ACOUSTICS 2012
HONG KONG

Differences in response to vibration induced in residential environments by railway and construction activities

James Woodcock[1], Eulalia Peris, Gennaro Sica, Andy Moorhouse and David Waddington
[1] Acoustics Research Centre, University of Salford, Salford, M5 4WT, UK

Abstract: This paper summarizes the results of the Defra (UK) funded project 'NANR209: Human response to vibration in residential environments'. The main aim of this project was to develop exposure-response relationships for the human response to environmental vibration as experienced by residents in their own homes. The sources of vibration considered were railway, construction, and internal sources outside of the resident's control. In this study, 1431 questionnaires were completed with UK residents in their own homes to determine self reported annoyance. Measurements of vibration inside and outside residences were conducted to determine each resident's vibration exposure. Presented in this paper are exposure-response relationships derived from these data indicating the percentage of people expressing annoyance above a given threshold for a given vibration exposure. In particular, this paper reports the differences in responses to vibration induced by railway and construction activities.

[Work funded by the Department of Environment, Food and Rural Affairs (Defra) UK]

Keywords: *Vibration, Community Response, Annoyance*

1 Introduction

Decades of research have gone into the development of exposure-response relationships for the human response to environmental noise (Schultz, 1978, Miedema & Oudshroon, 2001, for example). These relationships have gained international acceptance and are the basis of a variety of guidance documents and assessment procedures. However, such relationships do not exist for the evaluation of the human response to environmental vibration. Due to the lack of evidence and good quality data in this area, Defra in the UK funded seven years of research into the human response to vibration in residential environments. The aim of this project was to investigate the relationship between perceptible vibration experienced in dwellings and human response primarily in terms of annoyance. This paper summarizes some of the key results which arose from this project with particular emphasis on the differences in response observed to vibration from railway and construction sources.

The first section of this paper outlines the design and implementation of a large scale field survey which was carried out in the UK to determine both response and exposure to vibration from a number of environmental sources. Exposure-response relationships are then presented for vibration from railway and construction activities. Following this, a discussion of the differences between the relationships derived for the two sources is provided along with suggestions for future work. Finally, conclusions are drawn.

[1] J.s.woodcock@edu.salford.ac.uk

2 Determination of response and exposure

2.1 Selection of survey sites

For railway induced vibration, potential survey sites were first shortlisted via desk work using Google Maps. The main criteria on which sites were selected were that the site should be densely populated so as to maximize the number of potential respondents and also that the site should be subject to no confounding sources of environmental vibration. Sites which met these criteria were subject to a site reconnaissance to determine their suitability. In total, twelve measurement sites were selected across the North West and Midland regions of England.

The selection of sites exposed to vibration from construction activities proved more of a challenge than those exposed to railway induced vibration. A paradox was encountered in which sites were required where residents had already been exposed to vibration induced by construction activities but, as the vibration exposure from the entire lifecycle of the construction activity needed to be monitored, construction work should not have commenced at the site. To overcome this, two sites were identified around the construction of a new light rail system at which the construction activities proceeded along the site in a linear fashion. This provided a situation where areas of the sites had already been exposed to the entire lifecycle of the construction activities and areas of the sites at which construction was yet to commence.

2.2 Measurement of response

Response data were collected via questionnaires conducted with residents in their own homes. The questionnaire collected responses on, amongst other things, annoyance due to vibration and noise from various sources. The questionnaire was presented as a neighborhood satisfaction survey so as not to bias responses to the questions related to vibration and noise. Annoyance data were collected on both a 5-point semantic and 11-point numerical scales as per ISO 15666 (2003). The main annoyance question was posed as follows:

"Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed or disturbed have you been by feeling vibration or shaking or hearing or seeing things rattle vibrate or shake caused by…";

"…the railway including passenger trains, freight trains, track maintenance or any other activity from the railway."

for railway sources and;

"… construction activity including demolition, piling, road works, drilling, surface activity such as bulldozers and loading trucks and any other construction activity."

for construction sources.

Each questionnaire took, on average, 20 minutes to complete. In total, 1281 questionnaires were completed for the sources focused on in this paper with 931 for railway sources and 350 for construction sources. 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.

2.3 *Measurement of vibration from railway activities*

Due to the scale of vibration measurement required to fulfill the requirement of this study, a measurement approach was developed which encompassed elements of measurement and prediction. Long term vibration monitoring was conducted at external positions for a period of 24-hours. During the long term monitoring, short term 'snapshot' measurements which were synchronized with the long term measurements were conducted within the properties of residents who had completed a questionnaire. By determining the transmissibility 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 were conducted along with 522 'snapshot' measurements. This approach enabled the estimation of 24-hour internal vibration exposure in 755 dwellings.

2.4 *Measurement of vibration from construction activities*

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 transitory 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). The approach enabled the estimation of 24-hour internal vibration exposure in 321 dwellings.

2.5 *Analysis of vibration data*

One of the key challenges in the formulation of exposure-response relationships for this study was the determination of the most appropriate single figure descriptor of vibration exposure. Broadly, the two main considerations that go into the selection of the descriptor are the type of averaging and frequency weighting used. 60 different descriptors of vibration exposure were calculated for each case study to assess the most suitable descriptor.

An improvement in correlation with annoyance responses was observed when applying the appropriate frequency weightings during the calculation of vibration exposure. From all of the different averaging methods used it was found that all of the resulting descriptors were well correlated with each other suggesting that, for the dataset collected in this study, the averaging method used was largely unimportant. In the remainder of this paper, vibration exposure will be reported as W_b weighted Vibration Dose Value in the vertical direction (VDV_b) calculated as set out in BS 6472 – 1 (2008).

3 Determining exposure response relationships

3.1 *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):

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

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.

A major advantage of this model is that the entire annoyance distribution can be described by varying *C*. 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.

3.2 Mixed source model

Research into environmental noise has shown that different noise sources (namely road, railway, and aircraft) elicit different annoyance responses for the same level of noise exposure and it is generally accepted that separate exposure-response relationships are required for each noise source (Miedema & Oudshroon, 2001). However, a socio-vibration survey conducted in Norway (Klæboe et. al, 2003) has suggested that a single exposure response relationship is adequate for the human response to vibration from both railway and road traffic sources. To investigate the influence of the vibration source in the present study on self reported annoyance due to vibration exposure, data collected for the railway and construction vibration sources were pooled and a dummy variable was created for 'source type'. An exposure-response model was calculated using the statistical model described in section 3.1 using the 5-point semantic vibration annoyance scale as the dependent variable and vibration exposure ($VDV_{b,24hr}$ m/s$^{1.75}$) and the 'source type' dummy variable as independent variables. The inclusion of the 'source type' dummy variable in the model resulted in a significant improvement in the likelihood of the model ($p <$ 0.001). This result suggests that for construction and railway sources, separate exposure-response relationships are required for the two different sources.

3.3 Source specific exposure-response relationships

Using the data collected for railway induced vibration and the model outlined in section 3.1, the exposure-response relationship presented in Figure 1 was derived.

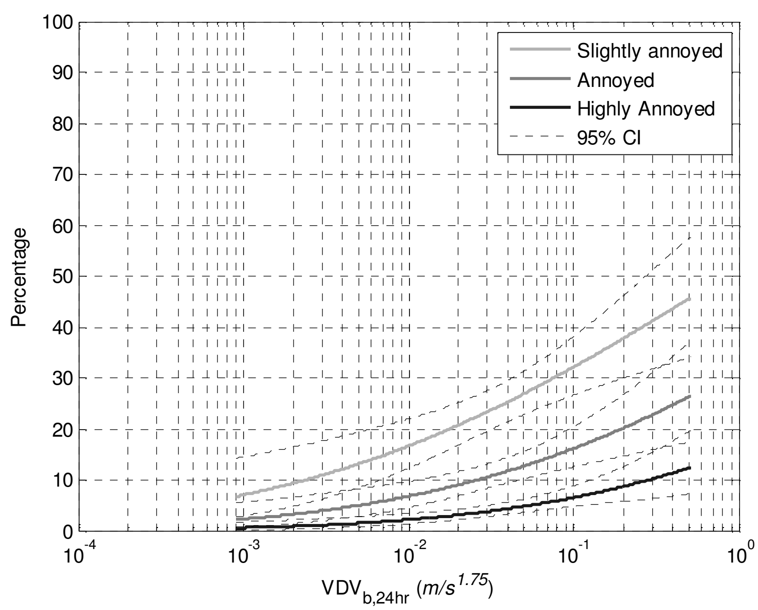

Figure 1 - Exposure response relationship for railway induced vibration. (N = 752, p < 0.001)

Figure 2 presents the exposure-response relationship derived for construction induced vibration. The relatively narrow confidence intervals for both of these relationships suggest that an adequate sample size and a good quality dataset were achieved.

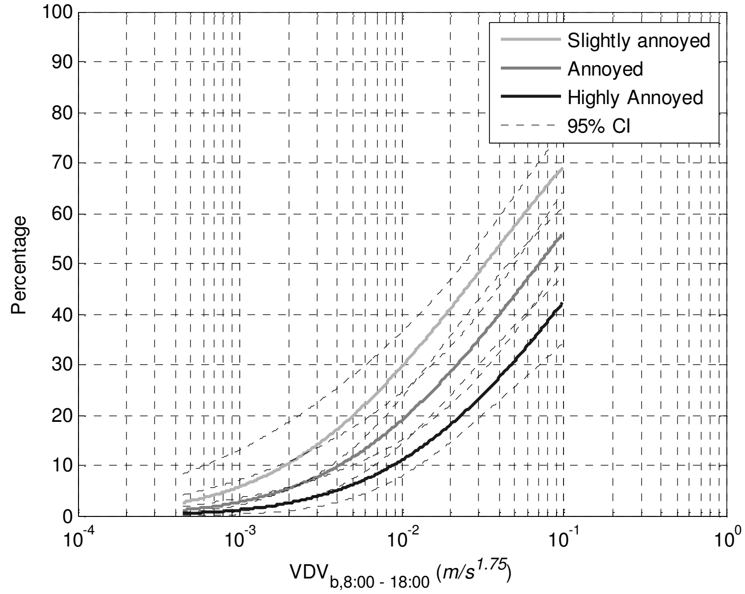

Figure 2 - Exposure-response relationship for construction induced vibration (N = 321, $p < 0.001$)

4 Discussion

It is clear from Figure 1 and Figure 2 that for the same magnitude of vibration exposure, railway induced vibration and construction induced vibration elicit significantly different responses. It can be seen in the relationships for both sources that the proportion of respondents expressing high annoyance starts at zero at a *VDV* of around 10^{-3} m/s$^{1.75}$ and increases monotonically with increasing *VDV*. However, it can be seen that annoyance increases much more rapidly with increasing vibration exposure from construction activities than it does for vibration from railway activities. Similar trends were observed in the data collected for annoyance caused by noise exposure from the two sources. These results are in line with previous research into community response to environmental noise where it has been found that significantly different responses can be observed for exposure to noise from railway, road, and aircraft sources (Miedema & Oudshroon, 2001).

The differences observed in responses for the two different sources could be attributed to both differences in the characteristics of the vibration generated by the different sources and also non-vibrational and non-acoustical factors. The perception of vibration is a complex phenomenon and by expressing vibration exposure over a 24-hour period as a single figure value such as *VDV*, many features of the vibration exposure such as temporal characteristics may not be characterized. Similarly, by expressing response as a single measure such as annoyance, much of the complexity and nuance of human response will be lost. This suggests two areas of further work which would be valuable in explaining the differences in reaction to different sources of environmental vibration. Firstly, research into the perception of vibration as a multidimensional phenomenon could lead to single figure metrics which are able to capture more features of the characteristics of vibration exposure. Secondly, the social survey collected data concerning residents' satisfaction with their neighbourhood and home, a variety of social and personal characteristics, and qualitative data collected via open questions. Analysis of these additional data could provide valuable insight into the differences in reactions provoked by the two sources.

5 Conclusions

This paper has presented a number of key results from a project into the human response to vibration from railway and construction activities in residential environments By means of a large scale field trail (1431 questionnaires), a database of responses for annoyance due to environmental vibration along with estimations of internal vibration exposure has been developed. Exposure-response relationships have been derived from these data for the human response to railway and construction induced vibration. In both of these relationships a monotonic increase in annoyance was found with increasing vibration exposure. Significant differences were observed in the response to the two sources with vibration from construction activity eliciting a higher annoyance than the same magnitude of vibration exposure from railway activities.

The study of the human response to vibration in a residential setting is a developing area of research. The results presented in this paper represent the first of their kind in the UK and as such provide evidence to inform future policy, guidance, and revisions of standards where previously such evidence did not exist. However, as highlighted by the differences in response to the sources of vibration presented in this paper, there is still much work to be done in this area.

Acknowledgments

This research was funded by the Department for Environment, Food and Rural Affairs (Defra) UK

References and links

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

ISO (2003). ISO/TS 15666 “Acoustics—assessment of noise annoyance by means of social and socio-acoustic surveys”

Groothuis-Oudshoorn, C. & Miedema, H., (2006). Multilevel Grouped Regression for Analyzing Self-reported Health in Relation to Environmental Factors: the Model and its Application. Biometrical Journal, 48(1), pp.67-82.

Klæboe, R., Turunen-Rise, I.H., Hårvik, L., & Madshus, C., (2003). Vibration in dwellings from road and rail traffic–Part II: exposure-effect relationships based on ordinal logit and logistic regression models. Applied Acoustics, 64(1), p.89–109.

Miedema, H. & Oudshoorn, C.G., (2001). Annoyance from transportation noise: relationships with exposure metrics DNL and DENL and their confidence intervals. Environmental health perspectives, 109(4), pp.409-16.

Schultz, T.J., (1978). Synthesis of social surveys on noise annoyance. The Journal of the Acoustical Society of America, 64(2), pp.377-405.

Sica, G., Woodcock, J., Peris, E., Koziel, Z., Moorhouse, A., & Waddington, D., (2011). Human response to vibration in residential environments: Estimation of vibration exposure in residential environments. In the proceedings of ICBEN2011. London, UK.