



University of Salford
A Greater Manchester University

**HUMAN RESPONSE TO VIBRATION IN
RESIDENTIAL ENVIRONMENTS
(NANR209)**

FINAL PROJECT REPORT

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David Waddington, Andy Moorhouse, Andy Steele, James Woodcock, Jenna Condie,
Eulalia Peris, Gennaro Sica, Zbigniew Koziel

FOREWORD

This research was commissioned by the previous government.

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

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PREFACE

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

The NANR209 Final Report consists of the following documents:

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

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

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

This project benefited from guidance in the design of the vibration measurement equipment from the suppliers Guralp Ltd.

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

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

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

PROJECT SUMMARY

INTRODUCTION

This project report summarises the findings of the Defra funded project “NANR209: Human response to vibration in residential environments”. The aim of the project was to develop an exposure-response relationship for vibration experienced in residential environments from sources outside of the residents’ control. A consensus decision was made in discussions with the Project Board that for experimental convenience and practical significance the vibrations arising from railways, construction and "internal" sources would be exploited.

DETERMINATION OF RESPONSE

Response data were collected using face-to-face interviews with residents in their own homes. The questionnaire was presented as a neighbourhood satisfaction survey and gathered information on, among other things, annoyance caused by vibration and noise exposure. The social survey questionnaire collected annoyance ratings on five-point semantic and eleven-point numerical scales for all potential sources of vibration and noise in the residential environment, source-specific annoyance responses for railway, construction activity and internal activities, and annoyance ratings during the day, evening and night. Other questions were included to gather information on the respondents’ characteristics, satisfaction with their neighbourhood and home, vibration and noise sensitivity and acceptability, and open questions to gather contextual information about the source in question. Development and findings of the questionnaire used for the collection of response data are detailed in Technical Report 2 and Technical Report 5.

DETERMINATION OF EXPOSURE

Vibration exposure was determined by measurement and prediction in such a way that, where possible, an estimation of internal vibration exposure was established for each residence in which a questionnaire was completed. The measurement procedures and methods employed to estimate vibration exposure are detailed in Technical Report 1 and Technical Report 3. Estimations of noise exposure were also derived for each residence using the methods detailed in Technical Report 4.

MEASUREMENT METHODOLOGY

Different measurement approaches were designed for each of the vibration sources. These individual approaches optimized the logistics of the interaction between vibration and social survey teams. Although it is important to standardise the methodology taken, each source of vibration is different, and different approaches may be required to gather data suitable to develop exposure-response relationships for sources other than those addressed in this project.

The measurement concept for measuring railway vibration consisted of long term vibration monitoring at a control position along with time synchronized short-term

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internal measurements at the residences. This approach was found to be impracticable for measuring construction activity vibration due to the unpredictable hours of operation and the dynamic nature of the source. Thus, the approach for construction required more emphasis on extrapolation and correction of measured levels from one location to estimate exposure in other locations. Flats were selected for the measurement of internal sources of vibration, and the vibration measurement concept was based on long-term monitoring instruments placed in strategic positions of the buildings. The levels of vibration exposure from internal activities were found to be very low in comparison to railway and construction. The uncertainties associated with the estimation of the residents' vibration exposure for each source considered are summarised below:

Vibration source	Measurement Type	Exposure Uncertainty
Railway	Internal	±2.2 dB
Railway	Extrapolation	±6.2 dB
Construction	Extrapolation	±10.4 dB
Internal	Internal	±2.2 dB

The estimation of noise exposure from railway traffic was based on calculation using the standard procedures presented in Calculation of Railway Noise (CRN) (Abbott et al. 1995; Hardy et al. 2007). Validation was performed using measurements conducted on selected sites. Noise exposures for construction sources were predicted using BS 5228:2009, with noise source characteristics determined by measurement at the construction sites. Noise exposures were calculated at the most exposed facade, since internal noise measurements proved unworkable. An uncertainty analysis estimated the accuracy of these calculations as follows:

Noise source	Calculation Type	Exposure Uncertainty
Railway	CRN	±3.3 dB
Construction	BS 5228	±4.0 dB

SUMMARY OF MEASUREMENT DATA

Social survey questionnaires were carried out with 1431 residents. In total, 931 interviews and 522 internal measurements of railway vibration were collected at 11 sites in the North-West and the Midlands of England. 350 interviews of construction activity were collected at two sites located in the Greater Manchester area. 150 interviews were collected for internal sources in the Greater Manchester area.

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For vibration from railways (N = 931) 9.7% were highly annoyed and for vibration from construction activity (N = 350) 37.9% were highly annoyed. It should be noted that the actual number of people HA at any one time are orders of magnitude lower for construction than for rail, since rail is permanent and in proximity to more dwellings than construction sites. The range of reported annoyance ratings for railway and construction activity was sufficient for the determination of exposure-response relationships. For internal sources of vibration (N = 150) a highly annoyed category could not be created as no respondents gave a rating of 8, 9, or 10 on the eleven-point scale. Such difficulties in gathering the range of responses needed to investigate a particular source in depth should be taken into consideration for future research.

PRELIMINARY LABORATORY STUDIES

A laboratory study tested the feasibility of using the methods of paired-comparison testing and multidimensional scaling analysis to investigate the perception of whole body vibration. The results indicate 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.

DEVELOPMENT OF EXPOSURE-RESPONSE RELATIONSHIPS

Exposure-response relationships have been developed for the human response to railway and construction induced groundborne vibration using the methods detailed in Technical Report 6. These relationships have been expressed in VDV^a as per the guidance provided in BS 6472-1:2008 and in weighted *rms* acceleration as per the guidance provided in ISO 2631-1:1997. The highest correlation with self reported annoyance was exhibited by vibration exposure in the 8 Hz 1/3 octave band. This suggests that further research could yield a more robust descriptor than those recommended in current standards. The analysis to determine the most appropriate averaging method found that, for the dataset generated by this project, the type of averaging used was largely unimportant with regards to human response.

For both railway and construction sources, the results indicate that the distance of a residence from the source is a useful proxy in the absence of vibration measurements. It was investigated whether a synthesis curve could be developed from the relationships derived for railway and construction sources. This analysis suggested that railway and construction vibration should be considered separately; however, it should be noted that differences in the methodology for the estimation of vibration exposure for the two sources may have had an influence on this result. In addition to exposure-response relationships for self reported annoyance, relationships have been derived for sleep disturbance due to vibration exposure.

^a Vibration Dose Value (VDV)

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FACTORS INFLUENCING REPORTED ANNOYANCE

Concern of damage to property caused by vibration has been shown to have a strong influence on the degree of reported annoyance. The time of day of exposure was shown to have an effect on the degree of annoyance caused by a given vibration exposure, with exposure at night shown to elicit a stronger response than exposure in the evening, and exposure in the evening shown to elicit a stronger response than exposure during the day.

Under no circumstances should the findings from this research, which has been carried out under steady state conditions, be used to predict human response when new railway lines are opened or rail services are altered substantially on existing lines.

COMBINED NOISE AND VIBRATION EXPOSURE-RESPONSE RELATIONSHIPS

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

^b L_{den} is the 24-hr L_{eq} calculated with a 5 dB weighting for evening and a 10 dB weighting for night

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1. INTRODUCTION

1.1 BACKGROUND

This Project Report presents the culmination of seven years of research funded by the Department for Environment, Food and Rural Affairs (Defra) UK. The aim of the research was to investigate the relationship between exposure to vibration in residential areas and the human response, primarily in terms of annoyance. Noise was also a consideration. The project has involved the three contractors who each delivered the scoping stage, the pilot stage and the main study respectively. The scoping stage was undertaken by David Trevor-Jones Associates. The pilot study was undertaken by a consortium from Arup, Temple, TRL & ISVR, and the report (Arup Acoustics et al., 2007) is available on the Defra website. The work by the University of Salford benefited from guidance by the Defra project steering group. The Defra project steering group and the research team made consensus decisions to allow best progress to be made. This should not be taken to imply that everyone who has contributed agrees with every decision reached. This report presents the findings made during the main study delivered by the University of Salford.

1.2 SCOPE OF THE STUDY

Unlike noise, perceptible vibration is almost absent from the ambient environment of most people, and this is perhaps one of the reasons why it has lagged behind noise in research. There is a need to produce a robust exposure-response dataset for human exposure to vibration, and to evaluate the most suitable index to be used to express associated levels of vibration. New rail schemes, the need to develop land close to existing transportation corridors, growing multiple occupancy of “lively” buildings, and increased public action about other sources such as construction vibration, has led to a change in public perception. These three sources; railway, construction, and internal sources, are addressed in this study.

1.3 OUTLINE OF THIS REPORT

The overall aim of the project was to determine whether exposure-response relationships exist for human vibration in residential environments, and if so, does this correlate with existing descriptors (such as ppv, VDV etc.) or some other descriptor. This report outlines the results of the main study;

- the measurement of vibration, i.e. the ‘exposure’ part of the required exposure-response relationship;
- the social science developments of the project, i.e. the ‘response’ part of the exposure-response relationship; and
- the analysis of the exposure response relationships and descriptors.

It does not address what the results may mean for future policy development on vibration.

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This report begins with a short literature review to provide context for the work. Then follows an overview of the methodologies employed for the collection of vibration and social survey data, along with a summary of the success rate of the measurement protocols for obtaining case studies. A general description of each of the measurement sites is presented. A brief summary is provided of the analysis techniques used to determine 24-hour vibration exposure from the data collected through the field work. Finally, the work conducted to coordinate the 'exposure' and 'response' data is summarised. Details can be found in the 6 Technical reports that accompany this Project report.

1.4 OVERVIEW OF APPROACH

In this study the determination of 'response' was achieved by means of face-to-face interviews with adults in their homes and the determination of 'exposure' was achieved by measurement and calculation. The measurement protocol for this study has been designed such that the collection of a large volume of data remains feasible whilst still ensuring a highly accurate estimation of 24-hour internal vibration exposure. The questionnaire used has been rigorously designed to adhere to current international best practice. Both questionnaire and supporting document were subjected to a peer review by independent internationally recognised experts in the field; Jim Fields, Larry Finegold, Evy Ohrstrom, Peter Brooker, Gary Raw, and members of the Defra research panel.

With very few exceptions, the human response to vibration from a specific source in residential environments is also influenced by exposure to noise caused by the source. This means that it is essential to obtain estimates of the exposure to noise from the vibration source for each case study. Likewise, data on annoyance due to noise from construction was obtained as a separate category in the questionnaire. Subsequent analysis therefore allows derivation of distinct exposure-response relationships for construction noise, with the intention of defining the contribution of noise in the exposure-response relationship due to vibration.

A case study is considered to be a completed case of questionnaire and accompanying measurements. This study yielded 1431 case studies, the first 931 of which were concentrated on environmental vibration caused by railways, the remaining being 350 from construction sources, and 150 from internal sources. It was the aim of the project that subsequent analysis should determine, if an exposure-response relationship exists, an index that relates vibration to levels of annoyance from a database of un-weighted vibration data in the x, y and z-axis, using existing or new descriptors as appropriate.

2. LITERATURE REVIEW

In the recent Defra-funded research ‘Estimating Dose-Response Relationships Between Noise Exposure And Human Health Impacts In The UK’, (Berry & Flindell 2009) the following possible non-auditory effects of noise are reviewed:

- Annoyance
- Mental health effects
- Cardiovascular and other physiological effects
- Sleep disturbance
- Cognitive effects on children

They mention that research studies generally measure *reported annoyance* using standardised questionnaires. This study is concerned primarily with reported annoyance. As discussed by Clark and Stansfeld (Clark & Stansfeld 2007), annoyance is the most reported problem caused by transport noise exposure and is often the primary outcome used to evaluate the effect of noise on communities. Acoustic factors such as noise source, exposure level and time of day of exposure only partly determine an individual’s annoyance response: many non-acoustical factors such as the extent of interference experienced, ability to cope, expectations, fear associated with the noise source, noise sensitivity, anger, and beliefs about whether noise could be reduced by those responsible are believed to influence annoyance responses (Berglund et al. 1999).

Berry and Flindell (Berry & Flindell 2009) also note the confusion between the two terms; noise dose and noise exposure. The noise dose describes the amount of sound energy absorbed by an exposed person's body, whereas the noise exposure is the amount of sound available to be absorbed by a person if that person was able to absorb it by being present and not otherwise protected against the noise. The two terms *dose-response* and *exposure response* are commonly used interchangeably. Technically speaking this project is concerned with exposure-response.

2.1 VIBRATION FROM RAILWAY

In comparison to air-borne noise, relatively little research has though been done into the human response to vibration from rail transportation. The exposure situation is not trivial as vibrations from railway may or may not be accompanied by vibration induced low frequency noise, airborne noise and in some occasions rattling noise from objects in the building. Only preliminary exposure-response relationships on specific datasets have been derived (Klaeboe et al. 2003). Existing criteria, such as DIN 4150 and ISO 2631, are mainly based on thresholds that were established for perception due to vibration on humans in laboratory situations. It is not clear whether these guidelines are relevant for assessing human response including annoyance and sleep disturbance in real life. There is some anecdotal evidence that these guidelines are too strict for railway traffic. For example, measurements are said to routinely show that

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within 50 to 100 meters from the track vibration levels in houses are much higher than the guidelines would allow, although widespread complaints are not reported.

Previous field studies into the effects of railway vibration have generally shown synergetic effects of vibration and airborne noise on annoyance (Ohrstrom & Skånberg 1996), (E Ohrstrom 1997). For sleep disturbance, which is expected to be the most serious adverse health effect for vibrations and vibration induced noise, only very little data exist. Freight trains were found to cause more awakenings as compared to passenger and automotive trains (Saremi et al. 2008) and exposure to nocturnal low frequency noise, an important factor in freight train noise, had a larger effect on physiological markers of stress as compared to nocturnal road traffic noise (Waye et al. 2003). Experimental investigation of railway noise and vibration was recently carried out in the sleep laboratories at Gothenburg University (E. Ohrstrom et al. 2009). The results show that while reported sleep disturbance due to noise increased with increased vibration amplitude, reported sleep disturbance due to vibration did not increase with noise level.

2.2 VIBRATION FROM CONSTRUCTION

Construction activity is generally considered in relation to damage to the building and settlement of soils especially when the energy level involved in the processes are high as in the case of dynamic compaction and piling activity. In addition, the human response to construction vibration is usually an important part of an Environmental Impact Assessment (EIA). The evaluation of vibration exposure is usually performed by measurement or by prediction using BS 5228-2 guidance, which is largely a database of measurement results and empirical predictors. Evaluation of the response for a given vibration level, usually expressed in peak particle velocity (PPV) or vibration dose value (VDV), is made against the value provided by the relevant standard. This approach can be found for example in works of Clough (Clough & Chameau 1980), and Athanasopoulos (Athanasopoulos & Pelekis 2000), especially in consideration of vibration from pile driving. Generally descriptions of the evaluation of the human response from construction are given in (J. Wiss 1981) and (Dowding 1996). A key source of guidance for UK practitioners to evaluate human response to construction vibration is the 'ANC Red Book' (ANC 2001). The most recent attempt to relate exposure and response to vibration in residential environments for construction vibration is BS 5228-2:2009 annex B using PPV as the descriptor for the exposure.

2.3 VIBRATION FROM INTERNAL SOURCES

The possibility that internal sources can cause annoyance has long been appreciated (Griffin 1996), not least where rhythmic human activity can cause the oscillation of high rise buildings. However, so far internal sources have not been used for the derivation of exposure-response relationships.

3. MEASUREMENT APPROACH

Detailed descriptions of the measurement protocol employed for each vibration source of interest are presented in Technical Report 1. In the technical report, practical issues concerning the measurement and determination of vibration exposure are also presented. The issues discussed include the characteristics of the measurement system, practical implementation of the measurement methodology, data storage and post-processing.

3.1 VIBRATION MEASUREMENTS

The key elements of the vibration measurement protocol implemented in this study are as follows:

- a) Long-term monitoring at a control position.
- b) Synchronised short-term snapshot measurement taken internally after each interview as far as possible
- c) Calculation of a control-to-internal velocity ratio from (a) and (b)
- d) Calculation of long-term exposure at internal position from the results of (a) and (c).

This section considers how and where measurements were taken, and the practical problems associated with both internal and external measurements for each of the vibration sources.

Velocity ratios between ground and point of entry to the resident's body can vary widely from one building type to another and for different storeys. This variation would be expected to span the range of human response. Consequently, the uncertainty introduced by external-to-internal velocity ratios would be a highly significant confounding factor when deriving exposure-response relationships. One method to reduce this uncertainty would be to perform measurements using synchronised instrumentation to accurately determine velocity ratios for the individual case studies, thus allowing more precise estimation of the vibration at the point of entry from external measurements.

Given the unexpectedly high rate of success in obtaining internal measurements, the alternative method chosen was to perform one continuous control measurement and to obtain snapshot internal measurements, and so calculate the control-to-internal velocity ratio. The control-to-internal velocity ratio was employed to more accurately estimate vibration exposure for correlation against the social survey responses. In addition, for railway this method also eliminated the uncertainties associated with the interpolation and extrapolation of data; where the external vibration would be determined by interpolation between regularly spaced measurements, and the internal vibration estimated by extrapolation using an external-to-internal velocity ratio.

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Also detailed are theoretical and laboratory studies into the effect of mounting the vibration measurement equipment on different surfaces commonly encountered in the field, conducted to reduce uncertainty associated with mounting effects. Practical experiences of implementing the measurement methodology and the interaction of the vibration and social teams on site are presented. Based on experience in the field, the refined approach to onsite interaction between the two teams is detailed.

3.1.1 EQUIPMENT

Vibration measurements were implemented in the field using Guralp CMG-5TD strong motion accelerometers with a low pass filter at 100Hz (Guralp 2003). These devices consist of a tri-axial accelerometer and digitiser in a self contained unit and possess a number of key features which make them ideal for the measurement procedure employed in this project. The low noise floor of the instrument coupled with a 24-bit digitiser provides a dynamic range that is large enough to remove the need for the operator to adjust the sensitivity of the instrument. Removing the need to adjust the sensitivity of the instrument eliminates the risk of over/under-loads due to operator error that can be quite common in large scale measurement surveys.

The second key feature of the Guralp CMG-5TD units is the ability to time synchronise via GPS meaning that phase-locked measurements can be conducted without the need for cabling between instruments. The Guralp CMG-5TD units proved to be fully capable and robust enough during the field measurements. It was found that the measurement procedure was easy to implement with minimal disruption to residents using the equipment provided.

Full details of this measurement system can be found in Technical Report 1. In that report the characteristics of the measurement system are detailed along with laboratory and theoretical studies of the effects of mounting the measurement system on different surfaces. This provided guidance on how to mount the accelerometers in different situations commonly encountered in the field.

3.1.2 UNCERTAINTY ANALYSIS FOR VIBRATION MEASUREMENTS

A detailed uncertainty analysis for the vibration measurements was performed and is presented in Technical Report 3. The uncertainty is due mainly to the measurement chain and not the instrument itself. Prominent sources of uncertainty were the variance of the external-to-internal velocity ratio and the measurement position in internal measurements.

3.1.3 RAILWAY

This section briefly describes the measurement protocol for the determination of internal vibration exposure from overground railway. The vibration measurement protocol consists of long term vibration monitoring at an external position (referred to as the *control* position) along with time synchronised short-term internal snapshot measurements. By determining the velocity-ratio between the control and internal measurements, an estimation of 24-hour internal vibration exposure can be obtained.

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This approach assumes that the short-term internal snapshots measurements are statistically representative of the internal vibration of the railway over the sample period. An illustration of this approach is given in Figure 1.

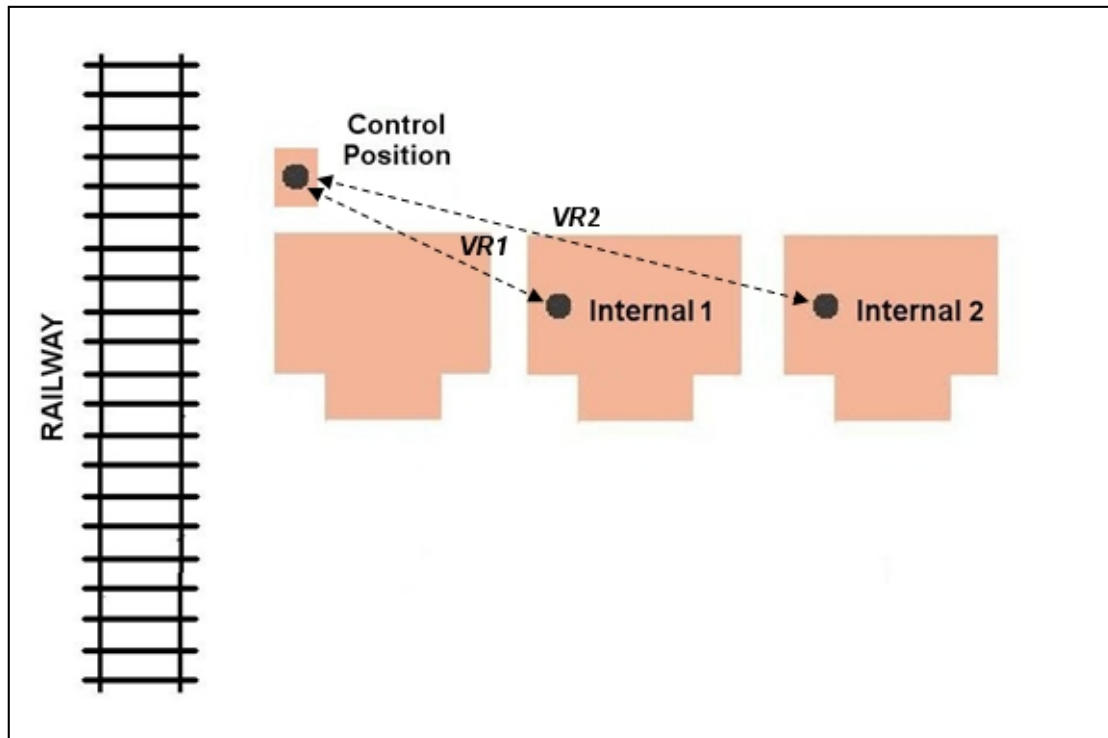


Figure 1 Schematic of measurement approach

Acceleration time histories were obtained both externally and internally at respondents' properties. Vibration events (e.g. train passes) in residences were reliably measured at distances over 120m from the railway. For railway activity the uncertainty in the exposure estimate has been evaluated as ± 2.2 dB when internal measurements were made, and ± 6.2 dB when no measurement was made at the residence and the exposure was estimated by extrapolation.

3.1.4 CONSTRUCTION

The approach of short internal measurements used for the measurement of railway vibration was not feasible for the measurement of construction activity. This was mainly due to the intermittent and transient nature of the source. The approach of characterising vibration using controlled external measurements coupled with the measurement of representative external-internal velocity ratios was therefore adopted. Measurement of vibration magnitude as a function of distance allowed the derivation of an attenuation law for each site. Analyses of the external measurements provided a conservative estimate of the extent of the near field to be around 40 m from the source.

Considering the unpredictable times of operation and the dynamic nature of the source the following approach was proposed:

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- The social survey team commenced surveying at areas of the site at which the major part of the construction activity had recently concluded; in this way all respondents should have experienced the same nominal vibration exposure.
- Detailed vibration measurements were timed so as to start at an area of the site where the major part of the construction was due to commence.

The measurement approach for construction involved the following:

- Long term monitoring of the entire lifecycle of the construction at that area (typically four weeks);
- Well controlled external measurements at different distances from the source using array techniques to determine site characteristics such as attenuation laws;
- Internal measurements in representative properties to determine external-to-internal velocity ratios from short term measurements taken during high magnitude vibration events.

Therefore, compared with the measurement protocol implemented for rail, the approach for construction required more emphasis on extrapolation and correction of measured levels from one site to estimate exposure in other sites. For construction activity, the uncertainty in the external exposure estimate has been evaluated as ± 6.6 dB, and ± 10.4 dB for the internal exposure estimate. The most important factor is the moving nature of the construction source.

3.1.5 INTERNAL SOURCES

Internal sources of vibration such as washing machines, door slams, foot falls etc. are not continuous or predictable. Other difficulties associated with measuring internal sources were the unknown location of these sources and the unknown magnitude of vibration. Ideally, long-term internal measurements would be conducted at the flat of each respondent. This is however not practicable for a survey of this size for the convenience of the occupants. The methodology for internal sources was based on long-term monitoring measurements in strategic points of the building to estimate vibration levels in all properties where a questionnaire was completed. As the estimation of the exposure for internal sources has been done with long term internal measurement the uncertainty associated is very small, ± 2.2 dB.

The interaction between the social survey and vibration measurement teams onsite was conducted as follows:

- Having obtained permission to access the building, the social survey team arrive on site ahead of the vibration team and conduct as many interviews as possible;
- The vibration team then arrange the measurement locations which are ideally empty flats or spare rooms.

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In virtually all the buildings for which permission could be obtained for measurement, vibration levels were found to be uniformly low compared with those obtained from railway and construction. Considered alongside the very low levels of annoyance reported and the time consuming nature of the surveys, internal source investigations were discontinued after 150 case studies in favour of obtaining further construction cases.

3.2 NOISE MEASUREMENTS

This section concerns the determination of noise levels to be used for the estimation of exposure of residents to each specific vibration source. Details are presented in Technical Report 4. These noise data were investigated as a covariate in the exposure-response model for annoyance from vibration exposure, and the findings are summarised in section 8.7. Details of the exposure-response analysis are presented in Technical Report 6.

Although for the measurement of ground-borne and structure-borne noise an internal measurement is ideal, it was seen that unattended measurements make it difficult to distinguish between events of interest and other internal sources. Due to this, an investigation was carried out to determine the best method of obtaining reliable estimations of internal noise exposure. The three main options considered to overcome this problem were:

- Attended internal measurements
- Internal measurements time synchronised with vibration measurements to allow the identification of events
- Internal measurements time synchronised with an external noise measurement to allow the identification of events

Internal measurement of noise from the specific vibration source proved to be unworkable. Not only was it impractical to perform 24 hour measurements of noise for each case study, but the source of interest was usually masked by extraneous internal sources. On the other hand, external measurements provided comprehensive and distinct recordings of events of interest clear of background noise. This was the approach successfully taken by Ohrstrom (Ohrstrom et al. 2007).

Noise exposures were therefore obtained in two steps:

1. Noise levels at the most exposed façade were determined by measurement or estimation (in the absence of measurements).
2. Average exposures in the form of L_{den} at the most exposed facade over 24 h were calculated.

The calculation of exposure is discussed further in section 5.4.

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3.2.1 RAILWAY

Noise levels from railway events were determined primarily by calculation using the CRN procedures. This is a well-known standardised routine in the UK which requires details of type of train, number of vehicles on the train and noise emission from a particular vehicle. Details about train events were obtained from two sources:

- All possible Control Positions monitoring vibration from railway traffic for 24 hours
- Time tables obtained from National Rail Enquiries website

In general, vibration recordings were preferred for the identification of train event since they provided details of freight trains that could otherwise not be reliably determined from timetables. Comparisons with measurement for selected locations are presented in Technical Report 4 together with explanations of assumptions and other observations.

3.2.2 CONSTRUCTION

Noise levels from construction work were determined by measurement. Activities were characterised by on-site measurement of sound power and work patterns were identified from long term vibration monitoring. The main problem encountered during measurements for construction sources was the influence of background noise, in particular road traffic. Such activities as saw-cutting, excavation, flattening etc. consequently have greater uncertainties associated with their determination for specific sites. Another problem was that some activities were not able to be captured, mostly due to frequent changes in the construction work schedule. The estimation of construction noise in the absence of measurement was based on BS 5228-1:2009.

3.2.3 INTERNAL SOURCES

Procedures based on BS EN ISO 16032:2004 were investigated to accurately determine the internal noise levels for each residence. However, the source of interest was most of the time masked by internal extraneous sources. Sample measurements and predictions proved to be unreliable, and it was impractical to perform 24 hour measurements of noise for each case study. For these reasons the determination of noise levels from specific internal vibration sources was found to be unworkable.

3.3 SOCIAL SURVEY MEASUREMENTS

3.3.1 DEVELOPMENT OF THE SURVEY

To measure the ‘response’ component for the required exposure-response relationship, a social survey questionnaire has been used to collect social data from respondents. The Pilot Study (Arup Acoustics et al. 2007) of this research developed a social survey questionnaire to measure ‘response’. Using the Pilot Study as a starting point for the development of the current social survey, the questionnaire was developed through a process of dialogue and negotiation, and through the exercise of pre-testing the questionnaire internally with colleagues and known associates. A preliminary field trial tested the railway source specific questionnaire with 33 respondents in December 2008. Following the field trial, the questionnaire was subject to an intensive peer review by five international experts in noise annoyance research^c. It should be noted that not all reviewers agreed with the decisions made.

The criteria for the development of socio-acoustic surveys that have been drawn upon in the development of this survey derive from the work of the International Commission on Biological Effects of Noise (ICBEN) (J. Fields et al. 2001) for the development of socio-acoustic surveys. Some of their criteria for socio-acoustic survey design have been included in the criteria developed for this social survey questionnaire. The criteria developed for this socio-vibration survey questionnaire are 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 (i.e. the response scale answers are equally spaced meeting the assumptions for analysis techniques).
- 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

3.3.2 INTRODUCING THE SURVEY

To avoid influencing responses the social survey questionnaire is introduced as a survey of neighbourhood satisfaction. As such, the initial sections of the questionnaire focus on respondents’ satisfaction with their neighbourhood and home, before moving onto specific questions regarding vibration and noise. This is because if respondents were aware that the purpose of the survey is to investigate vibration in residential

^c Jim Fields, Laurence Finegold, Evy Ohrstrom, Peter Brooker, Gary Raw

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environments, there is a risk of influencing motivations to take part in the research, which could potentially impact upon the answers and annoyance ratings given.

3.3.3 *QUESTIONNAIRE STRUCTURE*

The following provides a breakdown of the different sections of the social survey questionnaire.

- Section A: Dwelling information
- Section B: Neighbourhood satisfaction
- Section C: Satisfaction with home
- Section D: Vibration questions
- Section E: Noise questions
- Section F: Railway vibration
- Section G: Railway noise
- Section H: Construction vibration
- Section I: Construction noise
- Section J: Internal vibration
- Section K: Internal noise
- Section Y: Personal and occupancy information
- Section Z: Interviewer assessment of vibration and noise

The social survey questionnaire has source-specific vibration and noise sections for railway, construction and internal sources as appropriate.

3.3.4 *MODIFICATIONS TO THE QUESTIONNAIRE FOR CONSTRUCTION VIBRATION*

The following changes were made to the pre-existing railway questionnaire to create a questionnaire suitable for the investigation of response from construction activities.

The questionnaire for construction activity does not limit the sample based on length of time that the respondents have been living in their properties. Therefore, the reference to *the last 12 months* was replaced with the *time you have been living here*, throughout the sections. This ensures that the focus is still not yet placed on the construction activity.

The definition of construction activity was expanded to state that it includes *demolition, piling, road works, drilling, surface activity such as bulldozers and loading trucks and any other construction activity*. As with the previously expanded definition of the railway, this definition ensures that the respondents consider the different types of construction activity and therefore be successfully routed to the source specific sections of the questionnaire.

3.3.5 *MODIFICATIONS TO THE QUESTIONNAIRE FOR INTERNAL SOURCES*

The following changes were made to create a questionnaire suitable for the investigation response from internal sources. The definition of internal sources from neighbouring homes was amended to read *Sources of vibration outside your control from within the building, from human activity such as footsteps, doorslams or*

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machinery such as air conditioning and washing machines, or any other activity. Apart from these amendments, the questions remain unchanged.

3.3.6 THE ANNOYANCE RESPONSE SCALES

This response is characterised by a respondent's reported level of annoyance, the assessment of which is made possible by the implementation and resulting analysis of annoyance response scales. In the absence of international standards in socio-vibration studies, work from the field of socio-acoustics provided a suitable framework for development and justification. As this is an emergent area of research, in developing the response scales it was accepted that there is no consensus on the type of scales that should be used to measure the relationship between vibration and annoyance in the community. Some contributors to the project supported different response scales and presented strong arguments for their use.

However, there appears to be a growing consensus from international researchers, some of which have provided peer reviews of the development of this questionnaire, that the adoption of the standard ISO/TS: 15666:2003 employed in socio-acoustic surveys is a positive step for the study of vibration annoyance in residential environments. ISO/TS 15666:2003 states that socio-acoustic noise annoyance surveys should employ two response scales to effectively assess annoyance levels, the five-point semantic scale and the eleven-point numerical scale. An advantage of using these scales is that in addition to vibration annoyance the survey explores noise annoyance, and therefore the implementation of similar scales reduces respondent and interviewer confusion. Also using the same annoyance scales within both the noise and vibration sections allows the exploration of combined effects in the exposure-response analysis.

3.3.7 THE INCLUSION OF OPEN QUESTIONS

Initially, a number of open-ended questions were included in the social survey questionnaire to collect qualitative data. The open ended questions were required to provide context to cases that lie outside the exposure-response curve. If open ended questions were omitted from the questionnaire, such data would not be recorded and cases where the level of vibration is high, but the annoyance level low (and vice versa) would potentially be left unexplained. The responses to these open-ended questions were categorised and coded to create categorical variables within the dataset.

3.4 CO-ORDINATION OF VIBRATION MEASUREMENTS AND SOCIAL SURVEY

Based on practical experience in the field, the following interaction between the social and vibration teams developed:

- The social survey team arrive on site ahead of the vibration team and conduct as many interviews as possible

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- Following an interview, the respondent is asked if they are willing to allow a vibration measurement within the property at a later date and the telephone number of the respondent is taken
- The vibration team call to book appointments for internal measurements prior to arrival on site.

This approach yielded a success rate of 64% internal measurements from interviews with an internal agreement. On average the face-to-face interviews for railway and internal sources took 16-17 minutes to complete, while for construction sources the average was 35-40 minutes.

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4. OVERVIEW OF MEASUREMENT SITES

The measurement sites were chosen to provide overall representative socio-demographics and a robust sample size, as well as to maximize the range of exposures to vibration and maximize the potential number of respondents. This was achieved by selecting sites within a range of distances from the source, and different kinds of properties.

4.1 RAILWAY

For railway, the main criteria on which sites were identified were:

- The sites were required to have high railway traffic;
- Properties within a distance of 70 meters to the railway were targeted to increase the probability that a high enough vibration level would be perceptible for the respondents.

A shortlist of possible measurement locations was generated from desk studies, followed by a site reconnaissance to assess their suitability. Twelve locations were chosen at which to conduct the surveys. These are summarised in Table 1.

Table 1 Summary of railway sites

<i>LOCATION</i>	<i>TOTAL INTERVIEWS</i>	<i>TOTAL INTERNAL MEASUREMENTS</i>	<i>TOTAL CONTROL POSITIONS</i>	<i>% MEASUREMENTS OVER INTERVIEWS</i>	<i>% MEASUREMENTS OVER INTERNAL AGREEMENTS</i>	<i>CHARACTERISTICS OF THE SITE</i>
A	119	69	17	58%	62%	High speed line
B	29	9	3	31%	35%	High speed line
C	9	6	3	67%	86%	High speed line and freight line
D	72	47	14	65%	72%	High speed line and freight line
E	65	37	13	57%	64%	High speed and freight line
F	26	13	7	50%	59%	Underground railway
G	112	69	12	62%	64%	High speed line and freight line
H	159	85	16	53%	80%	High speed line, busy roads and airport nearby.
I	164	90	31	55%	62%	Low speed line, close to station.
J	78	48	13	61%	70%	High speed and freight line
K	51	22	8	43%	52%	High speed and freight lines
L	47	27	12	57%	66%	High speed and freight line
TOTAL	931	522	149	56%	63%	

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4.2 CONSTRUCTION ACTIVITY

Site identification for construction vibration sources was based on:

- The stage of the construction activity. The major part of this activity needed to take place during the spring, summer and autumn of 2010.
- Cooperation of the construction site management, due to the transient nature of the source.
- The vibration activities needed to comprise different types of construction sources.

Many of the identified sites were rejected as they did not meet the selection criteria or they proved to be impractical for the implementation of the measurement protocol. Consideration of a number of types of construction sites led to the selection of two sites in Greater Manchester that were most appropriate for meeting the aims of the project. Their suitability was based on the following criteria.

- High concentration of properties in close proximity to the construction activity
- Residences exposed only to the vibration caused by the construction.
- Safe and secure area.
- Construction activity taking place during spring, summer and autumn of 2010.
- The cycle of vibration activity repeats along the line.
- Opportunity to interview before, during and after construction activities.
- The vibration activity comprises different types of construction vibration sources.

Table 2 summarises the selected site characteristics.

Site A was an existing railway being remodelled for trams and some construction vehicles operated intermittently on the existing rail lines. Site B was a new tram line being built on a road, and trams had not run on it. The main advantages of these sites were that there is a high density of residential properties in close proximity to the source, the contractors for the project were cooperative, and the site was in various stages of completion meaning the whole lifecycle of the construction activity could be monitored.

These sites had the useful feature that the construction activity progresses along a “line”. Because of this feature, residences in one area of the site had been exposed to the entire life cycle of the construction activity and could be interviewed; in the mean time, vibration could be measured further along the site and the entire lifecycle of the construction fully characterized.

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Table 2 Summary of construction sites

<i>LOCATION</i>	<i>TOTAL INTERVIEWS</i>	<i>TOTAL INTERNAL MEASUREMENTS</i>	<i>MONITORING PERIOD</i>	<i>EXTERNAL ARRAYS</i>	<i>CHARACTERISTICS OF THE SITE</i>
Site A	161	1	1*30days	At distances from 10m to 60m	Existing railway, remodelling for tram. Activities measured: excavation, drainage and track works
Site B	79	4	1*14days 1*14days 1*21days 1*30days	At distances from 5m to 50m	Tram line being built on the road. Activities measured: excavation, drainage and track works
TOTAL	240	5	4	From 5 to 60m	

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4.3 INTERNAL SOURCES

The objective of the internal source specific field trials was to obtain a database that would allow comparison with that obtained for railway. The site selection followed a similar criterion to that adopted for the railway vibration component. The main aim was to maximize the number of respondents and minimize the number of measurements. This was achieved by selecting buildings of flats with easy access, with a particular emphasis on ‘lively’ buildings.

Apartment flats generally are managed by estate agent companies that were universally unwilling to give permission for measurements. Permission was made available for access to university accommodation which included tower blocks housing students and families. Likewise the project was successful in performing internal source specific field trials at sheltered accommodation managed by local authorities known to the project team. Table 3 summarises the site characteristics.

Table 3 Summary of sites for internal sources

<i>LOCATION</i>	<i>TOTAL INTERVIEWS</i>	<i>TOTAL CONTROL POSITIONS</i>	<i>CHARACTERISTICS OF THE SITE</i>
Student Accommodation	99	5*24h	Easy access student flats, 3level buildings.
Sheltered Accommodation	51	2*24h	Easy access flats, two level buildings.
TOTAL	150	7	

5. DETERMINATION OF EXPOSURE

This section is concerned with the conversion of measured vibration levels at the control position to internal vibration exposure estimates. The details are presented in Technical Report 3. Noise exposure estimations are also summarised. The details are presented in Technical Report 4.

5.1 CALCULATION OF VIBRATION EXPOSURE FOR RAILWAY ACTIVITY

The measurement protocol used for railway sources relies on the use of a 24 hour long term monitor (referred to as the control position) as close as possible to the residential environment, and synchronised vibration measurements within the property as close as possible to the point of entry to the resident. The velocity ratio from the control to the internal position is measured. The vibration activity monitored at the control position is propagated to the point of entry inside the property using the velocity ratio. In this way, the full time history of the internal activity is estimated.

5.1.1 *EVENT IDENTIFICATION*

For each case study, vibration events are identified on the Z-axis of the control position data via a process based on a short time average/long time average (STA/LTA) algorithm. STA/LTA is an event identification process commonly used in seismology and is defined as the ratio between short-term average and long term average of a time history.

5.1.2 *CALCULATION OF VELOCITY RATIOS*

As internal and external measurements of vibration were synchronised in time with the 24 hour control position measurement, it was possible to calculate velocity ratios for each event recorded during an internal or external measurement. For each case study, velocity ratios for each event were calculated. An average velocity ratio was then calculated for each case study by linearly averaging the velocity ratios calculated for each individual event. To predict internal vibration, the average velocity ratio for a case study was interpolated to the length of each individual event recorded at the control position. The velocity ratio was then applied to the complex Fourier spectrum of the event, resulting in a complex predicted spectrum.

5.1.3 *PREDICTION OF 24-HOUR EXPOSURE*

For each control position measurement, 24-hour time histories were extracted for analysis. Every event within the 24-hour period was identified using the STA/LTA method. For each internal measurement associated with a control position, the velocity ratio associated with that measurement was applied to each event identified on the control position. For each predicted event, a vibration exposure indicator was calculated to provide an estimation of 24-hour vibration exposure.

The high success rate of internal measurement, around 60%, permitted a good determination of the internal vibration activity at all the measurement sites. If there is no internal measurement available for a given respondent, a search is conducted for a

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property at the same site of a similar type and a similar distance from the source. The exposure estimated for this property is then assigned to the property for which there was no measurement available. Because all the properties were in a radius of 50 meters from the control position, the assumption of similarity between properties is well founded. Similarity for distance from the source can be found in the majority measurement sites where the line of the houses is parallel to the railway line.

5.2 CALCULATION OF VIBRATION EXPOSURE FOR CONSTRUCTION ACTIVITY

The exposure from construction activity is a combination of the exposures from all the various operations involved in the entire construction process. The daily exposure has been quantified as the vibration exposure measured over the normal working hours of the construction teams of 8 a.m. to 6 p.m. The worst case scenario was considered as the maximum daily exposure caused by the construction operations.

Compared with the measurement protocol implemented for rail, the approach for construction activity requires that more emphasis is placed on extrapolation and correction of measured levels from one site to estimate exposure at other sites. The measurement methodology is based on long term monitoring at a control position as close as possible to the boundary between the construction site and the residential environment. This measurement is used to capture the life cycle of the construction operations involved, and for identifying the periods and the events when a significant exposure occurs.

Controlled experiments based on array measurement were used for quantifying the attenuation of the vibration across the residential environment caused by the activities of the construction operation. During the controlled experiment, external-to-internal velocity ratios were also measured for the various types of property types.

5.2.1 MEASUREMENT SITE OVERVIEW

An overview of the measurement site is needed to define the characteristics of the construction operations affecting the residential environment. Together with the definition of the reference system this is needed to calculate the distances of the measurement positions from the vibration sources considered.

5.2.2 EVENT IDENTIFICATION AND INTEGRITY CHECK

The major construction activities were identified manually from the time histories recorded during the controlled experiments. Both control position and controlled experiments data were checked to avoid the presence of excessive background activity.

5.2.3 LONG TERM MEASUREMENTS

The cycle of the construction activity was analysed by examining the daily vibration exposures during the monitoring. This allowed identification of the maximum daily exposure caused by construction operations.

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5.2.4 CONTROLLED EXPERIMENTS

Using an array of the accelerometers, a typical decay of the vibration through the residential environment was obtained for each measurement site. The Barkan's law (Barkan 1962) was used for fitting the experimental data to provide the material attenuation coefficient for characterising the propagation of vibration through the measurement site under the assumption of Rayleigh wave propagation in an elastic half-space (Wiss 1967). An analysis of the decay of the vibration metric with distance shows that in a first approximation all metrics decay in the same way. This means that with different fitted values for each metric, the Barkan's law can also be used to describe the propagation of vibration metrics in the residential environment.

5.2.5 PREDICTION OF THE EXPOSURE

The days of maximum exposure from each set of operation involved in the construction process were identified from the control position recordings. Levels at other external locations were calculated from the control position measurements using Barkan's law with the attenuation parameters identified from the controlled experiments.

5.3 CALCULATION OF VIBRATION EXPOSURE FROM INTERNAL SOURCES

Internal sources were defined as the set of vibration sources acting inside the residential property, caused mainly by domestic appliances such as washing machines or by human activity. The measurement approach in this case relied on synchronised long term monitoring in different parts of the affected building. Ideally the measurements were conducted in empty apartments to ensure that the vibration was coming from outside the residence of interest.

5.3.1 INTEGRITY CHECK

The time histories of the long term recordings have been checked to avoid the presence of extraneous human activity.

5.3.2 EXPOSURE ESTIMATION

The exposure metrics have been calculated from each long-term measurement position for each property considered. As already mentioned, levels of exposure for internal activities were at the lower end of the range of exposures observed for railway and construction sources.

5.4 CALCULATION OF NOISE EXPOSURE

5.4.1 RAILWAY

Noise exposures from railway traffic were calculated at the most exposed façade of the residence for day, evening and night periods using the CRN procedures. It was possible to calculate exposures for each of these periods because residents are exposed to railway traffic noise 24 hours a day. Calculation was performed for all residences for which a questionnaire was conducted. An uncertainty analysis estimated the accuracy of these calculations as ± 3.3 dB.

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5.4.2 CONSTRUCTION

The calculated noise exposure was based on on-site measurements of sound power of activities and an identification of activities from a long term vibration monitoring. The methodology involves an estimation of a noise exposure at a most exposed external wall of each residence using techniques described in BS 5228-1:2009.

The data required for the exposure-response analysis is normally taken for a 24-hour noise exposure. The minimum detail required would be the A-weighted equivalent continuous sound pressure level L_{Aeq} , varying with time allowing for weightings to be applied for day, evening and night. Construction operations rarely operate for this duration for any length of time, and are far more likely to operate only during daytime hours. Consequently only the daily exposure was calculated. An uncertainty analysis estimated the accuracy of these calculations ± 4 dB.

Spectra and other noise indices including L_{peak} , L_{90} and L_{10} are also considered in Technical Report 4.

5.4.3 INTERNAL SOURCES

Noise exposures from internal sources were not estimated as determination of noise levels and event patterns proved impractical.

6. DETERMINATION OF RESPONSE

6.1 RAILWAY RESPONSES

6.1.1 *SUCCESS RATE*

From 5,252 residences contacted, 931 questionnaires were completed. 88.9% of social survey questionnaire respondents agreed at the time of interview to have an internal measurement taken in their property. Of those that agreed at the time of interview, 64% had internal measurements taken at their properties. This high proportion of internal measurements indicated that the participant recruitment methodology operated efficiently.

6.1.2 *DESCRIPTIVE PERCEPTION OF VIBRATION*

The descriptive analyses of the data indicated that a high percentage of respondents (71.5%) could either feel, hear and/or see the effects of vibration from the railway. This result indicated that the site identification procedure operated successfully. Of those that noticed vibration from the railway, a large proportion of respondents reported being not at all annoyed (58.3%).

6.1.3 *STATISTICAL PROPORTION HIGHLY ANNOYED*

Using the eleven point scale and creating a highly annoyed category by taking the top three points on the scale, 9.7% (64 respondents) of those who reported noticing railway vibration (feeling, hearing and/or seeing) in the residential environment were highly annoyed.

6.1.4 *MOST ANNOYING SOURCE AND TIME OF DAY*

Of those that reported being slightly or more annoyed by vibration from the railway (278 respondents), more reported being annoyed by vibration from freight trains (36.3%HA) than by railway track maintenance activity (19.5%HA) or passenger trains (8.9%HA). Respondents reported being more annoyed by vibration experienced during the night (30.6%HA), than during the evening (11.5%HA) or during the day (7.6%HA).

6.2 CONSTRUCTION RESPONSES

6.2.1 *SUCCESS RATE*

For construction activity, from 1114 residences contacted, 350 questionnaires were completed. At the time of interview approximately 86.9% of respondents agreed to allow an internal measurement of vibration.

6.2.2 *DESCRIPTIVE PERCEPTION OF VIBRATION*

The majority of respondents (67.1%) reported feeling vibration and 45.4% reported hearing or seeing things rattle, vibrate or shake in their homes due to the construction activity. This indicated that site identification was successful, particularly as other sources of vibration were felt by much fewer respondents.

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6.2.3 STATISTICAL PROPORTION HIGHLY ANNOYED

Using the eleven point numerical scale and the top three points to equate to highly annoyed, 37.9% of respondents noticing vibration from nearby construction activity were highly annoyed.

6.2.4 MOST ANNOYING SOURCE AND TIME OF DAY

In terms of being highly annoyed, respondents were more likely to mention piling (51.8%), followed by drilling (51.2%), surface activity (46.3%), demolition (27.9%) and other activities (2.4%). In comparison to the railway sample, respondents were more likely to be highly annoyed by construction vibration. Respondents were more annoyed by construction vibration during the day, rather than in the evening and at night. However, this is due to construction work not being carried out during night hours (7am – 7pm).

6.3 INTERNAL RESPONSES*6.3.1 SUCCESS RATE*

Of the 524 properties knocked on, 299 residents opened their door, of which 150 agreed to participate and completed a social survey questionnaire. Of this number, 56.3% agreed to internal vibration measurements being taken at their properties. This lower internal agreement rate compared with railway and construction was largely due to the internal source sample characteristics, and difficulties with arranging access to the buildings at a suitable time for internal measurements to be taken.

6.3.2 DESCRIPTIVE PERCEPTION OF VIBRATION

Slightly less than one fifth of respondents (18.7%) reported being able to feel vibration and 8.7% reported hearing or seeing the effects of vibration from internal sources of vibration from outside of the home but from within the same building.

6.3.3 STATISTICAL PROPORTION HIGHLY ANNOYED

It proved impossible to create a highly annoyed category using the top three internals (8, 9, 10) on the eleven-point scale as no one gave a rating above 7, indicating internal sources of vibration were not highly annoying. The lower levels of annoyance for internal sources of vibration may be due to the difficulties in identifying sites where internal sources of vibration produce significant levels of vibration exposure.

7. CONTROLLED INVESTIGATIONS

7.1 INTRODUCTION

A pilot laboratory test has been conducted to determine the feasibility of using the methods of paired comparisons and multidimensional scaling to investigate the perception of whole body vibration. Multidimensional scaling (MDS) is a method by which it is possible to reduce the dimensionality of a matrix of pairwise data. By considering pairwise judgments of similarity or dissimilarity obtained through perceptual testing, it is possible to obtain a configuration of points in low-dimensional space which represent the “*perceptual distance*” between the stimuli considered in the perceptual test. The greater the distance between two points in the MDS configuration the greater the judged dissimilarity of the two stimuli. As the dimensions of the configuration obtained through MDS are orthogonal, it is not unreasonable to assume that each dimension relates to a continuum of a unique perceptual attribute within the group of stimuli studied. By finding objective correlates to the axes revealed through MDS, it is possible to reveal the perceptual dimensions which underlie a group of stimuli.

Eleven subjects took part in paired comparison tests of similarity and annoyance on twelve synthesised vibration stimuli. A multidimensional scaling analysis of the paired comparison of similarity data was conducted. Analysis of a four dimensional solution showed that the vibration stimuli were well spread in perceptual space indicating that subjects were basing their similarity ratings on perceptual continua and not simply categorizing the stimuli. Initial analysis suggested that the first two perceptual dimensions were in some way related to the frequency content and energy of the vibratory stimuli. The perceptual dimensions were related to single figure annoyance judgements by means of multiple regression. Good agreement ($R^2=0.92$) between the measured and predicted single figure annoyance scores was found. The results of these tests 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 stimulus can be formulated.

8. DETERMINATION OF EXPOSURE-RESPONSE RELATIONSHIPS

8.1 METRICS AND FREQUENCY WEIGHTINGS CONSIDERED

One of the key challenges in the formulation of an exposure-response relationship for this project is the determination of the most appropriate descriptor of vibration exposure.

Table 4 Summary of vibration exposure descriptors considered. Where $\ddot{x}(n)$ is an acceleration time series and N is the number of samples in the acceleration time series.

Descriptor	Calculation
Root mean square (m/s^2)	$\ddot{x}_{rms} = \sqrt{\frac{1}{N} \sum_{n=1}^N \ddot{x}(n)^2}$
Root mean quad (m/s^2)	$\ddot{x}_{rmq} = \sqrt[4]{\frac{1}{N} \sum_{n=1}^N \ddot{x}(n)^4}$
Root mean hex (m/s^2)	$\ddot{x}_{rmh} = \sqrt[6]{\frac{1}{N} \sum_{n=1}^N \ddot{x}(n)^6}$
Root mean oct (m/s^2)	$\ddot{x}_{rmo} = \sqrt[8]{\frac{1}{N} \sum_{n=1}^N \ddot{x}(n)^8}$
Vibration dose value ($m/s^{1.75}$)	$\ddot{x}_{VDV} = \sqrt[4]{\frac{T_s}{N} \sum_{n=1}^N \ddot{x}(n)^4}$
Mean (m/s^2)	$\bar{x} = \frac{1}{N} \sum_{n=1}^N \ddot{x}(n)$
Standard deviation	$\sigma = \sqrt{\frac{1}{N} \sum_{n=1}^N (\ddot{x}(n) - \bar{x})^2}$
Skewness	$S_k = \frac{1}{N \cdot \sigma^3} \sum_{n=1}^N (\ddot{x}(n) - \bar{x})^3$
Kurtosis	$K_l = \frac{1}{N \cdot \sigma^4} \sum_{n=1}^N (\ddot{x}(n) - \bar{x})^4$
Peak particle acceleration (m/s^2)	Maximum deviation of the time series from the mean

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Broadly, the two main considerations that go into the selection of the most appropriate descriptor are the type of averaging used and the frequency weighting that is used. Table 4 provides a summary of the averaging methods considered.

To attempt to reduce the number of descriptors considered in the analysis, a principal component analysis was carried out on the descriptor space. It was found that more than 75% of the variance in the component space is accounted for in the first principal component. Each of the descriptors considered were found to have a similar weighting on the first principal component indicating that the descriptors are highly correlated with each other. This result suggests that, for the dataset under analysis in this project, the type of averaging used is unimportant.

Table 5 presents Spearman's correlation coefficient between the two annoyance rating scales and the *rms* descriptor calculated using different frequency weightings in the vertical and horizontal directions. Spearman's correlation was used as the response variable is categorical. It can be seen from this table that an improvement in correlation is observed when the appropriate frequency weighting is applied.

Table 5 Spearman's correlation coefficient between *rms* (m/s^2) vibration with different frequency weightings and reported annoyance (N = 751). * $p < 0.05$, ** $p < 0.01$, * $p < 0.001$.**

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

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Figure 2 presents Spearman's correlation coefficients between self reported annoyance and 24-hour *rms* (m/s^2) internal vibration exposure in individual 1/3 octave bands in the vertical direction. It can be seen from this figure that there is a clear peak in correlation between vibration exposure calculated in the 6.3 Hz and 8 Hz 1/3 octave bands and self reported annoyance. Compared with the correlations shown in Table 5, an improvement in correlation from 0.13 to 0.27 can be observed. Similar results were observed for vibration in the horizontal directions in the 8 Hz 1/3 octave band. This result suggests that further investigation into frequency weightings could yield a more robust descriptor than those recommended in current standards.

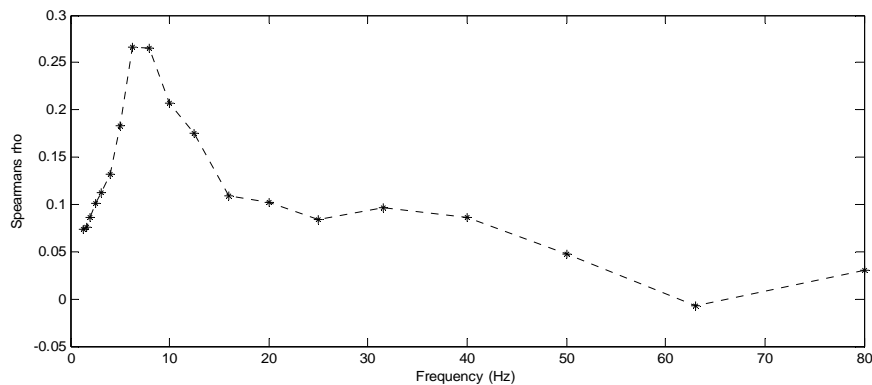


Figure 2 Spearman's correlation coefficient between self reported annoyance and 24-hour vertical rms acceleration in 1/3 octave bands (N = 751)

The choice of averaging method is therefore now dictated by a number of factors; namely, ease of calculation, interpretability, current practice, and measurement capability of the user to the exposure-response relationship. BS 6472-1:2008 suggests the use of *VDV* ($m/s^{1.75}$) for reporting whole body vibration exposure and ISO 2631-1:1997 suggests the use of weighted *rms* (m/s^2). Therefore the exposure-response relationships presented later in this report will be presented in terms of both *VDV* and *rms* acceleration with their appropriate weightings.

8.2 E-R MODEL

Exposure-response relationships were formulated using a grouped regression model. The model used is similar to that presented by (Groothuis-Oudshoorn & Miedema, 2006).

8.3 FUNCTIONAL FORM OF EXPOSURE DESCRIPTOR

Models were tested with the exposure descriptor described in absolute units and logarithmic units. The likelihoods of the two models were evaluated and in all cases the descriptor expressed in logarithmic form was found to exhibit a significant improvement in the model fit.

8.4 SOURCE SPECIFIC E-R RELATIONSHIPS

8.4.1 RAILWAY

Figure 3 and Figure 4 show exposure-response relationships for the proportion of respondents reporting feeling vibration and the proportion of respondents reporting annoyance above a given threshold. Vibration exposure was calculated based on guidance from BS 6472-1:2008. The relationships are shown for $VDV_{b,24hr}$ in the vertical direction of excitation and $VDV_{d,24hr}$ in the horizontal direction.

From Figure 3 it can be seen that approximately 50% of respondents report feeling vibration at exposures of around $7 \times 10^{-3} \text{ m/s}^{1.75}$ in the vertical direction and at around $1 \times 10^{-3} \text{ m/s}^{1.75}$ in the horizontal direction. At these magnitudes of vibration exposure, it can be seen from Figure 4 less than 5% around 3% of respondents report being highly annoyed by vibration. At exposures of $0.32 \text{ m/s}^{1.75}$ in the vertical direction and $0.021 \text{ m/s}^{1.75}$ in the horizontal direction, around 10% of respondents report being highly annoyed, 2022% report being annoyed, and 4140% report being slightly annoyed.

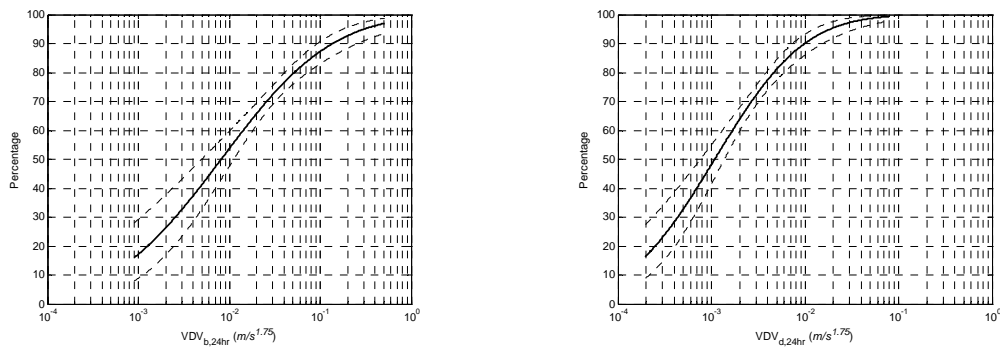


Figure 3 Exposure-response relationship showing the proportion of people reporting feeling vibration for a given vibration exposure. (N = 752). Left pane: vertical vibration. Right pane: Horizontal vibration

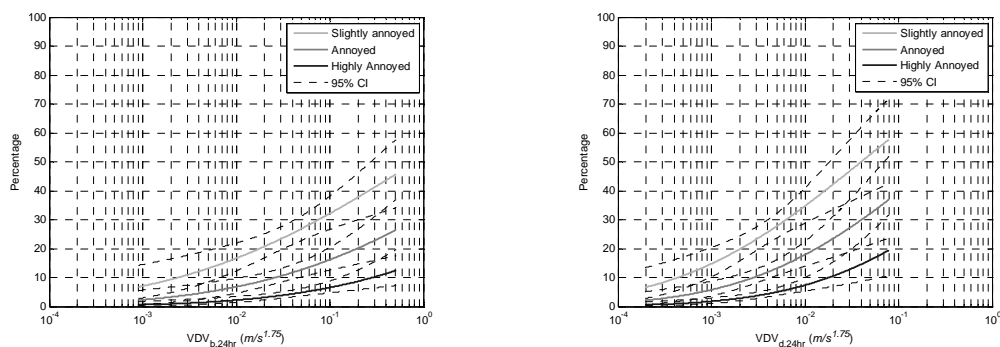


Figure 4 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure. Curves are shown in their 95% confidence intervals. (N = 752). Left pane: vertical vibration ($R^2_{\text{pseudo}} = 0.01$, $p \ll 0.001$). Right pane: Horizontal vibration ($R^2_{\text{pseudo}} = 0.02$, $p \ll 0.001$)

Figure 5 and Figure 6 show exposure-response relationships for the proportion of respondents reporting feeling vibration and the proportion of respondents reporting

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annoyance above a given threshold. Vibration exposure was calculated based on guidance from ISO 2631-1:1997. The relationships are shown for *rms* acceleration in the vertical and horizontal directions weighted with the W_k and W_d frequency weighting curves respectively.

From Figure 5 it can be seen that approximately 50% of respondents report feeling vibration at exposures of around $7 \times 10^{-4} \text{ m/s}^2$ in the vertical direction and at around $1 \times 10^{-4} \text{ m/s}^2$ in the horizontal direction. At these magnitudes of vibration exposure, it can be seen from Figure 6 that around 3% of respondents report being highly annoyed by vibration. At exposures of $21 \times 10^{-2} \text{ m/s}^2$ in the vertical direction and $21 \times 10^{-3} \text{ m/s}^2$ in the horizontal direction, around 10% of respondents report being highly annoyed, 20% report being annoyed, and 40% report being slightly annoyed.

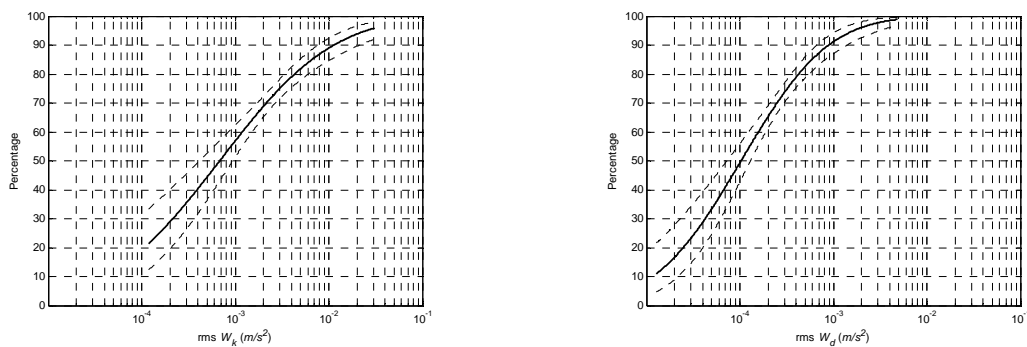


Figure 5 Exposure-response relationship showing the proportion of people reporting feeling vibration for a given vibration exposure. (N = 752). Left pane: vertical vibration. Right pane: Horizontal vibration.

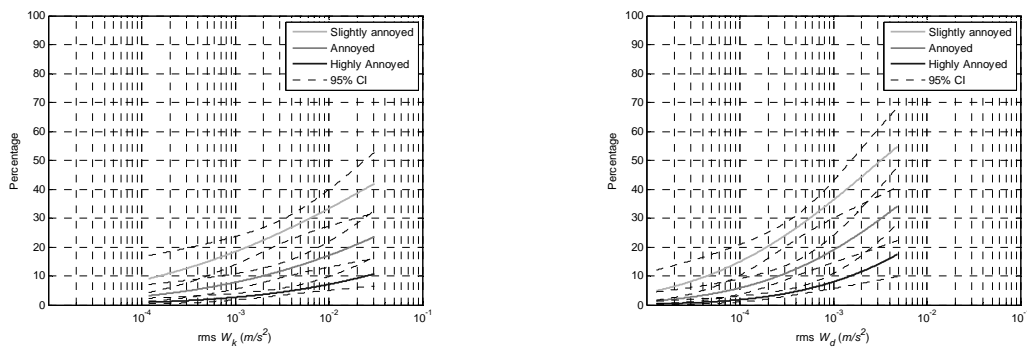


Figure 6 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure. Curves are shown in their 95% confidence intervals. (N = 752). Left pane: vertical vibration ($R^2_{\text{pseudo}} = 0.01$, $p \ll 0.001$). Right pane: Horizontal vibration ($R^2_{\text{pseudo}} = 0.02$, $p \ll 0.001$)

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8.4.2 CONSTRUCTION

Figure 7 shows an exposure-response relationship for annoyance caused by vibration exposure from construction sources as a function of VDV_b ($m/s^{1.75}$). Comparing this relationship with the exposure response relationship for railway induced vibration (see Figure 3 and Figure 4), it can be seen that the point at which 50% of respondents report feeling vibration is similar for the two different sources; however, the proportion of respondents reporting annoyance for this exposure raises from below 5% for railway induced vibration to more than 10% for construction induced vibration. The proportion of respondents reporting annoyance rises much more rapidly for construction vibration than for railway vibration. At exposures of $0.1 m/s^{1.75}$, 50% of respondents report being highly annoyed by vibration from construction sources compared with 10% of respondents for the same exposure from railway sources.

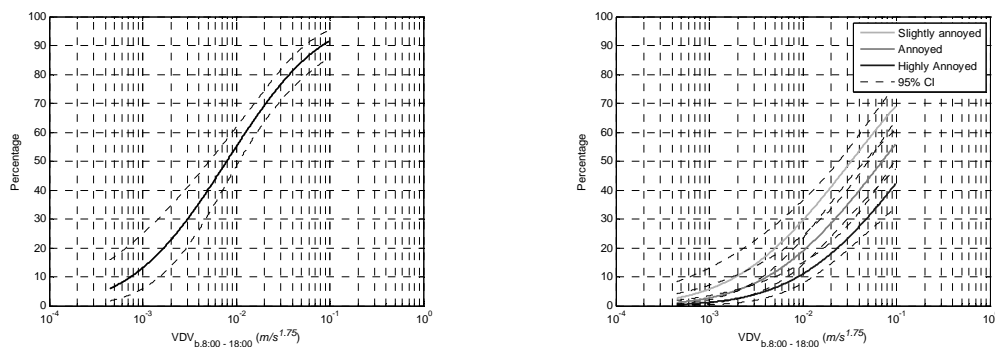


Figure 7 Exposure-response relationships for construction vibration exposure. Left pane: Proportion of people reporting feeling vibration for a given vibration exposure. Right Pane: Proportion of people reporting different degrees of annoyance for a given vibration exposure (N = 321) ($R^2_{\text{pseudo}} = 0.09$, $p \ll 0.001$)

8.4.3 INTERNAL

For the case of internal vibration sources outside of respondents' control, 150 case studies were conducted. Only 9% of this sample reported being able to feel vibration. None of the residents interviewed reported high annoyance due to vibration exposure. The mean annoyance rating for this sample calculated from the 5-point semantic scale was 0.18. The vibration exposures measured for internal sources ranged from 1.7×10^{-4} to $6.7 \times 10^{-4} m/s^2 W_b$ weighted 24-hour rms. Due to the low proportion of respondents reporting annoyance and the limited range of vibration exposures, this dataset was considered unsuitable for the derivation of an exposure-response relationship for annoyance caused by internal vibration sources.

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8.5 OTHER FACTORS AFFECTING RESPONSE TO VIBRATION

8.5.1 TIME OF DAY

Table 6 presents Spearman's correlation coefficients between self reported annoyance and day, evening, and night vibration exposure in the vertical and horizontal directions. Daytime is defined between 7:00 – 19:00, evening is defined as 19:00 – 23:00, and night is defined as 23:00 – 7:00. Vibration exposure expressed as VDV_b in the vertical direction and VDV_d in the horizontal direction are calculated over the three different time periods. It can be seen from this table that there is a significant correlation between self reported annoyance in the day, evening, and night for vibration exposures calculated over these time periods for both the vertical and horizontal directions. As with annoyance due to 24-hour vibration exposure (see Table 5), exposures calculated in the horizontal direction exhibit a slightly higher magnitude of correlation than exposures calculated in the vertical direction.

Table 6 Spearman's correlation coefficient between vibration exposure expressed as VDV in the vertical and horizontal directions for different times of day (N = 751). * $p < 0.05$, ** $p < 0.01$, * $p < 0.001$.**

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

Figure 8, Figure 9, and Figure 10 show exposure-response relationships for the proportion of respondents reporting annoyance above a given threshold for vibration exposure during the day, evening, and night respectively. It can be seen that, for a given vibration exposure, the percentage of respondents expressing a given annoyance above a given threshold is higher for night than it is for evening and higher for evening than it is for day. For a vibration exposure of $0.1 m/s^{1.75} VDV_b$, the proportion of respondents expressing high annoyance is around 2% in the daytime, 4% in the evening, and 12% during the night. Similar results have been observed for annoyance due to noise exposure where evening and nighttime noise exposure have been found to have a greater impact on annoyance than daytime noise exposure (Miedema et al. 2000).

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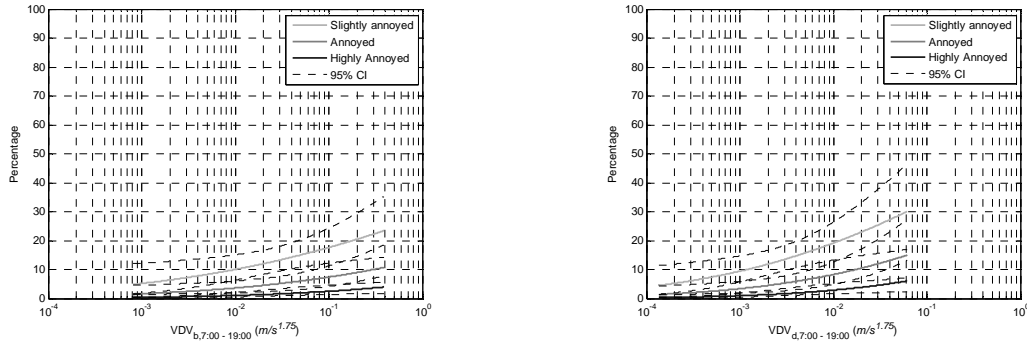


Figure 8 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure during the day. Curves are shown in their 95% confidence intervals. (N = 752). Left pane: Vertical vibration ($R^2_{\text{pseudo}} = 0.09$, $p \ll 0.001$). Right pane: Horizontal vibration ($R^2_{\text{pseudo}} = 0.09$, $p \ll 0.001$)

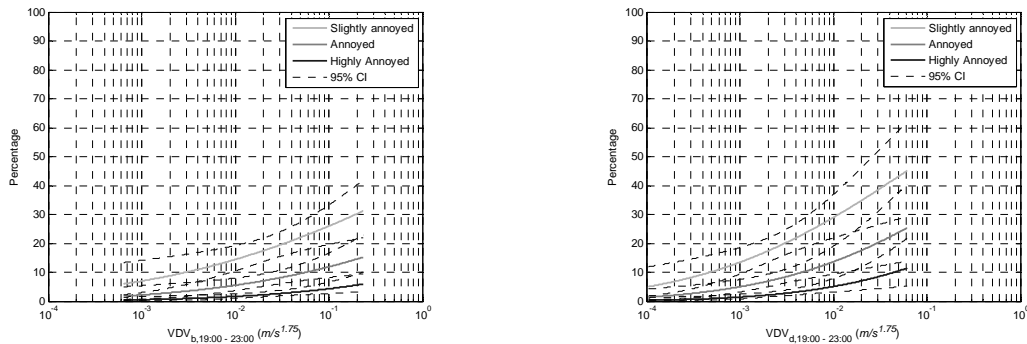


Figure 9 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure during the evening. Curves are shown in their 95% confidence intervals. (N = 752). Left pane: Vertical vibration ($R^2_{\text{pseudo}} = 0.03$, $p \ll 0.001$). Right pane: Horizontal vibration ($R^2_{\text{pseudo}} = 0.03$, $p \ll 0.001$)

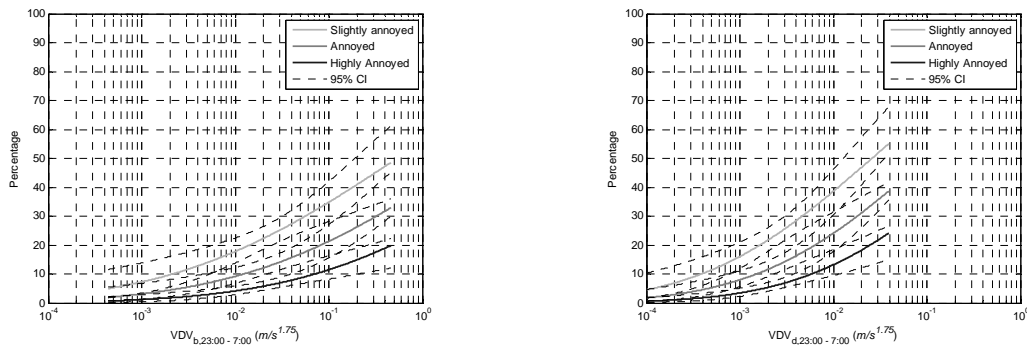


Figure 10 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure during the night. Curves are shown in their 95% confidence intervals. (N = 752). Left pane: Vertical vibration ($R^2_{\text{pseudo}} = 0.04$, $p \ll 0.001$). Right pane: Horizontal vibration ($R^2_{\text{pseudo}} = 0.04$, $p \ll 0.001$)

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8.5.2 CONCERN OF DAMAGE TO PROPERTY

In the social survey questionnaire, respondents were asked to quantify the extent to which they felt concerned that vibration caused by railway activity was causing damage to their property on a five-point semantic scale. An exposure-response model was calculated for three thresholds of concern, *highly concerned* (upper 28% of the concern scale), *concerned* (upper 50% of the concern scale), and *slightly concerned* (upper 72% of the concern scale). This model is presented in Figure 11. It can be seen from this figure that as vibration exposure increases, the proportion of respondents expressing concern of damage to property increases.

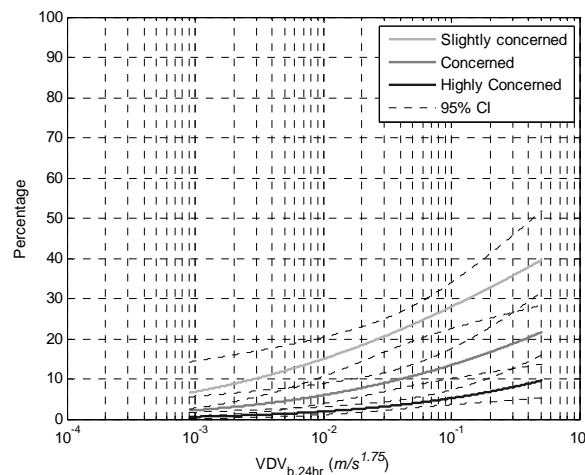


Figure 11 Exposure-response relationship showing the proportion of people reporting different degrees of concern of damage to property for a given vibration exposure from railway activities. Curves are shown in their 95% confidence intervals. (N = 752). ($R^2_{\text{pseudo}} = 0.02$, $p \ll 0.001$)

8.6 SYNTHESIS CURVE

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

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8.7 COMBINED NOISE AND VIBRATION CURVES

Noise exposures for the respondents of the railway vibration field study were calculated using the Calculation of Rail Noise 1995 (CRN), (see Technical Report 4). Exposure response models were calculated for annoyance caused by vibration and annoyance caused by noise using vibration exposure ($VDV_{b,24hr} \text{ m/s}^{1.75}$) and noise exposure ($L_{DEN} \text{ dB}$) as independent variables. For the vibration annoyance model, a significant improvement in model fit was observed ($p < 0.05$) when noise exposure was included as an independent variable. The same result was observed for the noise annoyance model when vibration exposure was included as an independent variable.

Figure 12 shows the proportion of respondents reporting high annoyance due to vibration for a given vibration exposure. Curves are presented for different magnitudes of noise exposure. It can be seen that, for a given magnitude of vibration exposure, the proportion of respondents reporting high annoyance due to vibration exposure increases with increasing exposure to noise.

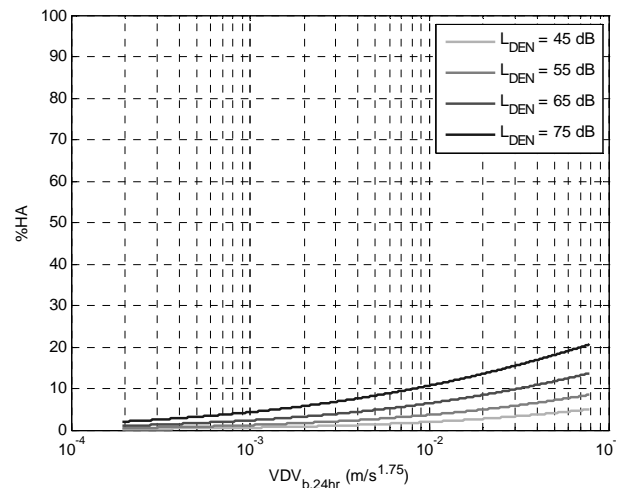


Figure 12 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance cause by vibration for a given vibration exposure and different levels of noise exposure (N = 698) ($R^2_{\text{pseudo}} = 0.02$, $p \ll 0.001$)

Figure 13 shows the proportion of respondents that report high annoyance due to noise for a given noise exposure. Curves are presented for different magnitudes of vibration exposure. It can be seen that, for a given magnitude of noise exposure, the proportion of respondents reporting high annoyance due to noise increases with increasing exposure to vibration.

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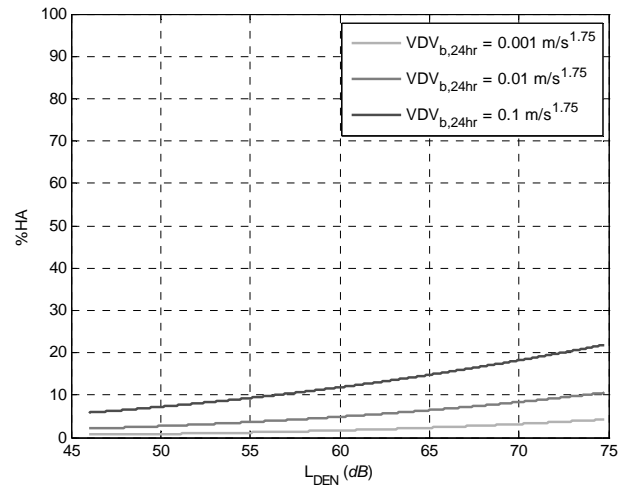


Figure 13 Exposure-response relationship showing the proportion of people reporting different degrees of annoyance cause by noise for a given noise exposure and different levels of vibration exposure (N = 698) ($R^2_{pseudo} = 0.02$, $p \ll 0.001$)

9. DISCUSSION AND RECOMMENDATIONS

Different measurement approaches to measure vibration are needed depending on the nature of the vibration source. Internal sources of vibration proved difficult to research, with few respondents reporting being able to feel or hear or see vibration, and fewer reporting annoyance for this source. The level of the exposure due to internal sources of vibration was found to be very low in comparison to the other sources considered. Railway and construction vibration at the levels of internal sources measured in this project would not be sources of significant annoyance.

For all three sources of vibration investigated, respondents had difficulties in describing the sensory experience of vibration in the residential environment. The primary effect of feeling vibration was explored separately to the secondary effects of vibration i.e. hearing and seeing things rattle, vibrate or shake. The qualitative data collected suggests that describing auditory and visual sensory aspects of vibration is easier than describing the haptic (feeling) and kinesthetic (movement) sensory aspects of vibration.

Vibration from construction activity caused more people to be highly annoyed (37.9%HA, N = 350) than vibration from railway activities (9.7%HA, N = 931). Likewise, noise was heard by more respondents and from more sources than felt vibration. Noise from construction activity was more annoying (31.6%HA, N = 350) than noise from railway activity (10.3%HA, N = 931) and noise from internal sources (5.5%HA, N = 150). An understanding of the context within which vibration and noise are experienced can offer insight into these responses. For railways, residents talked about getting used to the vibration and noise, and living in a home next to a railway line in general. Whereas for construction, although some respondents mentioned getting used to the vibration and noise they experienced, it was more likely to be considered unacceptable by respondents.

Caution should also be taken when focusing on annoyance as the measure of response. The response to vibration has been found to be influenced by a wide range of factors, some of which have been accounted for in the social survey questionnaire. These include socio-demographic variables (e.g. age, gender, employment etc), sensitivity to vibration and noise, acceptability of vibration and noise, expectations of vibration and noise in the future, plans to move, length of residency, tenure, and neighbourhood and home satisfaction. It is important that further research continues to explore these and other psychological concepts and social factors such as sensitivity (Miedema 2007), and other attitudinal factors (Fields 1993), (Guski 1999).

10. CONCLUSIONS

10.1 VIBRATION EXPOSURE-RESPONSE RELATIONSHIPS

Exposure-response relationships have been developed for the human response to railway and construction induced groundborne vibration in residential environments.

For a given vibration exposure, construction was found to be more annoying than rail.

A useful relationship synthesising railway and construction exposure-responses could not be derived. This is due to differences in the methodology for the estimation of vibration exposure for the two sources.

Under no circumstances should the findings from this research, which has been carried out under steady state conditions, be used to predict human response when new railway lines are opened or rail services are altered substantially on existing lines.

Data collected for internal sources was unsuitable for the formulation of exposure-response relationships, due to the uniformly low vibration exposures recorded and low proportion of respondents expressing annoyance.

Annoyance from internal sources should be considered on a case-by-case basis rather than as a community response.

10.2 MOST APPROPRIATE AVERAGING METHOD

For the dataset generated by this project, the type of averaging used was largely unimportant with regards to reported annoyance.

10.3 MOST APPROPRIATE FREQUENCY WEIGHTING

The application of frequency weightings defined in BS 6472-1:2008, ISO 2631-1:1997, and ISO 2631-2:2003 improves the correlation between vibration exposure and reported annoyance.

The highest correlation with self reported annoyance was exhibited by vibration exposure in the 8 Hz 1/3 octave band. This suggests that further research could yield a more robust descriptor than those recommended in current standards.

Due to the scatter associated with field surveys of this type, these investigations are likely to be better suited to a laboratory setting.

10.4 PRELIMINARY LABORATORY STUDIES

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.

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10.5 FACTORS INFLUENCING REPORTED ANNOYANCE

Concern of damage to property caused by vibration has a strong influence on reported annoyance.

Vibration exposure at night elicits a stronger response than exposure in the evening, and exposure in the evening elicits a stronger response than during the day.

10.6 COMBINED NOISE AND VIBRATION EXPOSURE-RESPONSE

RELATIONSHIPS

For a given vibration exposure, reported annoyance due to vibration increases with increasing noise exposure.

Similarly, for a given noise exposure, reported annoyance due to noise increases with increasing vibration exposure.

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11.1 STANDARDS

BS EN ISO 16032:2004: Acoustics. Measurement of sound pressure level from service equipment in buildings. Engineering method

BS 5228-1:2009: Code of practice for noise and vibration control on construction and open sites. Noise.

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

BS EN ISO 3745:2009: Acoustics — Determination of sound power levels of noise sources using sound pressure — Precision methods for anechoic and semi-anechoic rooms

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

DD ISO/TS 15666:2003 Acoustics. Assessment of noise annoyance by means of social and socio-acoustic surveys

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

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

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)

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