Quantification of the effects of audible rattle and source type on the human response to environmental vibration

J. Woodcock,[a)] G. Sica, E. Peris, C. Sharp, A. T. Moorhouse, and D. C. Waddington
Acoustics Research Centre, University of Salford, Greater Manchester, M5 4WT, United Kingdom

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The present research quantifies the influence of source type and the presence of audible vibration-induced rattle on annoyance caused by vibration in residential environments. The sources of vibration considered are railway and the construction of a light rail system. Data were measured in the United Kingdom using a socio-vibration survey ($N = 1281$). These data are analyzed using ordinal logit models to produce exposure-response relationships describing community annoyance as a function of vibration exposure. The influence of source type and the presence of audible vibration-induced rattle on annoyance are investigated using dummy variable analysis, and quantified using odds–ratios and community tolerance levels. It is concluded that the sample population is more likely to express higher levels of annoyance if the vibration source is construction compared to railway, and if vibration-induced rattle is audible. [http://dx.doi.org/10.1121/1.4944563]

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I. INTRODUCTION

The aim of this paper is to quantify the influence of two factors on exposure-response relationships for annoyance caused by vibration in residential environments: (1) whether the vibration is caused by a railway or construction source, and (2) whether the vibration induces audible rattling. This is achieved through further analysis of the dataset reported in Waddington *et al.* (2014).

Exposure-response relationships provide a method for predicting the percentage of a population expected to express a given degree of annoyance for a given level of exposure to vibration or noise. Exposure-response relationships for different sources of environmental noise (Miedema and Oudshoorn, 2001) have had a strong influence on European (EC/DG Environment, 2002) and North American (Fidell, 2003) noise policy. Similar relationships for environmental vibration are therefore of interest.

Field studies have been conducted in Europe (Turunen-Rise *et al.*, 2003; Klæboe *et al.*, 2003a, 2003b; Gidlöf-Gunnarsson *et al.*, 2012; Waddington *et al.*, 2014), North America (Zapfe *et al.*, 2009), and Japan (Yano, 2005) to collect the data necessary to derive exposure-response relationships to predict annoyance due to vibration. These studies have all focused on railway-induced vibration, with the exception of Turunen-Rise *et al.* (2003) where vibration from road traffic was investigated and Waddington *et al.* (2014) where vibration from railways and the construction of a light rail system were investigated.

A common feature of these field studies is that vibration exposure is found to explain a relatively small proportion of the variance in the exposure-response relationship, suggesting that there are other factors that mediate and moderate the relationship (Fidell *et al.*, 2011). Similar observations have been made in studies into the human response to environmental noise, with exposure-response relationships including only noise exposure as an independent variable typically explaining not more than 20% of the variation in annoyance (Fields, 1993; Job, 1988; Brink and Wunderli, 2012). The unexplained portion of the variance in the annoyance response to noise has been attributed to the inability of single figure noise exposure descriptors to properly describe human perception (Dittrich and Oberfeld, 2009; Kryter, 2007) and non-acoustical factors (Marquis-Favre and Premat, 2005; Marquis-Favre, 2005). "Non-acoustical factors" refer to situational, attitudinal, and socio-demographic factors that may not be related to noise exposure but nevertheless have an influence on the annoyance response.

A similar term, "non-exposure factors," has been suggested to describe factors that influence the response to vibration (Peris *et al.*, 2014). Peris *et al.* (2014) investigated the influence of attitudinal, situational, and socio-demographic factors on self-reported annoyance due to railway-induced vibration. This study led to the quantification of the influence of these factors on annoyance including concern of property damage, visibility of the vibration source, and age of the respondent. Sharp *et al.* (2014) analyzed this dataset to investigate the influence of different sources of railway vibration on annoyance, namely, passenger and freight trains. It was found that for the same level of vibration exposure, vibration from freight trains elicited a higher annoyance response than annoyance from passenger trains.

Vibration-induced rattle has been shown to influence the annoyance response to noise (Borsky, 1965; Hubbard and Mayes, 1967). Fidell *et al.* (1999, 2002) investigated the

[a)]Electronic mail: j.s.woodcock@salford.ac.uk

relationship between low-frequency aircraft noise and annoyance due to rattle and vibration. It was suggested that this relationship could complement the interpretation of the exposure-response relationships for aircraft noise, with high levels of annoyance explained in part by vibration-induced rattling of elements such as window frames and household objects such as crockery. There have been similar findings for helicopter noise (Schomer and Neathammer, 1987) and rail noise (Schomer *et al.*, 2012).

In a socio-vibration survey conducted in North America, Zapfe *et al.* (2009) found that 14.2% of respondents reported noticing rattling sounds when trains passed by, although the influence this had on the annoyance response was not investigated. In surveys conducted in the Netherlands and Poland, Janssen *et al.* (2015) found vibration-induced rattle to have a significant contribution to the annoyance response to vibration, largely mediating the effect of vibration exposure.

The present paper explores the influence of vibration source and vibration-induced rattle on annoyance due to railway- and construction-induced vibration. The study draws on data measured in a socio-vibration survey conducted in the United Kingdom (Waddington *et al.*, 2014), where it was shown that for the same magnitude of vibration exposure the annoyance response was significantly higher for construction-induced vibration than for railway-induced vibration. The methodology used to collect the exposure and response data, and the statistical methods applied to these data are described in Sec. II. The difference in the annoyance response to railway induced-vibration and construction-induced vibration is quantified in Sec. III, along with the influence of audible vibration-induced rattle. Finally, conclusions and recommendations for future work are presented in Sec. IV.

II. METHODS

A. Field survey

This section provides an overview of the field methodology used to collect the data analyzed in this paper. The aim of the field survey was to produce a database of responses to vibration and associated estimates of exposure from which robust exposure-response relationships could be derived. Further details of the methodology can be found in Waddington *et al.* (2014), and a validation of the prediction techniques can be found in Sica *et al.* (2014).

1. Measurement of response

Response to vibration was measured using a social survey questionnaire (Whittle *et al.*, 2015) that was conducted face-to-face with residents in their own homes by trained researchers from the Salford Housing and Urban Studies Unit. The questionnaire measured responses to annoyance due to various sources of environmental noise and vibration. As well as annoyance, responses were collected to various attitudinal, situational, and socio-demographic factors. To avoid biasing responses to the questions on noise and vibration, the questionnaires were presented as a survey of neighborhood satisfaction.

Surveys were conducted in areas that had dwellings situated within around 150 m of either an existing railway line or the construction of a new light rail system. Each questionnaire took, on average, 20 min to complete. In total, 931 questionnaires were conducted with residents living close to a railway and 350 questionnaires were conducted with residents living close to the construction of a light rail system.

After neutral filter questions asking whether the respondent was able to feel vibration or notice vibration-induced rattling in their home from a variety of different sources, the following questions were asked to measure their annoyance:

> *"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.

This question explicitly addresses two modalities of vibration perception, feeling vibration, and audible effects of vibration manifested as rattling. Responses to this question were recorded on a five-point semantic scale with the category labels "Not at all," "Slightly," "Moderately," "Very," and "Extremely" and also on an 11 point numerical scale with the anchor points Not at all and Extremely.

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. Survey sites were first identified via desk work, which was followed with a site reconnaissance to determine suitability. In total, 12 measurement sites that were subject to railway-induced vibration were selected across the North West and Midland regions of England. Additionally, two sites were identified around the construction of a new light rail system. At these sites, the construction activities proceeded along the site in a linear fashion, meaning that questionnaires could be conducted with residents who had already been exposed to the entire lifecycle of the construction activities associated with the site. It has been shown that the different sub-sites do not have a significant effect on the annoyance response for both the railway and construction sources of vibration (Woodcock *et al.*, 2011).

The socio-demographic characteristics of the sample were found to be broadly similar to what was reported in the 2011 UK census. Some slight differences were found in gender (an over-representation of female respondents), employment status (an over-representation of those describing themselves as unemployed), and tenure status (an over-representation of homeowners in the railway sample and a slight over-representation of those in social housing in the construction sample).

2. Estimation of vibration exposure

Vibration was measured using Guralp 5-TD strong motion accelerometers (Guralp Systems Ltd, Reading, UK) and digitized at a frequency of 200 Hz. A measurement based approach was used to ensure factors such as soil type, building type, and source characteristics were taken into account. Long term vibration monitoring was conducted at external positions for a period of 24-h. 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. The short term measurements were generally around 30 min in duration, or a period that encompassed 5 to 10 train passes. For the internal snapshot measurements, the measurement position was taken as close to the center of the floor as possible of the room in which the respondent of the questionnaire stated that they could feel the strongest magnitude of vibration. Estimations of 24-h internal vibration exposure were obtained by determining the transmissibility between the two measurement positions (Sica *et al.*, 2014).

In total, 149 long term measurements were conducted along with 522 snapshot measurements. Where it was not possible to obtain a snapshot measurement, either due to a respondent not being available or not allowing access to the property to conduct a measurement, vibration exposure was taken as the exposure in a dwelling of a similar type and distance from the source. As a similar property was not always available, it was not possible to estimate vibration exposure for all of the dwellings in which a questionnaire had been conducted. This approach enabled the estimation of 24-h internal vibration exposure in 752 dwellings.

The measurement approach adopted for railway was impracticable for measuring construction activity vibration due to the unpredictable hours of operation and the intermittent 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.*, 2014). Long term monitoring was conducted over a period of around 2 months to monitor the entire life-cycle of the construction activity. At times of high activity (during piling operations, for example), a linear array of external measurements was conducted to determine attenuation laws for each measurement site. The locations characterized enabled the estimation of 24-h internal vibration exposure in 321 dwellings.

B. Choice of vibration exposure descriptor

For the vibration data analyzed in this paper, all of the metrics suggested in current national and international standards are highly correlated with each other (Waddington *et al.*, 2014). This means that any of the metrics would be an equally good predictor of annoyance as any other. The results in this paper will be presented in terms of W_m weighted vibration dose value (VDV). The W_m frequency weighting is currently recommended in ISO 2631 (International Organization for Standardization, 1997, 2003) and the VDV metric is currently recommended in ISO 2631 and BS 6472 (International Organization for Standardization, 1997, 2003; British Standards Institute, 2008). The VDV metric is perceptually based and is derived from the fourth power relationship found in laboratory studies into the relationship between vibration exposure and annoyance (Howarth and Griffin, 1988, 1991). VDV is calculated using

$$\text{VDV} = \sqrt[4]{\int_0^T a_w^4(t)dt}, \qquad (1)$$

where $a_w(t)$ is the weighted acceleration time history and T is the duration of $a_w(t)$ in seconds.

For the current dataset, the logarithmic form of the vibration exposure metric exhibits a greater correlation with the annoyance a linear metric (Waddington *et al.*, 2014). The models calculated in this paper will therefore be derived using VDV expressed as a base 10 logarithm.

C. Statistical methods

The statistical models used in this paper are predominantly *cumulative link models*, namely, the ordered logit model (Agresti, 2002). This family of regression models is particularly suited to ordinal response variables (Long, 1997), as is the case with the annoyance response data measured in the social survey described in Sec. II A 1. They overcome the problems associated with using linear regression methods to model categorical data, such as the resulting models giving prediction outside of the permissible range of responses, and also avoid the violation of the standard assumptions required for linear models. These models have been successfully applied in previous studies to socio-vibration field data (Klæboe *et al.*, 2003b; Zapfe *et al.*, 2009; Peris *et al.*, 2014).

Given an ordinal response variable Y_i that can fall into $j = 1, ..., J$ categories, Y_i follows a multinomial distribution π where π_{ij} denotes the probability that the ith observation falls in response category j. The cumulative probability γ_{ij} that the ith observation falls into response category j or lower is defined as

$$P(Y_i \le j) = \pi_{i1} + ... + \pi_{ij}. \qquad (2)$$

The logit function is defined as

$$\text{logit}(\pi) = \ln\left(\frac{\pi}{1-\pi}\right). \qquad (3)$$

From Eqs. (2) and (3), the cumulative logit is defined as

$$\text{logit}(\gamma_{ij}) = \ln\frac{P(Y_i \le j)}{1 - P(Y_i \le j)} \quad j = 1, ..., J-1. \qquad (4)$$

The cumulative logit model is formed as a regression model for the cumulative logit as shown in Eq. (4)

$$\text{logit}(\gamma_{ij}) = \theta_j - \mathbf{x}_i^T \beta, \quad (5)$$

where θ_j is the intercept parameter for the jth category, $\mathbf{x}_i$ is a set of independent variables, and β are regression coefficients to be estimated. The coefficients for this model can be estimated via maximum likelihood.

This model differs from the model proposed by Groothuis-Oudshoorn and Miedema (2006), which is a type of ordinal probit model with fixed thresholds and as such allows any threshold of annoyance to be modeled. The advantage of using an ordinal logit model to address the questions posed in this paper is that the parameter estimates that result can be intuitively interpreted as odds–ratios, which is not the case for ordinal probit models. This is particularly useful for examining the influence of dummy variables.

Odds–ratios describe the odds that an outcome will occur given a particular condition, compared to the outcome occurring in the absence of that condition (Long, 1997). Odds–ratios are related to logistic regression models through the estimated β coefficients. All other variables held constant, e^{β_n} represents the odds of the modeled outcome occurring given the condition represented by the nth independent variable. For example, if $e^{\beta_n} = 2$ where β_n is the parameter estimate for a variable describing some binary factor in a model of the percentage of the population who are highly annoyed, this can be interpreted as meaning that, all other variables in the model held constant, the population for which this factor is present is twice as likely to be highly annoyed compared to the population for which this factor is not present. In the same model, an odds–ratio of 0.5 would be interpreted as meaning the population for which this factor is present is half as likely to be highly annoyed compared to the population for which this factor is not present. This can be extended to an ordinal variable with more than two levels, with the odds–ratio representing the odds of the modelled outcome occurring in a higher category.

In Sec. III, dummy variables for source type and whether rattle is noticed are included as additive effects to an exposure-response model with annoyance as the dependent variable and vibration exposure as the independent variable. Likelihood ratio tests (LRTs) are used to confirm whether the inclusion of a variable in the model results in a significant improvement in the model fit (Long, 1997) over the exposure only model. All reported models were calculated using the "ordinal" package (version 2016.6-28) in R (version 3.2.1). Reported probabilities were calculated using the "predict" function from the ordinal package and were converted to the probability of a response falling into the J-th category or higher by taking 1 minus the calculated probability.

III. RESULTS

A. Overview of dataset

1. Response data

Questionnaires (931) were conducted with residents living within 150 m of a railway line and 350 questionnaires were conducted with residents living within 150 m of the construction of a light rail system. It was possible to estimate a corresponding vibration exposure for 752 of the respondents in the railway dataset and 321 respondents in the construction dataset using the methods outlined in Sec. II A 2. All of the analyses in the present paper were performed using these 1073 data.

TABLE I. Number of respondents reporting being able to feel vibration or notice audible rattle from railway sources.

	Railway	
	Don't notice rattle	Notice rattle
Don't feel vibration	254 (34%)	19 (3%)
Feel vibration	312 (41%)	167 (22%)

Tables I and II show the number of respondents able to feel vibration or notice audible vibration-induced rattle for the railway and construction source, respectively. These tables show that, apart from respondents stating they are unable to feel vibration but are able to notice rattle, the distribution of responses both within and between the two source types is fairly even. Table III provides an overview of the annoyance responses to the two sources of vibration.

2. Exposure data

Figures 1 and 2 provide an overview of the estimated vibration exposure for the two sources of vibration in terms of W_m weighted VDV evaluated over a 24–hour period (see Sec. II B). It can be seen that vibration exposures estimated for the two sources each have a range of around 30 dB.

B. Relationships for the separate sources

Ordinal logistic regression models were calculated from the data measured for the railway and construction sources of vibration with the annoyance response as the dependent variable and the vibration exposure as the independent variable. The parameter estimates for the calculated models are presented in Tables IV and V. Each of the models was found to be significant compared to the intercept only model ($p < 0.001$).

Figures 3 and 4 show the exposure-response relationships for annoyance due to railway-induced vibration and construction-induced vibration, respectively. Unless otherwise stated, all parameter estimates presented in this paper are significant to at least the 0.01 level. The relationships are presented in terms of cumulative probabilities and can be interpreted as the percentage of respondents expressing annoyance in the given category or higher.

C. Influence of source type

To investigate the influence of whether the source of vibration is railway or construction on annoyance, a dummy

TABLE II. Number of respondents reporting being able to feel vibration or notice audible rattle from construction sources.

	Construction	
	Don't notice rattle	Notice rattle
Don't feel vibration	95 (30%)	4 (1%)
Feel vibration	105 (33%)	117 (36%)

TABLE III. Overview of annoyance responses to the two vibration sources.

	Railway	Construction
Don't notice	273 (36%)	99 (31%)
Not at all	255 (34%)	73 (23%)
Slightly	97 (13%)	28 (9%)
Moderately	67 (9%)	34 (11%)
Very	45 (6%)	29 (9%)
Extremely	15 (2%)	58 (18%)

variable was created for source type which took on a value of 1 if the source of vibration was railway or 0 if the source of vibration was construction. A LRT confirmed that the inclusion of the source type dummy variable into the exposure only model resulted in a significant improvement in the model fit (LRT = 33.2, $p < 0.001$). A Brant test (Long, 1997) indicated that the proportional odds assumption was violated with the inclusion of the source type dummy variable (LRT = 45.5, $p < 0.001$). To account for this, the model was re-calculated using a generalized ordinal logistic regression model. This model relaxes to proportional odds assumption by allowing the effect of an independent variable to vary across different category cut points of the ordinal dependent variable (Williams, 2006). The results of this model are shown in Table VI. The threshold coefficients appended with ".Source" indicate the difference between the coefficients for the two levels of the "Source" dummy variable. It can be seen that the effect of Source type increases from 0.10 at the lowest level on the annoyance scale and 2.05 at the highest level, suggesting that the influence of source type increases at higher levels of annoyance. This corresponds to an odds–ratio (i.e., the odds of reporting annoyance in a higher category if the source of vibration is construction) of 1.1 for the lowest category (Notice vibration or higher) up to 7.8 for the highest category (Very annoyed or higher).

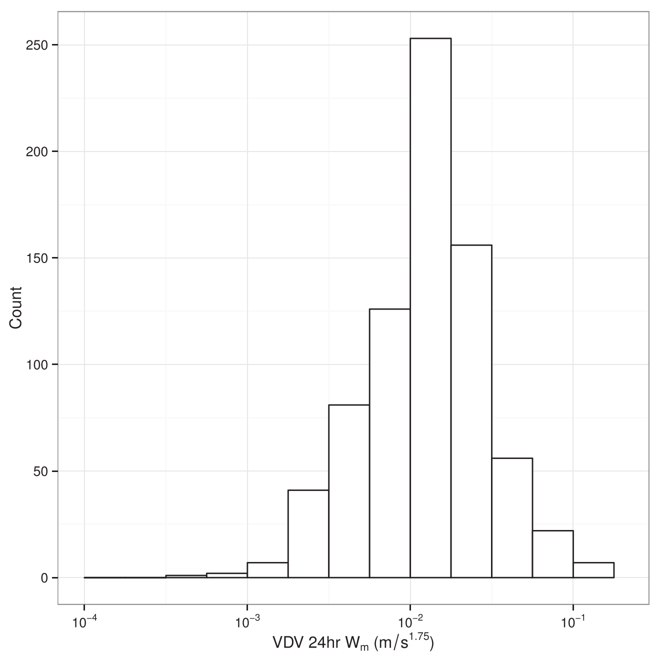

FIG. 1. Histogram showing the distribution of estimated vibration exposures for the railway dataset.

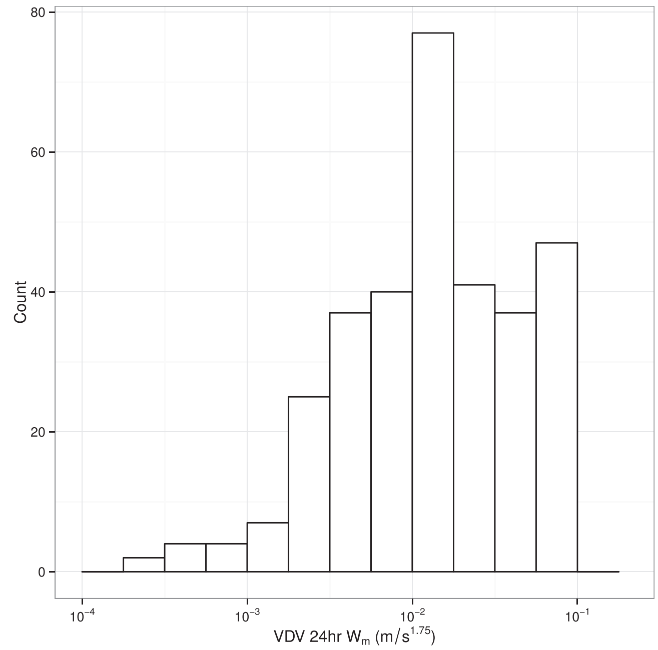

FIG. 2. Histogram showing the distribution of estimated vibration exposures for the construction dataset.

D. Influence of audible rattle

As discussed in Sec. I, there have been a small number of studies into the influence of audible vibration-induced rattle on annoyance due to environmental noise. The general finding of these studies is that, for the same noise exposure, higher annoyance ratings are observed if vibration-induced audible rattle is present. In the social survey questionnaire, respondents were asked whether they noticed windows, doors, or crockery rattle due to vibration from the source under investigation. The response to this question was recorded as either "Yes" or "No" for each object or element.

To investigate the influence of audible rattle on annoyance due to vibration, a dummy variable was created which took on a value of 1 if the respondent reported noticing rattle from any of the objects mentioned above, or 0 otherwise. This variable was included as an independent variable in the model detailed in Sec. III B. A LRT confirmed that the inclusion of the notice rattle dummy variable resulted in a significant improvement in the model fit (LRT = 229.1, $p < 0.001$). A Brant test confirmed that the proportional odds assumption was met for the notice rattle dummy variable (LRT = 6.5,

TABLE IV. Results of the ordered logit model for annoyance due to vibration from mixed rail ($N = 752$).

Coefficient	Estimate	SE	5%	95%
Threshold				
Don't notice—Not at all	−2.81	0.36	−3.4	−2.21
Not at all—Slightly	−1.19	0.35	−1.76	−0.61
Slightly—Moderately	−0.49	0.35	−1.06	0.09
Moderately—Very	0.30	0.36	−0.29	0.89
Very—Extremely	1.76	0.42	1.06	2.45
Variable				
log10(VDV m,24 h)	1.17	0.18	0.87	1.47

TABLE V. Results of the ordered logit model for annoyance due to vibration from construction ($N = 321$).

Coefficient	Estimate	SE	5%	95%
Threshold				
Don't notice—Not at all	−3.92	0.45	−4.66	−3.19
Not at all—Slightly	−2.71	0.42	−3.39	−2.02
Slightly—Moderately	−2.32	0.41	−2.99	−1.65
Moderately—Very	−1.78	0.4	−2.44	−1.11
Very—Extremely	−1.20	0.40	−1.86	−0.54
Variable				
log10(VDV m,24 h)	1.59	0.22	1.23	1.95

$p = 0.16$). The results of the model are shown in Table VII and the cumulative probabilities of a respondent falling into a given category as a function of vibration exposure are presented in Fig. 5. From Table VII, the estimated coefficient for the dummy variable which represents whether a respondent notices audible rattle is 2.03, which corresponds to an odds–ratio of 7.6. This result can be interpreted as indicating that for the same vibration exposure expressed in W_m weighted 24-h VDV, respondents are around seven and a half times more likely to report annoyance in a higher annoyance category if the vibration exposure is accompanied by audible rattle. It can be noted that the model coefficient for the source term is slightly reduced compared to the previous model.

Of the 307 respondents stating that they noticed rattle, 218 reported noticing rattling from windows, 203 noticed rattling from doors, and 137 reported noticing rattling from items of crockery. To investigate the influence that rattling from each individual source had on annoyance, three dummy variables indicating whether the respondent reported noticing rattle from the three different sources were included as independent variables in the model detailed in Sec. III B. Inclusion of these three variables resulted in a significant improvement in the model fit (LRT = 241.2, $p < 0.001$), and a forward–backward stepwise procedure based on the Akaike Information Criterion resulted in no variables being dropped from the model. From this model, the odds of a respondent expressing annoyance in a higher category are 2.27 if the respondent notices windows rattling, 3.10 if the

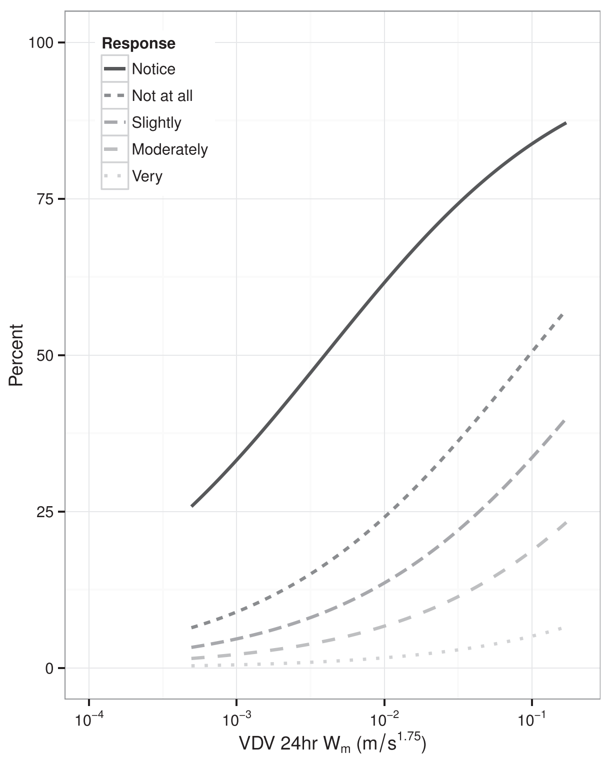

FIG. 3. Exposure–response relationship showing the percentage of the population reporting different degrees of annoyance for a given vibration exposure from railway.

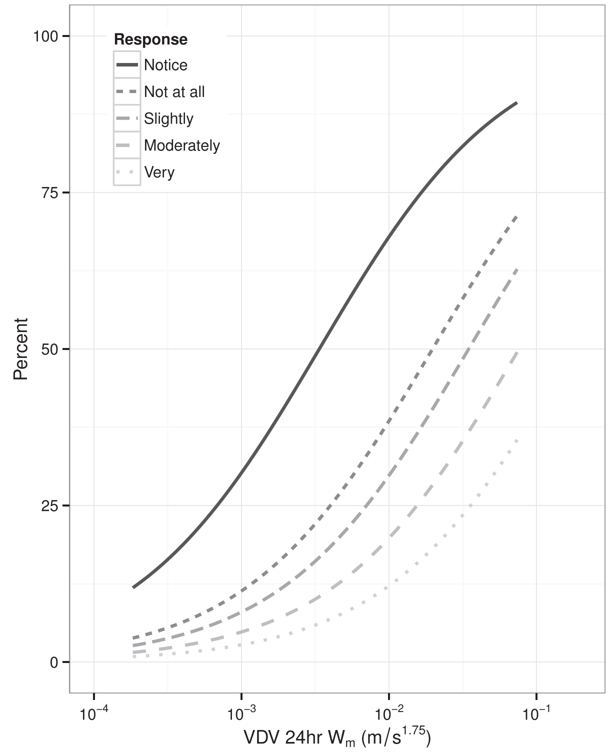

FIG. 4. Exposure–response relationship showing the percentage of the population reporting different degrees of annoyance for a given vibration exposure from construction.

TABLE VI. Results of the ordered logit model for annoyance due to vibration from mixed rail and construction including a dummy variable for source type ($N = 1073$). The coefficient for the source type variable has been allowed to vary across category cut points.

Coefficient	Estimate	SE	5%	95%
Threshold				
Don't notice	−3.15	0.28	−3.61	−2.69
Not at all	−1.52	0.27	−1.96	−1.07
Slightly	−0.81	0.27	−1.26	−0.36
Moderately	−0.03	0.29	−0.5	0.44
Very	1.44	0.36	0.84	2.03
Don't notice.Source	−0.3	0.15	−0.54	−0.06
Not at all.Source	−0.75	0.14	−0.99	−0.51
Slightly.Source	−1.07	0.16	−1.33	−0.81
Moderately.Source	−1.33	0.19	−1.64	−1.02
Very.Source	−2.22	0.30	−2.72	−1.73
Variable				
log10(VDV m,24 h)	1.35	0.14	1.12	1.58

TABLE VII. Results of the ordered logit model for annoyance due to vibration from mixed rail and construction including dummy variables for source type and whether the respondent notices vibration-induced rattle ($N = 1073$). The coefficient for the source type variable has been allowed to vary across category cut points.

Coefficient	Estimate	SE	5%	95%
Threshold				
Don't notice	−2.28	0.29	−2.76	−1.80
Not at all	−0.40	0.29	−0.87	0.07
Slightly	0.42	0.29	−0.06	0.91
Moderately	1.33	0.31	0.82	1.84
Very	2.89	0.38	2.27	3.52
Don't notice.Source	−0.10	0.16	−0.36	0.16
Not at all.Source	−0.55	0.16	−0.81	−0.29
Slightly.Source	−0.91	0.17	−1.19	−0.63
Moderately.Source	−1.16	0.2	−1.49	−0.83
Very.Source	−2.05	0.31	−2.56	−1.54
Variable				
log10(VDV m,24 h)	1.08	0.14	0.84	1.32
Notice rattle	2.03	0.14	1.80	2.26

respondent notices doors rattling, and 3.42 is the respondent notices crockery rattling.

IV. DISCUSSION

A. Validity of the exposure-response relationships

This paper has presented a number of different exposure-response relationships for annoyance due to environmental vibration. These relationships show the growth of community annoyance as a function of vibration exposure expressed as W_m weighted VDV assessed over a 24-hour period. The relationships present a basis to predict the impact of environmental vibration in terms of community annoyance. In interpreting these relationships, it is important to consider the assumptions adopted in their creation and their validity.

The relationships describe the situation on a population level, not the annoyance of individuals. Therefore, significant deviations from the predicted levels of response can be expected in the annoyance response of individuals and in specific local "*hotspot*" situations. As the relationships describe the steady-state community response, they are useful for policy and strategic planning purposes such as predicting the long term effect of a change in vibration.

In the field of environmental noise it has been shown that psychoacoustic metrics can be better predictors of annoyance than engineering type metrics such as L_{eq} and L_{DEN} (Fastl, 2005). Similar observations have been made by considering the perception of vibration as a multi-dimensional phenomenon (Woodcock *et al.*, 2014). The findings of laboratory studies cannot easily be applied to field situations, as relationships based on field data describe long term annoyance whereas laboratory studies describe short term annoyance. Nevertheless, the findings of laboratory studies suggest that there may be more appropriate psychologically-based vibration exposure metrics than those used in the current study.

Due to differences in the vibration exposure metric used, the comparison of results between different socio-vibration field studies is problematic. A meta-analysis of the data from Zapfe *et al.* (2009), Turunen-Rise *et al.* (2003), Waddington *et al.* (2014), and Janssen *et al.* (2015) suggested that, although there are differences in the annoyance responses between these studies, the data can be pooled to form a single relationship (Persson Waye *et al.*, 2014). However, no distinction is made between cases with rattle and no rattle within those datasets.

Although the vibration exposure metric may be different between the present paper and those used in previous studies, the ranges of vibration exposure and annoyance responses are similar. Despite their limitations and uncertainties, the relationships presented in this paper are valuable for assessing community annoyance and for practical and strategic planning.

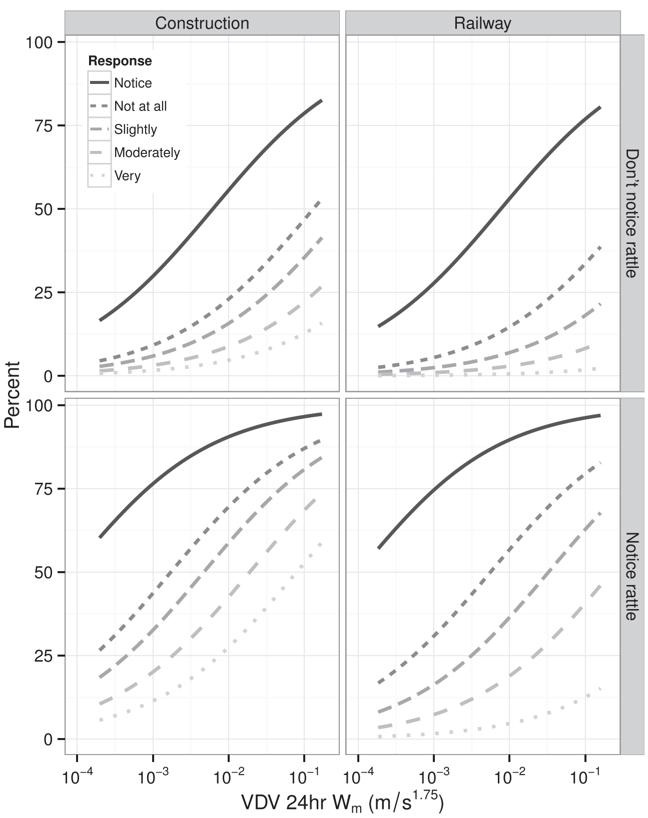

FIG. 5. Exposure–response relationship showing the percentage of the population reporting different degrees of annoyance for a given vibration exposure from railway and construction vibration with and without audible vibration-induced rattle.

B. Influence of source type

The results suggest that the human response to vibration in residential environments differs significantly depending on the source of vibration. As shown in Sec. III C, inclusion of a dummy variable for source type resulted in a significant improvement in the model fit over the exposure only model. For the same level of vibration exposure expressed as W_m weighted VDV assessed over a 24-h period, the sample population was found to be more annoyed by vibration from construction sources than they were by railway sources. This difference may be due to non-exposure factors, such as attitudes toward the source and features of the vibration that are not quantified by the single figure vibration exposure descriptor (in this case the VDV). This contrasts with the findings of Turunen-Rise *et al.* (2003), where no significant difference was found between annoyance due to vibration from railway and road traffic sources. This difference may be because the sources considered in Turunen-Rise *et al.* (2003) were both transportation sources, whereas these results compare a transportation source and a construction source.

Significantly different annoyance responses have also been observed for different sources of environmental noise [see, for example, Miedema and Oudshoorn (2001)]. Fidell *et al.* (2011) presents a method to quantify the differences observed in the response of communities to environmental noise. This measure, termed the community tolerance level (CTL), is defined as the level of exposure at which half of the community describe themselves as "*highly annoyed*" by a given environmental noise source. CTL is utilized here to quantify the differences in response to railway- and construction-induced vibration by examining the level of vibration at which the exposure-response model estimates that 50% of respondents would describe themselves as Very annoyed or higher. From the model presented in Table VII and setting the rattling term to 0, the CTL for railway is 67 dB (re 1×10^{-4} m/s$^{1.75}$) and the CTL for construction is 48 dB (re 1×10^{-4} m/s$^{1.75}$). This could be interpreted as the population studied being 19 dB more tolerant of railway-induced vibration than construction-induced vibration.

The perception of sound and vibration is traditionally studied according to an "information processing" framework, whereby it is assumed that the perceptual features of the stimulus are compared to an internal reference. It is useful to consider the findings according to the framework of ecological psychology (Gaver, 1993a,b), whereby sound and vibration are perceived directly as meaningful events rather than a collection of low level sensory features. It is not necessarily the objective characteristics of the vibration exposure that lead to annoyance, as these are only cues as to the nature of the source, but rather factors related to the source itself (i.e., attitudinal and situational factors).

Increases in annoyance due to a step change in noise exposure can be greater than that which would be predicted by exposure-response relationships derived under steady state conditions (Brown and van Kamp, 2009). It therefore may be expected that a step change in vibration exposure would have a similar outcome on the annoyance response. The construction source in the present study represents a step change in the vibration exposure whereas the railway source represents a permanent feature of the environment. Laszlo *et al.* (2012) conducted a review of studies on the human reaction to changed noise conditions, and found that non-acoustical factors also play a role in annoyance ratings due to changing noise conditions. This, and the consideration of the results within an ecological psychology framework, suggests that it is vital to consider factors other than just the vibration exposure in assessing human response. These findings highlight the need, first, for source specific data for annoyance due to environmental vibration and, second, for longitudinal studies to quantify the change in annoyance due to step changes in vibration exposure.

C. The influence of audible vibration-induced rattle

The results presented in Sec. III D suggest that annoyance depends on whether the vibration induces noticeable audible rattle. Inclusion of a dummy variable accounting for the presence of audible vibration-induced rattle resulted in a significant improvement in the model fit over the exposure only model. Similar observations have been made regarding the influence of rattling components on annoyance due to environmental noise (Borsky, 1965; Hubbard and Mayes, 1967; Fidell *et al.*, 1999, 2002).

From the model presented in Table VII and setting the source term to 0 (i.e., railway sources of vibration), the CTL for no rattle is 67 dB (re 1×10^{-4} m/s$^{1.75}$) and the CTL when rattle can be noticed is 48 dB (re 1×10^{-4} m/s$^{1.75}$). Setting the source term to 1 (i.e., construction sources of vibration), the CTL for no rattle is 48 dB (re 1×10^{-4} m/s$^{1.75}$) and the CTL when rattle can be noticed is 29 dB (re 1×10^{-4} m/s$^{1.75}$). These results indicate that the population studied was 19 dB more tolerant of vibration when there was no audible rattle.

It is seen in Tables VI and VII that by including the dummy variable for rattle, the coefficient for vibration exposure is reduced from 1.35 to 1.08. As the coefficient for vibration exposure is still significant, this suggests that noticing vibration induced rattle only partially mediates the effect of vibration exposure on annoyance. This supports work by Janssen *et al.* (2015) where presence of rattle was also shown to mediate the effect of vibration exposure on annoyance. To further investigate this mediation effect, a causal model in which the effect of vibration exposure on annoyance is mediated by rattle was tested. This model was calculated using MPlus Version 7.4. The outcome variable is expressed as percentage highly annoyed (i.e., respondents reporting annoyance in the top 2 categories on the 5 point annoyance scale) and the results before and after inclusion of the rattle variable are shown in Fig. 6. As the dependent and mediator

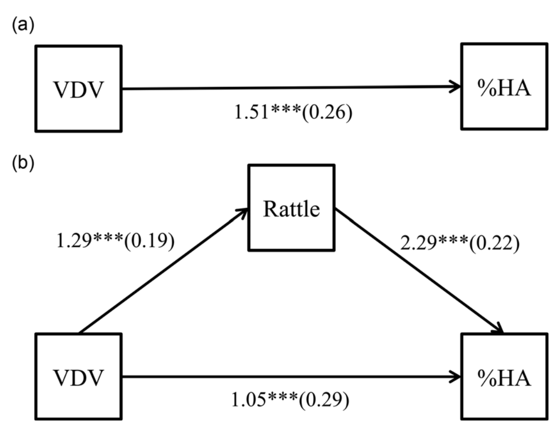

FIG. 6. Mediation model between vibration exposure, rattle, and percent highly annoyed (%HA). Un-bracketed values are the logit model coefficients and bracketed values are standard errors (***$p < 0.001$). (a) Shows the model before inclusion of the rattle dummy variable. (b) Shows the model after inclusion of the rattle dummy variable.

variables are dichotomous, the model was calculated via maximum likelihood using the logit link. As with the full ordinal logit model, with the inclusion of the dummy variable for rattle the coefficient for vibration exposure is reduced from 1.51 to 1.05 but remains significant. The results of this analysis showed that both the direct and indirect effects were significant ($p < 0.01$, estimated through bootstrapping 1000 replications), confirming that rattle partially mediates the effect of vibration exposure on annoyance.

These results are based solely on the influence of the respondent noticing rattle. As the quantification of this factor is purely qualitative, no inferences can be made about what specific features of vibration-induced rattle contribute to annoyance. Laboratory work is needed to investigate the perception of vibration-induced rattle.

V. CONCLUSION

Ordinal logit models have been used to estimate the influence of source type and the presence of audible vibration-induced rattle on annoyance due to vibration. Using dummy variable analysis these factors were found to have a significant influence on the annoyance response. The analyses presented suggested that respondents were more likely to express annoyance in a higher category if the vibration source was construction compared to railway. The magnitude of this effect was found to increase with increasing levels of annoyance, with the odds of reporting annoyance in a higher category of 1.1 for the lowest category (Notice vibration or higher) up to 7.8 for the highest category (Very annoyed or higher). It was also found that respondents were 7.6 times as likely to express annoyance in a higher category if audible rattle was noticed. The results indicate that additional source specific field data are needed if exposure-response relationships for other sources are to be derived. The findings highlight the importance of rattle in the annoyance response and suggest that further work is needed to characterize and quantify vibration-induced rattle and its effects on humans.

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Agresti, A. (**2002**). *Categorical Data Analysis* (John Wiley & Sons, Hoboken, NJ), pp. 274–286.

Borsky, P. N. (**1965**). "Community reactions to sonic booms in the Oklahoma City area," National Opinion Research Center, University of Chicago.

Brink, M., and Wunderli, J. M. (**2012**). "Response to comments on a field study of the exposure-annoyance relationship of military shooting noise," J. Acoust. Soc. Am. **131**, 3599–3600.

Brown, A. L., and van Kamp, I. (**2009**). "Response to a change in transport noise exposure: A review of evidence of a change effect," J. Acoust. Soc. Am. **125**(5), 3018–3029.

BS 6472-1:2008 (**2008**). "Guide to evaluation of human response to vibration in buildings (1 Hz to 80 Hz) Part 1: Vibration sources other than blasting" (British Standards Institute).

Dittrich, K., and Oberfeld, D. (**2009**). "A comparison of the temporal weighting of annoyance and loudness," J. Acoust. Soc. Am. **126**, 3168–3178 (2009).

EC/DG Environment (**2002**). Position paper on dose response relationships between transportation noise and Annoyance, In EC/DG Environment, Brussels.

Fastl, H. (**2005**). "Psycho-acoustics and sound quality," in *Communication Acoustics* (Springer-Verlag, Berlin, Heidelberg), pp. 139–162.

Fidell, S. (**2003**). "The Schultz curve 25 years later: A research perspective," J. Acoust. Soc. Am. **114**(6), 3007–3015.

Fidell, S., Mestre, V., Schomer, P., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2011**). "A first-principles model for estimating the prevalence of annoyance with aircraft noise exposure," J. Acoust. Soc. Am. **130**(2), 791–806.

Fidell, S., Pearsons, K., Silvati, L., and Sneddon, M. (**2002**). "Relationship between low-frequency aircraft noise and annoyance due to rattle and vibration," J. Acoust. Soc. Am. **111**(4), 1743–1750.

Fidell, S., Silvati, L., and Pearsons, K. (**1999**). "Field study of the annoyance of low-frequency runway sideline noise," J. Acoust. Soc. Am. **106**(3), 1408–1415.

Fields, J. M. (**1993**). "Effect of personal and situational variables on noise annoyance in residential areas," J. Acoust. Soc. Am. **93**(5), 2753–2763.

Gaver, W. W. (**1993a**). "How do we hear in the world? Explorations in ecological acoustics," Ecol. Psychol. **5**(4), 285–313.

Gaver, W. W. (**1993b**). "What in the world do we hear?: An ecological approach to auditory event perception," Ecol. Psychol. **5**(1), 1–29.

Gidlöf-Gunnarsson, A., Ögren, M., Jerson, T., and Ohrström, E. (**2012**). "Railway noise annoyance and the importance of number of trains, ground vibration, and building situational factors," Noise Health **14**(59), 190–201.

Groothuis-Oudshoorn, C. G., and Miedema, H. M. (**2006**). "Multilevel grouped regression for analyzing self-reported health in relation to environmental factors: The model and its application," Biometrical J. **48**(1), 67–82.

Howarth, H. V. C., and Griffin, M. J. (**1988**). "Human response to simulated intermittent railway-induced building vibration," J. Sound Vib. **120**(2), 413–420.

Howarth, H. V. C., and Griffin, M. J. (**1991**). "Subjective reaction to vertical mechanical shocks of various waveforms," J. Sound Vib. **147**(3), 395–408.

Hubbard, H. H., and Mayes, W. H. (**1967**). "Sonic boom effects on people and structures," NASA Special Publication **147**, 65–75.
ISO 2631-1:1997. (**1997**). "Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration—Part 1: General requirements" (International Organization for Standardization, Geneva, Switzerland).
ISO 2631-2:2003. (**2003**). "Mechanical vibration and shock—Evaluation of human exposure to whole-body vibration—Part 2: Vibration in buildings (1 Hz to 80 Hz)" (International Organization for Standardization, Geneva, Switzerland).
Janssen, S. A., Coelho, B. Z., Koopman, A., Peris, E., Groll, W., and Wisnewska, K. (**2015**). "Annoyance due to vibration from freight railway lines in the Netherlands and Poland," in *Proceedings of Euronoise 2015*.
Job, R. F. S. (**1988**). "Community response to noise: A review of factors influencing the relationship between noise exposure and reaction," J. Acoust. Soc. Am. **83**(3), 991–1001.
Klæboe, R., Ohrström, E., Turunen-Rise, I. H., Bendtsen, H., and Nykanen, H. (**2003a**). "Vibration in dwellings from road and rail traffic. Part III: Towards a common methodology for socio-vibrational surveys," Appl. Acoust. **64**(1), 111–120.
Klæboe, R., Turunen-Rise, I. H., Hårvik, L., and Madshus, C. (**2003b**). "Vibration in dwellings from road and rail traffic. Part II: Exposure-effect relationships based on ordinal logit and logistic regression models," Appl. Acoust. **64**(1), 89–109.
Kryter, K. D. (**2007**). "Acoustical, sensory, and psychological research data and procedures for their use in predicting effects of environmental noises," J. Acoust. Soc. Am. **122**(5), 2601–2614.
Laszlo, H., McRobie, E., Stansfeld, S., and Hansell, A. (**2012**). "Annoyance and other reaction measures to changes in noise exposure. A review," Sci. Total Environ. **435**, 551–562.
Long, J. S. (**1997**). *Regression Models for Categorical and Limited Dependent Variables* (Sage Publications, Thousand Oaks).
Marquis-Favre, C. (**2005**). "Noise and its effects. A review on qualitative aspects of sound. Part II: Noise and annoyance," Acta Acust. Acust. **91**(4), 626–642.
Marquis-Favre, C., and Premat, E. (**2005**). "Noise and its effects. A review on qualitative aspects of sound. Part I: Notions and acoustic ratings," Acta Acust. Acust. **91**(4), 613–625.
Miedema, H. M., and Oudshoorn, C. G. (**2001**). "Annoyance from transportation noise: Relationships with exposure metrics DNL and DENL and their confidence intervals," Environ. Health Persp. **109**(4), 409–416.
Peris, E., Woodcock, J., Sica, G., Sharp, C., Moorhouse, A. T., and Waddington, D. C. (**2014**). "Effect of situational, attitudinal and demographic factors on railway vibration annoyance in residential areas," J. Acoust. Soc. Am. **135**(1), 194–204.
Persson Waye, K., Janssen, S., Waddington, D. C., Groll, W., Croy, I., Hammar, O., Koopman, A., Moorhouse, A., Peris, E., Sharp, C., Smith, M. G., Vos, H., Woodcock, J., and Ögren, M. (**2014**). "Rail freight vibration impacts sleep and community response: An overview of CargoVibes," in *Proceedings of ICBEN 2014*.
Schomer, P., Mestre, V., Fidell, S., Berry, B., Gjestland, T., Vallet, M., and Reid, T. (**2012**). "Role of community tolerance level (CTL) in predicting the prevalence of the annoyance of road and rail noise," J. Acoust. Soc. Am. **131**(4), 2772–2786.
Schomer, P., and Neathammer, R. (**1987**). "The role of helicopter noise-induced vibration and rattle in human response," J. Acoust. Soc. Am. **81**(4), 966–976.
Sharp, C., Woodcock, J., Sica, G., Peris, E., Moorhouse, A. T., and Waddington, D. C. (**2014**). "Exposure-response relationships for annoyance due to freight and passenger railway vibration exposure in residential environments," J. Acoust. Soc. Am. **135**(1), 205–212.
Sica, G., Peris, E., Woodcock, J., Moorhouse, A. T., and Waddington, D. C. (**2014**). "Design of measurement methodology for the evaluation of human exposure to vibration in residential environments," Sci. Total Environ. **482**, 461–471.
Turunen-Rise, I. H., Brekke, A., Hårvik, L., Madshus, C., and Klæboe, R. (**2003**). "Vibration in dwellings from road and rail traffic. Part I: A new Norwegian measurement standard and classification system," Appl. Acoust. **64**(1), 71–87.
Waddington, D. C., Woodcock, J., Peris, E., Condie, J., Sica, G., Moorhouse, A. T., and Steele, A. (**2014**). "Human response to vibration in residential environments," J. Acoust. Soc. Am. **135**(1), 182–193.
Whittle, N., Peris, E., Condie, J., Woodcock, J., Brown, P., Moorhouse, A. T., Waddington, D. C., and Steele, A. (**2015**). "Development of a social survey for the study of vibration annoyance in residential environments: Good practice guidance," Appl. Acoust. **87**, 83–93 (2015).
Williams, R. (**2006**). "Generalized ordered logit/partial proportional odds models for ordinal dependent variables," Stata J. **6**(1), 58–82.
Woodcock, J., Moorhouse, A. T., and Waddington, D. C. (**2014**). "A multi-dimensional evaluation of the perception and annoyance caused by railway induced groundborne vibration," Acta Acust. Acust. **100**(4), 614–627.
Woodcock, J., Peris, E., Condie, J., Sica, G., Koziel, K., Evans, T., Moorhouse, A., Steele, A., and Waddington, D. (**2011**). "Human response to vibration in residential environments (NANR209)," Determination of Exposure-response Relationships Technical Report 6 (Defra, London).
Yano, T. (**2005**). "Community response to Shinkansen noise and vibration: A survey in areas along the Sanyo Shinkansen Line," in *Proceedings of Forum Acusticum 2005*, pp. 1837–1841.
Zapfe, J. A., Saurenman, H., and Fidell, S. (**2009**). "Ground-borne noise and vibration in buildings caused by rail transit" (Transportation Research Board).