The use of vibration health response information in the framework of environmental health impact assessments

Benedikt Tappauf
tappauf.consultants, Dr. Robert Graf Str. 15/18, 8010 Graz, Austria

Clemens Tappauf, Michael Cik
Graz University of Technology, Rechbauerstrasse 12/2, 8010 Graz, Austria

Peter Lercher
Division of Social Medicine, Medizinische Universität Innsbruck, Sonnenburgstrasse 16, A-6020 Innsbruck, Austria

Rainer Flesch
Graz University of Technology, Rechbauerstrasse 12/2, 8010 Graz, Austria

Summary

For an environmental health impact assessment of tramway noise and vibrations we carried out a series of detailed vibration measurements at 45 locations (4800 passbys). The measurement locations were considered being representative for a proper population assessment, some of them were considered being critical to a local citizen initiative.

Firstly, we followed the Austrian guidelines ONORM S 9012 (2010-02-01), where vibration calculation is based on $W_m(t)$-weighted acceleration. Secondly, we aimed to relate the obtained results from the vibration measurements to the few existing exposure-response curves, available in literature. It turned out, that the available exposure-response information was based on different vibration exposure factors and was difficult to translate for various times of the day. Although, the comparison revealed surprisingly good agreement for most of the reported exposure-response information, a substantial departure is observe in the newest compilation.

This paper presents and discusses some procedures for linking measured vibration data to the available relationships, needed in the framework of an environmental health impact assessment.

PACS no. 43.40.Nn

1. Introduction

Although the vibration levels elicited by tramways are smaller than those by conventional trains (higher speed and higher axle loads) the close proximity of the buildings to the tracks – especially in cities with old building structures – can lead to immission levels of disturbing character. Since 2010 in the city of Graz, several citizen initiatives issued complaints about new trams, because of higher vibrations. The company conducted vibration measurements, and started a program to optimize the tram. Although a significant reduction of the vibration levels was achieved, the concerned citizens were still complaining. Therefore, a health expert evaluating the complaints in an integrated assessment of vibration together with acoustics exposure-response information, basing on new measurement program was conducted.

2. Methodology

45 noise and vibrations measurement locations (4800 passbys) were considered being representative for a proper population assessment. Our survey contained different houses (from detached houses to tower blocks), types of construction (like wooden or concrete ceiling), situations (including switches, stops, and corners) and distances to the track. Some homes were considered being very critical by the local citizen initiative. In a first step we followed the Austrian guidelines ONORM S 9012 (2010-02-01), where vibration calculation is based on $W_m(t)$-weighted acceleration. It turned out, that in all homes vibration levels complied with standard requirements. Regularly, the work of engineers ends with comparing the measurements with the limits in the standards. Evaluating the complaints in

Table I. Measurement results for typical Homes.

	W_m weighted velocity running rms-integration time = 1 s (Mean)	W_m weighted velocity running rms-integration time = 1 s (Mean + 2S)	W_m weighted acceleration RMS over train passby (integration time 12 seconds)	W_m weighted acceleration RMS over 24 h)	W_k weighted acceleration RMS over train passby (integration time 12 seconds)	W_k weighted acceleration RMS over 24h
House with highest impact	0,18 mm/s	0,34 mm/s	5,9 E-3 m/s²	1,5 E-3 m/s²	13 E-3 m/s²	3,4 E-3 m/s²
Typical House with medium impact	0,10 mm/s	0,17 mm/s	2,3 E-3 m/s²	5,4 E-4 m/s²	4,8 E-3 m/s²	1,1 E -3 m/s²
Typical House with low impact	0,06 mm/s	0,08 mm/s	1,2 E-3 m/s²	2,6 E-4 m/s²	2,7 E-3	5,9 E -4 m/s²

an integrated assessment of vibration and noise, we compared our measurements to the few existing exposure-response curves available in literature. It turned out, that the available exposure-response information was based on quite different vibration exposure factors. The measurements were transferred into the required exposure factors as explained in Chapter 3.1 to 3.3. Our result showed the relationship between different exposure factors given in Chapter 3.4. Finally, we chose 3 buildings, a typical building with low impact, one with medium impact and a very exposed building, for comparing the measurements to exposure-response relationships. The different exposure factors are given in Table I .

Although we calculated the ground borne noise from the vibration signal and measured the passby noise of different tramway types, using a binaural dummy head measurement system to do additional psychoacoustic analysis, this paper concentrates on the vibration analysis only.

3. Exposure factors

First we calculated the W_m - slow weighted velocity (Running RMS - integration time 1sec.), and the RMS of the acceleration over 24h, using the weighting functions W_k and W_m.

In most objects the W_k weighted acceleration was about 2,2 times higher than the W_m weighted acceleration; since frequencies over 20 Hz were dominant in our frequency spectra.

3.1. Frequency weighting

Since [8], [9] and [4] use the weighting function W_m, [6] and [10] use W_k. For railway vibrations experience of over 500 measurements showed that - using velocity as input signal – mostly W_m weighting does not really effect the results, as the weighting factors are very similar within 10 to 80 Hz. In practical experience the measurement data are based on one specific national weighting. Most standards – and therefore most vibration data – is based on or is very similar to W_m weighted acceleration/velocities. In code of practise transforming these measurements using different weightings, leads to unwanted uncertainties. Exposure-response relationship using unweighted (but band passed) velocity descriptors might be more helpful.

3.2. Time weighting

The maximum velocity v_{max} – without any time integration – is not used in any of the mentioned studies. However, it would be a descriptor available in nearly all projects and all measurement reports.

3.2.1. RMS passby

The RMS is calculated as followed. If the passby RMS is needed T will be the passby time of the train (e.g. 10 to 30 seconds).

$$a_w = \sqrt{\frac{1}{T}\int_0^T a_w^2\,(t)dt} \tag{1}$$

The passby RMS is controlled by setting the measurement time (a long time leads to low values) which should be mentioned.

3.2.2. Running RMS

Running RMS consider transient and occasional shocks. It is defined as maximum of the rms evaluation a_{wt}.

$$a_w(t_0) = \sqrt{\frac{1}{\tau}\int_{t_0-\tau}^{t_0}\left(a_w(t)\right)^2 dt} \tag{2}$$

The result is extremely depending on the integration time or constant τ, 0,125sec (fast) or 1sec (slow) (a short integration time leads to high values) that must be mentioned.

3.3. Relationship between annoyance an number of events / exposure time

It is clear that annoyance increases with the number of events. National standards broadly take that into account.

3.3.1. RMS 24 hr/ assessment time

Some standards use a RMS value over the assessment period to calculate the impact, which then grows with the square root of the events or rather the impact time. A vibration occurring 100 times a day would produce the same level of annoyance as a vibration 30 % lower, occurring 200 times a day. The RMS value over a certain time is calculated:

$$a_{w,rms,24hr} = a_{w,rms,measured}\sqrt{\frac{T_{measured}}{T_{ass.(24hr)}}} \quad (3)$$

3.3.2. Vibration Dose Value

In laboratory experiments [2] a relationship between the number of passing trains N and the vibration magnitude V: n * $V^{3,7}$ was found, after testings with RMQ (n * V^{4}) and RMS (n * V^2) which were less satisfactory. A vibration occurring 100 times a day would produce the same level of annoyance as a vibration 15 % lower, occurring 200 times a day. The BS 6472-1:2008 uses the relationship:

$$VDV_{day,night} = VDV_{measured} * \sqrt[4]{\frac{T_{day/night}}{T_{measured}}} \quad (4)$$

For both calculation methods (RMS or VDV) the number of events respectively the impact time is less important than the vibration level. As in most cases the maximum velocity, or a running RMS is available, exposure-response relationships, based on the maximal occurring vibrations, are very efficient. If the number of referred passbys is given, the number of passbys can - if wished - be considered by using one of the given relationships.

3.4. Relationship between different exposure factors

As mentioned in the most cases, the measurement values have to be converted. Because the conversion requires a lot of effort there is a need for simplified recalculations. Our experience, derived from over 500 measurements, showed the following relationships between different exposure factors.

Table II. Relationship between different exposure factors

From	To	Factor
Frequency Weighting		
Velocity without weighting	W_m velocity	1
W_m acceleration	W_m velocity	1/35,7
W_m weighting	W_k weighting	2,2*
*(if frequencies lower than 12 Hz are dominant 1,2)		
Time Weighting		
RMS passby	Slow linear filter	1,7
RMS passby	Fast linear filter	2,2
RMS passby	Maximum	5

4. The studies used

Evaluating the annoyance information, we compared the measurement results with various exposure-response relationships. Table III shows the used surveys.

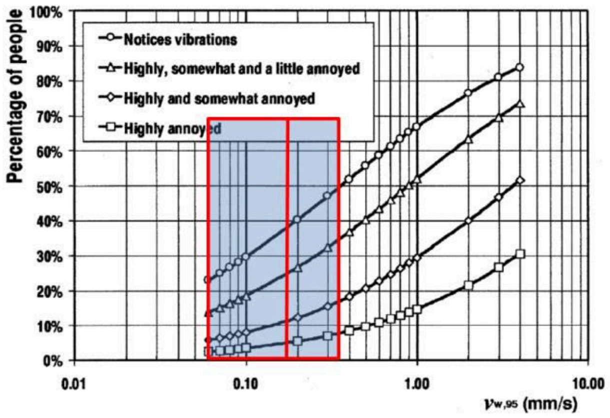
Table III. Used surveys.

Study	Descriptor Unit Direction	Time weighting	Frequency weighting
Norway	$v_{w,95}$ [mm/s] vertical	1 s	NS 8176/W_m
USA & Canada	Passby maximum velocity [dB] vertical	1 s	-
UK	RMS 24_{hour} [m/s²]	24h	W_m / W_k
Sweden	Maximum velocity mm/s	1 *s*	SS 460 48 61/W_m
Cargo-vibes	$v_{w,95}$ [mm/s] RMS 24_{hour} [m/s²] *VDV [m/s^{1,75}]*	0,125 s 24h 24h	W_k

4.1. Norway

In Norway a field survey of vibrations in homes near the road and the rail traffic (700 respondents) [8] was carried out. The objects of study were selected by their level of indoor sound, which should be low ($L_{Aeq,24h}$<30 dB). There was no significant difference between the vibration sources but unique exposure-response relationships were estimated for various degrees of annoyance (Figure 2). The results show that 5 % of the respondents were very disturbed at a vibration level of 0.1 mm/s and 30 % felt similar at a level of 4 mm/s. The Norwegian descriptors are based on velocity, $v_{W,95}$, (statistical 95- percentiles) derived from by W_m. weighted Running RMS quantities (time constant Slow) [10]. Results shown in Figure 2.

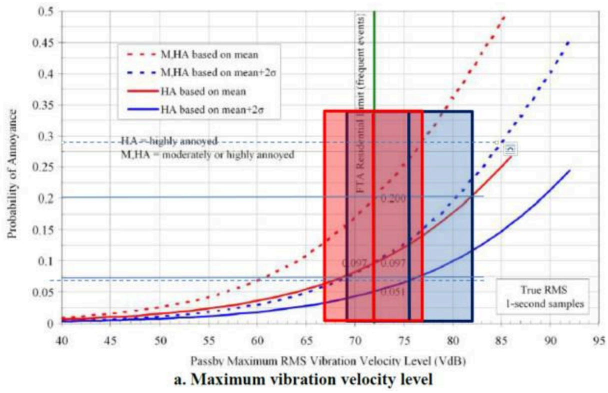
Figure 2. Exposure-response relationship [8].



4.2. American Studies

In 5 American cities 1300 interviews 41 and vibration- and sound-measurements were done. All kinds of rail (heavy, light, freight, commuter, Intercity rail) and alignment (underground, surface) were considered. The number of trains can be given by 117 to 530 during the day and 26 to 143 in the night. The developed exposure-response relationships[11] are based on velocity without frequency weighting and a time weighting of 1sec. The vibration annoyance relationship is given for the mean of the passbys (energy average vibration of all passbys) and the passby maximum (the mean plus 2 standard deviations is used), all values are expressed in dB with a reference of 1 μin/s = 2,54*10^{-5} mm/s). As the annoyance based on the mean or maximum values were different, the higher values of both were taken for the assessment. Results shown in Figure 3.

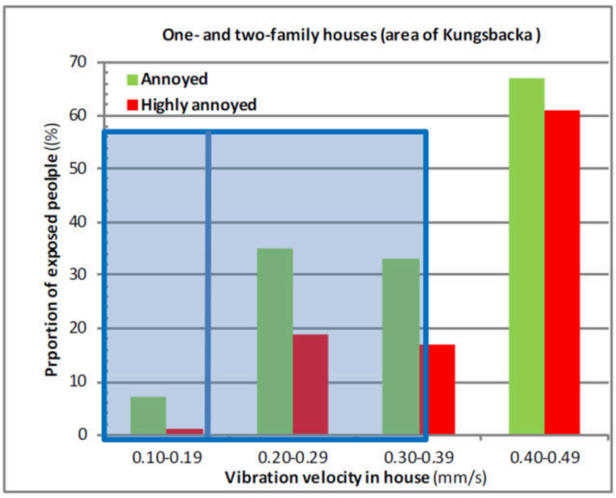
Figure 3. Exposure-response relationship [11].



4.3. Sweden

A Swedish field survey [4] showed a low probability of annoyance at vibration test levels between 0.10 and 0.19 mm/s. However, it is significantly higher than 17 % at levels between 0.20 and 0.39 mm/s, above 0.4 mm/s, it is higher than 61 %. The Swedish descriptors are based on velocity derived from W_m weighted running RMS quantities (time constant slow). Results shown in Figure 4.

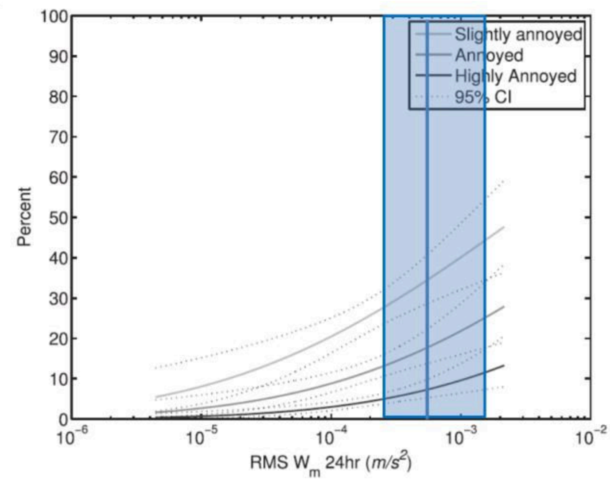
Figure 4. Exposure-response relationship [4].



4.4. UK

In the UK Questionnaires were completed with residents exposed to railway induced vibration (N=931) and vibration from the construction of a light rail system (N=350). [9] Using 60 different vibration exposure descriptors along with 6 different frequency weightings, none were found to be a better predictor of annoyance than any other. However, use of relevant frequency weightings was found to improve correlation between vibration exposure and annoyance. A unified exposure-response relationship could not be derived due to differences in response to the two sources so separate relationships are presented for each source. The UK published descriptors are based on W_m weighted acceleration RMS quantities over a 24h period. Results shown in Figure 5.

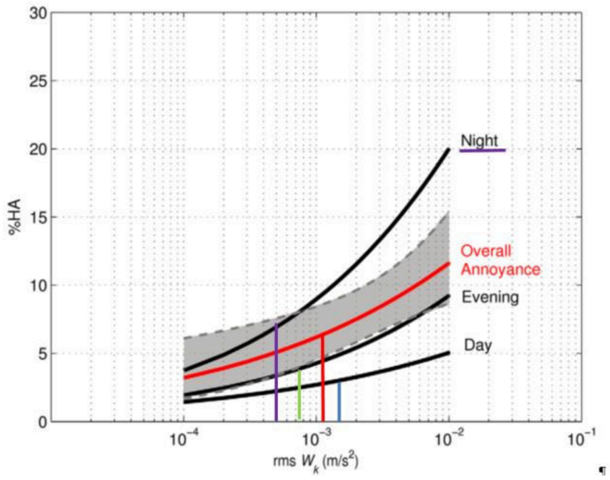
Figure 5. Exposure-response relationship [9].



4.4.1. Exposure-response relationships for different times of a day.

In [6] exposure-response relationships for different times of a day are published. It can be seen that Annoyance in the evening and at night is much more higher than during the day. Different weights for the evening 19:00-23:00 (factor 6,7) and at night 23:00-07:00 (factor 50) are suggested.

Figure 6. Exposure-response relationship [6].



The descriptors are based on W_k weighted acceleration RMS quantities calculated over daytime (07:00 – 19:00), evening (19:00 – 23:00) and night (23:00 -07:00). The results for a **typical home with medium impact** can be seen in Figure 6. This examination considers the diverse traffic over 24h. Surprisingly, the night seems to lead to the highest level of highly annoyed people, although the traffic is very low in these hours. Comparing the measurent to the national standards, the vibration dose during the day would be the more critical level!

4.5. Cargovibes

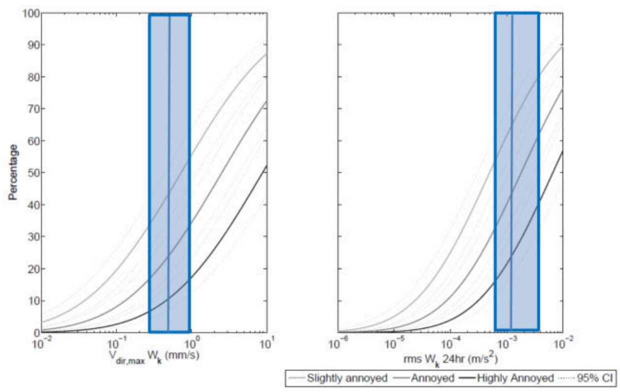
In [10] exposure-response relationships were derived from a sample of 4129 exposure and response data, drawn from 7 socio-vibration-studies in Europe and North America (4 of them were used for our assessment). The publication also contents some polynomial fits. The relationships are given for 3 different vibration descriptors:

- $V_{dir\ max}$, the maximum W_k weighted fast (0,125s) exponentially filtered RMS velocity over the 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.

The evaluation was done with the W_k weighted acceleration RMS over a 24h period and the maximum W_k weighted fast exponentially filtered RMS velocity. Results shown in Figure 7.

The results based on the W_k weighted acceleration RMS over a 24h period is much higher than all other results. It has to be mentioned that the descriptor W_k weighted acceleration RMS over a 24h gives usual values due to [6].

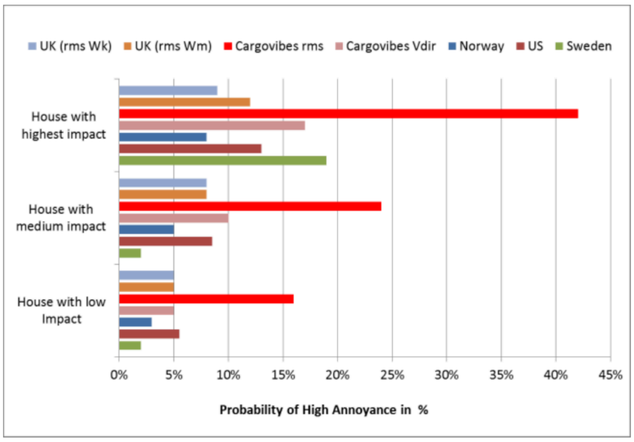
Figure 7. Exposure-response relationship [10].



5. Summary

The percentage of highly annoyed people based on various available exposure-response information was obtained (Figure 8). The calculation according to the studies in Norway, America and Sweden are only based on the maximum impact. As the train passbys of our project was within the passbys of the surveys, this should not lead to any uncertainty. The results according to the studies in the UK and the Cargovibes consider - as the RMS W_m 24hr is depending on the number of train passbys - the high frequency of passbys during the day but not especially the high frequency in the evening and the low traffic at night. This is considered in the exposure relationships according to [6].

Figure 8. Annoyance due to various exposure-response relationships.



The Cargovibes RMS data show a substantial deviation from the other survey data. However, among the homes with the highest impact the percentage of high annoyance differs also in this group up to 10% while the agreement for homes with medium impact is really good. Some differences in the annoyance response are always to be expected due to different soundscapes, building structures, tram types, operating schemes and environmental or social conditions [11].

From a practical point of view, exposure-response relationships based on a maximum Running RMS are more efficient than relationships using RMS values over a certain assessment time. In most cases maximum values are available in the measuring reports. Most standards – and therefore most of the vibration data – is based on W_m (or similar) weighted acceleration/velocities. In case using the velocity as input signal, experience of over 500 measurements showed, that for railway vibrations in most cases W_m weighting does not have very much influence on the results.

Most of the existing surveys base on a huge number of interviews but a weak number of measurements. Future studies should be based on the huge amount of existing measurement data - already conducted by the providers.

As in practical experience using different frequency weightings lead to unwanted uncertainty W_m or even unweighted (but band passed) maximum velocities should be used as exposure factors.

Acknowledgement

This project has been funded by Holding Graz Linien. The authors would like to thank J. Woodcock, giving us helpful information.

References

[1] Cik M, Lercher P, Fallast K. “Do current guidelines on vibration sufficient health protection at the community level independent of the accompanying soundscape”. Euronoise 2015.

[2] Howard H., Griffin M. “Human Response to Simulated Intermitted Railway-Induced Building Vibration” 1988, Journal of Sound an Vibration, Vol. 120(2) pp. 413-420

[3] Janssen S, Vos H. , Koopman A. “A meta-analysis of surveys into vibration annoyance from railway” Internoise 2013 Innsbruck

[4] Klaeboe R. Öhrström E., Turunen-Rise, Bendtsen H, Nykänen H. “Vibration in dwellings from road an rail traffic – Part II: towards a common methodology for socio-vibrational surveys” Applied Acoustics 64 (2003) 111-120

[5] Ohrstrom E. Effects of exposure to railway noise--a comparison between areas with and without vibration. J Sound Vib. 1997 Aug 28;205(4):555–60.

[6] Peris et al: „ Annoyance due to railway vibration at different times of the day” J. Acoust. Soc. Am. 131 (2), February 2012 and online publication University of Salford, UK 26.01.2012

[7] RIVAS „ Vibration in dwellings from road and rail traffic — Part II: exposure–effect relationships based on ordinal logit and logistic regression models “ Deliverable D 1.4 12.01.2011

[8] Turunen-Rise I “Sound and vibration comfort classification of buildings in Norway” Forum Acousticum Budapest 2005

[9] Waddington et al „Human response to vibration in resdential environments“J. Acoust. Soc. Am. 135 (1), Jan 2014

[10] Woodcock, Peris, Moorhouse, Waddington et al: „Guidance document for the evaluation of railway vibration” Cargovibes Deliverable D 1.5 University of Salford, UK 26.01.2012

[11] Zapfe J., Saurenman H. Fidell S. “Ground-Borne Noise and Vibration in Buildings Caused by Rail Transit “Contractor’s Final Report for TCRP Project D-12, Submitted December 2009