Vibration is one of the main problems associated with railways in residential areas. To ensure quality of life and well being of inhabitants living in the vicinity of route paths, it is important to evaluate, understand, control and regulate railway noise and vibration. Much attention has been focused on the impact of noise from railway but the consideration of railway-induced vibration has often been neglected. This paper aims to provide policy guidance based on results obtained from the analyses of relationships estimated from ordinal logit models between human response and vibration exposure. This was achieved using data from case studies comprised of face-to-face interviews and internal vibration measurements (N=755) collected within the study "Human Response to Vibration in Residential Environments" by the University of Salford. Firstly, the implications of neglecting vibration in railway noise policies are presented. Secondly, the main factors that were found to influence railway vibration annoyance are presented and expressed as weightings. This work will be of interest to researchers and environmental health practitioners involved in the assessment of vibration complaints, as well as to policy makers, planners and consultants involved in the design of buildings and railways.
INTRODUCTION

Transportation is one of the major needs of the today’s society. In Europe, freight transport by rail is expected to grow by 80% between 2007 and 2020 (EC, 2011). The environmental impacts of railway traffic must be therefore considered. Vibration is one of the main problems associated with railways in residential areas and should be taken into account in future environmental policies. This paper intends to provide policy guidance based on results obtained from the analyses of relationships estimated from ordinal logit models between human response and vibration exposure from the research project “Human Response to Vibration in Residential Environments” carried out by the University of Salford and funded by Defra (Waddington et al., 2011). This paper discusses and presents results from issues related to the human response from railway induced vibration such as the development of a combined noise and vibration exposure-response relationship for railway as well as factors and specific scenarios that have to be taken into account for an optimal assessment of railway effects in residential environments.

METHODS

Study Design and Sample

The data in this paper relate to measurements of, and response to, railway vibration and were collected in the United Kingdom, specifically in the North-West of England and the Midlands area during 2009 and 2010 as part of the study “Human response to vibration in residential environments” performed by the University of Salford (Waddington et al., 2011). The study sites were chosen to provide an overall representative and 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 that are within a range of distances from the railway, are exposed to different railway traffic and contain different kinds of properties. Mainly, the sites were identified according to their population density and distance from the vibration source. Properties within a distance of 100 m from the railway were targeted to ensure a relatively high and perceptible vibration level for the respondents. Face to face questionnaires were used and the total number of completed questionnaires relating to railway vibration was 931 with associated high-quality vibration data being obtained internally within respondent’s properties. A total of 755 estimates of internal vibration exposure could be derived and therefore 755 case studies were available for the analyses presented in this paper.

Vibration and Noise Exposure

The measurement of vibration was carried out using Guralp CMG-5TD accelerometers and the measurement protocol employed in the field consisted of long term vibration monitoring at an external position (e.g., a garage or a shed) along with time synchronized short-term internal snapshot measurements. By determining the velocity ratio between the control and the internal measurements, an estimation of 24-h internal vibration exposure was obtained. For each respondent, Vibration Dose Values (VDV), using the $W_b$ weighting curve, in accordance with BS 6472-1:2008, were calculated over 24 h. The exposures for railway traffic noise sources were obtained and calculated according to a routine based on “Calculation of Railway Noise”(Koziel et al., 2011).

Questionnaire

To measure the “response” component, a social survey questionnaire was used to collect data from the respondents. The questionnaire was introduced as a survey of neighborhood satisfaction and is divided into different sections. The sections in order as they are presented in the questionnaire were: dwelling information, neighborhood satisfaction, satisfaction with home, vibration questions, noise questions, railway vibration, railway noise and personal and occupancy information.

Within the vibration questions, respondents self-assessed their degree of overall annoyance on a five-point semantic scale, as recommended by the standard ISO/TS 15666 (2003) and through the following question: “Thinking about the last 12 months or so, when indoors at home, how bothered, annoyed, or disturbed have you been by feeling vibration or hearing or seeing things rattle, vibrate, or shake caused by the railway, including passenger trains, freight trains, track maintenance or any other activity from the railway, would you say not at all, slightly, moderately, very, or extremely?”
The respondents who stated they could not feel vibration were recoded to the lowest category of the five-point semantic annoyance scale. The annoyance response categories were converted to a scale ranging from 0 to 100 and centered to the midpoints of these categories. This conversion is based on the assumption that a set of categories divides the range from 0 to 100 into equally spaced intervals. Exposure–response relationships are generally analyzed for the percentage of highly annoyed people (%HA), which in accordance to the ICBEN recommendations (Fields et al., 2001) are the “very” or “extremely” categories in the five-point semantic scale.

**Statistical Analyses**

Most of the social survey data were archived and analyzed with SPSS. The number of variables that composed the questionnaire were large, thus a first attempt was made to select a relevant set of variables. To examine relationships between annoyance scores and vibration exposure featuring situational, attitudinal and personal factors, ordinal logit models (similar to Klæboe et al., 2003) were used to generate parameter estimates for the annoyance thresholds (not at all, slightly, moderately, very, and extremely). The following equation was used to obtain the estimated exposure–response relationships from the estimated parameters and indicates the probability of obtaining vibration annoyance response greater than or equal to j:

\[
P(Y \geq j | x_i = x_j) = 1 - \frac{(e^{\hat{\tau}_j - \beta x_i})}{(1 + e^{\hat{\tau}_j - \beta x_i})} 
\]

where \(\hat{\tau}_j\) indicates the jth estimated threshold, and \(\hat{\beta}\) is a vector of the estimated parameters for the exposure value and modifying factors. There are J annoyance categories. \(x_i\) is a vector of exposure for an individual i.

**RESULTS**

**Towards a combined noise and vibration-response curve for railway**

When comparing the three main modes of transportation (i.e. railway, road and aircraft) railway noise is less annoying at the same exposure level than road noise and aircraft noise (Miedema and Oudshoorn, 2001). This has led to the introduction of a “noise bonus” in the legal calculation schemes in many countries such as the Noise Annoyance Correction Factor (NACF). The causes for this difference in annoyance due to the two sources may be due to the existence of longer quiet periods without noise between train passes, the greater regularity and predictability of railway traffic, the difference in frequency and acoustical characteristics or the difference in attitude towards the source.

Vibration is one of the most widely experienced problems associated with railways. Railway traffic, in particular heavy freight trains and trains at high speed, often produce low-frequency vibration that can cause annoyance for people living and working in buildings along the track, out to distances up to 100-200m (Krylov, 2001). There are also vibration problems associated with road traffic and aircraft runways but one can assume that these are minor to the ones produced by railways. These vibration-related problems associated with railways should be taken into account when discussing the railway bonus. It has been shown that railway noise is less annoying than road and aircraft noise for the same L_{den} (Miedema and Oudshoorn, 2001). These curves were based on studies examined previously by Schultz (1978) and Fidell et al. (1991) which related noise exposure to noise annoyance responses. But should these annoyance curves include the vibration produced by the transportation sources? Should they take into account the annoyance due to vibration from the transportation source? The railway bonus could then be decreased when considering the effect of vibration as well as noise.

Deriving a combined noise and vibration-response curve for each transportation source would give a better understanding of the real effects of those on annoyance. Recent work associated with these issues such as the study “Human response to vibration in residential environments” by the University of Salford and from which the present paper is derived, has shown combined effects of railway noise and vibration. Woodcock et al. (2011) showed that annoyance due to vibration increases with an increase in both noise exposure and vibration exposure; although vibration exposure has a greater influence on vibration annoyance reporting (see Figure 1). The presence of vibration also increases the reported noise annoyance (Öhrström and Skånberg, 1996). The combined effects of railway noise and vibration on noise annoyance are shown in Figure 2. It can be seen that the implications of
neglecting vibration would result in an underestimation of 5% highly annoyed people for an exposure of 65 dB(A) at low levels of vibration (0.001 m/s$^{1.75}$) and an underestimation of 10% of highly annoyed people at high levels of vibration (0.1 m/s$^{1.75}$). Thus, there is a need for accounting for vibration into new railway noise policies as without reducing railway vibration, noise mitigation measures can become ineffective. To achieve a substantial decrease in annoyance future directions should address mitigation measures of combined noise and vibration. Moreover, vibration maps of the different modes of transportation in cities could be beneficial for decision making in urban planning.

**FIGURE 1.** The percentage highly annoyed persons (%HA) due to railway vibration as a function of vibration level ($V_{DBV_{b,24h}}$) and $L_{den}$ (dB(A)).

**FIGURE 2.** The percentage highly annoyed persons (%HA) due to railway noise as a function of vibration level ($V_{DBV_{b,24h}}$) and $L_{den}$ (dB(A)).
**Other factors to take into account when setting railway vibration limit values**

There are a number of acoustical and non-acoustical factors related to the railway that may influence the community response. Some of these factors have to be considered when designing new railway vibration limit regulations.

Factors influencing the vibration response due to railway vibration in residential environments are presented in Table 1. This table intends to give a better understanding of the community reaction due to railway vibration and could be used to set up different vibration limit values depending on the context, attitudes and demographics of a specific site. The weightings were derived following the same method explained in Peris et al. (2012) for estimating time-of-day weightings. It can be seen that the attitudinal factors constitute the most important annoyance parameter. Some of these factors could be considered when designing new railway noise limit regulations. From the results it can be seen that omitting these additional factors might result in an increase in the number of annoyed people, an increase in the number of people that suffer from vibration-induced effects, and an impairment of the living conditions of the community.

<table>
<thead>
<tr>
<th>Time of Day when Vibration Occurs</th>
<th>Weighting (w) at VDVb,24h of 0.01m/s$^{1.75}$</th>
<th>Weighting in dB</th>
<th>Impact on vibration annoyance due to railway vibration in residential environments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evenings</td>
<td>6.7</td>
<td>8</td>
<td>Vibration during the evening is perceived as more annoying than during the daytime</td>
</tr>
<tr>
<td>Night</td>
<td>50</td>
<td>17</td>
<td>Vibration during the night is perceived as more annoying than during the daytime</td>
</tr>
<tr>
<td>Attitudinal Factors</td>
<td></td>
<td></td>
<td>Mediates the relationship between annoyance and vibration exposure. Property damage concern accounts for about 55% of the effect of vibration exposure on vibration annoyance. One point increase in the concern scale corresponds to a 1.2 points increase in the annoyance scale which corresponds to a change in exposure of 0.049 m/s$^{1.75}$. People expecting vibration levels to get worse are more likely to be highly annoyed than people who believe vibration levels will get better or remain the same in the future.</td>
</tr>
<tr>
<td>Property Damage Concern</td>
<td>20 (for each point increase in the concern scale)</td>
<td>13 (for each point increase in the concern scale)</td>
<td>People living in a small town/village/countryside are more likely to be highly annoyed by railway vibration than those living in a city or large town. Residences with visibility to the railway are more likely to be highly annoyed than residents with no visibility to the railway line. People spending less than 10 hours at home are more likely to be highly annoyed than people spending more than 10 hours at home.</td>
</tr>
<tr>
<td>Age</td>
<td>10</td>
<td>10</td>
<td>Inverted U-shaped pattern. People in the middle age rank (45) are more likely to be highly annoyed than people aged 20 or 80.</td>
</tr>
</tbody>
</table>

**CONCLUSIONS**

In this paper, specific issues concerning current railway noise and vibration policy that have to be tackled in the scope of future development have been summarized and addressed with examples from the study “Human response to vibration in residential environments” by the University of Salford and from which the present paper is derived. The focus has been primarily on the community impact issues and the necessity of exploring specific scenarios for
an optimal assessment of railway effects on residential environments. The paper identified, discussed and addressed gaps such as:

1. The need to account for railway induced vibrations in noise and transport directives. Fig. 5.3 showed that the implications of neglecting vibration from railway would result in an underestimation of 5% highly annoyed people for an exposure of 65 dB(A) at low levels of vibration (0.001 m/s$^{1.75}$) and an underestimation of 10% of highly annoyed people at high levels of vibration (0.1 m/s$^{1.75}$).

2. The need to account for other factors specific to a particular residential environment that may modify the community response (see Table 1).

In conclusion, due to the awareness of the public authorities of the improvement of the living environment, additional factors should be integrated into the “average” noise limit values when assessing the noise impact of any railway line. One of the most important factors to take into account is vibration. Limit values of railway vibration should be included in conjunction with the railway noise emission limits and reception limits as without reducing railway vibration, noise mitigation measures can become ineffective (see Figure 2). Furthermore, non-acoustical factors have proven to play a role in the community response to railway vibration. A broader picture (not only considering and applying vibration limits) of each situation has to be studied to predict the community response. A first attempt of how to set vibration limits from railway is shown in Table 2 which compiles the community reaction to vibration from railway in terms of percentage %HA for different situations.

### TABLE 2. Community reactions to vibration from railway in terms of percentage %HA and VDV$^{b,24}$ for different situations (results extracted from Table 1)

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>0.001 m/s$^{1.75}$</th>
<th>0.01 m/s$^{1.75}$</th>
<th>0.1 m/s$^{1.75}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>1.3%</td>
<td>2.5%</td>
<td>5%</td>
</tr>
<tr>
<td>Evening</td>
<td>2%</td>
<td>4%</td>
<td>9.2%</td>
</tr>
<tr>
<td>Night</td>
<td>3.5%</td>
<td>8.5%</td>
<td>19.8%</td>
</tr>
<tr>
<td>Age</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1.5%</td>
<td>3%</td>
<td>8.5%</td>
</tr>
<tr>
<td>45</td>
<td>4%</td>
<td>8.5%</td>
<td>15%</td>
</tr>
<tr>
<td>80</td>
<td>1.5%</td>
<td>2.5%</td>
<td>6.5%</td>
</tr>
<tr>
<td>Location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>City/Large Town</td>
<td>2%</td>
<td>4%</td>
<td>8.5%</td>
</tr>
<tr>
<td>Small town/village/countryside</td>
<td>6%</td>
<td>9.8%</td>
<td>18.5%</td>
</tr>
<tr>
<td>Visibility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Railway Visible from home</td>
<td>3%</td>
<td>7%</td>
<td>12.5%</td>
</tr>
<tr>
<td>Railway no Visible from Home</td>
<td>2%</td>
<td>4%</td>
<td>9%</td>
</tr>
</tbody>
</table>

### ACKNOWLEDGMENTS

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### REFERENCES


