Human response to vibration in residential environments: Establishing exposure-response relationships

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ABSTRACT

This paper presents results from a large scale study investigating the human response to vibration in residential environments. The main aim of this study was to derive exposure-response relationships for annoyance caused by vibration experienced within residential properties from sources outside of residents' control. The study took the form of a questionnaire administered to UK residents in their own homes to determine self reported annoyance caused by vibration from a variety of sources along with measurements of vibration inside and outside residences to determine vibration exposure. In total, 1,431 case studies were conducted encompassing railway, construction, and internal vibration sources. Presented in this paper are the results of analyses which were conducted to determine the most appropriate descriptor for vibration exposure in residential environments for the dataset generated by this project. The main considerations for these analyses were the type of averaging used and frequency weighting. Following this, exposure-response relationships are presented for different vibration sources. The relationships take the form of curves indicating the percentage of people expressing annoyance above a given threshold for a given vibration exposure. Combined effects of vibration and noise exposure are also considered. [Work funded by the Department for Environment, Food and Rural Affairs (Defra) UK].

INTRODUCTION

For a given environmental stressor, exposure-response relationships are a vital tool for the prediction of the effect this stressor is likely to have on the population. Stemming from the pioneering work of Schultz (1978), internationally accepted exposure-response relationships have been developed for annoyance due to noise exposure which describe the proportion of the population expected to express annoyance above a given threshold for a given noise exposure (Miedema & Oudshoorn 2001). No such consensus has been arrived at for the assessment of annoyance due to whole body vibration in residential environments. This paper presents the results of a large scale study funded by Defra investigating the human response to vibration in residential environments (Waddington et al. 2011). The main aim of this study was to develop exposure-response relationships for vibration experienced in residential environments. Vibration sources considered were those outside of residents' control; namely vibration caused by railway traffic, construction work, and internal sources. Response data regarding annoyance caused by vibration and noise exposure were collected via face to face interviews with residents in their own homes. Vibration exposure was determined via measurement and prediction in such a way that, where possible, an estimation of internal vibration exposure was established for each residence in which a questionnaire was completed. From the data collected via this field study, exposure-response relationships have been derived.

BACKGROUND

The main source of literature concerned with the human response to vibration in residential environments derives from studies into annoyance caused by railway vibration. In a field survey conducted in Scotland (Woodroof & Griffin 1987), annoyance caused by railway induced building vibration was evaluated via a questionnaire with residents and measurements of vibration within a limited number of properties. By correlating different measures of vibration exposure against reported annoyance, it was found that the most appropriate descriptor for describing annoyance for this study was the number of train passes which occurred in a 24-hour period with annoyance found to increase with the number of train passes.

A field study has been conducted in Norway (Turunen-Rise et al. 2003; Klæboe et al. 2003a, b) with the aim of deriving an exposure-response relationship for community response to vibration caused by road and railway traffic. In this study, a social survey was conducted via telephone interview with 1,503 respondents to determine people's reaction to vibration experienced within their own homes. Vibration exposure was predicted in each respondent's property via a semi-empirical model. Logistic and ordinal logit regression models were then used to develop exposure-response relationships for annoyance caused by road and railway induced vibration.

In a recent study by the Transit Cooperative Research Program (Zapfe et al. 2009), a field study was implemented in the USA and Canada with a view to developing criteria for acceptable levels of railway induced groundborne noise and vibration in residential buildings. The main aim of this study was to develop an exposure-response relationship for predicting community annoyance due to groundborne vibration and noise caused by railway systems. The study consisted of questionnaires administered via telephone with 1,306 respondents along with measurements of external vibration. In this study, around 200 different noise and vibration descriptors were considered as potential independent variables for an exposure-response relationship. It was found that all of the calculated metrics were highly correlated with each other and it was therefore concluded that any of the descriptors would be as good a predictor of annoyance as any other. Exposure-response relationships calculated using a logistic regression model were presented for groundborne vibration using highest magnitude of vibration velocity level (*Vdb*) in any given 1/3 octave band as a predictor.

FIELD SURVEY

Social survey

The main aim of the fieldwork for the study described in this paper was to establish a database of response data for annoyance due to environmental vibration along with estimations of internal vibration exposure for each respondent. Response data were collected via face-to-face interviews with residents in their own homes (Condie et al. 2011). The questionnaire was presented as a neighborhood satisfaction survey and gathered information on, among other things, annoyance caused by vibration and noise exposure. The social survey questionnaire collected annoyance ratings on fivepoint semantic and eleven-point numerical scales for potential sources of vibration and noise in the residential environment including railway, construction activity and internal activities. Each questionnaire took, on average, 20 minutes to complete. In total, 1,431 questionnaires were completed with 931 focusing on railway sources, 350 focusing on construction sources, and 150 focusing on internal sources outside of the resident's control. Following the completion of a questionnaire, the respondent was asked if they were willing to allow a measurement of vibration to be conducted in their property at a later date.

Determination of vibration exposure from railway activities

Properties within a distance of around 70 m from railway lines in the North-West and Midlands of England were targeted. Potential survey sites were identified via desk studies followed by a site reconnaissance to assess the suitability of the site (Peris et al. 2011). The vibration measurement approach consisted of long term (24-hour) monitoring at an external position along with synchronised "snapshot" measurements within respondents' properties. By determining the velocity ratio between the two measurement positions, it was possible to estimate 24-hour internal vibration exposure (Sica et al. 2011). In total, 149 long term measurements along with 522 snapshot measurements were conducted.

Determination of vibration exposure from construction activities

Three construction sites were targeted on which a new light transit system was being constructed close to residences (Peris et al. 2011). The measurement approach adopted for railway was found to be impracticable for measuring construction activity vibration due to the unpredictable hours of operation and the dynamic nature of the source. Therefore, the measurement approach for construction vibration required more emphasis on extrapolation and correction of measured levels from one location to estimate exposure in other locations (Sica et al. 2011).

Determination of vibration exposure from internal sources

Residential flats were selected for the investigation of internal sources of vibration. The vibration measurement approach was based on long-term monitoring at strategic positions in the buildings. The levels of vibration exposure from internal activities were found to be very low in comparison to the railway and construction sources (Sica et al. 2011). Reported annoyance caused by this source was also found to be low (Condie & Steele 2011). Therefore the data collected for this source was not deemed suitable for the derivation of exposure-response relationships.

SELECTION OF VIBRATION EXPOSURE DESCRIPTOR

One of the key challenges in the formulation of an exposure-response relationship for this study is the determination of the most appropriate descriptor of vibration exposure. Broadly, the two main considerations which go into the selection of the most appropriate descriptor are the type of averaging and frequency weighting.

Numerous descriptors of vibration exposure were calculated from 24-hour acceleration time histories of internal vibration. Table 1 provides a summary of the vibration exposure descriptors considered. For railway vibration, these descriptors were calculated for each case study using all train events recorded during a 24-hour period; a train event was defined by its 10 dB down points. Additional to the descriptors presented in Table 1, 1st, 5th, 10th, 50th, 90th, 95th, and 99th percentiles were also calculated.

A principal component analysis was conducted on the descriptor space to attempt to reduce the number of descriptors considered. From this analysis it was found that the different descriptors were well correlated with each other suggesting that, for the database under consideration, the type of averaging used is largely unimportant.

Table 1: Summary of vibration exposure descriptors considered. Where $\ddot{x}(n)$ is an acceleration time series, *N* is the number of samples in the acceleration time series, and *T* is the duration of the event in seconds

Descriptor	Calculation	Descriptor	Calculation
Root mean square (m/s^2)	$\ddot{x}_{rms} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^2}$	Skewness	$S_k = \frac{1}{N\cdot\sigma^3}\sum_{n=1}^{N}(\ddot{x}(n)-\overline{x})^3$
Root mean quad (m/s^2)	$\ddot{x}_{rmq} = \sqrt[4]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$	Kurtosis	$K_t = \frac{1}{N\cdot\sigma^4}\sum_{n=1}^{N}(\ddot{x}(n)-\overline{x})^4$
Root mean hex (m/s^2)	$\ddot{x}_{rmh} = \sqrt[6]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^6}$	Peak particle acceleration (m/s^2)	Maximum deviation of the time series from the mean
Root mean oct (m/s^2)	$\ddot{x}_{rmo} = \sqrt[8]{\frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)^8}$	L_{max} (dB re $1x10^{-6}$ m/s^2)	Maximum 1 second exponential average *rms* over an event
Vibration dose value ($m/s^{1.75}$)	$\ddot{x}_{VDV} = \sqrt[4]{\frac{T}{N}\sum_{n=1}^{N}\ddot{x}(n)^4}$	L_{eq} (dB re $1x10^{-6}$ m/s^2)	$L_{eq} = 20\log_{10}\left(\frac{\ddot{x}_{rms}}{1E-6}\right)$
Mean (m/s^2)	$\overline{x} = \frac{1}{N}\sum_{n=1}^{N}\ddot{x}(n)$	L_E (dB re $1x10^{-6}$ m/s^2)	$L_E = 20\log_{10}\left(\frac{\ddot{x}_{rms}}{1E-6}\right)+10\log_{10}(T)$
Standard deviation	$\sigma = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(\ddot{x}(n)-\overline{x})^2}$		

There are a number of different frequency weightings suggested in national and international standards which are intended to reflect the frequency dependence of whole body vibration perception. It was found that application of the appropriate frequency weightings recommended in BS 6472-1:2008 (BSI 2008) and ISO 2631-1:1997 (ISO 1997) resulted in an improvement over unweighted vibration exposure in the Spearman's correlation coefficient against the annoyance responses.

Based on these results, in this paper vibration exposure will be assessed according to BS 6472-1:2008 (i.e. Vibration Dose Values (*VDV*) using the W_b weighting for vibration in the vertical direction and the W_d weighting for vibration in the horizontal direction).

EXPOSURE-RESPONSE RELATIONSHIPS

Statistical model

The statistical model used to formulate the exposure-response relationships presented in this paper is based upon the model proposed by Groothuis-Oudshoorn & Miedema (2006). The relationships take the form of curves indicating the percentage of people expressing annoyance above a given threshold (*C*) for a given vibration exposure (*X*):

$$p_C(X) = \text{Prob}(1 - \Phi\left[\frac{C - \mathbf{X\beta}}{\sigma}\right]) \qquad (1.1)$$

where Φ is the cumulative normal distribution function, $\mathbf{X}$ is a vector of vibration exposures, $\boldsymbol{\beta}$ are model coefficients to be estimated, and σ is the standard error. The coefficients of this model were estimated via maximum likelihood.

The annoyance thresholds *C* reported will be 28 %, 50 %, and 72 % of the annoyance scale which will be referred to "*percent slightly annoyed*" (*%SA*), "*percent annoyed*" (%A), and "*percent highly annoyed*" (*%HA*) respectively. Respondents stating that they are unable to feel vibration have been recoded to the lowest category on the annoyance response scale.

Exposure-response relationship for railway vibration

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

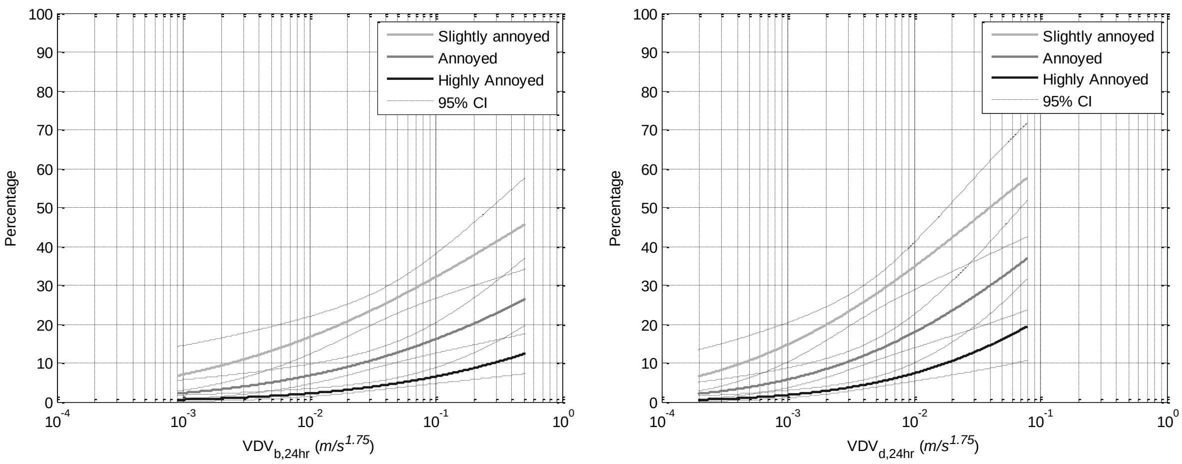

Figure 1: Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure caused by railway activities. Curves are shown in their 95% confidence intervals. Left panel: Vertical vibration (R^2_{pseudo} = 0.01, p<0.001, N = 752). Right panel: Horizontal vibration (R^2_{pseudo} = 0.02, p<0.001, N = 752)

Exposure-response relationship for construction vibration

Figure 2 presents exposure-response relationships showing the proportion of respondents reporting annoyance above a given threshold for a given exposure to vibration induced by construction activities. Vibration exposure is expressed in $VDV_{b,8:00-18:00}$ in the vertical direction.

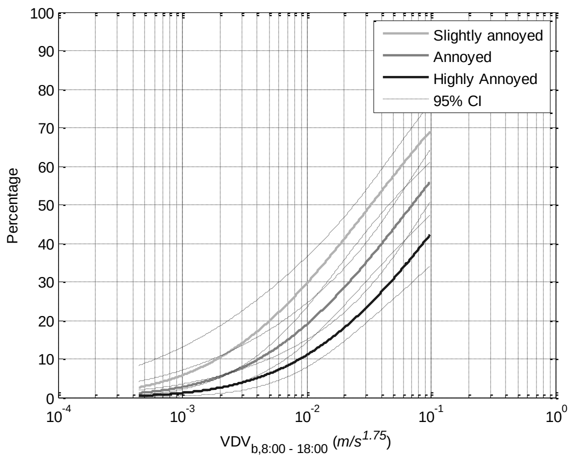

Figure 2: Exposure-response relationship showing the proportion of people reporting different degrees of annoyance for a given vibration exposure caused by construction activities. Curves are shown in their 95% confidence intervals. (R^2_{pseudo} = 0.09, $p<0.001$, N = 321)

Exposure-response relationship for mixed sources

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 ($p<<0.001$). 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.

COMBINED EFFECTS OF RAILWAY VIBRATION AND NOISE

In addition to vibration exposure, noise exposure was determined for each respondent (Koziel et al. 2011). For railway, noise exposures were predicted via the “Calculation of Railway Noise” method (Department of Transport 1995). Exposure-response models were calculated for annoyance caused by vibration using vibration exposure ($VDV_{b,24hr}$ $m/s^{1.75}$) and noise exposure (L_{DEN} dB) as independent variables. The improvement in likelihood when noise exposure was included as an independent variable was found to be significant ($p<0.05$). Figure 3 shows the proportion of respondents reporting high annoyance due to vibration for different vibration and noise exposures. It can be seen from this figure that annoyance due to vibration increases with an increase in both noise and vibration exposure. This result suggests an interaction effect between noise and vibration exposure on the total annoyance caused by vibration although it can be seen that vibration exposure has a greater influence.

CONCLUSIONS

This paper has aimed to give an overview of the main outcomes of the Defra funded project "*Human response to vibration in residential environments*". By means of a large scale field trail, a database of responses for annoyance due to environmental vibration along with estimations of internal vibration exposure has been developed.

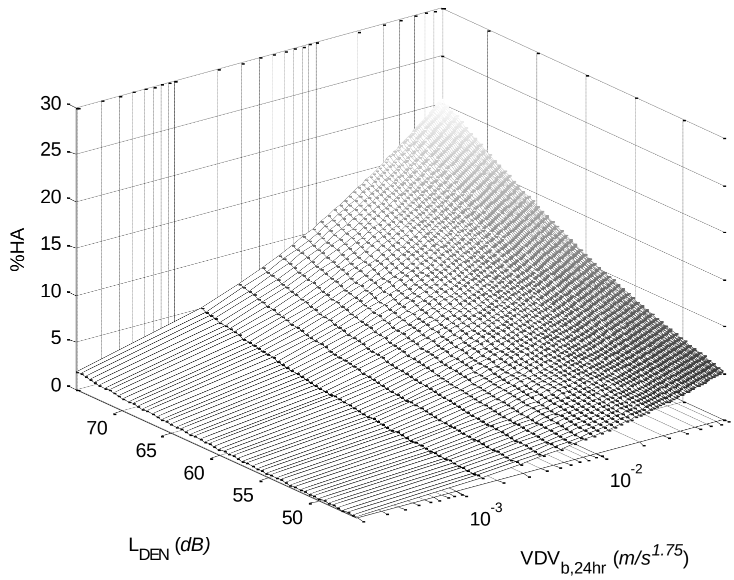

Figure 3: Exposure-response relationship showing the proportion of people reporting different degrees of annoyance caused by vibration for a given vibration exposure and different levels of noise exposure. (R^2_{pseudo} = 0.01, p<0.001, N = 698)

An analysis of vibration exposure descriptors revealed that, for the dataset under analysis in this project, the type of averaging used was largely unimportant with regards to human response. The application of frequency weightings defined in BS 6472-1:2008 and ISO 2631-1:1997 were found to improve the magnitude of correlation between vibration exposure and self reported annoyance. Exposure-response relationships have been developed for the human response to railway and construction induced groundborne vibration. These relationships have been expressed in terms of *VDV* as per the guidance provided in BS 6472-1:2008. Although not presented in this paper, relationships have also been derived expressing vibration exposure as per the guidance provided in ISO 2631-1:1997 (Waddington et al. 2011). For the case of vibration exposure from internal sources, the low magnitude of both vibration exposure and annoyance made the derivation of an exposure-response relationship impossible. In all of the derived relationships it was found that, as the magnitude of vibration exposure increases so does the proportion of respondents reporting annoyance above a given threshold. Finally, exposure-response relationships for combined noise and vibration exposure have been derived.

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