has been acceptable, acceptable, neither acceptable nor unacceptable, unacceptable or very unacceptable?

Very acceptable ☐
Acceptable ☐
Neither acceptable nor unacceptable ☐
Unacceptable ☐
Very unacceptable ☐

For railway sites only

SECTION F: Railway Vibration

[This section is only to be completed if the respondent has previously identified that they have been bothered, annoyed or disturbed by railway vibration]

You previously said that you have been bothered, annoyed or disturbed by vibration from the railway whilst in this home. The next set of questions is more specific to vibration from the nearby railway.

F1. Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by feeling vibration or hearing or seeing things rattle, vibrate or shake caused by **[insert sources below]**? Would you say not at all, slightly, moderately, very or extremely?

[Show card 4]

[Repeat question for all sources]

Source	Don't notice	Not at all	Slightly	Moderately	Very	Extremely
Passing passenger trains						
Passing freight trains						
Railway maintenance						
Other railway activity **[Record below]** ____________________						

F2. Thinking about the last 12 months or so, when indoors at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by feeling vibration or hearing or seeing things rattle, vibrate or shake caused by **[insert source identified at F1]**?

[Show card 5]

[Repeat question for all sources identified at F1]

[For sources not noticed at F1, record as 'Don't notice']

Source	Don't notice	Not at all										Extremely
Passing passenger trains		0	1	2	3	4	5	6	7	8	9	10
Passing freight trains		0	1	2	3	4	5	6	7	8	9	10
Railway maintenance		0	1	2	3	4	5	6	7	8	9	10
Other railway activity **[Record below]**												
____________________		0	1	2	3	4	5	6	7	8	9	10
____________________		0	1	2	3	4	5	6	7	8	9	10

F3. Looking at this scale **[show card 6]**, and thinking about the last 12 months or so, when indoors at home, how acceptable have you found the level of vibration you have experienced caused by the railway. Would you say it has been very acceptable, acceptable, neither acceptable nor unacceptable, unacceptable or very unacceptable?

Very acceptable ☐
Acceptable ☐
Neither acceptable nor unacceptable ☐
Unacceptable ☐
Very unacceptable ☐

F4. In giving this rating, are there particular aspects of the vibration that you are thinking of?
[Record below]

____
____
____

We would now like to find out if the vibration from the railway has bothered, annoyed or disturbed you more or less at different times of the day.

F5. Thinking about the last 12 months or so, when indoors at home how bothered, annoyed or disturbed have you been by feeling vibration or hearing or seeing things rattle, vibrate or shake caused by the railway between **[insert time of day]**? Would you say not at all, slightly, moderately, very or extremely?

[Show card 4]
[Repeat question for each time of day]

Time of day		**Not at all**	**Slightly**	**Moderately**	**Very**	**Extremely**
Day (7am to 7pm)						
Evening (7pm to 11pm)						
Night (11pm to 7am)						

F6. Thinking about the last 12 months or so, when indoors at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by feeling vibration or hearing or seeing things rattle, vibrate or shake caused by the railway between **[insert time of day]**?

[Show card 5]
[Repeat question for each time of day]

Time of day	**Not at all**										**Extremely**
Day (7am to 7pm)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Evening (7pm to 11pm)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Night (11pm to 7am)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

F7. Compared with the last quarter of an hour or so, would you say that you usually experience:

More vibration from the railway ☐
Less vibration from the railway ☐
The same amount of vibration from the railway ☐

F8. Do you have any other comments about vibration from the railway that we have not discussed?
[Record below]

____
____
____
____

For railway sites only

Section G: Railway Noise

[This section is only to be completed if the respondent has previously identified that they have been bothered, annoyed or disturbed by railway noise]

You previously said that you have been bothered, annoyed or disturbed by noise from the railway whilst in this home. The next set of questions is more specific to noise from the nearby railway.

G1. Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by hearing noise caused by **[insert sources below]**? Would you say not at all, slightly, moderately, very or extremely?
[show card 4]

Noise	Don't hear	Not at all	Slightly	Moderately	Very	Extremely
Passage of trains						
Train horns						
Noise from stations such as loud speakers						
Goods yards (shunting, freight handling)						
Railway/track maintenance						
People going to or from the station (in cars or walking)						
Other railway activity **[Record below]**						
____________________						

G2. Thinking about the last 12 months or so, when indoors at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by hearing noise caused by **[insert source identified at G1]**?

[Show card 5]
[Repeat question for all sources identified at G1]
[For sources not noticed at G1, record as 'Don't notice']

Source	Don't notice	Not at all										Extremely
Passage of trains		0	1	2	3	4	5	6	7	8	9	10
Train horns		0	1	2	3	4	5	6	7	8	9	10
Noise from stations such as loud speakers		0	1	2	3	4	5	6	7	8	9	10
Goods yards (shunting, freight handling)		0	1	2	3	4	5	6	7	8	9	10
Railway/track maintenance		0	1	2	3	4	5	6	7	8	9	10
People going to or from the station (in cars or walking)		0	1	2	3	4	5	6	7	8	9	10
Other railway activity **[Record below]**												
____________________		0	1	2	3	4	5	6	7	8	9	10
____________________		0	1	2	3	4	5	6	7	8	9	10

G3. Looking at this scale **[show card 6]**, and thinking about the last 12 months or so, when indoors at home, how acceptable have you found the level of noise you have experienced caused by the railway? Would you say very acceptable, acceptable, neither acceptable nor unacceptable, unacceptable or very unacceptable?

Very acceptable ☐
Acceptable ☐
Neither acceptable nor unacceptable ☐
Unacceptable ☐
Very unacceptable ☐

G4. In giving this rating, are there particular aspects of the noise that you are thinking of?
[Record below]

____

____

____

We would now like to find out if the noise from the railway bothers, annoys or disturbs you more or less at different times of the day.

G5. Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you personally been by hearing noise caused by the railway between **[insert time of day]**? Would you say not at all, slightly, moderately, very or extremely?

[Show card 4]
[Repeat question for each time of day]

Time of day		Not at all	Slightly	Moderately	Very	Extremely
Day (7am to 7pm)						
Evening (7pm to 11pm)						
Night (11pm to 7am)						

G6. Thinking about the last 12 months or so, when indoors at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by hearing noise caused by the railway between **[insert time of day]**?

[Show card 5]
[Repeat question for each time of day]

Time of day	Not at all										Extremely
Day (7am to 7pm)	0	1	2	3	4	5	6	7	8	9	10
Evening (7pm to 11pm)	0	1	2	3	4	5	6	7	8	9	10
Night (11pm to 7am)	0	1	2	3	4	5	6	7	8	9	10

G7. Compared with the last quarter of an hour or so, would you say that you usually hear:

More noise from the railway ☐
Less noise from the railway ☐
The same amount of noise from the railway ☐

G8. Do you have any other comments about noise from the railway that we have not discussed?

[Record below]

Section Y: Personal and Occupancy Information

This is the final section of the questionnaire. We would just like to finish by getting some basic information about you.

Y1. During a typical weekday, that is, Monday to Friday, what times are you usually at home? Are you at home between:

	Yes	No
06:01 and 09:00	☐	☐
09:01 and 12:00	☐	☐
12:01 and 15:00	☐	☐
15:01 and 18:00	☐	☐
18:01 and 21:00	☐	☐
21:01 and 00:00	☐	☐
00:01 and 03:00	☐	☐
03:01 and 06:00	☐	☐

Y2. During a typical weekend, that is, Saturday and Sunday, what times are you usually at home? Are you at home between:

	Yes	No
06:01 and 09:00	☐	☐
09:01 and 12:00	☐	☐
12:01 and 15:00	☐	☐
15:01 and 18:00	☐	☐
18:01 and 21:00	☐	☐
21:01 and 00:00	☐	☐
00:01 and 03:00	☐	☐
03:01 and 06:00	☐	☐

Y3. Do you mind me asking how old you are?

[Record specific age] _______________

If respondent does not want to give their age ask "Would you mind telling me which age group you fit into?" [Show card 7]

17–24 ☐
25–39 ☐
40–49 ☐
50–59 ☐
60–74 ☐
75–84 ☐
85+ ☐

Y4. Thinking about the people who you live with:

i) How many members of the household are there, including you? ______________

ii) How many members of the household are aged 18 or over? ________________

iii) How many members of the household are aged under 18? ______________

Y5. From this list **[show card 8]**, how would you describe your ethnicity?

A. White

- British ☐
- Irish ☐
- Romany Gypsy ☐
- Irish Traveller ☐
- Other white background ☐ please specify ______________

B. Mixed

- White & Black Caribbean ☐
- White & Black African ☐
- White & Asian ☐
- Other mixed background ☐ please specify ______________

C. Asian or Asian British

- Indian ☐
- Pakistani ☐
- Bangladeshi ☐
- Other Asian background ☐ please specify ______________

D. Black or Black British

- Caribbean ☐
- African ☐
- Other black background ☐ please specify ______________

E. Chinese or other ethnic group

- Chinese ☐
- Any other ☐ please specify ______________

Y6. From this list **[show card 9]** what best describes your employment status. Are you:

	Yes	No	
Employed	☐	☐	**[If yes go to Y7]**
Self-employed/business owner	☐	☐	**[If yes go to Y7]**
Student	☐	☐	**[If yes go to Y8]**
Retired	☐	☐	**[If yes go to Y8]**
Unemployed	☐	☐	**[If yes go to Y8]**
Carer/homemaker	☐	☐	**[If yes go to Y8]**
Volunteer worker	☐	☐	**[If yes go to Y8]**
Other	☐	☐	**[If yes go to Y8]**

[If yes to 'other' ask: "How would you describe your employment status?"]

[Record below]

____

Y7. We would like to ask a few questions about your work.

a. What type of industry is it in?

[Record below]

____

b. What is your job title

[Record below]

____

c. Are you employed in shift work?

Yes ☐

No ☐

[If yes, ask: "Can you summarise what the shifts are?"]

[Record below]

____

____

Y8. Is there anything else you would like to say about noise and vibration in this home?

[Record below]

____

____

____

____

____

____

Y9. Record if respondent is

Male ☐
Female ☐

Thank you for your time and for taking part in this survey.

The research is for the Department for the Environment, Food and Rural Affairs and, as you have seen, is particularly looking at how people respond to vibration and noise experienced within their homes. The purpose of this survey was to gather information about how you feel about the nearby railway and the vibration and noise you experience from it. We were not able to tell you this at the start as we did not want to influence your answers.

In order to provide some context to your answers we would like, if possible, to take some vibration measurements inside you home. This will involve a member of our team placing a small measuring device on the floor for no more than half an hour so that we can measure how much vibration there is in this home. It is powered by a battery so they will not need to plug it in and you won't need to do anything with it. Is it okay for them to do this?

If you would like any further information about the project, I can give you the phone numbers of the project managers at the University of Salford who will be able to answer any more questions you have about the project. Would you mind if we recorded your telephone number in case we need to contact you again? It will not be passed on to any other organisations or made public in any way. **[Record on front sheet if given]**

Thank you once again for taking part.

Allowed vibration measurement

Yes ☐
No ☐

SECTION Z: Interviewer Assessment of Vibration and Noise

Z1. Whilst in the property, did you feel vibration of any of the following?

	Yes	No
The floor	☐	☐
The chair you were sitting on	☐	☐
Other **[Record below]**	☐	☐

____

Z2. What do you think this was caused by?

	Yes	No
Cars, lorries, buses and other road vehicles	☐	☐
Aeroplanes	☐	☐
Helicopters	☐	☐
The railway, including passenger trains, freight trains, track maintenance or any other activity from the railway	☐	☐
Underground trains (i.e. tube or metro)	☐	☐
Trains in tunnels	☐	☐
Quarrying or mining	☐	☐
Construction activity, including building, demolition and road works	☐	☐
Footsteps, slamming doors, domestic appliances inside the home	☐	☐
Footsteps, slamming doors, domestic appliances in neighbouring homes	☐	☐
An unidentified source	☐	☐
Any other source **[record source below]**	☐	☐

____

Z3. While in the dwelling did you hear or see any of the following?

	Yes	No
Rattling of windows	☐	☐
Rattling of objects **[record objects below]**	☐	☐

____

	Yes	No
Swaying of pendulum lights	☐	☐
Other **[record below]**	☐	☐

____

Z4. While in the dwelling, did you hear noise from the following?

	Yes	No
Cars, lorries, buses and other road vehicles	☐	☐
Aeroplanes	☐	☐
Helicopters	☐	☐
The railway, including passenger trains, freight trains, train horns, track maintenance, any noise from nearby stations, people or vehicles going to or from the stations or any other activity from the railway	☐	☐
Underground trains (i.e. tube or metro)	☐	☐
Trains in tunnels	☐	☐
Quarrying or mining	☐	☐
Construction activity, including building, demolition and road works	☐	☐
Footsteps, slamming doors, domestic appliances inside the home	☐	☐
Footsteps, slamming doors, domestic appliances in neighbouring homes	☐	☐
An unidentified source	☐	☐
Any other source **[record source below]**	☐	☐

____

Z5. Any other comments you would like to make about vibration and/or noise in this property?

[Record below]

____

____

____

____

____

____

____