Rail freight vibration impacts sleep and community response: An overview of CargoVibes

K. Persson Waye[1], S. Janssen[2], D. Waddington[3], W. Groll[4], I. Croy[1], O. Hammar[1], A. Koopman[2], A. Moorhouse[3], E. Peris[3], C. Sharp[3], G. Sica[3], M. G. Smith[1], H. Vos[2], J. Woodcock[3], M. Ögren[1]

[1] Occupational and Environmental Medicine, The Sahlgrenska Academy at the University of Gothenburg, Gothenburg, Sweden kerstin.persson.waye@amm.gu.se ilona.croy@amm.gu.se michael.smith@amm.gu.se mikael.ogren@amm.gu.se

[2] TNO (Netherlands Organization for Applied Scientific Research), Delft, The Netherlands sabine.janssen@tno.nl arnold.koopman@tno.nl

[3] Acoustics Research Centre, The University of Salford, Salford, UK d.c.waddington@salford.ac.uk a.t.moorhouse@salford.ac.uk e.peris@salford.ac.uk c.sharp@edu.salford.ac.uk j.s.woodcock@salford.ac.uk

[4] Railway Institute, Warsaw, Poland wgroll@ikolej.pl

ABSTRACT

The European Union funded project: CargoVibes involving ten partners from eight nations has aimed to examine ground-borne vibration affecting residents close to freight railway lines. The paper presents an overview of the work package investigating human response to vibration, with particular focus on physiological and psychological impact on sleep, community annoyance and the development of guidance in evaluating response. Existing field studies of community response were supplemented with further field work in the Netherlands and Poland, and a meta-analysis conducted to determine dose-response relationships for railway vibration. The effects of vibration on sleep were measured in a series of laboratory trials at the University of Gothenburg. Numerous outcomes of vibration exposure were found, with physiological markers such as greater heart rate response and cortical reactions during sleep, and annoyance and sleep disturbance increasing with higher vibration amplitudes. A guidance document considering current state of the art regarding vibration measurement and assessment was produced pertaining to human perception, evaluation methods, annoyance, sleep impacts, and non-exposure factors. The outcomes of this work represent a significant advance in the understanding of the human response to railway vibration and a step towards a much needed harmonization of assessment methods. The findings presented in this paper highlight the importance of considering environmental vibration in the planning, construction, and maintenance of railways in residential environments.

INTRODUCTION

As pointed out in the White paper for European transport the rail transportation is aiming to increase its market share of goods transportation from 8 % in 2001 to 15 % in 2020 (EC 2001). To facilitate this within the existing railway, most of this transportation will be done during night time slots. Noise and vibration will potentially increase and may constitute a serious hinder for this development. While quite many studies lend guidance for assessment of noise induced annoyance and sleep disturbance from rail traffic, very little is known of adverse reactions due to vibration from rail traffic. Guidance for the assessment of human response to vibration varies

between countries and there is currently no consensus as to the most appropriate 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 overall objective of the CargoVibes project was therefore to develop and assess measures to ensure acceptable levels of vibration for residents living in the vicinity of freight railway lines in order to facilitate the extension of freight traffic on rail. Existing evaluation criteria in use are not properly underpinned by scientific data and there are no uniform assessment methods available to compare exposure from various studies.

AIMS

- The overall aim for the specific work package pertaining to human response was to establish acceptable levels of vibration from railway transportation, and was subdivided with the following objectives:
- Objective 1: To describe and assess reported health impacts of vibration among residents living near railway lines.
- Objective 2: Experimentally evaluate sleep disturbance due to whole body vibration from railway transportation.
- Objective 3: Provide a guidance document on how to apply the results in practice.

METHODS

The main responsibility for Objective 1 was with TNO, Objective 2 with the University of Gothenburg (UGOT) and Objective 3 with the University of Salford (USAL). Shared initial work involved the development of questionnaire for the field study and the laboratory study, and later also the input given to the guidance document. All reports were distributed and improved by meetings and discussions.

Objective 1

First, a state of the art overview was given of the results from various field studies done so far on the evaluation of vibration from several railway sources. On the basis of experience gained from these studies (e.g. (Klaeboe et al. 2002, Öhrström et al. 2011, Waddington et al. 2014)) and from many previous studies on effects of noise on humans, a questionnaire was developed to measure self-reported response to vibration and noise, such as perception, annoyance and sleep disturbance. The process was carried out by a series of meetings, used previously in noise research, while also addressing specific issues related to vibration, for example the exact formulation of the vibration disturbance question and of attitudinal questions related to vibration. Furthermore, a set of questions on sleep quality was included to obtain comparable data for some parameters in the field as in the laboratory (see Objective 2).This questionnaire was translated from English into Dutch and Polish and checked by several native speakers. It was used in field surveys in the vicinity of a railway line with freight traffic in the Netherlands (N=156) and in Poland (N=104) to assess the response to (measured) vibration in combination with other individual and situational factors. Next, these survey data were combined with the original data from available earlier railway vibration field studies, providing complementary data for exposure-

response analysis. To enable the comparison of the various metrics used in the separate studies, a conversion matrix was developed that allows the conversion of one metric into another. Subsequently, in a comparative meta-analysis, the expected degree of annoyance due to railway vibrations at a given vibration level was quantified in exposure-response relationships (Equations (1) to (12)).

Objective 2

The experimental studies were designed using vibration signals representative of the spectral content and amplitude of freight trains, based on field measurements provided by TNO, UGOT and USAL. Based on the field measurements and the technical range of the laboratory system we used a 10 Hz signal at three amplitudes ranging from a maximal weighted (W_d) amplitude of 0.0058 m/s^2 to 0.0204 m/s^2. Horizontal vibration was rated as subjectively more annoying in a pilot study and so was used in the main trials (Smith et al. 2012). Different numbers of passages and interactions between noise and vibration exposure were examined. Across three studies a total of 59 young healthy volunteers participated. Gender and sensitivity to noise was balanced within the design. Physiological changes in cardiac activity and sleep macro- and micro- structure were recorded polysomnographically, and subjective ratings were collected in the morning and evening using questionnaires (Persson Waye et al. 2014, Smith et al. 2014).

Objective 3

Guidance on how to apply the results of this work package in practice was developed in the form of a best practice guidance document. The objective of this deliverable was 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.

On 14th May 2013, a workshop was held at USAL that gathered international experts in the field of railway vibration from industry, consultancy, and academia. The aim of this 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 were used to shape and inform the contents of the guide. Additionally, a draft of the document was presented at the 11th International Workshop on Railway Noise in Uddevalla, Sweden and made available online for comment prior to it being finalized. These activities were undertaken to ensure the guidance document is relevant to the needs of operators, infrastructure managers, planners, consultants, scientists, and policy makers.

MAIN OUTCOMES

Objective 1

The surveys in the Netherlands and in Poland revealed influences of vibration and several individual and situational factors on annoyance and sleep disturbance. The survey data were combined with the original data from available earlier railway vibration field studies. In a comparative meta-analysis, the expected degree of annoyance due to railway vibrations was quantified for three different metrics in exposure-response relationships (Table 1 to Table 3 show the polynomial

approximations of the underlying exposure-response model). Despite differentiation in the annoyance response between studies, partly explained by source of vibration, it can be concluded that there is a clear relationship between vibration exposure and the annoyance response of residents, which can be used as a basis of criteria for the evaluation of railway vibration (see also (Janssen et al. 2013)).

Table 1 Polynomial equations for proportion of respondents being slightly annoyed (SA), annoyed (A) and highly annoyed (HA) by vibration (directionally weighted maximum velocity $V_{dir,max}$, as used in DIN/SBR but directional). These equations must not be used outside the range 0.01 to 10 mm/s $V_{dir,max}$.

$$\%SA_{Vdir,\max} = -0.559X^4 - 2.594X^3 + 4.681X^2 + 31.802X + 36.118 \quad \textbf{(1)}$$

$$\%A_{V_{dir,\max}} = -0.863X^4 - 0 - 811X^3 + 8.602X^2 + 23.181X + 18.527 \quad \textbf{(2)}$$

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

$$\text{where } X = \frac{\log_{10}\left(V_{dir,\max}\right) + 0.5}{0.86733} \quad \textbf{(4)}$$

Table 2 Polynomial equations for proportion of respondents being slightly annoyed (SA), annoyed (A) and highly annoyed (HA) by vibration (weighted root mean square acceleration rms, as used in ISO). These equations must not be used outside the range 0.001×10^{-3} to 10×10^{-3} m/s^2 rms.

$$\%SA_{rms} = -1.806X^4 - 3.198X^3 + 11.812X^2 + 35.059X + 25.390 \quad \textbf{(5)}$$

$$\%A_{rms} = -1.648X^4 - 0.0.13X^3 + 13.826X^2 + 22.510X + 11.380 \quad \textbf{(6)}$$

$$\%HA_{rms} = -0.527X^4 + 2.089X^3 + 9.850X^2 + 10.785X + 3.910 \quad \textbf{(7)}$$

$$\text{where } X = \frac{\log_{10}\left(rms\right) + 4}{1.1564} \quad \textbf{(8)}$$

Table 3 Polynomial equations for proportion of respondents being slightly annoyed (SA), annoyed (A) and highly annoyed (HA) by vibration (weighted vibration dose value VDV, as used in BS). These equations must not be used outside the range 0.1×10^{-3} to 1000×10^{-3} m/s$^{1.75}$ VDV.

$$\%SA_{VDV} = -1.751X^4 - 4.019X^3 + 10.845X^2 + 38.038X + 29.118 \quad \textbf{(9)}$$

$$\%A_{VDV} = -1.952X^4 - 0.768X^3 + 14.679X^2 + 26.054X + 13.832 \quad \textbf{(10)}$$

$$\%HA_{VDV} = -0.885X^4 + 1.834X^3 + 11.605X^2 + 13.529X + 5.086 \quad \textbf{(11)}$$

$$\text{where } X = \frac{\log_{10}\left(VDV\right) + 2}{1.1564} \quad \textbf{(12)}$$

Objective 2

From the experimental studies it can be concluded that nocturnal vibration may have a negative impact on sleep, and that the effect increases with greater vibration levels.

Both noise only and noise accompanied by low vibration had little effect, while noise and high vibration level was found to significantly influence both subjective evaluated sleep (Figure 2) and physiological measures of sleep (Figure 1). The effect of number of trains was less conclusive and requires additional research. Further details are available elsewhere at the congress (Persson Waye et al. 2014, Smith et al. 2014).

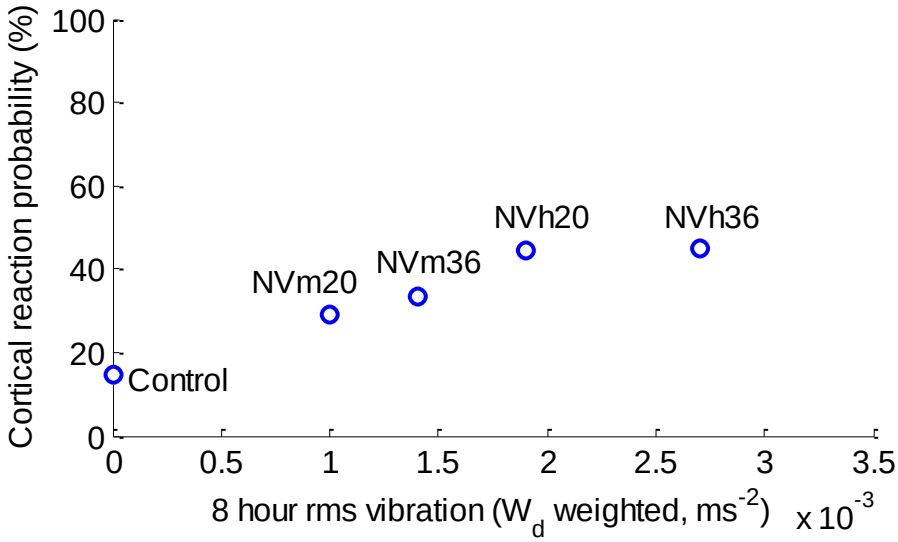

Figure 1 Event-related cortical reaction probability (EEG arousals and awakenings) to freight trains in the UGOT laboratory study. Nights with noise and moderate (m) or high (h) vibration and 20 or 36 trains.

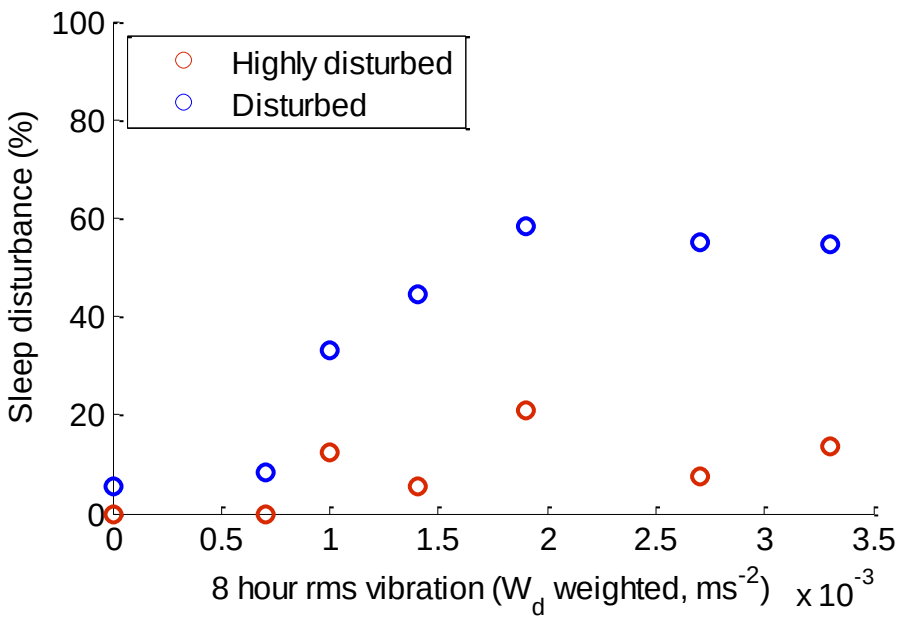

Figure 2 Sleep disturbance by vibration in the UGOT laboratory studies

Objective 3

A guidance document was produced, derived from the main conclusions of the work package and other published literature, describing how to apply the results in practice (Woodcock et al. 2014). This represents a significant first step towards harmonization

of methods in the assessment of human response to railway vibration. It provides a set of practical tools to assess railway induced environmental vibration including a summary of current national standards, polynomial fits to the exposure-response curves, proportions of people annoyed at current guidelines as predicted by the meta-analytic curves (Table 5), information on the significant effects of vibration on sleep, and the influence of non-exposure factors (Table 4). The document is intended to provide an extension to the currently available body of guidance in light of the current state of the art, allowing assessments of vibration to be conducted based on the most up to date scientific information.

Table 4 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 of 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*
	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

*This result was observed for freight trains and may not be generalizable to mixed railway

A summary of all conference papers and peer reviewed journal articles published as part of the work package is given at the end of this document.

NEXT STEPS

The work performed represents a significant step in understanding human response to vibration in residential environments. However, further field studies examining the effects on annoyance and sleep are desirable, as is deeper understanding of non-exposure factors. Laboratory studies to determine threshold values for the effects of vibration on sleep, and field and laboratory studies on the interactions of noise and vibration and human response to groundborne noise and rattle, all present interesting future avenues of research. The work package members will continue to disseminate our findings in the scientific literature in the near future.

Table 5 Percentage of population being highly annoyed (HA), annoyed (A), and slightly annoyed (SA) by vibration at current guideline limits predicted by the meta-analytic exposure-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	Max. slow-weighted velocity	Moderate disturbance	0.4-1.0	10.1-19.0	23.1-36.7	42.1-58.0
		Probable disturbance	>1.0	>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	45.9-57.7	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

ACKNOWLEDGEMENTS

The work was performed within the EU CargoVibes project, funded by the 7th Framework Programme (grant number 266248). We thank the respondents in the field studies and the volunteers in the sleep trials for their participation.

REFERENCES

EC (2001). White Paper - European transport policy for 2010: time to decide. Brussels, Commission of the European Communities.

Janssen, S., H. Vos and A. Koopman (2013). A meta-analysis of surveys into vibration annoyance from railway. Internoise 2013. Innsbruck, Austria.

Klaeboe, R., et al. (2002). "Vibration in dwellings from road and rail traffic- Part II: exposure-effect relationships based on ordinal logit and logistic regression models." Applied Acoustics **64**(1): 89-109.

Persson Waye, K., et al. (2014). The impact of railway freight with regard to vibration level, noise and number of trains on sleep. ICBEN 2014. Nara, Japan.

Smith, M. G., et al. (2014). Freight trains, nocturnal vibration and noise, and their physiological effects during sleep. ICBEN 2014. Nara, Japan.

Smith, M. G., M. Ögren and K. Persson Waye (2012). "Vibration and noise induced sleep disturbance from trains - The importance of vibration direction." Proceed. of Meetings on Acoustics **15**.

Waddington, D. C., et al. (2014). "Human response to vibration in residential environments." J Acoust Soc Am **135**(1): 182-193.

Woodcock, J., et al. (2014). Cargovibes. Attenuation of ground-borne vibration affecting residents near freight railway lines. Deliverable D1.5 Guidance document for the evaluation of railway vibration.

Öhrström, E., et al. (2011). Resultat och slutsatser från forsningsprogrammet TVANE - Effekter av buller och vibrationer från tåg- och vägtrafik - tågbonus, skillnader och samverkan mellan tåg- och vägtrafik (Results and conclusions from the research project TVANE - Effects of noise and vibration from railway and road traffic - railway bonus, differences and interactions between railway and road traffic noise). Gothenburg, Occupational and Environmental Medicine, University of Gothenburg.

PUBLICATIONS FROM THE PROJECT (AS OF APRIL 2014)

Croy, I., Smith, M. G. and Persson Waye, K. (2013) Effects of train noise and vibration on human heart rate during sleep: An experimental study. BMJ Open, **3**(5): e002655

Janssen, S., Vos, H. and Koopman, A. (2013). A meta-analysis of surveys into vibration annoyance from railway. Internoise 2013. Innsbruck, Austria

Moorhouse, A., Waddington D., Peris, E., Woodcock, J., Sharp, C. and Sica, G. (2013) Outline proposal for a good practice guide on the evaluation of human response to vibration from railways in residential environments. Proceedings of Meetings on Acoustics, **19**

Peris, E., Woodcock, J., Sica, G., Sharp, C., Moorhouse, A. and Waddington, D. (2013) Guidance for new policy developments on railway vibration. Proceedings of Meetings on Acoustics, **19**

Persson Waye, K., Janssen, S., Waddington, D., Groll, W., Croy, I., Hammar, O., Koopman, A., Moorhouse, A., Peris, E., Sharp, C., Sica, G., Smith, M. G., Vos, H., Woodcock, J. and Ögren, M. (2014). Rail freight vibration impacts sleep and community response: An overview of CargoVibes. ICBEN 2014. Nara, Japan.

Persson Waye, K., Smith, M. G., Ögren, M. and Croy, I. (2014). The impact of railway freight with regard to vibration level, noise and number of trains on sleep. ICBEN 2014. Nara, Japan.

Sharp C., Woodcock J, Peris E., Sica G., Moorhouse A.T., Waddington, D.C. (2013) Analysis of railway vibration signals using supervised machine learning for the development of exposure-response relationships. Proceedings of Meetings on Acoustics, **19**

Smith, M. G., Croy, I., Ögren, M. Hammar, O., and Persson Waye, K. (2014). Freight trains, nocturnal vibration and noise, and their physiological effects during sleep. ICBEN 2014. Nara, Japan.

Smith, M. G., Croy, I., Hammar, O. and Persson Waye, K. (2013) Noise sensitivity impacts the evaluation of sleep due to vibration and noise from freight trains. Internoise 2013. Innsbruck, Austria

Smith, M. G., Croy, I., Hammar, O., Ögren, M. and Persson Waye, K. (2013) Nocturnal vibration and noise from freight trains impacts sleep. Proceedings of Meetings on Acoustics, **19**: 040114

Smith, M. G., Croy, I., Ögren, M. and Persson Waye, K. (2013) On the influence of freight trains on humans: A laboratory investigation of the impact of nocturnal low frequency vibration and noise on sleep and heart rate. PLoS ONE, **8**(2): e55829.

Smith, M. G., Ögren, M. and Persson Waye, K. (2012) Vibration and noise induced sleep disturbance from trains – The importance of vibration direction. Proceedings of Meetings on Acoustics, **15**: 040001

Woodcock, J., Peris, E., Moorhouse, A. and Waddington, D. (2014) Guidance document for the evaluation of railway vibration.

Woodcock, J., Peris, E., Waddington, D. and Moorhouse, A. (2013) Developing a good practice guide on the evaluation of human response to vibration from railways in residential environments. 11th International Workshop on Railway Noise. Uddevalla, Sweden.