DELIVERABLE D1.5

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PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for the members of the consortium (including the Commission Services)	

Nature of Deliverable

R	Report	√
P	Prototype	
D	Demonstrator	
O	Other	

Acknowledgements

On 14^{th} May 2013, a workshop held at the University of Salford gathered together international experts in the field of railway vibration from industry, consultancy, and academia. The aim of the workshop was to discuss key aspects and challenges of the evaluation of vibration in residential environments with respect to human response. The outcomes of this workshop have been used to shape and inform the contents of this document.

The workshop was divided into three plenary sessions on the topics of annoyance, sleep disturbance and non-exposure factors. Each session was chaired by two experts in the respective topics, one from academia and one from industry/policy. The attendees represented a wide range of expertise in the field of railway vibration from industry, consultancy, and academia and provided useful comments and suggestions.

We appreciate their time and efforts in this endeavour. We would like to acknowledge all the participants for their contributions to this document.

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The final contents of the document do not necessarily reflect the individual views of the workshop participants.

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Part I

Executive summary

1.1 Objective of the deliverable

The objective of this deliverable is to provide guidance on the evaluation of human response to vibration from railways in residential environments. The deliverable outlines the currently available methods for the evaluation of disturbance from railway-induced vibration in residential environments. In addition, the deliverable presents the current state of the art in the human response to whole body vibration in the ranges of frequency and amplitude relevant to railway-induced vibration. The deliverable is intended to provide an extension to the currently available body of guidance in light of the current state of the art.

1.2 Main results

This deliverable provides guidance on the evaluation of human response to vibration from railways in residential environments. The guidance is derived from the main conclusions of WP1 of the CargoVibes project and other published literature. The main results presented in this deliverable are meta-analytic exposure-response curves for the estimation of annoyance due to vibration, a table detailing the effects of vibration on sleep, and a table detailing the influence of non-exposure factors on response.

1.3 Potential impact and use

The deliverable details current methods to evaluate human response along with current scientific evidence. Guidance on the evaluation of vibration, annoyance, and the effects of vibration on sleep will be of interest to consultants and scientists. The exposure-response relationships and tables of effects will be of use to policy makers, infrastructure managers, operators, and planners.

1.4 Partners involved and their contribution

The deliverable was written by USAL.

The meta-analysis of existing socio-vibration surveys reported in this deliverable was conducted by TNO.

The laboratory analysis of the effects of vibration on sleep reported in this deliverable was conducted by UGOT.

TNO and UGOT provided comments on the deliverable.

1.5 Conclusions

A review of current standards revealed a variety of documents available on a national and international level offering guidance on the evaluation of perceptible vibration in buildings. These documents differ in terms of the single figure vibration exposure descriptors advocated, frequency weightings, measurement methods, and guideline values for the prevention of adverse effect. The evaluation method that takes precedence depends upon the country in which the evaluation is being conducted.

There is presently insufficient evidence to recommend one vibration exposure descriptor over another. Therefore this document does not advocate a change in current evaluation methods. In this document guidance has been provided where possible in terms of three vibration exposure descriptors that can easily be related to those found in national and international standards. It is recommended, where possible, that future vibration surveys be reported in terms of these three descriptors and that raw time histories are retained for future analysis.

To assess annoyance due to railway-induced vibration, meta-analytic exposure-response curves have been derived within the CargoVibes project. These relationships can be used to estimate the percent highly annoyed ($\%HA$), percent annoyed ($\%A$), and the percent a slightly annoyed ($\%SA$) at different levels of vibration exposure. The curves are suitable for the prediction of community annoyance due to steady-state railway-induced vibration. A number of situational, attitudinal, and socio-demographic factors that influence these relationships have been identified and reported.

To assess the effects of vibration on sleep, a laboratory investigation has been conducted within the CargoVibes project. These experiments, along with a review of published literature, have identified a number of adverse effects on sleep that can result from exposure to railway-induced vibration. There is insufficient data to derive exposure-response relationships or to determine thresholds for adverse effects on sleep.

The document is intended as an extension to current guidance informed by the most up to date scientific evidence and therefore may be considered best practice at the time of writing. The document will be of interest to operators, infrastructure managers, planners, consultants, scientists, and policy makers.

Part II

Specific recommendations

1 Introduction

Guidance for the assessment of human response to vibration varies from country to country. There is currently no consensus as to the most appropriate single figure descriptor of vibration exposure or appropriate criteria to prevent adverse effects. These differences in evaluation methods have hampered the development of policy and standards in this field and affect the consistent application of current policy and standards. There is therefore a need for clear guidance on the assessment of vibration that is based on the current best available scientific evidence.

The main objective of this document is to deliver formal guidance on the evaluation of human response to vibration from railways in residential environments. This part of the document provides specific recommendations on descriptors for vibration exposure, the evaluation of annoyance, and the effects of vibration on sleep. Meta-analytic exposure-response relationships for the evaluation of annoyance are provided, an overview of situational, attitudinal, and socio-demographic factors that influence the annoyance response is presented, and the effects of vibration on sleep are summarised.

Details of the evidence that led to the recommendations presented in this part of the document are contained in a technical annex.

2 Descriptors

2.1 Vibration exposure

There is currently no clear evidence as to what is the most appropriate single figure descriptor of vibration exposure. A meta-analysis of the data from all socio-vibration surveys to date was conducted. It was found that each of the considered descriptors accounted for a similar proportion of the variance in the resulting exposure-response relationship. There have been no systematic studies on the most appropriate vibration descriptor for the effects of vibration on sleep. Therefore there is insufficient evidence to advocate a deviation from current standards. As a minimum requirement, vibration exposure should be quantified according to the standard relevant to the locale of the survey area. Preferably, vibration exposure should be reported as a frequency-weighted *rms* acceleration over a 24-hour period, a maximum freqeuncy-weighted running *rms*, and the cumulative vibration dose value. Where possible, the raw time histories should be retained.

2.2 Annoyance

The percentage highly annoyed (%HA), percentage annoyed (%A), and percentage slightly annoyed (%SA) should be used as descriptors of the vibration induced annoyance of a population. These metrics describe the proportion of the population expected to express annoyance above a given threshold. Percentage highly annoyed describes the proportion of the population responding in the upper 28% of the annoyance response scale, the percentage annoyed the upper 50%, and percentage slightly annoyed the upper 72%.

2.3 Sleep

Indices of self-reported sleep disturbance may be formed by averaging the responses to a number of specific questions on the effects of vibration on sleep.

The percentage highly sleep disturbed (%HSD), percentage sleep disturbed (%SD), and percentage slightly sleep disturbed (%SSD) should be used as descriptors of the self reported sleep disturbance of a population. These metrics describe the proportion of the population expected to express sleep disturbance above a given threshold. Percentage highly sleep disturbed describes the proportion of the population expressing sleep disturbance in the upper 28% of a sleep disturbance response scale, the percentage sleep disturbed the upper 50%, and percentage slightly sleep disturbed the upper 72%.

Objective polysomnographic (PSG) data should be scored according to the method set out by the American Academy of Sleep Medicine.

3 Recommendations, applications, and limitations

3.1 Annoyance

The exposure-response relationships shown in Figure 3.1 represent the best currently available estimate of community annoyance due to railway-induced vibration exposure under steady-state conditions. They are derived from a sample of 4129 exposure and response data drawn from 7 socio-vibration surveys conducted in 7 countries in Europe and North America. The curves are presented in terms of three different vibration exposure descriptors to allow a reasonable estimate of annoyance to be obtained from a measure of vibration exposure using any of the major standards. The three vibration exposure descriptors are:

- $V_{dir,max}$: Maximum W_k weighted fast exponentially filtered *rms* velocity over the entire assessment period.
- *rms*: W_k weighted *rms* acceleration taken over the entire assessment period.
- VDV: W_k weighted vibration dose value taken over the entire assessment period.

If these descriptors cannot be estimated directly, the relationship expressed in the descriptor that is closest to the estimate of vibration exposure that is available should be used. For example, the exposure-response relationship expressed in $V_{dir,max}$ may be used to estimate annoyance from vibration exposure assessed using the KB descriptor. Due to differences in the frequency weightings used by the $V_{dir,max}$ and KB descriptors, some additional uncertainty in the estimate of annoyance will be introduced. These uncertainties can be reduced through the application of the correction factors shown in Table 3.1.

Table 3.1: Correction factors to transform between common vibration exposure descriptors

From	To	Factor
W_m weighting	W_k weighting	1.15[1]
W_m acceleration	W_m velocity	35.2
Fast exponential filter	Slow linear filter	1.25

[1] This factor holds for broadband signals with dominant frequency content between 4 Hz and 12 Hz. For signals with higher frequency content a factor of 2.3 should be used.

The exposure-response relationships detailed in this document should only be used for the estimation of annoyance due to steady-state railway vibration. The relationships should not be used to estimate annoyance due to other sources of vibration. Under no circumstances should the relationships, which have been derived from data collected under steady state conditions, be used to predict human response when new railway lines are opened or rail services are altered substantially on existing lines. The relationships describe the situation on a population level, not the annoyance of individuals. Therefore, significant deviations from the average response may be expected in the annoyance responses of individuals and specific local "*hotspot*" situations.

Polynomial approximations to the meta-analytic curves are given in equations 3.1 to 3.11. These equations **MUST NOT** be used outside of the indicated ranges. Use of these equations outside of the indicated ranges will result in highly inaccurate estimations of the annoyance response. The accuracy of the polynomial fits are indicated in Figure 3.2. Tables 3.2, 3.3, and 3.4 provide estimations of $\%HA$, $\%A$, and $\%SA$ for different levels of $V_{dir,max}$, rms, and VDV respectively.

Airborne noise, groundborne noise, and vibration induced rattle all have an influence on the annoyance response to vibration and induce annoyance in their own right. There is presently insufficient data to explore this interaction in detail or to derive reliable exposure-response relationships for annoyance due to groundborne noise and vibration induced rattle.

3.2 Sleep

There is currently insufficient data to derive generalisable exposure-response relationships or thresholds for the effects of vibration on sleep. Exposure to vibration has been found in laboratory and field studies to be significantly related to a number of adverse effects on sleep. A summary of the effects of vibration on sleep for which a statistically significant finding has been reported are shown in Table 3.5.

3.3 Non-exposure factors

A number of factors that are not directly related to characteristics of the vibration exposure have a significant influence on the annoyance response to vibration. These non-exposure factors can be broadly characterised as situational, attitudinal, and socio-demographic. A summary of the non-exposure factors that have been identified so far as having a significant effect on the annoyance response to vibration from railways is given in Table 3.6. There is currently insufficient evidence to derive generalisable magnitudes for the influence of these factors on annoyance because these findings are based on only two studies.

$$\%SA_{V_{dir,max}} = -0.559X^4 - 2.594X^3 + 4.681X^2 + 31.802X + 36.118 \quad (3.1)$$

$$\%A_{V_{dir,max}} = -0.863X^4 - 0.811X^3 + 8.602X^2 + 23.181X + 18.527 \quad (3.2)$$

$$\%HA_{V_{dir,max}} = -0.460X^4 + 0.850X^3 + 7.620X^2 + 12.720X + 7.522 \quad (3.3)$$

$$\text{where } X = \frac{log_{10}(V_{dir,max}) + 0.5}{0.86733} \quad (3.4)$$

These equations **MUST NOT** be used outside the range 0.01 to 10 mm/s $V_{dir,max}$

$$\%SA_{rms} = -1.806X^4 - 3.198X^3 + 11.812X^2 + 35.059X + 25.390 \quad (3.5)$$

$$\%A_{rms} = -1.648X^4 - 0.013X^3 + 13.826X^2 + 22.510X + 11.380 \quad (3.6)$$

$$\%HA_{rms} = -0.527X^4 + 2.089X^3 + 9.850X^2 + 10.785X + 3.910 \quad (3.7)$$

$$\text{where } X = \frac{log_{10}(rms) + 4}{1.1564} \quad (3.8)$$

These equations **MUST NOT** be used outside the range 0.001 x 10^{-3} to 10 x 10^{-3} m/s^2 rms

$$\%SA_{VDV} = -1.751X^4 - 4.019X^3 + 10.845X^2 + 38.038X + 29.118 \quad (3.9)$$

$$\%A_{VDV} = -1.952X^4 - 0.768X^3 + 14.679X^2 + 26.054X + 13.832 \quad (3.10)$$

$$\%HA_{VDV} = -0.885X^4 + 1.834X^3 + 11.605X^2 + 13.529X + 5.086 \quad (3.11)$$

$$\text{where } X = \frac{log_{10}(VDV) + 2}{1.1564} \quad (3.12)$$

These equations **MUST NOT** be used outside the range 0.1 x 10^{-3} to 1000 x 10^{-3} $m/s^{1.75}$ VDV

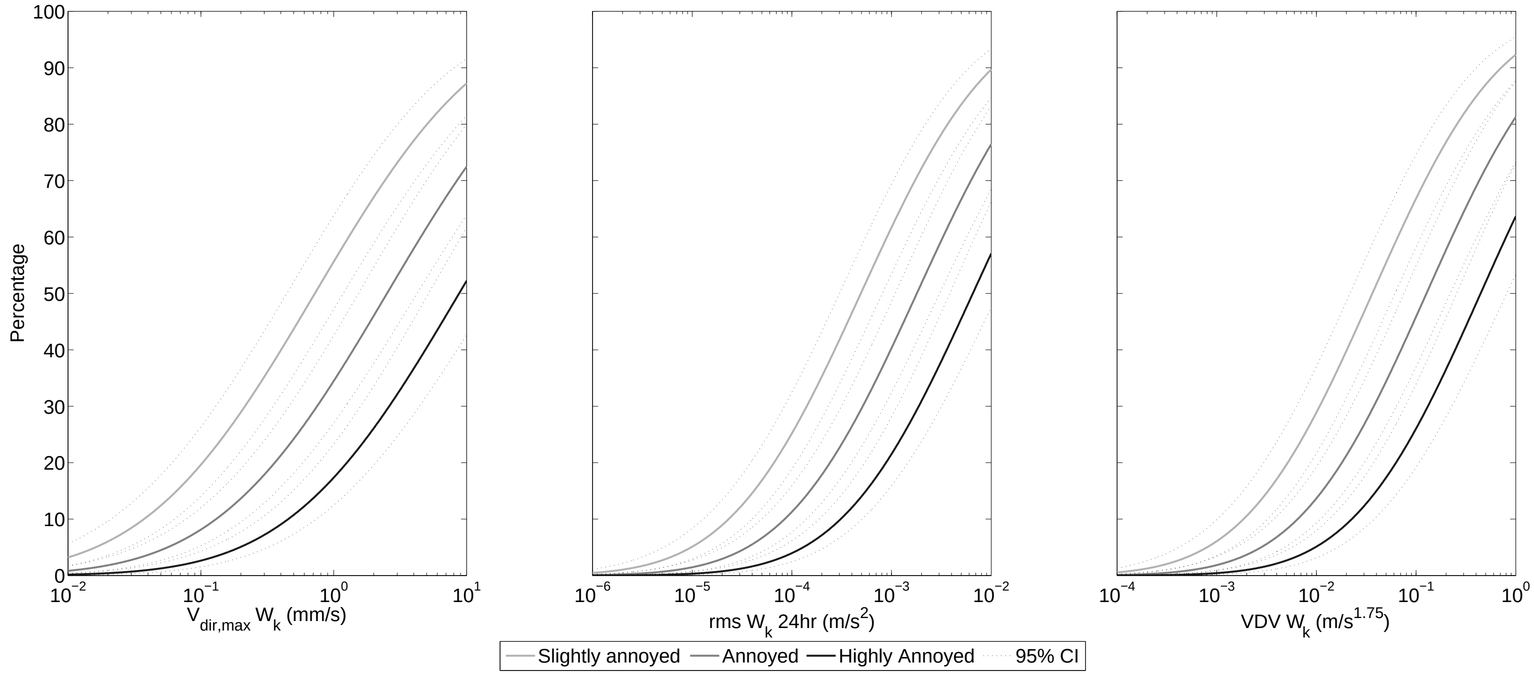

Figure 3.1: Meta-analytic exposure-response relationships for community annoyance due to railway-induced vibration (N = 4129)

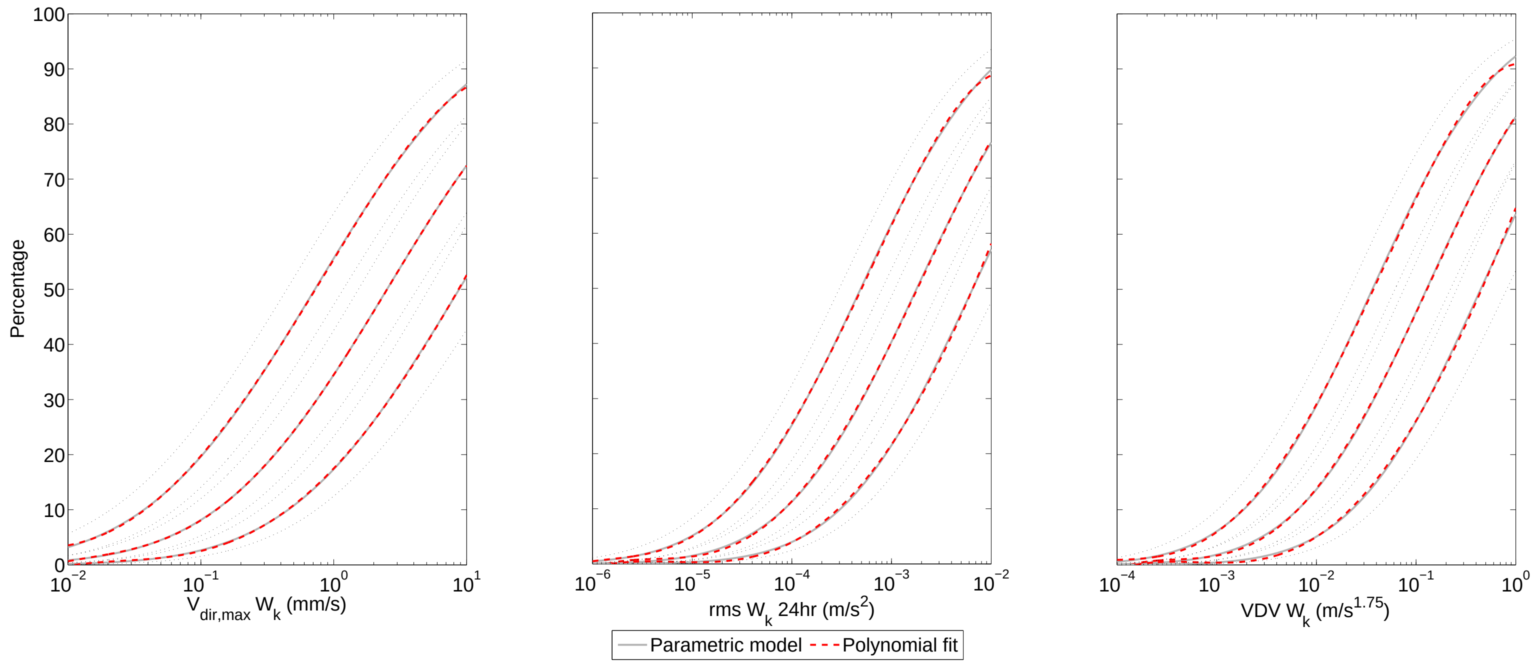

Figure 3.2: Polynomial fits to the meta-analytic exposure-response relationships (N = 4129)

Table 3.2: Estimated percentage highly annoyed ($\%HA$), percentage annoyed ($\%A$), and percentage slightly annoyed ($\%SA$) at different levels of $V_{dir,max}$

$V_{dir,max}$	$\%HA$	$\%A$	$\%SA$
0.01	0.2	0.8	3.2
0.03	0.7	2.8	8.4
0.05	1.3	4.5	12.4
0.07	1.8	6.1	15.7
0.09	2.4	7.5	18.4
0.1	2.6	8.1	19.6
0.3	7.2	17.9	35.2
0.5	10.8	24.2	43.7
0.7	13.7	29	49.5
0.9	16.2	32.8	53.8
1	17.4	34.5	55.6
3	32.1	53	73.1
5	40.4	61.7	79.9
7	46.1	67.1	83.7
9	50.4	70.9	86.3
10	52.3	72.5	87.2

Table 3.3: Estimated percentage highly annoyed ($\%HA$), percentage annoyed ($\%A$), and percentage slightly annoyed ($\%SA$) at different levels of W_k weighted RMS acceleration over a 24-hour period

RMS	$\%HA$	$\%A$	$\%SA$
0.001 x 10^{-3}	0	0.1	0.5
0.003 x 10^{-3}	0.1	0.4	1.6
0.005 x 10^{-3}	0.1	0.7	2.7
0.007 x 10^{-3}	0.2	1	3.7
0.009 x 10^{-3}	0.3	1.3	4.7
0.01 x 10^{-3}	0.3	1.5	5.1
0.03 x 10^{-3}	1.2	4.3	12
0.05 x 10^{-3}	2	6.7	16.9
0.07 x 10^{-3}	2.8	8.7	20.7
0.09 x 10^{-3}	3.6	10.5	23.8
0.1 x 10^{-3}	4	11.3	25.2
0.3 x 10^{-3}	9.8	22.6	41.8
0.5 x 10^{-3}	14	29.6	50.3
0.7 x 10^{-3}	17.4	34.6	55.9
0.9 x 10^{-3}	20.3	38.6	60
1 x 10^{-3}	21.5	40.3	61.7
3 x 10^{-3}	37.2	58.5	77.6
5 x 10^{-3}	45.5	66.6	83.5
7 x 10^{-3}	51.1	71.6	86.7
9 x 10^{-3}	55.3	75.1	88.9
10 x 10^{-3}	57.1	76.4	89.7

Table 3.4: Estimated percentage highly annoyed ($\%HA$), percentage annoyed ($\%A$), and percentage slightly annoyed ($\%SA$) at different levels of W_k weighted VDV over a 24-hour period

VDV	$\%HA$	$\%A$	$\%SA$
0.1 x 10^{-3}	0	0.1	0.6
0.3 x 10^{-3}	0.1	0.5	1.9
0.5 x 10^{-3}	0.2	0.9	3.2
0.7 x 10^{-3}	0.3	1.3	4.4
0.9 x 10^{-3}	0.4	1.7	5.6
1 x 10^{-3}	0.4	1.8	6.1
3 x 10^{-3}	1.6	5.3	14.1
5 x 10^{-3}	2.7	8.2	19.6
7 x 10^{-3}	3.7	10.6	23.9
9 x 10^{-3}	4.7	12.7	27.4
10 x 10^{-3}	5.1	13.7	28.9
30 x 10^{-3}	12.3	26.7	46.7
50 x 10^{-3}	17.4	34.4	55.4
70 x 10^{-3}	21.3	39.9	61.1
90 x 10^{-3}	24.6	44.1	65.2
100 x 10^{-3}	26	45.9	66.8
300 x 10^{-3}	43.3	64.4	81.8
500 x 10^{-3}	52	72.2	87
700 x 10^{-3}	57.8	76.9	89.8
900 x 10^{-3}	61.9	80	91.6
1000 x 10^{-3}	63.7	81.3	92.3

Table 3.5: Summary of the effects of vibration on sleep

	Effect	Significant findings[1]
Biological changes	**Change in cardiovascular activity**	Increase in heart rate[2]
	Change in sleep structure	Reduction in REM sleep Greater number of sleep stage shifts[3] Greater probability of sleep stage shifts[2] Shorter period between falling asleep and first awakening Shorter maximum length of uninterrupted time spent in slow wave sleep
	EEG awakening	Increase in probability of EEG awakening[2]
Sleep quality	**Waking in the night/too early**	Increase of reported awakenings/waking too early
	Difficulty in getting back to sleep	Greater difficulty in getting back to sleep once awoken for higher amplitudes of vibration
	Self-reported sleep disturbance from vibration	Increase in proportion of people reporting sleep disturbance Self-reported sleep disturbance related to vibration amplitude Decrease in self-reported sleep quality
	Self-reported sleep disturbance from noise	Vibration related to increase in proportion of people reporting sleep disturbance from noise
	Decreased restoration	Decrease in self-reported restoration

[1] The effects presented in this column are those for which a statistically significant result has been observed relating the effect to vibration exposure. However, it should be noted that these effects do not occur irrespective of vibration level.
[2] This response relates to individual vibration events.
[3] This response relates to the sleep macro-structure.

Table 3.6: Summary of the effects of non-exposure factors on annoyance

	Factor	Significant findings
Time of day	**Evening**	Annoyance greater during the evening than during the day at the same level of vibration exposure
	Night	Annoyance greater during the night than during the evening at the same level of vibration exposure
Situational	**Visibility of source**	Annoyance greater if the source is visible
	Time spent at home	Annoyance greater for people who spend fewer than 10 hours per day at home
	Type of area	Annoyance greater for people living in rural areas
Attitudinal	**Concern of damage**	Annoyance greater for those concerned that vibration is damaging their property or belongings
	Expectation regarding future vibration	Annoyance greater for those expecting vibration to get worse in the future
	Necessity of source	Annoyance greater for those considering the source unnecessary[1]
	Noise sensitivity	Annoyance from vibration greater for those considering themselves as noise sensitive
Socio-demographic	**Age**	Annoyance greater for those in the middle age group

[1] This result was observed for freight trains and may not be generalisable to mixed railway.

4 Future developments

Further field studies are needed to increase the statistical strength and generalisability of the meta-analytic exposure-response relationships. This can be facilitated by the use of common vibration exposure descriptors, common annoyance response scales, and the retention of raw data. Future socio-vibration surveys should further explore the effects of non-exposure factors as evidence suggests that these factors have at least as large an influence on the annoyance response as vibration exposure expressed in current descriptors.

Field and laboratory data are needed to understand the interaction between noise and vibration exposure. In particular, data is needed to derive relationships for human response to groundborne noise and vibration-induced rattle.

Further work in both the laboratory and field is needed to derive thresholds and exposure-response relationships for the effects of vibration on sleep. Epidemiological studies are needed if the effects of vibration on health are to be explored.

Part III

Technical Annex

A Introduction

A.1 Background

Groundborne vibration that propagates into buildings may be felt by residents or heard as groundborne noise or vibration induced rattle. For surface rail, these phenomena are generally also accompanied by airborne noise. Exposure to this noise and vibration can result in adverse effects such as annoyance and sleep disturbance. Because of these adverse environmental impacts there has been an interest in railway-induced groundborne vibration since the 1970s [1]. With a projected increase in the market share of freight traffic on rail from 8% in 2001 to 15% in 2020 [2] and a shift of freight from road to water and rail, of 30% by 2030 and 50% by 2050 [3], a clear understanding of the human response to noise and vibration is needed to avoid a corresponding increase in adverse impacts on the neighbours of freight railway lines.

Compared with human response to environmental noise, human response to environmental vibration has been a relatively neglected area of research. Guidance available for the assessment of human response to vibration varies from country to country in the form of national and international standards. There is currently no consensus as to the most appropriate single figure descriptor of vibration exposure or appropriate criteria to prevent adverse effects. Since the criteria on which the assessment methods advocated in these standards are based are often derived from psychophysical investigations performed in laboratory conditions, it is not clear whether they are relevant for assessing the adverse impacts of vibration in residential environments. These difficulties have consequently hampered policy and standard development in this field, and also affect the consistent application of current policy and standards. Therefore there is a need in industry and consultancy for clear guidance on the assessment of vibration that is based on the current best available scientific evidence.

This document, produced within the CargoVibes project, is intended to address some of these issues. In the previous part of the document, specific recommendations were given for the evaluation of human response to railway-induced vibration. This part of the document is a technical annex that presents in detail the evidence upon which these recommendations are based.

On 14th May 2013, a workshop held at the University of Salford gathered together international experts in the field of railway vibration from industry, consultancy, and academia. The aim of the workshop was to discuss key aspects and challenges of the evaluation of vibration in residential environments with respect to human response. The outcomes of this workshop have been used to shape and inform the contents of this document.

A.2 Scope of the document

The main objective of this document is to deliver guidance on the evaluation of human response to vibration from railways in residential environments. To realise this objective, the document aims to outline currently available methods for the evaluation of disturbance from railway-induced vibration in residential environments along with the current state of the art in human response to vibration. This document is therefore intended to provide an extension to the currently available body of guidance in light of the current state of the art. It is intended that the guidance will provide some cohesion between the different assessment methods. The human response to vibration is by no means fully understood, and the recommendations presented in this document should be revisited as further evidence becomes available.

The document is divided into five parts. The first part provides a general overview on the human perception of vibration and describes the effects of magnitude, frequency content, and duration. The second part covers evaluation methods that are currently available in national and international standards. The third and fourth parts address the adverse effects of vibration on humans in terms of annoyance and the effect of vibration on sleep, respectively. These sections present the best available current evidence regarding these adverse effects. The fifth part addresses factors that are not related to the physical characteristics of vibration exposure but have an influence on human response, such as the time of day in which the vibration exposure occurs, and whether the resident is concerned that vibration is damaging their property.

B The human perception of vibration

B.1 Introduction

(NOTE: This section is based on the literature review presented in [4].)

The human body is subjected to vibration in a variety of day-to-day situations ranging from travelling in a vehicle to environmental vibration experienced in the home. Above certain magnitudes and within certain ranges of frequency, vibration can be sensed by humans through the somatic, auditory, and visual systems. Exposure to vibration can occur locally, through the hand-arm system for example, or it can act on the whole body. This document is concerned with vibration induced by railway activities and the secondary effects of this vibration, such as groundborne noise and rattling. Human exposure to vibration can result in annoyance, discomfort, fear, positive tactile feedback, motion sickness, and injury, the latter occurring only at vibration exposures orders of magnitude higher than those of interest in this document. In order to predict or control the effects of vibration on humans, an understanding is needed of how measurable, quantitative aspects of vibration correlate with the sensations they evoke in human subjects.

The perception of vibration is governed in part by mechanoreceptors in the skin that respond to a vibratory excitation by producing a pulse train of action potentials. For a sinusoidal vibration excitation, each pulse corresponds to one cycle of the sinusoidal oscillation and the density of pulses produced by the mechanoreceptors is linearly related to the amplitude of the excitation. There are four main mechanoreceptors that respond to vibration in the frequency range related of interest in this document. Merkel disk receptors are sensitive to vibration in the range of frequencies 5–15 Hz, Meissner's corpuscles are sensitive in the range 20–50 Hz, Pacinian corpuscles are sensitive in the range 60–400 Hz, and Ruffian endings are sensitive in the range 100–500 Hz [5]. Vibration can also be perceived visually and by the auditory system. Changes in the relative position of objects on the retina can occur due to low frequency vibration, and aural perception can occur at frequencies above 20 Hz via airborne pathways and bone conduction.

Whole body vibration may be perceived kinaesthetically via forces and movements within the body. Proprioceptors provide information to the brain regarding the position and forces in joints, muscles, and tendons. Visceral perception may also occur via receptors in the abdomen [6]. The biodynamic response of the body to vibration has been shown consistently to be non-linear. For example, a number of studies [7–9] have demonstrated a lowering of the resonance frequency of the seated human body with increasing magnitude of vibratory excitation in the vertical direction. Similar nonlinearities have been demonstrated for vibration excitation in the horizontal directions [10] and for standing subjects [11].

B.2 Subjective magnitude

For over a century psychophysicists have attempted to derive mathematical expressions that describe relationships between the perceived intensity of a stimulus and some objective measurable feature of the stimulus (see for example the psychoacoustical concept of loudness [12]). Stevens' power law [13] is a classical psychophysical relationship quantifying the physical magnitude and perceived intensity of a stimulus. The form of Stevens' power law is given below.

$$\psi = k\vartheta^n \tag{B.1}$$

where ψ is the sensation level, k is a proportionality constant that depends on the units of the physical stimulus, ϑ is the magnitude of the physical stimulus and n is a growth constant.

A number of studies have utilised Stevens' power law to determine psychophysical relationships between the magnitude and perceived intensity or discomfort of vibration exposure. Subjective testing involving magnitude estimation is generally employed to estimate the growth constant n in the equation above. This methodology requires subjects to provide a numerical estimation of the relative subjective intensity or discomfort of two stimuli. Another method by which the growth constant n may be estimated is the method of magnitude production. This method requires subjects to adjust the magnitude of a stimulus until the perceived intensity or discomfort is a given factor greater than that of a reference stimulus.

One of the earliest studies that aimed to estimate the growth constant n for the perceived intensity of vibration was performed in 1968 by Miwa [14]. In this study, ten male subjects adopting a seated posture were presented with pairs of vibration stimuli. The magnitude of the second stimulus was adjusted by the experimenter until the subject judged it to be half the magnitude of the reference stimulus. This procedure was conducted for sinusoidal vibration at three frequencies (5 Hz, 20 Hz, and 60 Hz) and at six magnitudes of reference stimuli in the vertical and horizontal (fore and aft) directions. The results of this study indicated that the growth constant n did not differ significantly with frequency. Significant differences in the growth constant were however observed at different magnitudes of vibration exposure. As such, two psychophysical relationships were derived. In the first relationship, for vibration magnitudes below 1 m/s^2, a growth constant of 0.60 was found. In the second relationship, for vibration magnitudes above 1 m/s^2, a growth constant of 0.46 was found.

A relatively large amount of research into the perceived intensity and discomfort of whole body vibration followed these early studies, the results of which are summarised in [15]. Within the results summarised, a large amount of inter- and intra-study variability is reported, with the results of studies into perceived discomfort varying sometimes by orders of magnitude. Differences in results between studies from this period have been attributed to poor experimental design, unrealistic laboratory environments, use of inadequate rating scales, and small sample sizes. Prompted by the variability observed in the results reported in this research, a study was conducted that aimed to systematically assess the functional form of the psychophysical relationship underlying the perceived intensity of vibration, and also to assess the relationship between subjective intensity and discomfort. Two notable studies are identified in this paper [16, 17] that present data which support the hypothesis that subjective intensity obeys Stevens' power law with respect to the objective magnitude of vibration, and that the growth constant of this power law ranges between 0.86 and 1.04. The fluctuation of the reported growth constant in these studies around unity led to the question of the functional form of the psychophysical relationship; if the growth constant of Steven's power law is unity then the psychometric relationship is linear. Twenty-four subjects participated in tests of magnitude estimation of subjective intensity and an additional twenty-four subjects participated in magnitude estimation tests of subjective discomfort. Vertical sinusoidal vibration exposures were assessed at 2, 5, 8, 11, 14, 17, 20, 23, 26, and 28 Hz with reference magnitudes ranging between 0.49 and 4.41 m/s^2. Four different psychophysical relationships were assessed as potential fits to the data gathered through the perceptual tests:

$$
\begin{aligned}
&\psi = k\vartheta^n \\
&\psi = k + nlog(\vartheta) \\
&\psi = k10^{n\vartheta} \\
&\psi = k + n\vartheta
\end{aligned} \tag{B.2}
$$

The effectiveness of each these relationships was assessed via comparison of the correlation coefficients that resulted from the fit of each of the relationships to the subjective intensity and discomfort data. These correlations were assessed both on the individual level and averaged across the subject group. No significant differences were found between the correlation coefficients for the various relationships. Based on these results, it was proposed that the linear psychophysical relationship ($\psi = k + n\vartheta$) be adopted as there appeared to be no scientific basis for using the more complicated power law relationship ($\psi = k\vartheta^n$).

Unity growth constants have also been found in subsequent studies (for example [18, 19]). However, a number of studies have indicated that the growth constant is not equal over all frequencies and directions of excitation. For example, the growth constant of the subjective magnitude at 5 Hz has been found to be significantly greater than at 7, 15, and 20 Hz [16]. More recent studies have also suggested that in the lower frequency range the rate of increase of discomfort is greater than at higher frequencies [20–22].

B.3 Perception thresholds and equal comfort contours

Early laboratory studies into the human response to vibration found the perception of vibration to be frequency dependant [23]. Studies into the frequency dependency of vibration perception have generally aimed to determine absolute perception thresholds (for example [24]) or equal sensation and comfort contours (for example [19]). The results of a number of studies into perception thresholds are summarised in Figure B.1 taken from [25]. Although there is some agreement between the results of these studies, a large amount of inter-study variance can be observed. For vertical vibration of seated persons the greatest sensitivity is generally observed in the 5-6 Hz region. For horizontal vibration, the greatest sensitivity has generally been found to be in the 1-2 Hz region. Recent studies however have indicated that the threshold of perception in the vertical direction is relatively flat with acceleration above around 10 Hz [20], [26].

The perceived discomfort caused by whole body vibration has also been found to be dependant on frequency. Equal comfort contours for different postures and different directions of excitation have been derived in a number of studies [19, 27–31] and have generally been found to follow the reciprocal of the

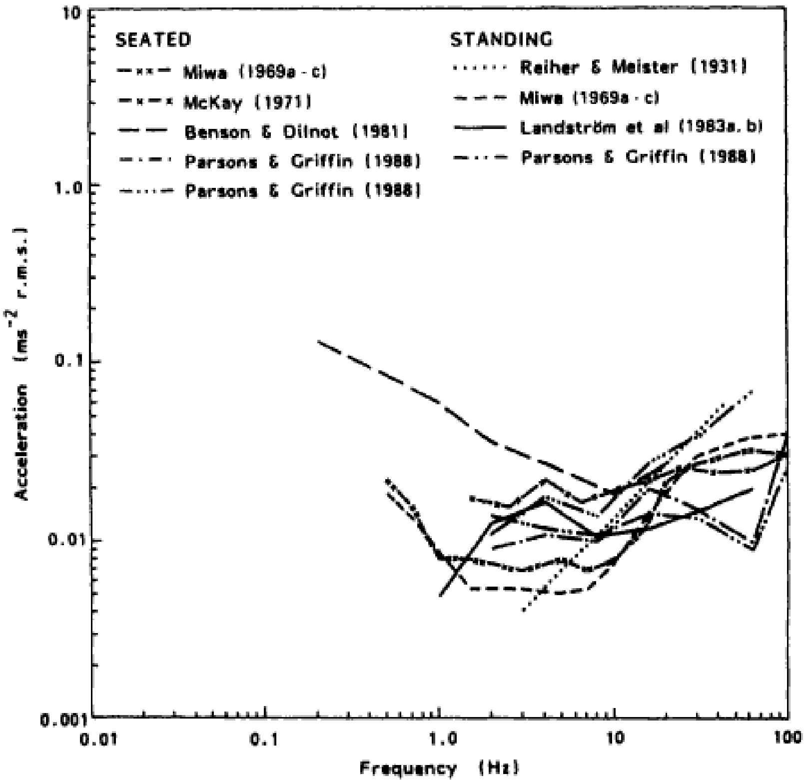

Figure B.1: Vibration perception thresholds in the vertical direction for a number of laboratory studies as presented in Handbook of Human Vibration [25]

perception threshold. Differences found in the rate of growth of subjective intensity and discomfort with respect to frequency mean that the shape of equivalent comfort contours is dependent on magnitude. Figure B.2 shows the results of a study investigating the magnitude dependence of equivalent comfort contours for whole body vibration in the vertical direction [20] from which this magnitude dependency can be observed. The magnitude dependency of equivalent comfort contours has implications on the applicability of the frequency weightings used in the assessment of the human response to vibration.

B.4 Just-noticeable differences

Studies into just-noticeable difference aim to determine the smallest perceivable change in some objective measure of a stimulus. The results of studies into just-noticeable differences are generally expressed in terms of Weber fractions [32]:

$$\frac{\Delta I}{I} = K \tag{B.3}$$

where ΔI is the absolute difference threshold, I is the magnitude of the reference stimuli, and K is a constant.

In a study into just-noticeable difference thresholds for changes in magnitude of vertical whole body vibration [33], subjects were presented with pairs of stimuli and asked to judge whether the first or second stimulus had the greater magnitude. This task was conducted for two magnitudes of sinusoidal vibration (0.1 and 0.5 m/s^2) at two frequencies (2 and 20 Hz). It was found that the median relative difference threshold for a change in vibration magnitude was around 10%. This difference threshold was found to be independent of the magnitude and frequency of the stimulus. This result suggests that a change in vibration magnitude of less than around 10% will not be detectable by human subjects.

Laboratory studies to investigate just-noticeable differences in level and frequency have also been conducted [26]. To determine the just-noticeable difference in level, automatic forced choice tests were conducted using sinusoidal stimuli in the vertical direction at 1/3 octave band centre frequencies between 5 and 50 Hz. Relative difference thresholds of around 18% were found that were independent of frequency. In a similar experiment, the just-noticeable difference in changes of frequency was found to be around 34%.

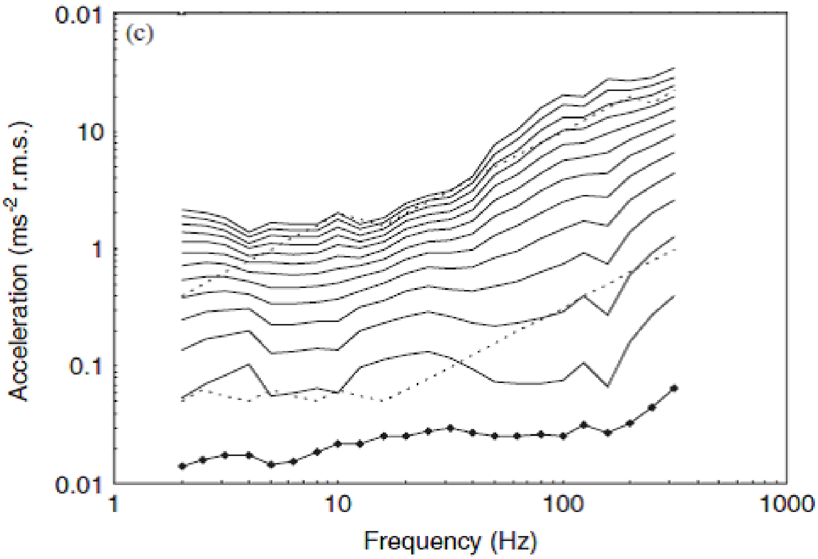

Figure B.2: Absolute perception threshold (dot markers) and equivalent comfort contours (solid lines) for vertical whole body vibration at different subjective intensities [20]

B.5 Duration

There is a limited amount of data regarding the effect of vibration duration on discomfort and perception thresholds. Study into the effect of the duration of vibration exposure on discomfort [14] found that discomfort increases with increasing duration of vibration exposure up to around 2 seconds for vibration in the frequency range 2–60 Hz and up to around 0.8 seconds for vibration in the frequency range 60–200 Hz. For 16 Hz sinusoidal vibration exposure, a decrease in the perception threshold has been observed for exposures with 4 cycles or greater [34].

In a study conducted to investigate the time dependency of discomfort due to vibration, subjective evaluations of sinusoidal excitations in the vertical direction with frequencies of 4, 8, 16, and 32 Hz and durations between 1 cycle and 32 seconds were conducted [35, 36]. The time dependency of discomfort due to vibration exposure reported in this study was found to approximate a fourth power relationship suggesting that a 16-fold increase in duration would require a two-fold decrease in magnitude to provoke an equivalent discomfort. In a similar study [18], multiple regression techniques were employed to determine a power law to describe the rate of change in discomfort with respect to the duration of vertical sinusoidal vibration exposure. The results of this study suggested a less than second power relationship contradicting the findings reported in [35, 36]. It was however suggested that the methodology used in this investigation may have overestimated the effect of vibration duration on discomfort. The fourth power relationship between duration and discomfort found in [35, 36] is partly the basis of the vibration dose value descriptor advocated in BS 6472-1:2008 [37].

B.6 Transient vibration

A study reported in [38] presents a relationship for the subjective response to transient vibrations based on frequency, amplitude, and floor damping. An increase in perception threshold was observed for transient vibration compared with the threshold for steady-state vibration. In a study into the perception of vertical mechanical shocks [39] two experiments were conducted, the first investigating the perception of single shocks, and the second investigating the perception of repeated shocks. For single shocks, the rate of growth of discomfort with respect to vibration magnitude was found to be around unity and was independent of frequency, duration, and the direction of excitation. For multiple shocks, a fourth power relationship was found between discomfort and the number of shocks presented in the stimulus. This result is in agreement with studies into the effect of vibration duration on discomfort [35, 36].

A study reported in [40] investigated the human response to mechanical shocks in the vertical direction in terms of frequency, magnitude, damping, and direction. Fifteen seated subjects were exposed to mechanical shocks produced by the response of a one degree-of-freedom mass spring damper system to a half-sine input force. Various different excitation waveforms were generated by this model with different fundamental frequencies (from 0.5 to 16 Hz), magnitudes (vibration dose values between 0.35 and 2.89 $m/s^{1.75}$), and damping ratios (between 0.05 and 0.4). Subjects performed a magnitude estimation task to determine discomfort for each of the excitations with respect to a reference shock stimulus. These data were used to estimate psychophysical relationships for discomfort due to mechanical shocks based on Stevens' power law. The growth function for the estimated psychophysical relationships was found to decrease from around 1.2 to 0.6 with decreasing fundamental frequency. Equal comfort contours were determined for the different magnitudes of excitation, the shape of which were found to vary with magnitude.

B.7 Summary

Despite the varied perceptual mechanisms and the complex biodynamic response of the human body, laboratory based psychophysical studies have gone some way towards characterising the perception of vibration in terms of subjective magnitude, perception thresholds, equal comfort contours, and duration of exposure. As will be seen in the next section, some of the results presented in this section have informed the development of international standards on the evaluation of vibration in residential environments, namely frequency weightings and the vibration dose value descriptor recommended in international and British standards. However, due to the laboratory based nature of these studies it is unknown how these findings relate to the human response to vibration under field conditions. Nevertheless, the studies discussed in this section provide valuable insight into how different features of vibration relate to human perception.

C Current evaluation methods

C.1 Introduction

There are many different standards in place for the evaluation of vibration with respect to human response. Which of these standards takes precedence will depend upon the country in which the vibration assessment is taking place. Generally, the evaluation methods suggested in the available standards recommend methods of expressing vibration exposure as a single figure value and frequency weightings that are intended to reflect the frequency dependence of the human perception of vibration. This section aims to give a brief overview of the methods and criteria currently available for the assessment of vibration from railways in residential environments.

C.2 ISO 2631 series

The ISO 2631 series of standards provide guidance on the measurement and evaluation of the human exposure to whole body vibration. Although they are international standards, in practice these standards are often superseded by national standards. The ISO 2631–1:1997 [41] and ISO 2631–2:2003 [42] standards from this series are particularly relevant to this document.

ISO 2631–1:1997 provides general guidance on the evaluation of human exposure to whole body vibration. The primary aim of this standard is to define methods of quantifying whole body vibration in relation to human health and comfort, the probability of vibration perception, and the incidence of motion sickness. The standard suggests that a frequency range of 0.5 Hz to 80 Hz be considered for the evaluation of health, comfort, and perception. In this standard the primary quantity used is acceleration, which is expressed in the units m/s^2. The standard does not propose specific vibration exposure limits for the prevention of adverse effects.

It is advised that vibration should be quantified by measurements of acceleration at the location in the room where the *highest magnitude of the frequency-weighted vibration occurs*. In practice for railway-induced vibration in residential dwellings this will likely be the centre of the room.

Three different vibration exposure descriptors are defined in the standard, all of which are calculated from frequency-weighted acceleration time histories. The standard proposes a number of different frequency weightings that can be used depending on the purpose of the evaluation. To evaluate vibration with respect to comfort and perception, the standard states that the frequency-weighted *rms* acceleration should be determined in three orthogonal directions at the surface supporting the person. The W_k frequency weighting should be used for vibration in the vertical direction and the W_d frequency weighting should be used for vibration in the horizontal direction. The W_k and W_d frequency weightings are shown in Figure C.1

The basic evaluation method suggested by this standard is an energy equivalent root-mean-square (*rms*) value that is calculated using equation C.1.

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)dt} \quad \text{(C.1)}$$

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

The standard states that the weighted *rms* values in each direction should be reported separately, along with a combined value that is obtained through root-sum-square summation of the weighted value in the three directions, as in equation C.2.

$$a_v = \sqrt{a_{wx}^2 + a_{wy}^2 + a_{wz}^2} \quad \text{(C.2)}$$

where a_{wx}, a_{wy}, and a_{wz} are the weighted *rms* acceleration in the orthogonal x, y, and z axes respectively.

It is suggested in the standard that this evaluation method is sufficient when the crest factor of $a_w(t)$ is less than 9. Crest factor is defined as the maximum instantaneous peak value of $a_w(t)$ to its *rms* value. Where the crest factor of $a_w(t)$ exceeds a value of 9, the standard suggests two alternative vibration exposure descriptors designed to better take into account transients and occasional shocks. If either of these alternative descriptors are used, the standard states that they should be reported alongside the energy equivalent *rms* acceleration.

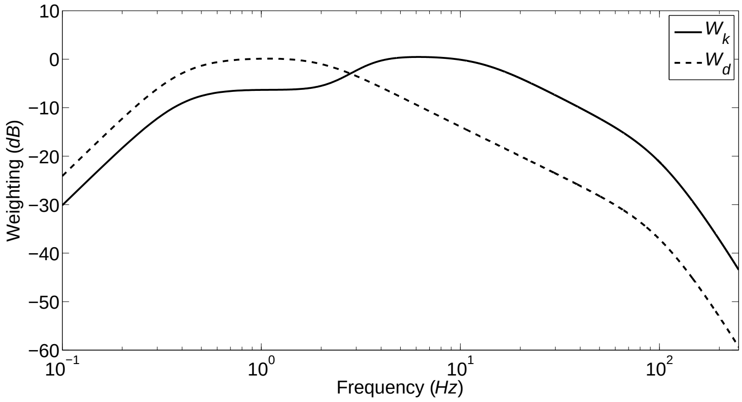

Figure C.1: W_k and W_d frequency weightings expressed in $20log_{10}$(Weighting)

The first of these alternative measures is the maximum transient vibration value (MTVV) that is defined as the maximum of a running *rms* evaluation of $a_w(t)$. The running *rms* is calculated using equation C.3.

$$a_w(t_0) = \sqrt{\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w^2(t)dt} \quad \text{(C.3)}$$

where τ is the integration time constant.

$a_w(t_0)$ is also defined in the standard as an exponential integration, as in equation C.4.

$$a_w(t_0) = \sqrt{\frac{1}{\tau}\int_{-\infty}^{t_0} e^{\frac{t_0-\tau}{\tau}} a_w^2(t)dt} \quad \text{(C.4)}$$

It is recommended in the standard that a value of 1 second is used for the integration constant τ, corresponding to a "slow" integration time constant on most sound level meters. The MTVV is defined as the maximum value of $a_w(t_0)$ over the evaluation period, as defined in equation C.5

$$MTVV = max[a_w(t_0)] \quad \text{(C.5)}$$

The second vibration exposure descriptor proposed by the standard for vibration with crest factors greater than 9 is the vibration dose value (VDV). This method utilises a fourth power integration of the acceleration time history making this descriptor more sensitive to peaks in the vibration signal compared to *rms* averaging. Due to the fourth power integration of acceleration, VDV has the unconventional units of $m/s^{1.75}$. VDV is calculated using equation C.6.

$$VDV = \sqrt[4]{\int_0^T a_w^4(t)dt} \quad \text{(C.6)}$$

Although the standard does not propose specific vibration exposure limits, some guidance is provided in an informative annex to the standard. A table suggesting different degrees of comfort for different ranges of weighted *rms* vibration is provided in this annex. However, these values relate to vibration in public transportation and are therefore unlikely to be applicable for the assessment of railway-induced vibration in residential buildings. On this issue the standard states that *[the] occupants of residential buildings are likely to complain if the vibration magnitudes are only slightly above the perception threshold*. The standard states that fifty percent of alert, fit persons can just detect a W_k weighted vibration with a peak magnitude of 0,015 m/s^2.

ISO 2631–2:2003 provides guidance on the evaluation of human exposure to vibration in buildings. In this standard, vibration in considered in the frequency range 1 Hz to 80 Hz contrary to Part 1 of the standard in which the lower limit for perception, health, and comfort is 0.5 Hz. As with ISO 2631–1:1997, ISO 2361–2:2003 does not provide limits for acceptable magnitudes of vibration exposure.

ISO 2631–2:2003 suggests that the evaluation methods set out in ISO 2631–1:1997 are applied to the vibration in the direction with the greatest magnitude. The main deviation from the methods set out in

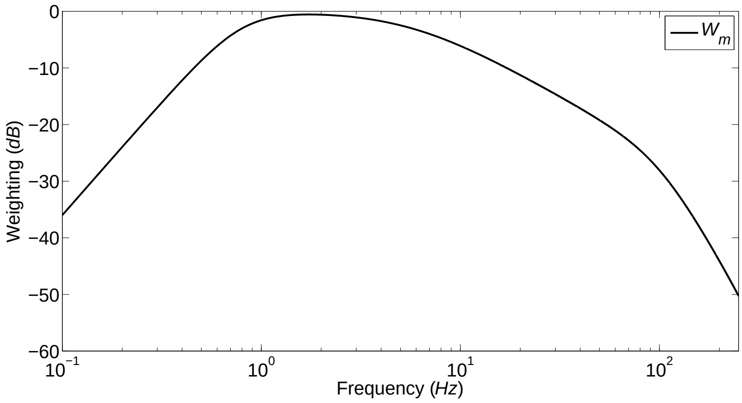

Figure C.2: W_m frequency weighting expressed in $20log_{10}(\text{Weighting})$

ISO 2631–1:1997 is in the use of the W_m frequency weighting. This weighting is an amalgam of the W_g (see section 3.7) and W_d weighting curves and can be applied to vibration measured in any direction. The W_m weighting curve is shown in Figure C.2. It is however stated that the frequency weightings defined in ISO 2631–1:1997 can be used if the posture of the occupant is defined. These weighing functions can be expressed by means of digital filters, the coefficients of which are provided in ISO 8041:2005 [43]. It is recommended that where possible the unweighted vibration time histories are retained to allow for future analysis.

ISO 2631–2:2003 stresses the importance of non-exposure factors to human response to vibration. It is stressed that vibration criteria are likely to be related to *"general expectations and to economic, social and other environmental factors"*. The importance of re-radiated noise, airborne noise, vibration induced rattle, movement of furniture, and visual effects is also stressed in the standard. However, no method is proposed for the evaluation of such effects.

C.3 ISO 14837 series

ISO 14837 is a series of standards relating to groundborne noise and vibration arising from rail systems. ISO 14387–1:2005 [44], Part 1 of this series, was published in 2005 and provides general guidance on the topic. Five additional parts to this standard are under preparation and cover the topics of prediction models, measurement, evaluation criteria, mitigation, and asset management.

For the assessment of groundborne vibration, ISO 14387–1:2005 suggests that vibration should be assessed following the relevant national standard but states that the assessment should be based principally on the overall and running *rms* frequency-weighted acceleration in the three orthogonal directions. The standard states that the raw vibration time history should be retained to allow future analysis. The standard states that except in tall buildings, vertical vibration measurements made in the centre of the floor will sufficiently characterise the vibration exposure.

Some guidance is also provided in this standard regarding the assessment of groundborne noise. It is suggested that groundborne noise is evaluated using the maximum A-weighted sound pressure level with a slow time constant ($L_{AS,max}$) and that the raw time history be retained for the derivation of new descriptors in the future such as the event L_{Aeq} or frequency analysis. It the recommended that these descriptors be evaluated close to the centre of the room.

C.4 DIN 4150 series

One of the most widely used assessment methods across EU member states is the German DIN 4150 series. DIN 4150–1:2001 [45] and DIN 4150–3:1999 [46] provide guidance on predicting vibration parameters and the effects of vibration on structures respectively. Most pertinent to this document is DIN 4150–2:1999 [47] that deals with human exposure to vibration in buildings.

In this standard, vibration is assessed in the frequency range 1 Hz to 80 Hz. From the vibration velocity measured at the location being evaluated, a weighted time history $KB(t)$ is obtained by applying the KB weighting function described by equation C.7. This weighting function is shown in Figure C.3.

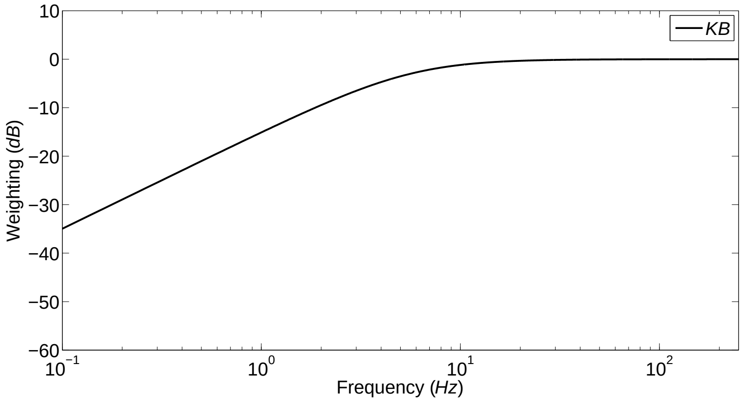

Figure C.3: KB frequency weighting expressed in $20log_{10}(\text{Weighting})$

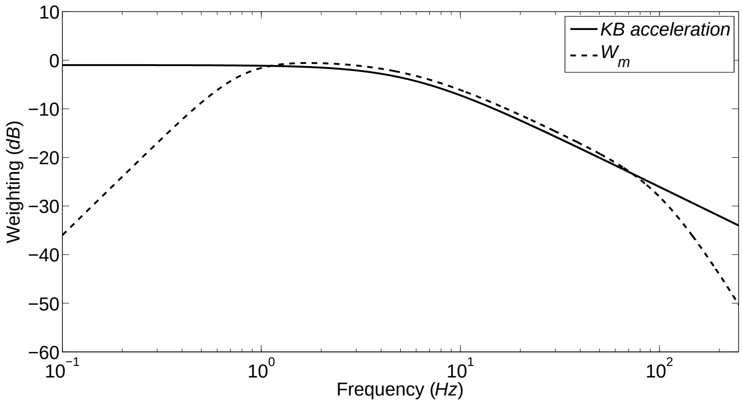

Figure C.4: Comparison of the KB and W_m frequency weightings expressed in $20log_{10}(\text{Weighting})$

$$|H_{KB}(f)| = \frac{1}{\sqrt{1 + (f_0/f)^2}} \tag{C.7}$$

where f_0 is 5.6 Hz and f is the frequency in Hz.

This weighting function is for an unspecified body posture combining elements of the human sensitivity to vibration in the standing and seated positions. If this weighting function were expressed in terms of acceleration, it would be similar above 1 Hz to the W_m weighting function defined in ISO 2631–2:2003. A comparison of the W_m weighting function and the KB weighting function expressed in terms of acceleration is shown in Figure C.4. The running *rms* value of $KB(t)$ is then obtained using equation C.8.

$$KB_T(t) = \sqrt{\frac{1}{\tau}\int_{\xi=0}^{t} e^{\frac{t-\xi}{\tau}} KB^2(\xi)d\xi} \tag{C.8}$$

where the time constant τ is 0,125 s. The 0,125 s time constant is equivalent to the fast time weighting in sound level meters. A number of parameters are then derived from $KB_T(t)$. KB_{Fmax} is defined as the maximum value of $KB_T(t)$ that can be attributed to the vibration source of interest over the evaluation period.

KB_{FTi} is defined as the maximum value of $KB_T(t)$ in each non-overlapping 30-second window. KB_{FTm} is defined as the *rms* value for the KB_{FTi} signal that is obtained using equation C.9.

$$KB_{FTm} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} KB_{FTi}^2} \tag{C.9}$$

where N is the number of non-overlapping 30-second cycles in the evaluation period.

Finally, the vibration severity KB_{FTr} can be calculated using equation C.10.

$$KB_{FTr} = KB_{FTm}\sqrt{\frac{T_e}{T_r}} \tag{C.10}$$

where T_e is the exposure period and T_r is the evaluation period (16 hour day from 6.00 – 22.00 and 8 hour night from 22.00 – 6.00).

If the total exposure period comprises several partial periods $T_{e,j}$ then equation C.11 may be used to obtain KB_{FTr}.

$$KB_{FTr} = \sqrt{\frac{1}{T_r}\sum_j T_{e,j}KB^2_{FTm,j}} \tag{C.11}$$

If vibration exposure occurs during defined rest periods (6.00 – 7.00 and 19.00 – 22.00 Monday – Saturday and 6.00 – 22.00 Sundays and public holidays) then KB_{FTr} is evaluated using equation C.12.

$$KB_{FTr} = \sqrt{\frac{1}{T_r}\sum_j T_{e1}KB^2_{FTm1} + 2T_{e2}KB^2_{FTm2}} \tag{C.12}$$

where T_{e1} is the exposure period outside rest periods, T_{e2} is the exposure period during rest periods and KB_{FTm1} and KB_{FTm2} are the KB_{FTm} values outside and during rest periods respectively.

The KB_{Fmax} and KB_{FTr} parameters can then be compared to a table of criteria for different buildings and different times of day to determine if the requirements of the standard have been met. The criteria for different buildings types are given in Table C.1 and a flow chart for the assessment method is shown in Figure C.5. These two parameters are calculated in three orthogonal directions, and the direction with the highest magnitude is used in the evaluation. The A_u and A_0 categories are action values for the KB_{Fmax} parameter and the A_r category is the action value for KB_{FTr} the parameter.

Specific recommendations are provided in this standard for the evaluation of vibration from railways. The multiplying factor of 2 used in the calculation of KB_{FTr} is removed. If the vibration source is urban surface transportation such as trams and city trains the A_u and A_r values in Table C.1 are multiplied by a factor of 1,5. Special allowances are made for rail traffic allowing the night time A_o value to be exceeded as long as the value is not exceeded frequently. It is however stated that if the KB_{FTi} values during the night exceed 0,6 for surface rail for all building categories and 0,3 for underground rail in the final 3 categories of Table C.1 then the cause should be identified and remedied as swiftly as possible.

Table C.1: Guideline values for evaluating human exposure to vibration as set out in DIN 4150–2:1999

	Day			**Night**		
Location of building	A_u	A_o	A_r	A_u	A_o	A_r
Purely industrial	0,4	6	0,2	0,3	0,6	0,16
Predominantly commercial	0,3	6	0,15	0,2	0,4	0,1
Mixed commercial and residential	0,2	5	0,1	0,15	0,3	0,07
Predominantly or purely residential	0,15	3	0,07	0,1	0,2	0,05
Specially protected areas such as hospitals or health resorts	0,1	3	0,05	0,1	0,15	0,05

C.5 SBR guidelines

There are three guidance documents, published in 1993 and updated in 2002, by the Dutch Stichting Bouwresearch SBR (Foundation for Building Research) on the assessment of vibration. These documents provide guidance on damage [48], nuisance [49], and equipment [50]. The second of these guidance documents, which relates to nuisance, has much in common with the German DIN 4150–2:1999. In the guidelines, vibration is assessed in the frequency range 1 Hz to 80 Hz.

The vibration parameter to be assessed in the guidelines is the dimensionless V_max that is calculated from weighted vibration signals. Acceleration signals are weighted using equation C.13 and velocity signals are weighted using equation C.14

$$|H_a(f)| = \frac{1}{v_0}\frac{1}{2\pi(f_0)}\frac{1}{\sqrt{1+(f_0/f)^2}} \tag{C.13}$$

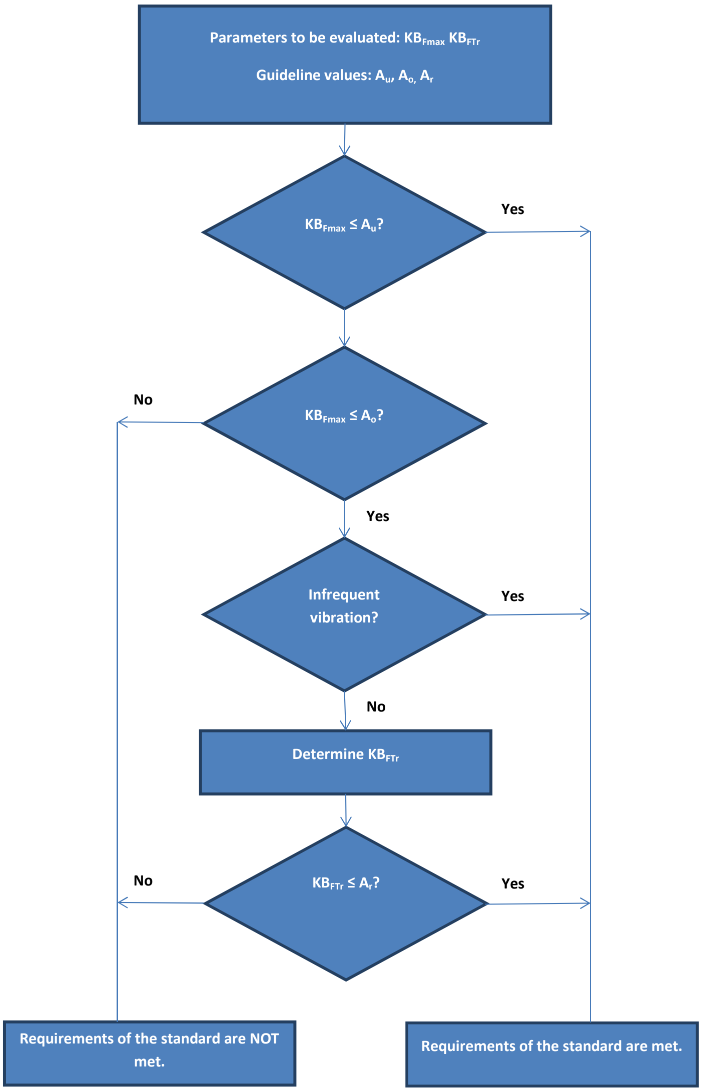

Figure C.5: Evaluation scheme suggested by DIN 4150–2:1999

$$|H_v(f)| = \frac{1}{v_0}\frac{1}{\sqrt{1+(f_0/f)^2}} \tag{C.14}$$

where v_0 is 1 mm/s, f_0 is 5.6 Hz, and f is frequency in Hz. It can be noted that these weighting functions are identical to those given in DIN 4150–2:1999 with the exception of the $1/v0$ factor.

From the weighted vibration signal $v(t)$, the running *rms* value $v_{eff}(t)$ is calculated using equation C.15.

$$V_{eff}(t) = \sqrt{\frac{1}{\tau}\int_0^t g(\xi)v^2(t-\xi)d\xi} \tag{C.15}$$

where $g(\xi) = e^{\frac{-\xi}{\tau}}$ and τ = 0.125 s. Note that this is identical the calculation of $K_{BT}(t)$ in DIN 4150–2:1999 (see equation C.8).

From V_{eff}, $V_{eff,max,30,i}$ is determined as the maximum value in each non-overlapping 30-second interval of V_{eff}. Finally, V_{max} is determined as the maximum value of $V_{eff,max,30,i}$ over the evaluation period. The V_{max} parameter is then compared to the limit values shown in Table C.2 using the following criteria:

- If $V_{max} < A_1$ then nuisance is not expected
- If $V_{max} > A_2$ then nuisance is expected
- If $A_1 < V_{max} < A_2$ then an additional parameter V_{per} is calculated and compared to A_3

V_{per} is an average vibration level based on $V_{eff,max,30,i}$ and is calculated using equation C.16. Annex V of SBR-B provides categories of annoyance for different values of V_{max} as shown in Table C.3.

$$V_{per}(t) = \sqrt{\frac{1}{n}\sum_{i=1}^{n} V^2_{eff,max,30,i}} \tag{C.16}$$

Any value of $V_{eff,max,30,i}$ that is less than 0.1 is set to 0 in this calculation.

Table C.2: Guideline values for evaluating human exposure to vibration as set out in SBR-B

Building categories	Day and evening			Night		
	A_1	A_2	A_3	A_1	A_2	A_3
Healthcare	0,1	0,4	0,05	0,1	0,2	0,05
Residential	0,1	0,4	0,05	0,1	0,2	0,05
Office and education	0,15	0,6	0,07	0,15	0,6	0,07
Meeting places	0,15	0,6	0,07	0,15	0,6	0,07
Critical working area	0,1	0,1	-	0,1	0,1	-

Table C.3: Categories of annoyance for different levels of v_{max} as set out in SBR-B

V_{max}	Level of annoyance
$<$ 0,1	Not annoyed
0,1 – 0,2	A little annoyed
0,2 – 0,8	Moderately annoyed
0,8 – 3,2	Annoyed
$>$ 3,2	Significantly annoyed

C.6 NS 8176:2005

Norwegian standard NS 8176:2005 [51] suggests the use of the statistical maximum weighted acceleration or velocity level ($a_{w,95}$ or $v_{w,95}$). These descriptors are calculated from 1-second *rms* averages (linear or exponentially weighted, see equation C.3 or C.4) of W_m weighted acceleration or velocity signals. These descriptors are calculated using equation C.17 and C.18.

$$v_{w,95} = \overline{v_{w,max}} + 1.8\sigma_v \tag{C.17}$$

$$a_{w,95} = \overline{a_{w,max}} + 1.8\sigma_a \tag{C.18}$$

where $v_{w,max}$ and $a_{w,max}$ are the maximum 1-second average weighted velocity or acceleration level over a single train passby. $\overline{v_{w,max}}$ and $\overline{a_{w,max}}$ are the mean value of the maximum weighted velocity and acceleration respectively for all train passbys in the evaluation period. σ_v and σ_a are the standard deviation of the maximum weighted velocity or acceleration for all train passbys in the evaluation period.

The standard provides four classes of comfort for dwellings with respect to vibration exposure expressed in $v_{w,95}$ and $a_{w,95}$ (see Table C.4). These four classes are based upon the results of a socio-vibration survey that was conducted in Norway in 1998. It is interesting to note that these are the only European vibration criteria that are based on the findings of experimental field data. In a Class A dwelling it is expected that occupants will not notice vibration; in a Class B dwelling it is expected that occupants be disturbed to some extent by vibration; it is expected that 15% of occupants of Class C dwellings be disturbed by vibration; it is expected that 25% of occupants of a Class D dwelling by disturbed by vibration.

Table C.4: Guidance classification of dwellings with the upper limits for the statistical maximum value for weighted velocity $v_{w,95}$ or acceleration $a_{w,95}$

Type of vibration value	Class A	Class B	Class C	Class D
Statistical maximum value for weighted velocity $v_{w,95}$ (mm/s)	0,1	0,15	0,3	0,6
Statistical maximum value for weighted acceleration $a_{w,95}$ (mm/s^2)	3,6	5,4	11	21

C.7 BS 6472 series

The BS 6472 series of standards provides guidance in the United Kingdom on the measurement and assessment of vibration in buildings in the frequency range 0.5 Hz to 80 Hz. The standard is in two parts that relate respectively to vibration in buildings [37] and blast induced vibration [52]. Part 1 of this series of standards, BS 6472–1:2008, is of particular interest to this document.

The descriptor used to evaluate vibration in this standard is the vibration dose value (VDV). This descriptor is calculated from a frequency-weighted acceleration time history using the same procedure described in ISO 2631–1:1997 (see equation C.6). The standard recommends the use of the W_b frequency weighting for vibration in the vertical direction and the W_d frequency weighting for vibration in the horizontal direction. Prior to the 2008 revision of the standard, the W_g frequency weighting was recommended for vibration in the vertical direction. The W_b frequency weighting is shown in Figure C.6 and the W_g frequency weighting is shown in Figure C.7. Mathematical representations of these weighting filters in the Laplace domain are provided in BS 6841:1987 [53].

The frequency weightings recommended in BS 6472–1:2008 differ from what is currently recommended by ISO 2631–1:1997, ISO 2631–2:2003, and other European national standards. Contrary to ISO 2631–1:1997, the coordinate system used to define the direction of vibration is centred with respect to the earth rather than the position of subject who is exposed to the vibration.

BS 6472–1:2008 provides a table giving the probability of adverse comment for five categories of VDV. However, the meanings of adverse comment and the source of the different probabilities are not given in the standard. It is stated that below the ranges presented in the table that *”adverse comment is not expected”* and above the ranges presented in table that *”adverse comment is very likely”*.

Table C.5: Probability of adverse comment for different categories of VDV as given in BS 6472–1:2008

Place and time	Low probability of adverse comment	Adverse comment possible	Adverse comment probable
Residential buildings 16hr day	0,2–0,4	0,4–0,8	0,8–1,6
Residential buildings 8hr night	0,1–0,2	0,2–0,4	0,4–0,8

An empirical relationship to convert *rms* acceleration to estimated $VDV (eVDV)$ is provided in an informative annex to the standard. This relationship is given in equation C.19. It is noted in the standard that this relationship will overpredict the true VDV for vibration with crest factors lower than 3 and underpredict the true VDV for vibration with crest factors greater than 6.

$$eVDV = 1.4 a_w t^{0.25} \tag{C.19}$$

where a_w is the weighted *rms* acceleration and t is the duration of the evaluation period in seconds.

C.8 ÖNORM S 9012:2010

The Austrian standard ÖNORM S 9012:2010 provides guidance on the evaluation of vibration and structure-borne noise emission from railways and road traffic [54]. In this standard, vibration is assessed in the frequency range 1 Hz to 80 Hz. Two vibration exposure descriptors are recommended in this standards, the maximum 1-second running exponentially weighted *rms* acceleration and an energy equivalent *rms* acceleration. The use of the W_m frequency weighting is recommended.

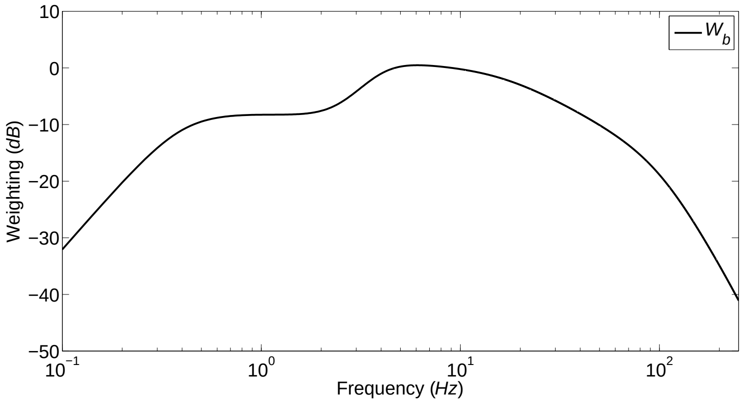

Figure C.6: W_b frequency weighting expressed in $20log_{10}($Weighting$)$

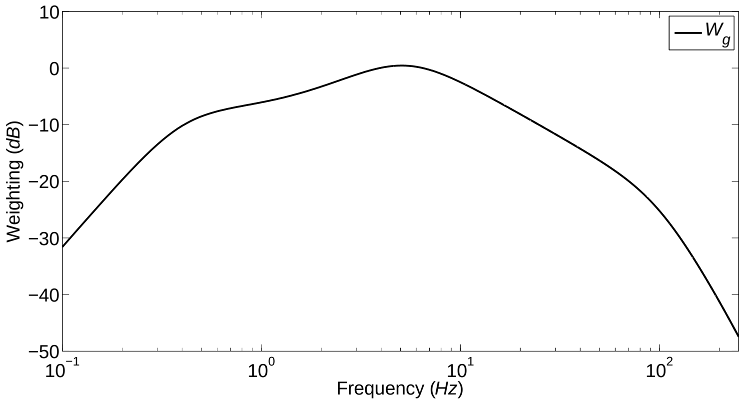

Figure C.7: W_g frequency weighting expressed in $20log_{10}($Weighting$)$

C.9 SS 460 38 61:1992

The Swedish standard SS 460 48 61:1992 provides guidelines for the measurement and evaluation of vibration and shock in buildings [55]. In this standard, vibration is assessed in the frequency range 1 Hz to 80 Hz. It is recommended that vibration be assessed using the maximum 1-second running exponentially weighted *rms* acceleration or velocity expressed in decibels re $10^{-6}m/s^2$ for acceleration and $10^{-9}m/s$ for velocity. This standard provides expected levels of disturbance for two ranges of vibration exposure that are shown in Table C.9.

Table C.6: Levels of disturbance for different ranges of vibration as given in SS 460 38 61:1992

	Velocity	Acceleration
Moderate disturbance[1]	0,4 - 1,0 mm/s	14.4 - 36,0 mm/s^2
Probable disturbance[2]	$>$ 1 mm/s	$>$ 36 mm/s^2

[1] Translated from the Swedish ”Måttlig störning”
[2] Translated from the Swedish ”Sannolik störning”

C.10 FTA and FRA guidelines

In the USA, guidance is available for predicting and assessing the noise and vibration impacts of mass transit projects [56] and high speed railway [57]. The descriptor used for basic vibration assessments in guidelines is maximum running 1-second *rms* velocity expressed in decibels re 1x10^{-6} inches/second (VdB). No frequency weighting is used in this evaluation method. Vibration impact criteria for residential buildings are provided for frequent events ($>$ 70 per day) at 72 VdB, occasional events (between 30 and 70 per day) at 75 VdB, and infrequent events ($<$ 30 per day) at 80 VdB. For detailed vibration assessments, it is recommended that the running 1-second *rms* velocity is evaluated in 1/3 octave bands and compared to receiver specific curves in the guidelines.

The importance of the secondary effects of vibration are acknowledged in this document that states *"[o]ther phenomena such as ground-borne noise, rattling, visual effects such as movement of hanging objects, and time of day (e.g., late at night) all play some role in the response of individuals."* The guidelines also address the assessment of groundborne noise. It is stated that the A-weighted level of groundborne noise can be estimated in a room with average acoustic absorption by applying A-weighting to the measured vibration velocity of the floor. Groundborne noise is assessed using the maximum running 1-second *rms* A-weighted sound pressure level. Groundborne noise impact criteria for residential buildings are provided for frequent events ($>$ 70 per day) at 35 $dB(A)$, occasional events (between 30 and 70 per day) at 38 $dB(A)$, and infrequent events ($<$ 30 per day) at 43 $dB(A)$.

D Annoyance

Annoyance is a concept that is used widely for the evaluation of the negative impact an environmental stressor has on a population. It is a broad concept that describes the negative evaluation of environmental conditions and may encompass activity disturbance, emotional responses, and attitudinal responses towards the source of annoyance. Guski [58] identifies annoyance as being associated with disturbance, aggravation, dissatisfaction, concern, bother, displeasure, harassment, irritation, nuisance, vexation, exasperation, discomfort, uneasiness, distress, and hate. It is currently the stance of the World Health Organisation that noise annoyance should be considered as an environmental health burden [59]. Despite lacking a theoretical underpinning, annoyance is widely used in environmental noise policy such as the EU endorsed exposure-response relationships for annoyance caused by transportation noise [60].

This section aims to give an overview of the tools and methods that are currently available to assess annoyance due to railway-induced vibration in residential environments. Firstly, approaches to measuring annoyance and vibration exposure are discussed. Following this a discussion of the various descriptors that can be derived from the data collected using these tools is provided. Finally, synthesis curves based on a meta-analysis of data from previous socio-vibration field surveys are presented along with a discussion of their potential application and limitations.

D.1 Measurement of response

The measurement of annoyance via socio-acoustic surveys is standardised in ISO/TS 15666:2003 [61]. The development of this standard was heavily influenced by the work of Team 6 of the International Commission on the Biological Effects of Noise (ICBEN) [62, 63]. This standard provides specifications recommendations on: questions to be asked in surveys investigating the effects of noise, response scales, aspects of conducting socio-acoustical surveys, and recommendations on the reporting of results.

A rationale for the wording of questions and the semantic labelling of scales is provided in an annex to the standard. No guidance is provided with regards to sampling procedures and analysis of data. It is recommended that two questions along with two rating scales are used in the measurement of noise annoyance. The first recommended question is posed as follows:

"Thinking about the last (12 months or so), when you are here at home, how much does noise from (noise source) bother, disturb or annoy you?"

The second recommended question is introduced as:

"This uses a 0-to-10 opinion scale for how much (source) noise bothers, disturbs or annoys you when you are here at home. If you are not at all annoyed choose 0; if you are extremely annoyed choose 10; if you are somewhere in between, choose a number between 0 and 10."

and the following question is posed:

"Thinking about the last (12 months or so), what number from 0 to 10 best shows how much bothered, disturbed or annoyed by (source) noise?"

Although the overall aim of the measurement of annoyance due to environmental vibration is similar to the measurement of annoyance due to environmental noise, there are some significant differences to be taken into account in the measurement approach. Environmental vibration may be perceived kinesthetically via forces and movements within the body, viscerally through receptors in the abdomen, tactilely through mechanoreceptors in the skin, visually through the relative change of the position of objects, and aurally through re-radiated noise and vibration-induced rattle. Coupled with the fact that people may be less adept at talking about experiencing vibration than they are about the perception of sound, the choice of wording for a question to measure self-reported vibration is not a trivial matter.

The only formal guidance available for the assessment of annoyance caused by vibration in residential environments comes in the form of the Nordtest method [64]. This guidance provides two questions that can be used to measure annoyance using two response scales. The first question, recorded using a four-point semantic scale, is as follows:

"When you think about the last 12 months or so, how do you consider tremors or vibrations from (source) when indoors: highly annoying, moderately annoying, a little annoying, not annoying or do you not notice vibrations at all?"

An optional neutral filter question is provided in this method to determine if the respondent is able to notice vibration when indoors. If this filter question is used, those respondents able to feel vibration are asked the following:

"When you think about the last 12 months or so, do you consider these tremors or vibrations: highly annoying, moderately annoying, a little annoying, or not annoying?"

An optional second question for the measurement of annoyance on an eleven-point numerical scale is provided as follows:

"When you think about the last 12 months or so when indoors, how would you rate your annoyance with tremors or vibrations from (source)? Pick a number from 0 to 10 where 0 denotes not noticeable and 10 denotes extremely annoyed."

Table D.1 shows the wordings of the questions used to measure annoyance in a number of socio-vibration surveys. There are some significant differences in the wording of this question between different studies that mainly stem from whether secondary effects of vibration such as rattling and groundborne noise are taken into account in the question.

Table D.1: Wording of annoyance questions used in previous socio-vibration surveys

Study	Wording of routing question	Wording of annoyance question	Response scale
Germany [65]	N/A	How annoyed do you feel by vibration caused by the railway?	11-point numerical scale
Norway [66]	Can you notice shaking or vibration caused by the railway?	Is the shaking/these vibrations highly annoying, somewhat annoying, a little annoying or not annoying for you?	4-point semantic scale
Japan [67]	N/A	How do you rate vibration of the house caused by passage of the Shinkansen?	5-point semantic scale
USA & Canada [68]	Do you notice low rumbling sounds inside your home when subway trains pass by?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by low rumbling sounds inside your home when trains pass by?	5-point semantic scale
	Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when subway trains pass by?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by rattling sounds in your home when trains pass by?	
	Do you ever feel your home shake or the floors, walls, counters, or furniture vibrate when subway trains pass by?	Would you say that you are not at all, slightly, moderately, very or extremely annoyed by shaking or vibrations in your home when trains pass by?	
United Kingdom [**?**]	Thinking about the last 12 months or so, when indoors at home, have you felt any vibration or shaking anywhere that you think was caused by the railway, including passenger trains, freight trains, track maintenance or any other activity from the railway.	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?	5-point category scale + Dont notice category
	Thinking about the last 12 months or so, when indoors at home, have you heard or seen things rattle, vibrate or shake that you think was caused by the railway, including passenger trains, freight trains, track maintenance or any other activity from the railway	Thinking about the last 12 months or so, when indoors at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by feeling vibration or shaking or hearing or seeing things rattle, vibrate or shake caused by the railway?	11-point numerical scale + Dont notice category
Sweden [69–71]	N/A	Thinking about the last 12 months or so, when you are here at home, how much does vibration from the railway annoy or disturb you?	6-point category scale 11-point numerical scale
Netherlands and Poland [72]	N/A	Thinking about the last 12 months or so, when at home, what number from 0 to 10 best shows how bothered, annoyed or disturbed you have been by vibration from specific railway sources mentioned below? {*passenger trains; freight trains; maintenance; other*}	11-point numerical scale + Dont notice category

Table D.1 also indicates the different scales that were used to record the response to the annoyance questions. The guidelines set out by ICBEN and ISO/TS 15666:2003 for the measurement of annoyance due to environmental noise state that response scales to measure noise annoyance should:

- Be clear and comprehensible for the respondent to provide a valid rating of annoyance.
- Allow exploration of any combined effect of vibration and noise on annoyance.
- Yield an interval-level measurement scale (i.e. the response scale answers are equally spaced meeting the assumptions for analysis techniques).
- Yield data suitable for analysing exposure-response relationships with objective vibration and noise measurements.
- Permit consistency throughout the questionnaire for ease of administration and comprehension for interviewers, respondents, policy makers and report readers.
- Adhere to current best practice in the research field.

Don't notice		Not at all	Slightly	Moderately	Very	Extremely
		1	2	3	4	5

Figure D.1: Five point semantic response scale for recording responses for annoyance due to vibration

Don't notice		Not at all										Extremely
		0	1	2	3	4	5	6	7	8	9	10

Figure D.2: Eleven point numerical response scale for recording responses for annoyance due to vibration

- Permit valid international comparisons of survey results between languages.
- Be recognised at an international level as world leading research on vibration and noise in residential environments.

Based upon these criteria, it is recommended in ISO/TS 15666:2003 that annoyance responses are measured using two different scales: a five-point semantic scale labelled Not at all; Slightly; Moderately; Very; Extremely and an eleven-point numerical scale labelled ”Not at all” at the 0 end of the scale and ”Extremely” at the 10 end of the scale. Similar guidance is provided in the Nordtest method [64] that also suggests that annoyance be measured on both a five-point semantic and eleven-point numerical scale. The scales recommended in the Nordtest method differ from the scales recommended in ISO/TS 15666:2003 in the use of the lower anchoring points of ”Does not notice” and ”Not at all” respectively.

For consistency with environmental noise surveys, it is recommended that socio-vibration surveys should adopt the annoyance response scales recommended in ISO/TS 15666:2003 with an additional category of ”Don't notice”. This approach has been adopted in the questionnaires used in the socio-vibration surveys conducted in the United Kingdom, the Netherlands, and Poland. An example of these response scales taken from the socio-vibration survey conducted in the United Kingdom are shown in Figure D.1 and Figure D.2. If postal questionnaires are being used, the presentation of the scales such as the placement of anchoring labels should be carefully considered so as not to influence responses.

There is strong evidence of a synergistic effect between vibration and noise (for example [71]). Therefore, where possible responses should be collected for annoyance due to airborne noise, groundborne noise, and vibration induced rattle using the procedures set out in ISO/TS 15666:2003.

There is evidence that the response to vibration is dependant upon the vibration source [73]. It is therefore recommended that where possible annoyance responses to different sources of railway vibration (for example, passenger trains, freight trains, and maintenance) are collected.

In the guidance provided in the Nordtest method, as well as in the reports of a number of the socio-vibration surveys that have been conducted (for example [66, 72, 73]), the importance of measuring non-exposure factors is highlighted. Non-exposure factors are attitudinal, situational, and socio-demographic factors that may have an influence on the annoyance response. Section F of this document discusses which of these factors have been found to have an influence on the annoyance response to vibration from railways in residential environments. Where possible, responses should be collected for factors such as noise sensitivity, concern of damage, fear of the vibration source, expectations regarding future vibration levels, type of area, visibility of the vibration source, the perceived necessity of the source, and tenure type. This list is not exhaustive and careful thought should be given as to which non-exposure factors are of interest when designing a social survey.

D.2 Measurement of exposure

In the various socio-vibration surveys that have been conducted, different approaches have been adopted to estimate vibration exposure. The survey conducted in Norway used a semi-empirical model that relied on a number of assumptions regarding the statistical properties of vibration from railway activities [74]. The survey in the USA and Canada relied on a small number of long term measurements coupled with attenuation relationships determined through array measurements to propagate the vibration exposure to different distances from the railway [68]. In the survey conducted in Japan [67] vibration measurements were conducted at different distances from the track to determine attenuation relationships for the different survey sites. The survey conducted in the United Kingdom relied on long term external (24-hour) measurements at reference positions and short term internal (30 minute) measurements of railway vibration to estimate vibration exposure at the mid-point of a room in the residence of interest [73]. In the socio-vibration surveys conducted in the Netherlands and Poland [72], measurements were taken at the foundation and floors in reference houses over a period of eight days along with array measurements to estimate distance attenuation relationships for each site.

Although there are differences in the methods used to measure vibration in the various socio-vibration surveys that have been conducted, the common aim of all of these methods is to evaluate the human exposure to railway-induced vibration over a defined period. Every method for the quantification of vibration exposure has inherent uncertainties that should be borne in mind when designing a method to quantify vibration exposure. Whichever method is used, the uncertainties associated with the measurement procedure should be quantified and reported. A procedure for the assessment and quantification of measurement uncertainties is available in [75].

The equipment used in the measurement of vibration should conform to ISO 8041:2005 and it must be ensured that the entire measurement chain has sufficient dynamic range and bandwidth to evaluate human response. The standards outlined in section C cite the frequency range for whole body vibration as 0,5 or 1 Hz to 80 Hz; in practice this means data should be acquired at a sampling rate of at least 200 Hz. If vibration measurements are being used to indirectly evaluate groundborne noise, this frequency range should be extended accordingly. The measurement system should be capable of measuring well below the threshold of human perception and up to around 10 m/s^2 to prevent overloads. Considering the wide dynamic range required, 24- or 32- bit digitisation is preferable to avoid the manual setting of dynamic ranges as this is a common source of operator error.

In the standards and guidelines outlined in section C, it is often recommended that vibration exposure be assessed near the centre of the room at which the greatest magnitude of vibration is expected or reported by the resident in three orthogonal directions. Accelerometers should be mounted in such a way as to ensure a faithful coupling to the measurement surface. If measurements of vibration in a dwelling are being conducted, potential mounting resonances between transducers and resilient floor coverings should be addressed. If measurements must be made on surfaces such as carpets, accelerometers should be mounted on a heavy plate or using spikes that are able to pierce the carpet to provide good coupling with the floor. The influence of the human load should be borne in mind if measurements are being taken on lightweight floors.

Groundborne noise can be assessed either directly though measurement or indirectly through measurements of vibration on the floor or walls. If measured directly, sound level meters should conform to Type 1 of IEC 6172–1:2002 [76]. Methods for estimating groundborne noise from measurements of floor and wall vibration are given in [56].

D.3 Response metrics

Although the measurement of annoyance due to environmental noise is standardised there is no standardisation regarding the analysis of data collected using this method. Through the history of field studies into the community response to environmental noise, expressing annoyance as a percentile based metric such as Percent Highly Annoyed ($\%HA$), Percent Annoyed ($\%A$), or Percent Slightly Annoyed ($\%SA$) has emerged as a de facto standard. This convention has also been adopted in field studies investigating the community response to vibration.

The $\%HA$, $\%A$, and $\%SA$ metrics describe the proportion of respondents to a socio-acoustic survey in a given band of noise exposure expressing annoyance in the upper 28%, the upper 50%, and the upper 72% of the annoyance response scale respectively. A major advantage of percentile based metrics to describe community response is the ease of interpretability, especially from a policy and public engagement perspective. The use of these metrics to express community annoyance is recommended in the EU position paper on dose response relationships between transportation noise and annoyance [60].

D.4 Exposure descriptors

In the standards outlined in section C , there are four types of vibration exposure descriptor that are recommended for the evaluation of human response. A maximum running *rms* is recommended in the DIN, SBR, ISO, Önorm, SS, and FTA/FRA guidelines. An equivalent energy *rms* is recommended in the ISO, BS, Önorm, DIN, and SBR guidelines. A cumulative vibration dose value is recommended in the ISO and BS guidelines. A statistical maximum running *rms* is recommended in the NS guidelines. Additionally, different frequency weightings are recommended across the different standards. BS 6472–1:2008 recommends the W_b and W_d weightings, ISO 2631–1:1997 recommend the W_k and W_d weightings, most other standards recommend either the KB or W_m weightings.

In the various socio-vibration surveys that are reported in the literature, a variety of vibration exposure descriptors have been used as the dependent variable for the resulting exposure-response relationship. Table D.2 gives an overview of the various vibration exposure descriptors used. The descriptors used in the studies all have some similarity to the descriptors recommended in ISO 2631–1:1997 and DIN 4150–2:1999 with the exception of the Norwegian statistical descriptors.

Table D.2: Vibration exposure descriptors used in previous socio-vibration surveys

Study	Descriptor	Unit	Time weighting	Frequency weighting	Direction
Germany [65]	KB $VCKBL25$	–	0.125 s	KB	Vertical
Norway [66]	$v_{w,95}$	mm/s	1 s	NS 8176/W_m	Vertical
Japan [67]	$L_{v,max}$	dB re $10^{-5} m/s^2$	0.63 s	JIS C1510	Vertical
USA & Canada [68]	Passby maximum velocity	dB re 1 $\mu inch/s$	1 s	–	Vertical
United Kingdom [73]	Passby RMS	m/s^2	–	W_k and W_d	Vertical/Horizontal
	24 hour *VDV*	$m/s^{1.75}$		W_b and W_d	
Sweden [69–71]	Maximum velocity	mm/s	1 s	SS 460 48 61/W_m	Vertical
Netherlands and Poland [72]	$V_{dir,max}$	–	0.125 s	W_k and W_d	Vertical/Horizontal

D.5 Current evidence and relationships

D.5.1 Vibration exposure-response synthesis curve

In the past two decades, socio-vibration surveys have been conducted in Germany [65], Norway [66, 74, 77], Japan [67], the USA and Canada [68], the United Kingdom [73, 78], and Sweden [69–71]. Through the CargoVibes project, the Netherlands Organisation for Applied Scientific Research (TNO) have gathered the original data from these surveys along with two new surveys conducted in the Netherlands and Poland [72] with the aim of deriving meta-analytic exposure-response curves for annoyance due to railway-induced vibration. This resulted in a dataset of 4490 responses and associated vibration exposure estimates.

Where possible, the vibration exposure data from these studies were converted to three common vibration exposure descriptors by means of a conversion matrix. Details of the method used to convert the descriptors is given in [72]. The three vibration exposure descriptors were: $V_{dir,max}$, weighted *rms* acceleration, and *VDV*. The frequency weightings used for each of these descriptors were the W_k and W_d weightings as defined in ISO 2631–1:1997 for the vertical and horizontal direction respectively. $V_{dir,max}$ is defined as the maximum running *rms* velocity over the entire evaluation period. The running *rms* is exponentially weighted with a time constant of 0.125 seconds. The frequency-weighted *rms* acceleration and the *VDV* are calculated as set out in ISO 2631–1:1997 (see section C.2) over the entire evaluation period.

As there were differences between the scales used in the different studies, the annoyance responses in the combined dataset were translated to a scale ranging from 0 to 100. This translation was conducted based on the assumption that the categories used for each of the different annoyance response scales divide the range 0 to 100 into equally spaced intervals. For scales that used "Do not notice" as the lower anchoring

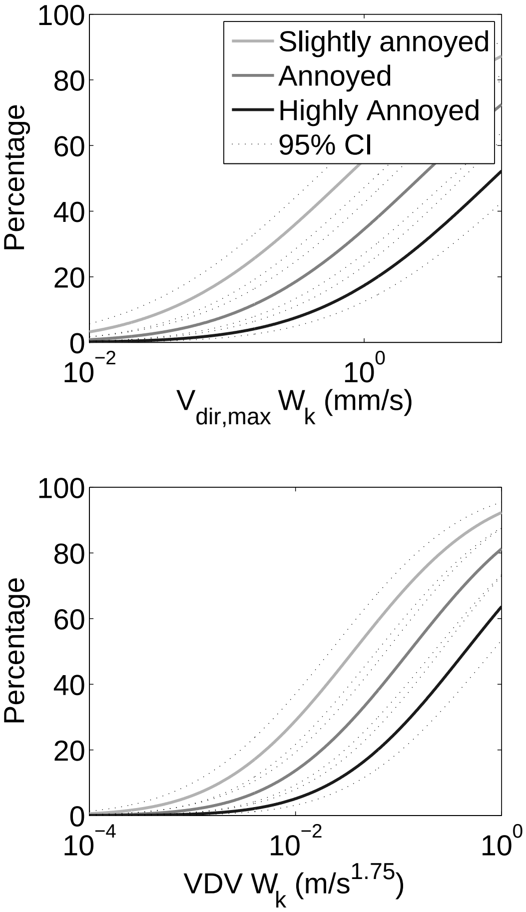

Figure D.3: Meta-analytic exposure-response relationships for community annoyance due to railway-induced vibration (N = 4129)

point, respondents stating that they did not notice vibration were recoded to the lowest annoyance category. Comparison of the annoyance responses between the different socio-vibration studies revealed that, for the same level of $V_{dir,max}$, the Japanese study had a much higher annoyance response than the other studies in the dataset. This may be due to the focus of that study being on high speed rail. Hence, the data from the Japanese study was excluded from the meta-analysis.

Exposure-response curves were derived from these data using the same model that was used to derived the EU endorsed exposure-response curves for annoyance due to transportation noise [79]. The model takes into account the entire distribution of annoyance responses and both inter- and intra-study variation allowing any percentile based annoyance metric to be expressed. Figure D.3 shows the exposure-response curves calculated for each of three vibration exposure descriptors. For each vibration exposure descriptor, relationships have been calculated in terms of three response metrics: Percent Highly Annoyed ($\%HA$) describing the proportion of respondents expressing annoyance in the upper 28% of the response scale, Percent Annoyed ($\%A$) describing the proportion of respondents expressing annoyance in the upper 50% of the response scale, and Percent Slightly Annoyed ($\%SA$) describing the proportion of respondents expressing annoyance in the upper 72% of the response scale. Each of the curves are shown in their 95% confidence intervals (dashed lines in Figure D.3). Each of the descriptors were found to account for a similar proportion on the variance in the exposure-response models.

D.5.2 Groundborne noise

There is very little literature available on the relationship between groundborne noise from railways and annoyance. In a survey of environmental noise and vibration induced by London Underground train operations [80], it was estimated that around 56,000 residences in London were subject to groundborne noise

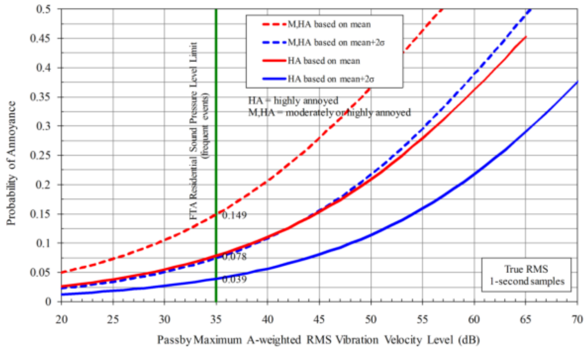

Figure D.4: Exposure-response relationship between annoyance and railway-induced groundborne noise produced by the socio-vibration survey conducted in the USA and Canada (source [68])

levels of over $L_{AS,max}$ 40 *dB(A)*. In 1996, complimentary laboratory and field studies were carried out to investigate human response to groundborne noise [81, 82]. From the field study reported in [81] it was concluded that at groundborne noise levels below $L_{AF,max}$ 32 *dB(A)* residents are not bothered by noise or vibration, at levels between 32 and 42 *dB(A)* some residents were bothered by noise but none by vibration, and at levels above 42 *dB(A)* all residents were bothered by both noise and vibration with vibration deemed to be the most annoying factor. In a complementary laboratory study [81], it was found that annoyance due to groundborne noise was related to frequency content, level of the noise, and background noise levels. A study conducted in Norway [83] found that noise annoyance and self-reported sleep disturbance were significantly related to groundborne noise levels.

The socio-vibration survey conducted in the USA and Canada [68] collected responses on annoyance due to groundborne noise along with estimations of internal groundborne noise exposure. The exposure-response relationship resulting from these data is shown in Figure D.4.

D.5.3 Vibration induced rattle

There have been a limited number of studies investigating the human response to vibration-induced rattle. Two related field studies [84, 85] investigated the relationship between low-frequency aircraft noise and annoyance due to rattle and vibration. In this study, questionnaires were conducted with 495 residents living close to an airport runway. Residents were asked about general noise annoyance and annoyance due to vibration induced rattle. One of the outcomes of this study was a relationship between annoyance due to vibration induced rattle and a measure of low frequency sound exposure. Although no concrete conclusions were drawn in this study, it was suggested that this relationship could complement the interpretation of the exposure-response relationships for aircraft noise in situations with low flying aircraft or ground noise from aircraft. It is suggested that high levels of annoyance may be explained in part by vibration induced rattling of elements such as window frames and household objects such as crockery.

In the field surveys conducted in the Netherlands and Poland [72] under the CargoVibes project, respondents to the social survey were asked *"Thinking about the last 12 months or so, when at home, did you notice any of the objects mentioned below rattling, vibrating or shaking due to vibration from railway?"* The response to this question was recorded as a binary Yes/No response for doors, windows, crockery, and any other objects. In a stepwise regression to investigate the influence of various different factors on annoyance due to vibration exposure, vibration induced rattle was found to have a significant contribution to the annoyance response even largely mediating the effect of vibration exposure.

In the socio-vibration survey conducted in the USA and Canada [68], respondents were asked *"Do you ever hear rattling sounds from windows, doors, wall hangings, or other items in your home when [region specific] trains pass by?"* The following narrative account of the data collected through this question is provided in the report:

"Rattling sounds in their homes when trains passed by were reported by 14.2% of all respondents. Those who reported hearing rattling sounds were asked how often they heard rattling: 17.4% reported hearing rattle about once a week, 19.3% reported hearing rattle about once a day, 34.2% reported hearing rattle several times a day, and 29.2% reported hearing rattle many times a day."

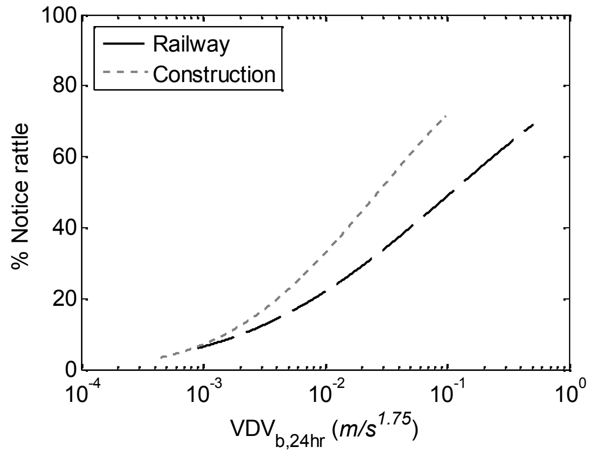

Figure D.5: Proportion of respondents reporting hearing or seeing objects and structures rattle for a given vibration exposure in the UK study [73] from railway sources (N = 752) and construction sources (N = 321) (source: [4])

A socio-vibration survey conducted in the United Kingdom [73] included a question that asked the respondent *"Have you personally ever heard or seen any rattling, vibrating or shaking of: {The windows; The doors; Any other part of the home; Crockery, like plates, or glasses in your cupboards; Any other objects in this home}"*. This question was recorded as a binary Yes/No response for each of the rattling sources. Figure D.5 shows the proportion of respondents stating that they noticed vibration from any of the elements of their home asked about for a given vibration exposure from railway and construction sources [4].

D.5.4 Combined noise and vibration

Perceptible vibration is rarely unaccompanied by noise. The synergistic effects of vibration and noise is a relatively unexplored area. There is however a consensus in the published literature that noise influences the response to vibration and vice versa. Much of the work in this area has been conducted via laboratory studies due partly to the difficulties in studying the effect of different combinations of noise and vibration in the field.

In a laboratory study to investigate the subjective response to combined noise and vibration exposure [86], subjects were presented with simulations of railway-induced noise and vibration. Six magnitudes of vibration and noise were considered. The study was split into three sessions in which subjects were presented with every possible combination of the noise and vibration stimuli. In the first session, subjects were asked to rate annoyance caused by vibration. In the second session, subjects were asked to rate annoyance caused by noise. In the third session, subjects were asked to rate annoyance cause by combined noise and vibration. The magnitude of noise exposure was found to have a significant effect on the on the judgement of annoyance caused by vibration. No significant effect of vibration exposure was found on the judgement of annoyance caused by exposure to noise. From the results of the third session, relationships were developed between annoyance and combined vibration and noise exposure.

In a similar study, that aimed to investigate the combined effects of noise and vibration [87], four magnitudes of vibration and noise were presented to subjects in every possible combination, and subjects were asked to make a judgment on perceived intensity and annoyance. The phrasing of the questions posed to subjects was found to have a strong influence on the annoyance annoyance response. It was found that if subjects were asked to judge annoyance caused by vibration, then their annoyance judgments for a given vibration exposure were largely independent of the magnitude of the noise exposure. However, it was found that if subjects were explicitly asked about annoyance due to noise exposure, the magnitude of vibration exposure had an influence on their annoyance ratings. Relationships were developed between annoyance and combined noise and vibration exposure. The gradient of the vibration exposure term in the relationship was found to be shallower that that reported in [86].

In a study conducted into the relative contribution of noise and vibration to comfort in diesel engine cars running at idle [88], three perceptual tests were conducted using sound and vibration measured in a car

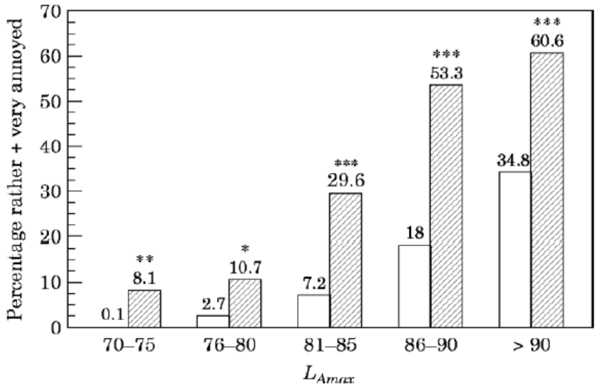

Figure D.6: Percentage of respondents expressing high annoyance to noise in areas with weak (white bars) and strong (shaded bars) vibration (Source [69])

as stimuli. In the first test, subjects were required to judge the noise comfort and were exposed to only the sound stimuli. In the second test, subjects were required to judge the noise comfort and were exposed to the noise and vibration stimuli. In the third test, subjects were required to judge the overall comfort and were exposed to the sound and vibration stimuli. From the results of the first two tests, it was concluded that vibration has a small but significant influence on noise perception. The results of the third test suggested two groups of subjects, the first group basing their responses only on vibration and the second group basing their responses on both sound and vibration.

A field survey was carried out in Sweden to investigate the effects of exposure to noise and vibration from railway traffic [69, 70]. One of the aims of this study was to compare annoyance due to noise in the presence of strong vibration levels with annoyance due to noise alone. In this study, areas were defined as having strong vibration if the vibration caused by railway traffic exceeded 2 mm/s and weak vibration if the vibration was less than 1 mm/s. Vibration exposure was weighted according to Swedish standard SS 460 48 61. It was found that in areas with strong vibration, annoyance was greater than in areas with weak vibration for the same noise exposure. This finding is illustrated in Figure D.6. It is suggested that, in order for annoyance to be equal, noise exposure should be 10 *dB(A)* lower in areas with high vibration levels. In a subsequent field study conducted as part of the Swedish TVANE project [71] it was found that the percentage of respondents annoyed by noise was higher in areas with high levels of vibration. It was found that noise exposure should be 5-7 *dB(A)* lower in areas with high levels of vibration for the annoyance levels to be equal.

In a field study that aimed to investigate the combined effect of railway-induced noise and vibration [89], a social survey of 1056 respondents from 565 households was conducted. The results of this study suggested that the vibration perception threshold is increased in the presence of high noise exposure ($>$ 55 *dB(A)*).

In the socio-vibration field survey conducted in the United Kingdom [73], a preliminary exposure-response relationship was derived for annoyance caused by vibration exposure ($VDV_{b,24hr}\ m/s^{1.75}$) and airborne noise exposure (L_{DEN} *dB*) as independent variables. Noise exposure was calculated for each respondent using the calculation of railway noise procedure [90], meaning that there is potentially considerable uncertainties noise exposure data. Inclusion of the estimated airborne noise exposure as an independent variable in the exposure-response model resulted in a significant parameter estimate for the variable (p ¡ 0.001). Figure D.7 shows the proportion of respondents reporting high annoyance due to vibration as a function of vibration and noise exposure. It can be seen from this figure that annoyance due to vibration increases with both noise and vibration exposure. This result suggests that noise exposure has an influence on annoyance due to vibration although in the calculated model vibration exposure has the greatest influence in the relationship.

In the socio-vibration survey conducted in Den Bosch in the Netherlands and Poland [72], annoyance due to vibration exposure was found to be higher for respondents who reported being able to hear trains daily.

D.5.5 Response to different sources

There is some evidence to suggest that annoyance due to vibration is source dependent. For example, annoyance due to construction activities has been found to be greater for the same magnitude of vibration exposure than annoyance due to railway vibration [103]. Differences in annoyance response to both

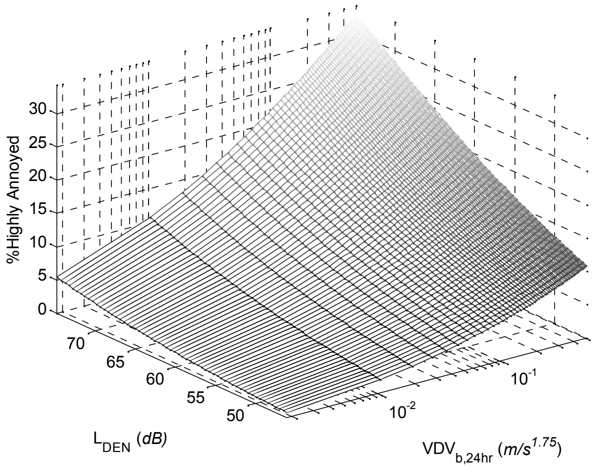

Figure D.7: Preliminary relationship showing annoyance due to vibration as a function of vibration exposure and noise exposure (source [73])

noise and vibration have been found between passenger trains, freight trains, and maintenance activities [91]. This suggests that these differences should be considered if assessing annoyance due to mixed rail operations. The difference in response to different sources of vibration may be due to attitudes towards the source and also characteristics of the vibration exposure that are not properly characterised by current vibration exposure descriptors.

D.6 Applications and limitations of current evidence

D.6.1 Validity of the meta-analytic exposure-response relationships

Of the evidence presented in this section, the most useful tools are the meta-analytic exposure-response curves. These curves represent the first attempt to harmonise international field data collected in socio-vibration surveys. Potential applications of these relationships include strategic planning, target setting, cost-benefit analysis, and environmental impact assessments (to give insight into the situation that may be expected in the long term). The curves should only be used for the assessment of ”steady-state” railway vibration. That is to say, in areas where there has been no recent step change in vibration exposure. They are therefore not applicable for the assessment of ”vibration hotspots” or local complaint type situations. The curves are also only applicable to the adult population.

It should always be borne in mind that in the use of exposure-response relationships for the prediction of annoyance in a specific population, substantial deviations from the *’average’* response described by the curves is expected. These deviations could be due to inadequacies in the exposure descriptor, attitudinal factors, situational factors, and exposure to other environmental stressors that may have synergistic effects with vibration. However, the confidence intervals of the derived meta-analytic curves are of a similar width to those for the EU endorsed exposure-response relationships for noise, and the relationships appear to be equally fit to predict the community response (as opposed to the individual response that is very much dependent on respondent characteristics).

Berry and Flindell [92] provide a useful framework for the assessment of the scientific robustness and relevance with respect to policy of exposure-response relationships for environmental noise. They suggest the following criteria:

1. The relevance, statistical representativeness, and measurement accuracy of the [exposure], or input variables, measured in the research study.
2. The relevance, statistical representativeness and measurement accuracy of the response, or outcome, variables in the research study.
3. The range of applicability to other types of noise exposure and/or environment not included in the research study.
4. The range of applicability to other types of adverse health effects not included in the research study.
5. The statistical strength of the observed [exposure]-response relationship in relation to known and/or estimated statistical uncertainty and in relation to the statistical power of the research study as designed.

6. The relative absence of potential confounding variables that could have been equally or more responsible for the observed [exposure]-response relationships.
7. The scientific plausibility of the observed [exposure]-response relationship considered in terms of known or theoretical biological mechanisms.

The methods of estimating vibration exposure that were employed in the studies from which the data for the meta-analytic curves were taken differ. As such, the uncertainties associated with the estimates of vibration exposure will differ between studies. The proportion of variance explained by the meta-analytic models was similar of each of the three vibration exposure descriptors.

There is evidence that the human response to vibration is dependent upon the source. Therefore the exposure-response relationships presented in this report should only be used for the prediction of railway-induced vibration. Through the comparative meta-analysis presented in section D.5.1, it was suggested that the synthesis curves may under-predict the response to high speed rail. It is also important to note that the data from which the meta-analytic exposure-response curves were derived were collected under ”steady-state” conditions. In the human response to noise exposure, there is evidence that for a step-change in exposure the annoyance response will be under-predicted if exposure-response relationships collected under steady-state conditions are used [93, 93]. However, analysis of the Norwegian faade insulation study [94] found no evidence of a change effect, suggesting that the response to a change in noise exposure can be predicted by exposure-response relationships derived under steady-state conditions.

The proportion of variance explained by the meta-analytic exposure-response relationship is of the same order as that described by the EU endorsed exposure-response relationships for annoyance due to transportation noise (around 16% for railway noise [79]). Furthermore, a sensitivity analysis was conducted by excluding the $2,5^{th}$ and $97,5^{th}$ percentile of the $V_{dir,max}$ data in the combined dataset. The resulting exposure-response relationship was almost identical to the one based on the whole dataset suggesting that the relationships are not sensitive to extreme values.

Evidence has been presented in this section that suggests that the annoyance response to vibration is influenced by exposure to both airborne and groundborne noise and vice versa. There is however insufficient data on this subject to derive quantitative relationships describing this influence. This combined effect should be borne in mind when specifying mitigation measures.

There is evidence that vibration induced rattle has a strong influence on the response to railway-induced vibration. However, as with airborne and groundborne noise, there is currently insufficient data to quantify this effect.

D.6.2 Comparison of current limits with synthesis curve

Table D.3 shows the percent highly annoyed, annoyed, and slightly annoyed at current guideline limits as predicted by the meta-analytic curves shown in section D.5.1. The meta-analytic exposure-response curves predict annoyance using vibration exposure evaluated over a 24-hour period whereas a number of the limits in Table D.3 are specifically for the day or night period. Adjustment factors derived in the meta-analysis have been applied to transform the guideline values into the descriptors used in the meta-curves. Namely, a factor of 1.15 to take into account the differences between the W_k and W_m frequency weightings and a factor of 1.25 to take into account the differences between fast and slow time weightings.

D.7 Future developments

Although meta-analytic curves have been derived within the CargoVibes project, more field data needs to be gathered to increase the applicability of the curves. This will be facilitated through the sharing of field data that should be stored and labelled in a standard way.

There is strong evidence that vibration induced rattle has a large influence on the annoyance response. There has however been very little work to characterise both the physical mechanisms that result in vibration induced rattle, and the perception of this phenomenon. Further work in both the laboratory and the field is needed to investigate the perception of vibration induced rattle and quantify the contribution it has to the overall response to vibration from railways.

It is clear that both airborne and groundborne noise influence the response to vibration and vice-versa. There is however insufficient field data to explore this interaction in detail. Future socio-vibration surveys should ensure that responses to noise annoyance questions are collected and reliable estimates of noise exposure are made. Noise mapping could also be used to estimate noise exposure in previous socio-vibration field surveys.

Table D.3: Percent highly annoyed, annoyed, and slightly annoyed at current guideline limits predicted by the meta-analytic exposure-response relationships

Standard	Descriptor	Effect/Threshold	Value	%HA	%A	%SA
DIN 4150:2:1999	KB	A_u Day	0.15	4.5	12.3	26.8
		A_0 Day	3	34.3	55.4	75.1
		A_u Night	0.1	3	9.1	21.4
		A_0 Night	0.2	5.8	15	31.1
SBR	Vmax	A_1 Day	0.1	3	9.1	21.4
		A_2 Day	0.4	10.1	23.1	42.3
		A_1 Night	0.1	3	9.1	21.4
		A_2 Night	0.2	5.8	15	31.1
		Not annoyed	$<$ 0.1	$<$ 3	$<$ 9.1	$<$ 21.4
		A little annoyed	0.1 - 0.2	3 - 5.8	9.1 - 15	21.4 - 31.1
		Moderately annoyed	0.2 - 0.8	5.8 - 16.5	15 - 33.2	31.1 - 54.2
		Annoyed	0.8 - 3.2	16.5 - 35.3	33.2 - 56.5	54.2 - 76.0
		Significantly annoyed	$>$ 3.2	$>$ 35.3	$>$ 56.5	$>$ 76.0
NS 8176	$v_{w,95}$	Class A	0.1	3.8	10.8	24.3
		Class B	0.15	5.4	14.4	30.1
		Class C	0.3	9.6	22.3	41.2
		Class D	0.6	15.8	32.2	53.1
SS 460 38 61:1992	Maximum slow-weighted velocity	Moderate disturbance	0.4 - 1.0	10.1 - 19.0	23.1 - 36.7	42.1 - 58.0
		Probable disturbance	$>$ 1	$>$ 19.0	$>$ 36.7	$>$ 58.0
BS 6472	VDV	Low probability of adverse comment - Day	0.2 - 0.4	36.6 - 48.2	57.7 - 68.9	76.8 - 84.9
		Adverse comment possible - Day	0.4 - 0.8	48.2 - 60.0	68.9 - 78.6	84.9 - 90.8
		Adverse comment probable- Day	0.8 - 1.6	60.0 - 70.9	78.6 - 86.2	90.8 - 94.8
		Low probability of adverse comment - Night	0.1 - 0.2	26.0 - 36.6	45.9 - 68.9	66.8 - 76.8
		Adverse comment possible - Night	0.2 - 0.4	36.6 - 48.2	57.7 - 68.9	76.8 - 84.9
		Adverse comment probable- Night	0.4 - 0.8	48.2 - 60.0	68.9 - 78.6	84.9 - 90.8
FTA	VdB	Vibration impact criteria ($>$ 70 events per day)	72 VdB (approx 0.1 mm/s)	3	9.1	21.4

E Sleep

E.1 Introduction

It is well accepted that sleep is an important biological function that is necessary for the health of humans [95]. According to Muzet [96], *"[s]leep is a physiological state that needs its integrity to allow the living organism to recuperate normally"*; this statement is echoed by the World Health Organization who state that sleep is a biological necessity the disturbance of which is associated with a number of health problems [95]. There is sufficient evidence of a relationship between exposure to environmental noise and sleep disturbance for limit values to be set to protect against noise induced sleep disturbance. For example, the World Health Organisation recommend a limit of 40 *dB* $L_{night,outside}$ for noise measured outside [95]. This limit value was arrived at through comparative analyses of many different studies into the effects of noise exposure on sleep.

The pathways though with noise can disturb sleep are complex and numerous. The complexity of these processes are illustrated in a hypothetical model for the disturbances of sleep by noise shown in Figure E.1 (taken from [97]). The model shown in Figure E.1 categorises the effects of noise exposure on sleep according to the delay of their occurrence relative to the onset of the noise exposure. Primary effects are identified as autonomic, motoric and cortical arousals, and awakening responses that can result in alteration of the sleep structure. The potential after effects (termed "Secondary Effects" in the model shown in Figure E.1) of noise exposure are reduced subjective sleep quality, sleepiness, and impairments of mood and performance. It is further suggested that long term exposure to noise may lead to chronic alterations in behaviour or health. Much of what is hypothesised in this model can be generalised to the disturbances of sleep by vibration. Care should however be taken as it is presupposed in this model that the disturbance of sleep by noise leads to long-term health effects, which may not necessarily be the case for vibration.

Compared to nocturnal noise, there are much less experimental data on the effects of vibration on sleep. This section aims to give an overview of the tools and methods that are currently available to assess sleep disturbance due to railway-induced vibration in both laboratory and field conditions. Firstly, approaches to measuring and quantifying sleep disturbance are discussed. Following this a discussion of the field and laboratory studies that have explored vibration induced sleep disturbance is provided. Finally, a table detailing the known effects of vibration on sleep is provided to help facilitate the application of current evidence in practice.

E.2 Measurement of response

E.2.1 Objective measures of sleep disturbance

Sleep can be evaluated objectively using polysomnographic (PSG) recordings. Guidance for the use of PSG is available from the American Academy of Sleep Medicine [98]. PSG records different physiological functions during sleep through electroencephalography (EEG) to record electrical brain activity, electrooculogram (EOG) to record eye activity, electromyography (EMG) to record muscular activity, electrocardiogram (ECG) to record cardiac activity, and measures of respiration, leg movements, oxygenation, and cardiac rhythm.

E.2.2 Subjective measures of sleep disturbance

Subjective measures of sleep disturbance are most often recorded via questionnaires. Questionnaires to measure subjective sleep disturbance have been used in both field and laboratory studies. Table E.1 provides an overview of the wording of questions used in different studies into the effects of vibration on sleep along with the scale used to measure the response.

E.3 Measurement of exposure

There is no specific guidance available for the quantification of vibration exposure in residential environments with respect to sleep disturbance. As the main focus of the socio-vibration field surveys that have been conducted to date has been the assessment of annoyance, investigations into the effects of vibration on sleep have been limited to using vibration exposure data measured for the assessment of annoyance (see section D.2).

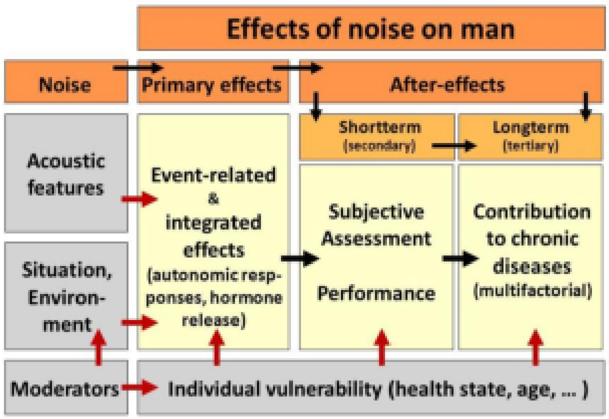

Figure E.1: Hypothesis for the disturbances of sleep by noise presented in [97]

Table E.1: Wording of response question used to measure subjective sleep disturbance in previous socio-vibration surveys and laboratory studies

Study	Wording of response question	Response scale
Norway [66]	Does shaking/vibrations lead you to having problems falling to sleep? Does shaking/vibrations lead you to awakening at night? Does shaking/vibrations lead you to wakening too early in the morning?	Binary Yes/No
USA and Canada [68]	While you've been at home over the past year, have you ever been awakened by low rumbling sounds, rattling, shaking, or vibration inside your home when subway trains pass by?	Binary Yes/No
UK [73]	Has feeling vibration or shaking of the floor, chair, bed or other surfaces bothered, annoyed or disturbed you personally when you have been sleeping?	Binary Yes/No
Netherlands and Poland [72]	Thinking about the last 12 months or so, when at home, what number from 0 to 10 best shows how much your sleep is disturbed by vibration from the sources mentioned below? {passenger trains; freight trains; maintenance; other}	11-pont numerical scale + Dont notice category
	When you are at home, how often does vibration from railway prevent you from falling asleep; wake you up; impair your sleep quality?	Almost never/Sometimes/Often
	If you answered sometimes or often, how disturbing or annoying would you say this is?	A bit/Rather/Very
CargoVibes laboratory study [100]	How would you rate your sleep quality during the night?	11-point numerical scale from "Very Good" to "Very Bad" + 5-point semantic scale
	How disturbed was your sleep by vibration from trains during the night?	11-point numerical scale from "Not at all" to "Extremely"

If vibration exposure is being measured to evaluate sleep, a greater number of assumptions can be made regarding the orientation and location of the respondent than for the evaluation of annoyance. For example, it is likely that during sleep the respondent will be in a recumbent position. Also, bedrooms are usually located on the upper floors of multi-storey residences. As it is currently unknown which exposure descriptors best correlate with disturbances of sleep, which direction of excitation has the greatest impact, and which frequency weightings (if any) are suitable for the evaluation of the effects of vibration on sleep, it is recommended that if vibration be measured in the field that full time histories in three orthogonal directions are retained.

E.4 Response metrics

The scoring of sleep from polysomnogram (PSG) measurements is standardised by the American Academy of Sleep Medicine [98]. Using this method, PSG measurements are analysed in non-overlapping 30-second windows referred to as epochs and scored according to the sleep stage that occupies the greatest portion of the epoch. Table E.2 provides descriptions of the different sleep stages as defined in [98].

In socio-acoustic surveys, sleep disturbance has been quantified in a similar manner to annoyance by deriving exposure-response relationships describing the percentile based metrics percent highly sleep disturbed (%HSD), percent sleep disturbed (%SD), and percent a little sleep disturbed (%LSD) [101]. With the exception of the surveys conducted in the Netherlands and Poland [72] and in the TVANE project in Sweden [99], sleep disturbance in field surveys that consider the effects of vibration has generally been measured on a binary response scale (see Table E.1). As such, the measure of response generally used in models based on these data has been the percentage of respondents expressing sleep disturbance. In the TVANE

Table E.2: Description of different sleep stages

Sleep stage	Description
Stage W	Waking stage ranging from full alertness through early stages of drowsiness. Characterized by alpha activity, eye blinks, reading eye movements, and rapid eye movements.
Stage 1	Characterized by slow eye movements, low amplitude 4–7 Hz activity, vertex sharp waves, sleep onset. Colloquially known as ”light sleep”.
Stage 2	Characterised by the presence of K complexes and sleep spindles.
Stage 3	Characterised by slow wave activity.
Stage R	Characterised by rapid eye movements, low chin EMG tone, sawtooth waves, and transient muscle activity.
Arousals	Abrupt shifts in the frequency of the EEG signal lasting at least 3 seconds.

project, a ”sleep index” was created by taking the arithmetic mean of the various questions measuring the effects of noise and vibration on sleep [99]. A similar approach was taken in the socio-vibration surveys conducted in the Netherlands and Poland [72].

Objective measures of sleepiness can be obtained using multiple sleep latency tests [102].

E.5 Exposure descriptors

There have been no systematic studies investigating different vibration exposure descriptors for the prediction of the effects of whole body vibration on sleep. In the socio-vibration surveys that have investigated the effect of vibration on sleep, vibration exposure has been expressed in the same single figure descriptor as used for annoyance (see section E.3). As there is little to no evidence regarding vibration exposure descriptors and sleep, full time histories of any assessment of vibration with respect to sleep should be retained.

E.6 Current evidence and relationships

E.6.1 Field data

In the socio-vibration survey conducted in Norway [66], the relationship between the disturbance of various activities and vibration exposure was investigated. Figure E.2 shows the relationship between vibration exposure and the disturbance of various activities including rest, waking too early, waking at night, and difficulties in getting to sleep. Between 10 and 15% of respondents reported rest and sleep disturbance at vibration values ($v_{w,95}$, see section C.6) of around 0,1 mm/s.

Questions on sleep disturbance were included in a socio-vibration field survey conducted in the USA and Canada [68], although relationships were not derived from these data. The following narrative account of the questionnaire data is provided in the report:

”Awakenings in the year prior to interviewing due to rumble, rattle, or vibrations from train passbys were reported by 6.6% of all those interviewed. About a quarter (24%) of those who reported awakening were awakened less often than once a week. Another 24% reported awakening at least one night per week; 9% reported awakening at least two nights per week; 12% reported awakening on at least three nights per week; 8% reported awakening 4 nights per week; 6% reported awakening at least five nights per week, and 17% reported awakening 6 or 7 nights a week Among those who were awakened, 44% were highly annoyed by the sleep disturbance.”

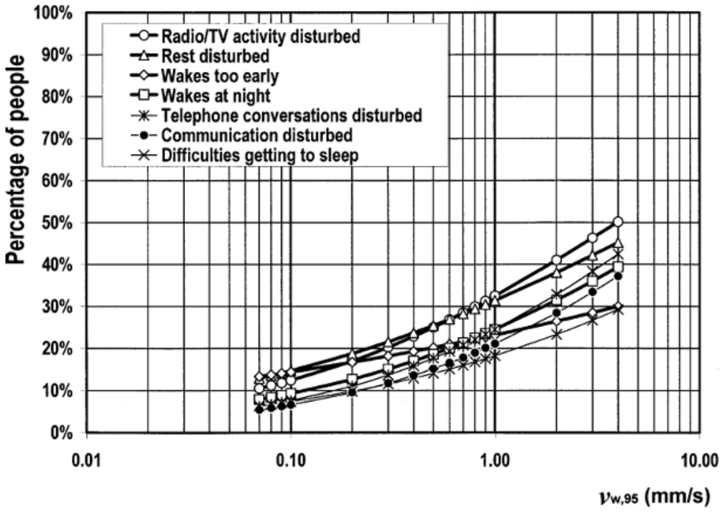

Figure E.2: Percentage of people reporting disturbance to, amongst other things, rest and sleep as a function of vibration from surface transportation (source [66])

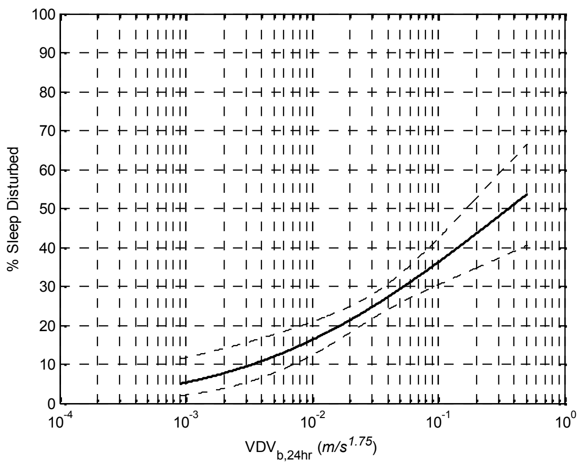

Figure E.3: Exposure-response relationship showing the proportion of people reporting sleep disturbance for a given vibration exposure (N = 752) (source [103])

The social survey conducted in the United Kingdom [73] included a question asking respondents to state if their sleep was ever disturbed by vibration caused by the railway. The response to this question was either Yes or No. Figure E.3 shows the proportion of respondents reporting sleep disturbance for a given magnitude of vibration exposure.

In a field study conducted as part of the TVANE project in Sweden [99], self-reported sleep disturbance by noise was found to be higher at similar levels of L_{night} in areas classified as having ”strong vibration”. This finding is illustrated in Figure E.4. The sleep disturbance index reported in this figure is the mean value of responses to question regarding ”How often” and ”How much” respondents had difficulties falling asleep, woke up, and experienced worse sleep quality.

In the socio-vibration field surveys conducted in the Netherlands and Poland [72], respondents were asked to complete questions regarding sleep disturbance due to railway vibration. Figure E.5 provides an indication of the prevalence of sleep disturbance in the three areas that were surveyed. This figure shows the number of respondents expressing different degrees of sleep disturbance due to vibration from mixed rail in the left pane and freight rail in the right pane.

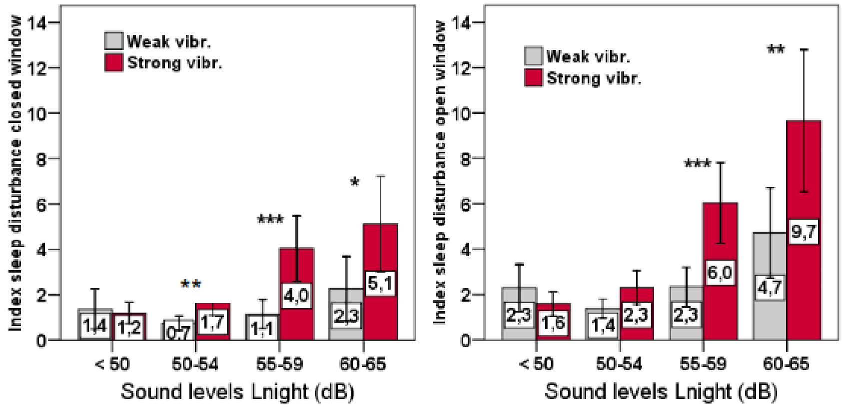

Figure E.4: Mean value of self-reported sleep disturbance due to railway noise as a function of Lnight in areas with weak and strong vibration (source [99])

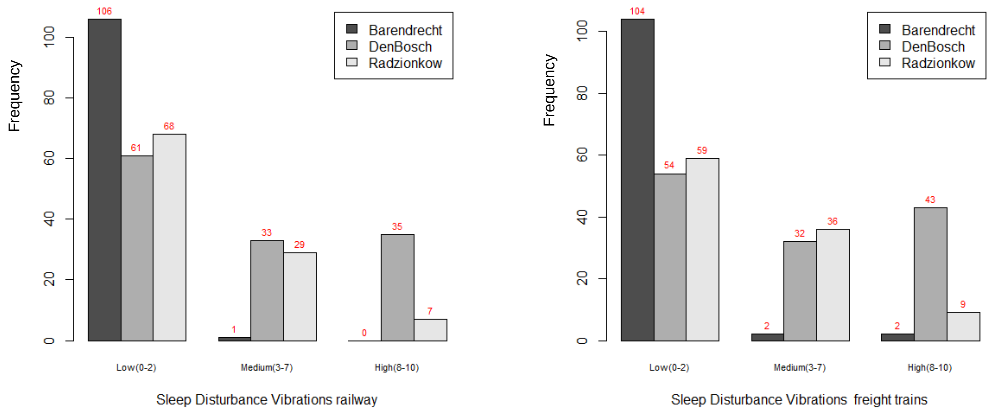

Figure E.5: Prevalence of self-reported sleep disturbance in the three survey areas studied in the CargoVibes project (source [72])

E.6.2 Laboratory data

There are very few laboratory studies that have investigated the effect of whole body vibration on sleep. A study by Arnberg [104] investigated the influence of vibration, noise, and a combination of the two from heavy road traffic. In this study three experiments were conducted. In the first experiment, four subjects after three habituation nights were exposed for three consecutive nights to 140 simulations of vibration from heavy road traffic in the vertical and horizontal directions simultaneously. In the second experiment, the same four subjects as the first experiment were exposed to three consecutive nights of vehicle noise with a maximum level of 50 *dB(A)* ($L_{p,max}$); the on the second exposure night the vehicle noise was accompanied by vibration. In the third experiment, five subjects after two habituation nights were exposed for five nights to the same vibration exposure as the first experiment. Following a break of a week, the same subjects spent another four nights in the laboratory without any exposure to serve as a control period. Following another break of a week, the same subjects spent another four nights in the laboratory and were exposed to higher levels of vibration than the first exposure period. The study concluded that *"when traffic noise [50 dB(A) peak level] is accompanied with vibrations with peak levels of 0.24 m/s^2 vertically and 0.17 m/s^2 horizontally as measured on the frame of the bed (stimulus duration approximately 2 s, dominant frequency approximately 12 Hz), sleep is more disturbed than is the case when noise occurs alone"*. The study also suggested that vibration exposure reduced the amount of REM sleep and an increase in this reduction was observed in the higher vibration exposure condition.

The effects of vertical whole body vibration on sleep have been investigated within the Swedish project TVANE [99, 105]. In this study, 21 subjects slept for five nights in a sleep laboratory during which they were exposed to different combinations of noise and vibration from freight trains, passenger trains, and high speed trains; the first two of the five nights were habituation nights. Vibration exposure was only included for the freight train passages and was synthesised using a modulated 10 Hz sine wave. Two levels of vertical vibration exposure were used in the study, which were classified as "weak" and "strong". The maximum running *rms* (1 second time weighting) SS 460 48 61 weighted velocity of the two exposure conditions was 0.2 to 0.4 mm/s for the "weak" condition and 1.1 to 1.5 mm/s for the "strong" condition. Two levels of noise exposure were used in the experiment, having an $L_{p,max}$ of 54 *dB(A)* and 48 *dB(A)* respectively. The vibration exposure values are presented as ranges due to uncertainties associated with non-linearity in the test setup. Subjects completed a questionnaire in the mornings and evenings to measure sleep quality, tiredness during the day, remembered awakenings, and annoyance. A decrease in subjective sleep quality was observed in nights with increased vibration levels.

A series of experimental studies investigating the effects of vibration and noise from freight trains on sleep have been conducted by the Occupational and Environmental Medicine department at the University of Gothenburg within the CargoVibes project [106, 107]. A total of 59 subjects participated in three different experiments (not all subjects participated in all experiments). In these experiments, sleep was evaluated objectively and subjectively during and after exposure to different noise and vibration conditions. Polysomnogram (PSG) recordings were used to measure the macro- and micro-structure of sleep parameters including sleep stage, heart rate, and cortical arousals and awakenings. Questionnaires were used to measure aspects such as self-reported sleep disturbance, sleep quality, tiredness, stress, emotion, mood, and restoration. Freight train vibration signals were synthesised using a 10 Hz modulated sine wave. Subjects were exposed to in the head-to-foot horizontal direction. Audio recordings of train passages were filtered so as to correspond to the sound in a bedroom with a closed window.

In the first experiment, twelve subjects slept for six nights in the laboratory. This period consisted of a habituation night, a control night, and four exposure nights. Each exposure nights consisted of 36 train passages. One exposure night consisted only noise, one noise and low vibration levels, one noise and moderate vibration levels, and one high vibration levels. The "low", "moderate", and "high" vibration excitations had unweighted *rms* acceleration levels of 0.020, 0.036, and 0.072 m/s^2 respectively. In the second experiment, the influence of the number of events during the night was investigated. Twenty-four subjects slept for six nights in the laboratory that included one habituation and one control night. In this experiment, two levels of vibration were used and each exposure night consisted of either 20 or 36 train passages. The levels of vibration were the same as the moderate and high levels used in the first experiment. The third experiment aimed to investigate the contribution of noise and vibration to the response and also to introduce an exposure condition with a higher number of trains. As with the previous two experiments, twenty-three subjects slept in the laboratory for one control night, one habituation night, and four exposure nights. The exposure nights consisted of one night with noise and vibration from 36 train passages, one night with noise only from 36 train passages, one night with vibration only from 36 train passages, and one night with noise and vibration from 52 train passages. The high vibration condition from the previous two experiments was used for all of the train passages for which vibration was included.

Data from the three experiments were combined and analysed to address the following four research questions:

1. *Does vibration and noise from freight trains disturb sleep?*
2. *How does vibration amplitude affect sleep?*
3. *How does the number of trains in a night affect sleep?*
4. *What is the relative importance (compared to noise)?*

From the combined analysis of the three experiments, it was found that subjects reported worse sleep quality (as measured using the questionnaire) and greater disturbance during the nights in which they were exposed to noise and vibration compared with the control night. This finding was confirmed by the PSG data where, compared to the control night, a greater number of sleep stage shifts, a shorter period between falling asleep and the first awakening, and a shorter maximum length of uninterrupted time spent in slow wave sleep were found in nights where subjects were exposed to 36 trains with unweighted *rms* levels of 0.072 m/s^2. An increased probability of event related arousals and awakenings and sleep stages changes compared to the control night was observed at even the lowest level of vibration exposure used in the study.

The experiments showed that self-reported sleep disturbance is related to the amplitude of vibration. Nights in which the *rms* levels of the train passbys were 0.036, and 0.072 m/s^2, self-reported sleep disturbance was found to be significantly higher than nights in which the *rms* level of the passbys was 0.020 m/s^2. All of the nights in which subjects were exposed to vibration were found to be significantly more disturbing than the control nights. Event related changes in heart rate was observed in the nights in which the *rms* levels of the train passbys were 0.036, and 0.072 m/s^2. An increase in heart rate of at least 3 beats per minute

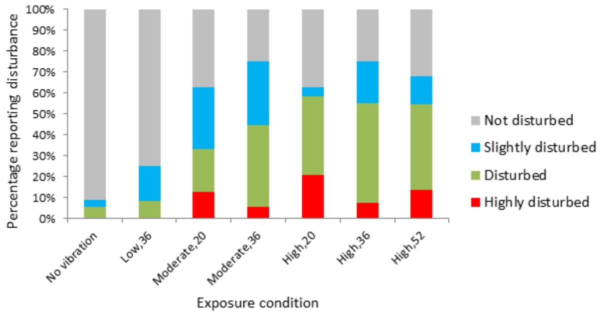

Figure E.6: Proportion of subjects reporting different degree of sleep disturbance at the different vibration exposure conditions used in the laboratory tests conducted at the University of Gothenburg

in 50% of the subjects in the 0.036 m/s^2 vibration condition and 83% of the subjects in the 0.072 m/s^2 condition was observed. It was also observed in the 0.072 m/s^2 condition that sleep was more fragmented and the probability of an EEG awakening and arousal was higher than in the lower vibration conditions.

In the 0.036 m/s^2 condition, greater self-reported sleep disturbance was observed when the frequency of trains was 36 per night compared to 20 per night. However, this effect was not observed in the other vibration conditions.

Subjects were found to be significantly more sleep disturbed during the 0.072 m/s^2 condition both with and without noise exposure compared to the control night and the noise only night. It was also found that subjects were able to differentiate between vibration induced and noise induced sleep disturbance.

Figure E.6 shows the proportion of subjects reporting different degree of sleep disturbance at the different vibration exposure conditions used in the laboratory tests.

E.7 Application and limitations of current evidence

As highlighted by the limited number of studies available on the subject, the understanding of the effects of vibration on sleep is still in its relative infancy. A summary of the effects on sleep for which a statistically significant finding has been reported is provided in Table E.7. This table is the same as is presented in the ”Specific Recommendations” section earlier in this document and is reproduced here for convenience. Based on the findings presented in the table, it is clear that vibration has a negative impact on sleep. It appears that vibration also has an influence on noise induced sleep disturbance as well as having an impact on sleep in its own right. However, due to the lack of data it is impossible to draw concrete limits for the prevention of the negative effects of vibration on sleep with any confidence at this stage.

All of the available evidence regarding the effects of vibration on sleep has been collected from adult populations. Vulnerable groups such as children, the elderly, or the infirm exposed to vibration may have different or more severe effects. There is currently insufficient evidence to link the effects fo vibration on sleep to health effect. Further epidemiological studies are needed if relationships between the effects of vibration on sleep and health are to be explored.

E.8 Future developments

As much of the data on the effects of vibration on sleep is derived from laboratory studies, a better understanding is needed of how the findings of these studies translate to the effect of vibration exposure on sleep in field conditions.

Further work is needed to determine the most appropriate single figure descriptor of vibration exposure and frequency weighting for the assessment of the impacts of vibration on sleep.

The laboratory studies conducted thus far have used vibration exposures with a dominant frequency of around 10 Hz. Further work is therefore needed to understand the effects of vibration at different frequencies on sleep.

Epidemiological studies are needed to determine whether the effects of vibration on sleep have an adverse effect on health.

Table E.3: Summary of the effects of vibration on sleep

	Effect	Significant findings[1]
Biological changes	**Change in cardiovascular activity**	Increase in heart rate [106, 107][2]
	Change in sleep structure	Reduction in REM sleep [104] Greater number of sleep stage shifts [100][3] Greater probability of sleep stage shifts [100][2] Shorter period between falling asleep and first awakening [100] Shorter maximum length of uninterrupted time spent in slow wave sleep [100]
	EEG awakening	Increase in probability of EEG awakening [100]
Sleep quality	**Waking in the night/too early**	Increase of reported awakenings/waking too early [66] (see Figure E.2)
	Difficulty in getting back to sleep	Greater difficulty in getting back to sleep once awoken for higher amplitudes of vibration [100]
	Self-reported sleep disturbance from vibration	Increase in proportion of people reporting sleep disturbance [66, 73] (see Figure E.2 and E.3) Self-reported sleep disturbance related to vibration amplitude [100] Decrease in self-reported sleep quality [100]
	Self-reported sleep disturbance from noise	Vibration related to increase in proportion of people reporting sleep disturbance from noise [99] (see Figure E.4)
	Decreased restoration	Decrease in self-reported restoration [100]

[1] The effects presented in this column are those for which a statistically significant result has been observed relating the effect to vibration exposure. However, it should be noted that these effects do not occur irrespective of vibration level.
[2] This response relates to individual vibration events.
[3] This response relates to the sleep macro-structure.

F Non-exposure factors

F.1 Introduction

Exposure-response relationships derived from field data for annoyance due to vibration generally explain a relatively low amount of variance. This is similar 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 [108–110]. The unexplained portion of the variance in the annoyance response is generally attributed to the inability of single figure noise exposure descriptors to properly describe human perception [111, 112] and non-acoustical factors [113, 114]. ”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. Many such factors have been found to have an influence on the annoyance response to transportation noise. Attitudinal factors that have been found to influence the response are self-reported sensitivity to noise [108, 115–117], fear of the noise source [108, 109, 115, 118], expectations of future noise levels [116], and the perception of the neighbourhood [109, 119]. Situational factors that have been found to influence the response are whether the area in which the respondent lives is urban or rural [120], visibility of the noise source [121, 122], and the amount of time spent at home [123, 124]. Socio-demographic factors have generally been found to have little or no influence on the annoyance response [108, 115] with the exception of age where a higher prevalence of annoyance has been observed in the middle age ranges [125].

The meta-analytic exposure-response curves developed in the CargoVibes project (see section D.5.1) were found to explain around 20% of the variance in the annoyance responses depending on the vibration exposure descriptor used as the independent variable in the model [72]. It can therefore be expected that factors that are not directly attributable to the vibration exposure have an influence on the annoyance response. In this document, these factors are termed *”non-exposure factors”*.

This section aims to give an overview of available evidence on the influence of various attitudinal, situational, and socio-demographic factors on the response to railway-induced vibration in residential environments. An understanding of these non-exposure factors can help interpret the observed exposure-response relationships. Some of these factors have important implications in terms of railway operations and the management of human response. The section begins with an overview of the non-exposure factors that have been found in previous studies to have an influence on the annoyance response and self-reported sleep disturbance caused by railway-induced vibration in residential environments. A table detailing the influence of these non-exposure factors on annoyance is then presented to facilitate the application of current evidence in practice. Finally, future developments in this area are suggested.

F.2 Current evidence and relationships

F.2.1 Time of day

Based on the findings of a socio-vibration survey conducted in the United Kingdom [73], there is evidence that the annoyance response to vibration is dependant upon the time of day [126]. In this study, annoyance responses for the day, evening, and night period were collected using five point sematic scales. The day period was defined as being between 07:00 and 19:00, the evening between 19:00 and 23:00, and the night between 23:00 and 07:00. Figure F.1 shows the exposure-response relationships describing Percent Highly Annoyed at different levels of W_k weighted *rms* acceleration averaged over all train passbys in the evaluation period. It can be seen from these curves that, for the same magnitude of vibration exposure, annoyance at night is greater than that in the evening, and in turn annoyance in the evening is greater than that in the daytime. Taking the daytime curve as a baseline, a reduction of vibration exposure corresponding to 16.5 *dB* in the evening and 34 *dB* in the night would be required for equal annoyance. These findings suggest that a night-time vibration indicator or a day-evening-night weighted 24-hour descriptor may be appropriate. In operational terms, this implies that annoyance can be mitigated by controlling the times of day that trains run.

F.2.2 Situational factors

The socio-vibration field survey conducted in Poland showed that the annoyance response to vibration was higher when the railway track was visible from the respondent’s living room [72]. Visibility of the railway was

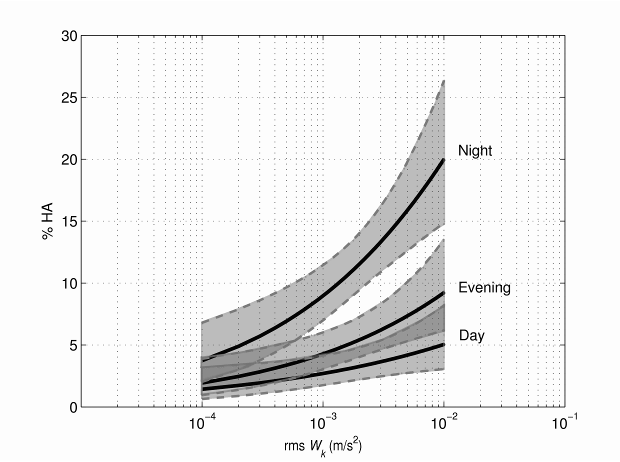

Figure F.1: Exposure-response relationship showing the percentage of highly annoyed persons at different time of the day (N = 755) (source [126])

also found to significantly influence the annoyance response in the socio-vibration survey conducted in the United Kingdom [127] with those respondents able to see the railway from any room in their house more likely to express high annoyance.

In the socio-vibration field survey conducted in the United Kingdom, the amount of time the respondent spent at home was found to have an influence on the reported annoyance, with people who spend less than 10 hours per day at home being more likely to express high annoyance than those who spend more than 10 hours a day at home [127]. It was found in this study that respondents living in rural areas were more likely to be annoyed by railway-induced vibration than respondents living in urban areas [127].

F.2.3 Attitudinal factors

The relationship between the concern that railway-induced vibration is causing damage to a resident's property and vibration exposure has been investigated based on the data collected in the socio-vibration survey conducted in the United Kingdom [127]. In the survey respondents were asked *"We would like to know if you are concerned that the vibration may damage this home or your possessions inside it in any way. Are you not at all concerned, slightly concerned, moderately concerned, very concerned, or extremely concerned?"* Exposure-response curves for concern of damage were derived from these data and are shown in Figure F.2. These curves show the proportion of respondents expressing concern above a given threshold for a given level of vibration exposure. Similar to the percentile based metrics used to express annoyance, the "Percent Highly Concerned" curve shows the proportion of respondents expressing concern in the top two categories of the five-point semantic scale, the "Percent concerned" in the top three categories, and the "Percent Slightly Concerned" in the top four categories. In this study, concern that vibration is causing damage to the property was also shown to partially mediate the relationship between annoyance to and exposure to railway-induced vibration.

A similar result was observed in the field surveys conducted in the Netherlands and Poland [72] where higher annoyance was found for those residents concerned about property damage. In this study concern of damage and worry about accidents were also found to be related to higher self-reported sleep disturbance from vibration.

The levels of vibration generated by railway traffic in residential environments are generally unlikely to reach magnitudes capable of causing even cosmetic damage [128]. As concern of damage appears to have such a strong influence on the annoyance response, this suggests that better community engagement could help reduce annoyance caused by railway vibration.

The socio-vibration survey conducted in the United Kingdom explored the influence of expectations regarding the future severity of vibration from railway activities on annoyance. In the social survey, respondents were asked whether they thought that vibration from the railway would get better, stay the same, or get worse over time. Inclusion of this variable in the exposure-response model showed that expectations regarding the level of vibration strongly influenced the annoyance response with those expecting the vibration level to get worse expressing higher annoyance [127].

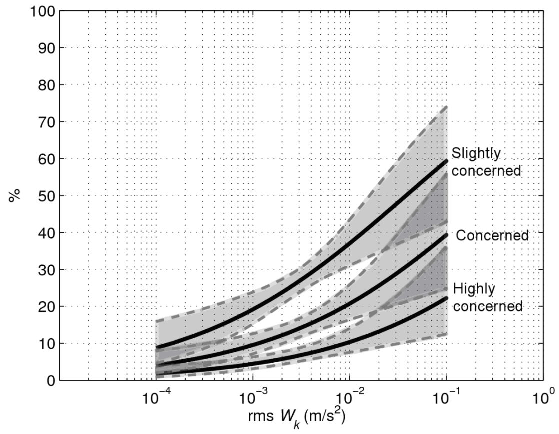

Figure F.2: Proportion of respondents expressing concern of property damage above a given threshold for a given level of vibration exposure (N = 755) (source [127])

Residents who took part in the survey conducted in Den Bosch in the Netherlands and Poland [72] were found to report both higher annoyance and higher self-reported sleep disturbance if they considered themselves to be sensitive to noise. Interestingly, self-reported sensitivity to vibration has not been found to significantly influence the annoyance response [127].

In the socio-vibration survey conducted in Poland [72], the perceived necessity of the freight trains that operated in the area was found to have an influence on annoyance with a greater perceived necessity relating to a lower annoyance response.

F.2.4 Socio-demographic factors

From the field surveys conducted in the Netherlands and Poland [72], the respondent's age was not found to have a significant influence on the annoyance response. However, from the data collected in the United Kingdom field survey, the inclusion of age and the square of age $(age + age^2)$ as variables in the exposure-response relationship were found to significantly influence the annoyance response. Inclusion of this variable in the exposure-response relationship suggested that in the study conducted in the United Kingdom annoyance was higher for people in the middle age ranges [127].

The socio-vibration field survey in Den Bosch in the Netherlands [72] found that those respondents who owned their home reported greater sleep disturbance from vibration than those who were in rented accommodation. In the study conducted in the United Kingdom, tenure type was not found to be related to annoyance but was correlated significantly with the concern of property damage [127].

F.3 Applications and limitations of current evidence

As highlighted in the previous section, the annoyance response to vibration from railways is strongly influenced by a number of attitudinal, situational, and, to a lesser extent, socio-demographic factors. A summary of the non-exposure factors that have an influence on the annoyance response is provided in Table F.1. This table is the same as is presented in the "Specific Recommendations" section earlier in this document and is reproduced here for convenience. Some of these factors such as concern of damage may help is the design of community engagement programmes for new or existing developments. Others, such as the influence of time of day have implications in operational terms. However, caution should be taken in the application of these results as they are based upon only two studies.

F.4 Future developments

Future work should explore specific scenarios for an optimal assessment of railway effects on residential environments. People's response to vibration from railway in residential environments is a comparatively undeveloped area and large sample studies are needed in order to draw conclusions on the extent of the influence of each non-exposure factor. Future developments should look at the extent of the effect of combined non-exposure factors. In real world environments, many of these non-exposure factors interact. There may be other external factors that haven't been accounted for that interact with the non-exposure

Table F.1: Summary of the effects of situation, attitudinal, and socio-demographic factors on annoyance

	Factor	Significant findings
Time of day	**Evening**	Annoyance greater during the evening than during the day at the same level of vibration exposure [126]
	Night	Annoyance is greater during the night than during the day and evening at the same level of vibration exposure [126]
Situational	**Visibility of source**	Annoyance greater if the source is visible [72, 127]
	Time spent at home	Annoyance greater for people who spend less than 10 hours per day at home [127]
	Type of area	Annoyance greater for people living in rural areas [127]
Attitudinal	**Concern of damage**	Annoyance greater for those concerned that vibration is damaging their property or belongings [72, 126]
	Expectation regarding future vibration	Annoyance greater for those expecting vibration to get worse in the future [127]
	Necessity of source	Annoyance greater for those considering the source unnecessary [72][1]
	Noise sensitivity	Annoyance from vibration greater for those considering themselves as noise sensitive [72]
Socio-demographic	**Age**	Annoyance greater for those in the middle age group in [126], no significant effect in [72]

[1] This result was observed for freight trains and may not be generalisable to mixed railway.

factors. Knowing that attitudinal factors have a large effect on the vibration annoyance response, further investigations could concentrate on linking psychometric measures to levels of annoyance. Finally, more information is needed on how non-exposure factors relate to different sources of railway vibration. For instance, non-exposure factors could also differ depending on a specific source such as freight or passenger.

G Conclusions

This document delivers guidance on the evaluation of human response to vibration from railways in residential environments. This is achieved by outlining the currently available methods of evaluation in light of the current state of the art and therefore may be considered best practice at the time of writing. A review of current standards revealed a variety of documents available on a national and international level offering guidance on the evaluation of perceptible vibration in buildings. These documents differ in terms of the single figure vibration exposure descriptors advocated, frequency weightings, measurement methods, and guideline values for the prevention of adverse effects. The evaluation method that takes precedence depends upon the country in which the evaluation is being conducted. There are three types of descriptors that are advocated in current standards: maximum running *rms* velocity or acceleration, energy equivalent *rms* velocity or acceleration over a given evaluation period, and the cumulative vibration dose value.

The weight of evidence to favour one of these descriptors over another is at present insufficient to advocate a change in current evaluation methods. Therefore, guidance has been provided where possible in terms of three common vibration exposure descriptors. It is suggested that future vibration surveys be reported in terms of these three descriptors and that raw time histories are retained for future analysis.

To assess annoyance due to railway-induced vibration, meta-analytic exposure-response curves have been derived. These may be used to estimate the percent highly annoyed ($\%HA$), percent annoyed ($\%A$), and the percent slightly annoyed ($\%SA$) at different levels of vibration exposure. The curves are suitable for the prediction of community annoyance due to steady-state railway-induced vibration. A number of situational, attitudinal, and socio-demographic factors that influence these relationships have been identified and reported. Future socio-vibration surveys should further explore the effects of non-exposure factors as evidence suggests that these factors have at least as large an influence on the annoyance response as vibration exposure expressed in current descriptors.

To assess the effects of vibration on sleep, a laboratory assessment has been conducted. These experiments, along with a review of published literature, have identified a number of the adverse effects that vibration exposure has on sleep. At present there is insufficient data to derive exposure-response relationships or to determine thresholds for these effects. Future studies should therefore focus on quantifying the levels of vibration at which these effect begin. Epidemiological studies are needed if the effects of vibration on health are to be explored.

Field and laboratory data are needed to understand the interaction between noise and vibration exposure. In particular, data is needed to derive relationships for human response to groundborne noise and vibration-induced rattle.

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