RIVAS

Railway-Induced Vibration Abatement Solutions
Collaborative project

Review of existing standards, regulations and guidelines, as well as laboratory and field studies concerning human exposure to vibration

Deliverable D1.4

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Work Package WP1: Assessment and monitoring procedures
Task T1.1: Assessment of human exposure

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EXECUTIVE SUMMARY

RIVAS deliverable D1.4 is a review of existing standards, regulations and guidelines, as well as field and laboratory studies dealing with vibration of buildings near railways causing annoyance as whole body vibration and vibration-induced noise (groundborne noise). The combined effect of vibration and noise is also considered.

The document is divided into four parts. In Part 1, knowledge and recent findings on human response to vibration from railway traffic are summarized. Standards and guidelines are reviewed for vibration (Part 2) and indoor noise (Part 3), including the combined effect of indoor noise and vibration. In Part 4, the current state of descriptors and limits currently used are commented, leading to potentially more appropriate descriptors.

Part 1: Human response to vibration from railway traffic

Recent laboratory and field studies help to clarify the notions of absolute perception threshold (which genuinely differs from acceptable annoyance level as a reference for regulations and guidelines), difference threshold (minimum perceived difference in vibration levels), annoyance (related to quality of life) and disturbance (related to quality of sleep). Both vibration and indoor noise are considered.

For vibration, recent findings give evidence that absolute thresholds for the perception of vibration are inconsistent with current standards whose frequency weightings might underestimate people's sensitivity. As for difference thresholds, studies show that people can feel a minimum change of 25 % in the vibration magnitude. Subjective annoyance and disturbance are absolutely different from perception. Field surveys have led to exposure-response relationships which are used to determine proper vibration criteria for acceptable annoyance level.

For noise and low-frequency noise (below 100 Hz, corresponding to the frequency range of groundborne noise), there is a more general agreement on perception thresholds and on the associated A-weighting. Field surveys lead to exposure-effect relationships showing that the effect of noise is influenced by the presence of vibration.

Part 2: Vibration

As appears from the presented international and national standards as well as guidelines, there is a great variety of descriptors, defined by different mathematical operators (maximum running r.m.s. value, r.m.s. equivalent value, and vibration-dose value), based on different physical quantities (acceleration or velocity), using single number values calculated from different frequency weightings and expressed in different units. However, there is an agreement on measuring vibration on floors at mid-span, often dominant in vertical direction.

In general, national limit criteria are set above perception thresholds. But few of them are derived from a clear cutoff annoyance level, resulting from exposure-response relationships. Vibration criteria are based on maximum values and/or mean equivalent values. Quality schemes of buildings vis-à-vis vibration have already been developed in some countries. In spite of the variety of used descriptors, a provisional comparison between national criteria is given. Further investigation will be performed within RIVAS when evaluating the effects of mitigation measures for typical cases.

Concerning the minimum perceived difference in vibration levels, a 40 % variation has often been considered, higher than the lab findings (25 %) mentioned in Part 1.

Part 3: Indoor Noise

Fewer standards and guidelines (than for vibration) exist for groundborne noise from railways, but several documents deal with indoor low frequency noise in general. Fewer descriptors are proposed, all expressed as A-weighted SPLs. However, there is no agreement on indoor noise measurement.

The measurement uncertainty of low-frequency indoor noise as well as the difficulty in identifying groundborne noise from airborne noise have led several countries to estimate groundborne noise by calculation.

National criteria obviously relate to acceptable levels well above a perception threshold (0 dB). Maximum values and/or mean equivalent values are used. A few countries propose sound classes with different limit sound levels. National limits are quite different, probably because the corresponding standards and guidelines focus on general indoor noise (structure-borne or airborne, low-frequency or broadband) from different sources inside or outside buildings. Two documents clearly state that low-frequency noise is perceived louder than broadband noise and specific criteria should be set for low-frequency noise. A procedure to detect low-frequency noise is proposed in several countries from the difference between C-weighted and A-weighted sound levels.

Laboratory experiments and field surveys show that both vibration and indoor noise influence the overall annoyance of exposed people and must be observed (measured or estimated).

Part 4: Final comments

Overall annoyance of exposed people results from the combined effect of vibration and noise. Consistent metrics (log-scale levels) should be used for both, whether measured or estimated, unless their descriptors badly correlate subjective annoyance. Two types of indicators seem equally meaningful: maximum values (of running r.m.s. quantities) and traffic-oriented equivalent (r.m.s.) values. The former are more related to sleep disturbance, the latter are more related to annoyance. Vibration as well as noise is concerned. The corresponding criteria for acceptable annoyance and disturbance may have an impact which differs to some extent regarding the railway traffic (freight, passenger, light train).

Frequency weightings that are more consistent with the findings of recent studies might substitute those (international W_m/KB and British W_b/W_d) in the current standards. They would result in rather flat curves for acceleration instead of the present flat curves for velocity.

National vibration criteria should be determined from exposure-effect relationships. Field studies should be strongly supported to this end.

Finally, there is an agreement in several countries on setting low-frequency noise criteria lower and more severe than for broadband noise. The detection of low-frequency noise can then be performed by comparing C- and A-weighted sound levels.

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INTRODUCTION

Work Packages of the RIVAS project aim at developing measures in order to mitigate annoyance of people exposed to railway-induced vibration and joint noise. The task of WP1.1 is defining appropriate procedures to assess the benefits of these abatement solutions. The two main goals are the following:

(*i*) identify descriptors and criteria used in Europe so that the performance of the mitigation measures developed in RIVAS could be translated in terms of descriptor attenuation understandable by each partner and evaluated according to the corresponding national standards;

(*ii*) identify the most appropriate descriptors and limits in order to more properly evaluate the effects of the mitigation measures.

The first step consists in a review of existing standards, regulations and guidelines, as well as laboratory and field studies on the topic. This deliverable D1.4 synthesizes the results of the review. Chapter 1 deals with knowledge on human response to vibration and groundborne noise (focusing on railway when possible): perception, annoyance and response-exposure relationships.

Then, international and national standards as well as guidelines are scrutinized first for vibration (chapter 2), then for vibration-induced noise – also called groundborne/structure-borne noise (chapter 3). The combined effect of vibration and noise is also considered in chapter 3. For each stimulus (vibration or vibration-induced noise), the descriptors used in the reference standards and guidelines are overviewed before they are analysed in a comparative way. Then the limit criteria expressed as comfort requirements in the different reference documents are given, also followed by a comparative study; perception thresholds are analysed when information is given.
In the last chapter (chapter 4), a critical analysis of the existing descriptors and limit values is performed.

In the annex A are summarized the terms and definitions of the quantities that are mentioned in the reviewed standards and guidelines.

This document aims at providing a basic state-of-the-art on human exposure to railway vibration. While proceeding, the RIVAS project might make available further information and comments. The deliverable will then be updated before the end of the project (end of 2013).

We are very grateful to our colleagues and partners of the RIVAS project for their helpful comments and suggestions.

1. HUMAN RESPONSE TO VIBRATION FROM RAILWAY TRAFFIC

1.1 Perception of vibration

Railway traffic brings about vibration which propagates through ground and is transmitted into nearby buildings throughout their structure (walls, columns and floors). Low-frequency noise (rumble) is also radiated from the vibrating floors and walls. Vibrations cause other phenomena to happen: rattle (windows, doors, furniture, glasses on tables, etc.), movements of objects (visual effects). Furthermore, surface traffic induces simultaneous airborne noise.

"*Human response to vibration in buildings is very complex*" (ISO 2631-2). Laboratory experiments have shown for long how widely the perception of vibration varies among tested subjects (Parsons and Griffin, 1988; for a review Griffin, 1990). Notwithstanding the used experiment method, many internal and external factors can influence the individual's detection sensitivity: among others, magnitude, frequency and duration of vibration, position (sitting, standing, lying), direction (vertical, horizontal, rotational), location (hand, seat, foot, recumbent), activity (resting, reading, sight), frequency of occurrence, and so on. As Tables 1.1 illustrates, standards and guidelines may include some indicative information about vibration perception.

Table 1.1 Vibration magnitude and perception (sinusoidal vibration)

r.m.s. weighted acceleration (m/s^2)	**Perception**
< 0.01	Not perceptible
0.015	Threshold of perception
	Barely perceptible
0.02	
	Easily perceptible
0.08	
	Strongly perceptible
0.315	
> 0.315	Extremely perceptible

Source: VDI 2057 Blatt1.

In ISO 2631-1:1997, the **absolute threshold of perception** of W_k-weighted vertical vibration is reckoned to be about 0.015 m/s^2 [84 dB re 10^{-6} m/s^2]. It represents the median peak magnitude detected by "alert, fit persons" (interquartile range: 0.01-0.02 m/s^2). In terms of KB value (DIN 4150) the threshold is set at 0.1. The American FTA (2006) and FRA (2005) manuals mention about 0.045-0.08 mm/s for vibration velocity (see section 3.3).

ISO 2631-2:1989 proposed base curves for the perception of vibration in buildings. "*In general no adverse comments, sensations or complaints have been reported*" for values (acceleration or velocity) below the curves (Figure 1.1).

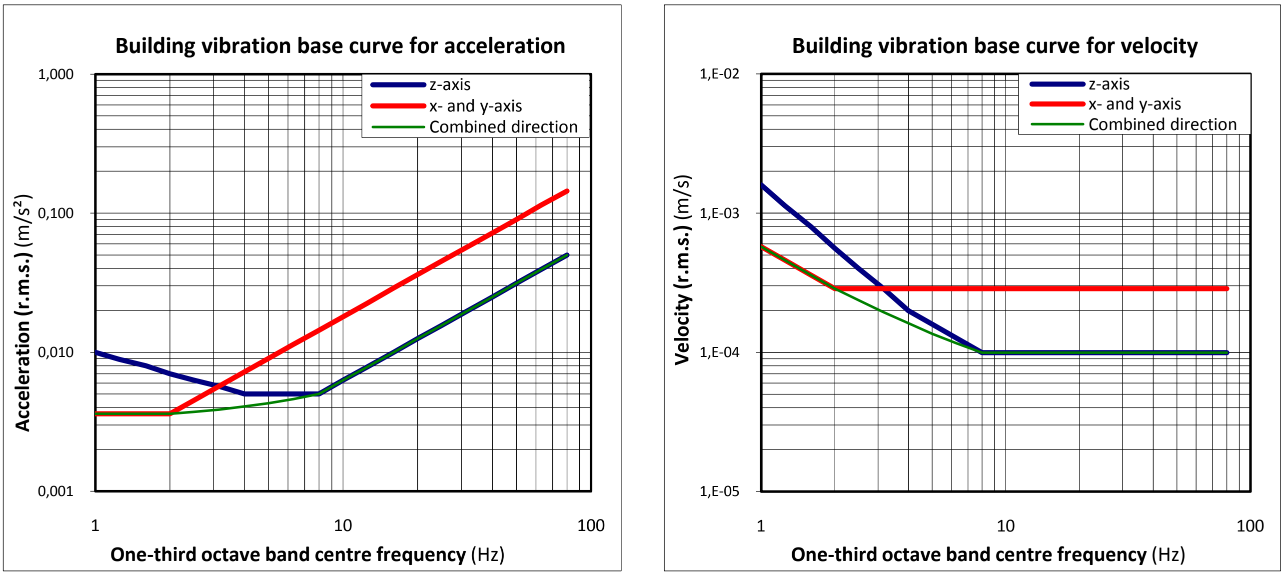


Figure 1.1 Building vibration base curves of ISO 2631-2:1989

The standards specify weightings that represent the human sensitivity to vibration varying with frequency and differing with direction. Even so, recent findings (Bellmann, 2002 and Bellmann *et al.*, 2004; Morioka and Griffin, 2006, 2008) give evidence that absolute perception thresholds of vibration are rather constant for acceleration at frequencies above 8 Hz. They are inconsistent with current standards whose weightings might underestimate actual sensitivity to vibration (Figure 2.1). As Morioka and Griffin (2008) point out, "*the unweighted acceleration is a better predictor than weighted acceleration of whether vertical vibration of seated subjects will be felt*".

Recumbent position is representative of real situations at night-time in dwellings. But there are fewer perception studies for this posture than for seating and standing (Miwa *et al.*, 1984; 1988; Yonekawa *et al.*, 1999; Maeda *et al.*, 1999). Matsumoto *et al.* (2011) recently investigated perception thresholds of vertical whole-body vibration for recumbent subjects (supine position) in two laboratory experiments. Three groups of 12 subjects took part in the first test. Perception thresholds of sinusoidal continuous vibrations in the vertical direction (duration of 4 s at constant amplitude) were measured at 2, 4, 8, 16, 31.5 and 63 Hz (up-and-down method). No significant effect of gender was found while vibration perception might diminish with age. The group of 12 young males also took part in the second experiment on the effect of vibration duration, by using sinusoidal vibrations at the same frequencies, modulated by Hanning windows with different durations (0.5, 1, 2 and 4 s). The peak vibration acceleration at the perception threshold was lower when duration increased. The perception threshold of vibrations with different durations was reasonably evaluated by running r.m.s. acceleration (MTTV) with an integration time between 0.63 and 0.8 s as long as vibration duration was longer than 0.5 s[1]. When using the vibration-dose value (VDV), the perception threshold depended less on vibration duration; however it depended more on frequency.

The **difference threshold** (or Just Noticeable Difference JND) is the difference in magnitude between two stimuli that a person can discriminate 50 percent of the time (usually accepted proportion of time). The JND can be expressed as the relative difference threshold $\Delta I/I$ (or Weber ratio) where ΔI is the absolute difference threshold of the stimulus and I is its magnitude. A few studies can be found on difference thresholds for vibration. Morioka and Griffin (2000) determined difference thresholds for seated subjects exposed to vertical sinusoidal vibration at two magnitudes (0.1 and 0.5 m/s² r.m.s.) and two frequencies (5 and 20 Hz). They found that Weber fractions were

[1] The Japanese standard JIS C 1510 uses a time constant of 0.63 s.

about 10% without significant difference regarding magnitude or frequency. Bellmann (2002) measured JNDs for subjects exposed to vertical whole-body vibration with an acceleration of 0.063 m/s² at frequencies from 5 to 50 Hz. He found a median level difference of about 1.5 dB (19 %) without frequency-dependency. Matsumoto *et al.* (2002) found lower Weber ratios (from 5.2 to 6.5 %) for a vibration of 0.7 m/s² r.m.s. at six frequencies (4, 8, 16, 31.5, 63 and 80 Hz). The results may be rather different because of the method and the range of the experiments.

Said et al. (2001) studied vibration discrimination with simultaneous noise in a lab experiment with twenty persons (10 males and 10 females). At each of three sound levels (below 30 dBA, 45 dBA and 55 dBA), twenty participants (ten male and ten female) had to respond "same" or "different" when they were presented a pair of vibration stimuli (a reference signal and a 25-percent higher comparison signal). Four reference magnitudes (KB_{Fmax} values) were chosen: 0.2, 0.4, 0.8 and 1.6. The sensitivity index d' lay between 0.96 and 1.2, which means a proportion of correct answers between 56 % and 60 % (Macmillan and Creelman, 2005). But the authors emphasized that a 25 % increase in KB_{Fmax} values does not always result in the same change for KB_{FTr} values.

From recent studies, one might infer that the more exposed people can feel a change in vibration by 25 % (2 dB), the lower background noise level is.

1.2 Annoyance and disturbance from vibration

Exposure to vibration affects not only wellbeing, but also health. Indeed health may properly mean (WHO Charter) "*a state of complete physical, mental, and social well-being and not merely the absence of disease or infirmity"* (EPA, 2011). At common levels, whole-body vibration causes annoyance, *i.e.* a negative evaluation of environmental conditions (Guski, 1999). This state of the individual is associated with disturbance, nuisance, discomfort, aggravation, dissatisfaction, concern, bother, displeasure, anger, harassment, irritation, vexation, exasperation, anxiety, depression, helplessness, distress, hate. It also stems from reasons such as somatic damage, covariation with failure, loss of orientation, loss of control, negative evaluation of the source, and high magnitudes of stimuli (Guski *et al.*, 1999). In the following, we distinguish rather artificially, for clarity, **annoyance** (as **discomfort**) and **disturbance** (as **awakening**, **sleep trouble**). ISO 2631-1:1997 suggests discomfort reaction with respect to vibration magnitude (Table 1.2): discomfort may be expressed at a vibration acceleration as low as 0.315 m/s².

Table 1.2 Vibration magnitude and discomfort reaction

r.m.s. acceleration (mm/s²)	Reaction
Less than 0.315	Not uncomfortable
0.315 to 0.63	A little uncomfortable
0.5 to 1.0	Fairly uncomfortable
0.8 to 1.6	Uncomfortable
1.25 to 2.5	Very uncomfortable
More than 2.5	Extremely uncomfortable

Source: ISO 2631-1:1997.

Discriminating between physical quantity and subjectively perceived quantity, several authors (*e.g.* Howarth and Griffin, 1988) studied a relationship (known as Stevens' power law) between the psychophysical subjective magnitude ψ (discomfort/annoyance intensity) of the vibration stimulus and its physical quantity φ (vibration amplitude):

$$\psi = k\varphi^n$$

where the exponent n is the rate of growth of discomfort.

Comfort and annoyance are notions that cannot be grasped in too simplistic a way. Physical comfort could mean the absence of pain and the feeling of wellbeing while physiological comfort would result from factors that influence the individuals' physiological state (Dumur *et al.*, 2004). As a personal judgment, annoyance is affected by social and contextual co-determinants. Following other scholars, (Guski, 1999) distinguishes between 'mediating' variables and 'moderating' variables[1]. And annoyance moderators are 'personal' and 'social' factors (Table 1.3):

– "personal factors are variables that are tightly linked to an individual, show a considerable stability over time and situations, and vary between individuals considerably";

– "social factors are linked to situations and are shared to a considerable degree between individuals of a society".

Table 1.3 Annoyance moderators

Personal Moderators	Social Moderators
Sensitivity to vibration/noise	Evaluation of the source
Anxiety about the source	Suspicion of source controllers
Personal evaluation of the source	History of vibration/noise exposure
Coping capacity with respect to vibration/noise	Expectations

Source: adapted from Leventhall *et al.* (2003).

Figure 1.2, adapted from Leventhall *et al.* (2003), illustrates the central role that personal factors could play in annoyance from vibration, as they did for noise.

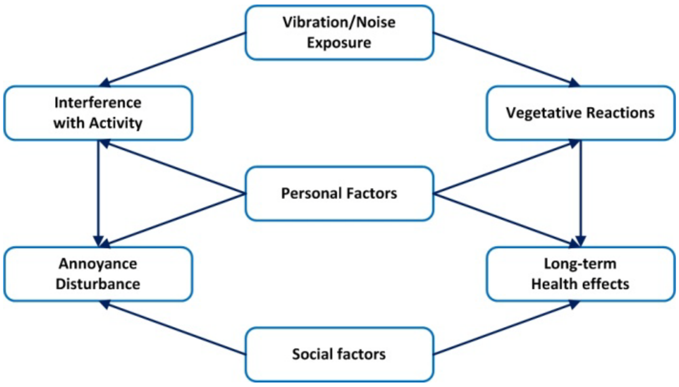


Figure 1.2 Factors 'moderating' annoyance/disturbance
Source: adapted from Leventhall *et al.* (2003).

Then any magnitude of physical descriptor (*i.e.* a vibration level) encompasses only part of subjective annoyance. This can also explain why some people may complain as they are exposed to vibration below the perception threshold. Comfort and discomfort are not symmetrical notions: lack of discomfort is a prerequisite for comfort, but it is not a synonym of comfort. Therefore, produced quality is not perceived quality.

Regarding change in the situation of residents, various contextual factors will influence annoyance. In particular, as for noise (Guski, 2004), a new nuisance might be accepted not so widely as an old one. In the same way, residents might surreact to a change in vibration condition: in case of a rise, they might react much more annoyed than predicted in steady-state conditions (like exposure-response relations). Conversely, in case of a fall, they might be much less annoyed. Furthermore, expecting an increase (resp. a decrease), they might be more (resp. less) annoyed than predicted.

Stallen (2002) presents annoyance by noise as a form of psychological stress. His approach can also apply to annoyance by vibration. However high annoyance may be, perceived control is another influent factor. In this respect, railway-induced vibration and groundborne noise may be perceived as a threat nearby dwellers cannot cope with so easily as with noise (Table 1.4). Maramotti (1994) put forward that the harder his/her working conditions, the more sensitive an individual might be to

[1] Mediating variables can be seen as "primary reactions", they depend on the stimulus variable, and they also influence the "secondary reaction". Moderating variables are independent of the stimulus, but they covary with each other, i.e. moderating and reaction variables may depend on each other.

environmental nuisance at home: discomfort will be seen all the worse so as he/she cannot cope with.

Table 1.4 Perception and sensation for noise, vibration and structure-borne noise

Nuisance	Perception	Sensation
Noise	Hearing	Annoyance and disturbance As long-distance stimulus: Possible escape Possible location
Vibration	Tactile through whole body	Annoyance and disturbance As short-distance stimulus: No possible escape No possible location
Structure-borne noise	Hearing	Annoyance and disturbance As short-distance stimulus: No possible escape No possible location

Source: from ÖNORM S 9012:2010.

Studies confirm that annoyance from vibration increases as the number and duration of vibration events increase. From laboratory experiments Howarth and Griffin (1988) found a relationship between the number of passing trains N and the vibration magnitude V: $N \propto V^{3.7}$ for equal annoyance. After testing two relationships: $N \propto V^4$ and $N \propto V^2$, they concluded that the r.m.s. vibration value was less satisfactory than the vibration-dose value.

A field survey on vibration in dwellings due to road and rail traffic (Turunen-Rise *et al.*, 2003; Klæboe *et al.*, 2003a and 2003b) was undertaken in 1997 and 1998 in Norway. The surveyed areas were selected so that indoor sound levels should be low ($L_{Aeq,24h}$ < 30 dB). Annoyance from vibration was reported from about 700 respondents on a categorical scale. Since there was no significant difference between the vibration sources, unique exposure-response relationships were estimated for various degrees of annoyance (Figure 1.3)[1]. They show that 5 % of the respondents were very disturbed at a vibration level of 0.1 mm/s, but the proportion amounted to 30 % at a level of 4 mm/s. By analogy with a limit noise exposure of 55 dB (L_{Aeq}) corresponding to 7-8 % highly annoyed people, the limit value of velocity $v_{w,95}$ of class C in NS 8176 was set at 0.3 mm/s for the reference class C.

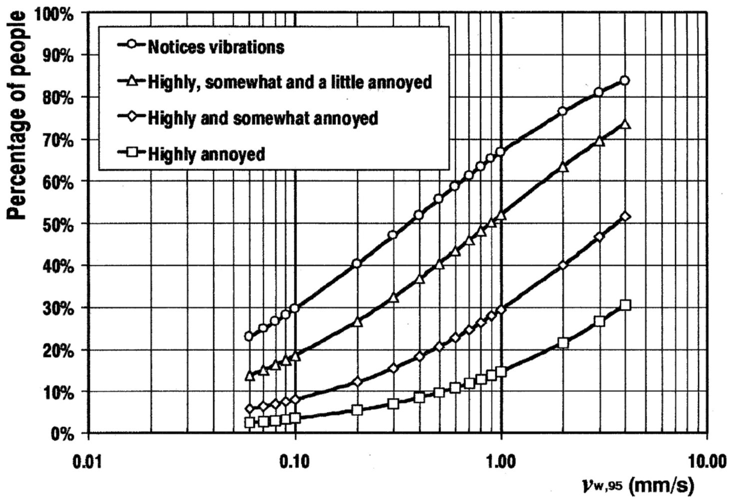


Figure 1.3 Exposure-response relationships for different degrees of annoyance reported by exposed people ($v_{w,95}$: statistical 95-percentile r.m.s. weighted velocity)

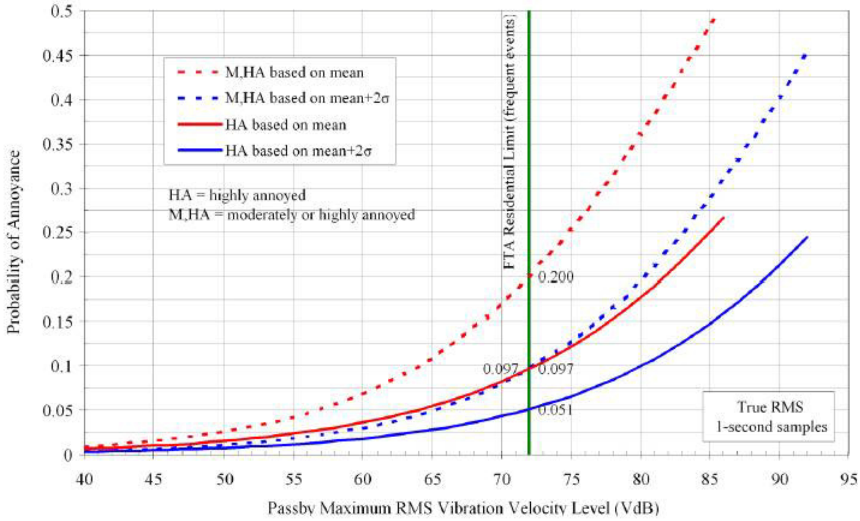
Source: Klæboe *et al.*(2003a).

[1] The vibration velocity in the dwellings was calculated from the measured ground velocity.

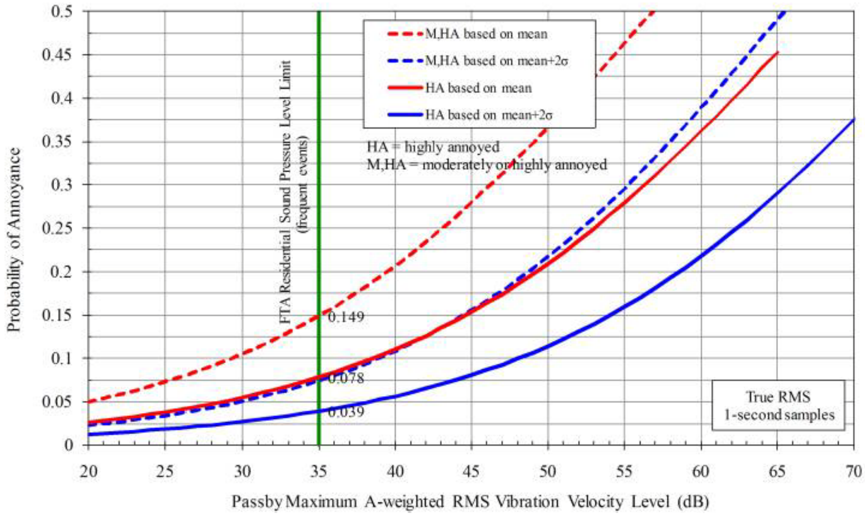
Following the same way, DEFRA aims to provide better knowledge on exposure-response relationships as a reliable basis for developing standards and guidance for the assessment of vibration in residential buildings (DEFRA 2007). First, they commissioned a pilot study in order to test a methodology (measurement of vibration and survey questionnaire for residents). A subsequent large-scale survey is carrying out at Salford University.

A research was performed under the American Transit Cooperative Research Program D-12 project (Zapfe *et al.*, 2009). The study was based on a survey in five North American cities. About 1,300 respondents reported about annoyance from vibration due to rail transit systems (more than 70 events per day, the FTA 'Frequent' service category – see below sections 2.2.1 and 3.2.1)[1]. Following Fidell (2003), the authors developed exposure-response relationships with confidence intervals for predicting community annoyance from vibration and groundborne noise (Figure 1.4). Groundborne noise is directly estimated from A-weighted floor velocity.

Figure 1.4 Exposure-response relationships for railway-induced vibration in dwellings



a. Maximum vibration velocity level



b. A-weighted maximum vibration velocity/groundborne noise level

Source: Zapfe *et al.* (2009).

At 72 VdB (the FTA limit in dwellings for 'Frequent' service), the probability of high annoyance would be 5 to 10 %. The maximum A-weighted radiated sound level should be 5.5 dB lower than

[1] No detail is given about how the combined effect of noise was accounted for

the floor velocity level[1]. At the proper groundborne noise limit (40.5 dBA for the FTA 35 dB criterion), the probability of high annoyance would be 5.6 to 11 %.

TVANE (Train Vibration And Noise Effects) is a Swedish research project which aimed at studying the effects of noise and vibration from railway traffic on dwellings. Sponsored by Banverket (the Swedish Rail Administration), it was carried out from 2006 to 2011 (Öhrström *et al.*, 2011). One of its aims was to investigate annoyance and exposure from noise and vibration. A field survey was carried out in two areas: one with low ground vibration (less 0.4 mm/s in Töreboda and Falköping) and the other with strong ground vibration (more than 1.4 mm/s in Kungsbacka and Alingsås). The probability of being annoyed (not of being highly annoyed) – without confidence interval – with respect to ground vibration up to 0.50 mm/s was determined from 459 dwellings in Kungsbacka and Alingsås. As all dwellings in Kungsbacka were one- or two-family houses with rather similar building structure, their study could have been detailed.

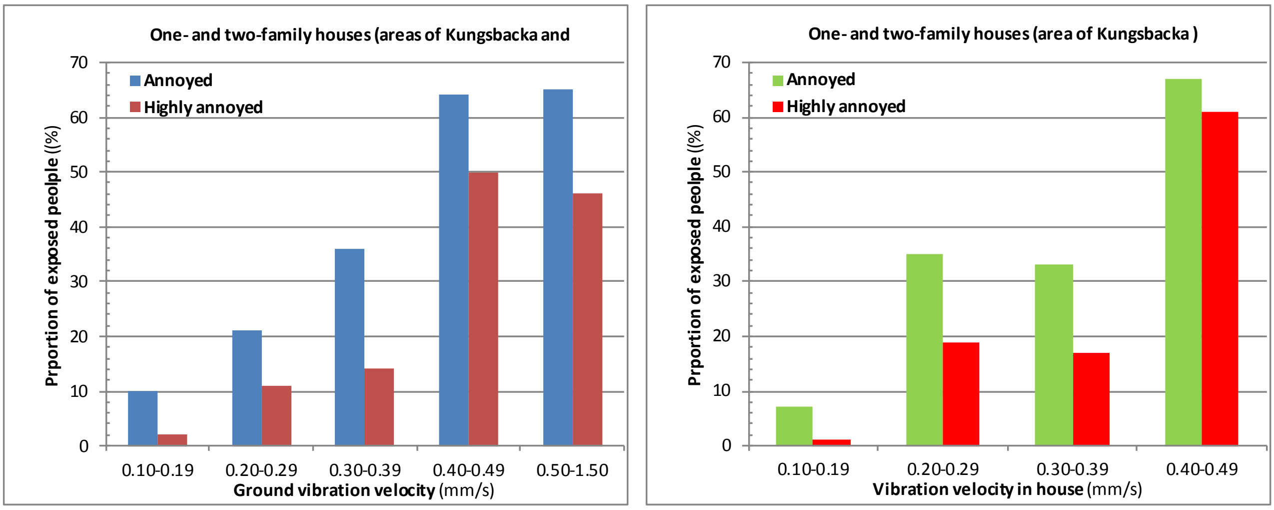


Figure 1.5 Annoyance of residents in houses from railway vibration

Left: ground velocity (Kungsbacka and Alingsås: 331 houses) – Right: indoor velocity (Kungsbacka: 218 houses)

Source: after Öhrström *et al.* (2011).

As Figure 1.5 (left) shows, the proportion of highly annoyed in one- and two-family houses rises sharply at ground vibration velocity levels over 0.40 mm/s. It reaches 11 (resp. 14 %) for a ground velocity range of 0.2-0.29 mm/s (resp. 0.30-0.39 mm/s). In Kunsbacka (right Figure 1.5), vibration velocity within houses could have been predicted. It followed that the probability of annoyance is low at vibration levels between 0.10 and 0.19 mm/s. It clearly exceeds 17 % at levels between 0.20 and 0.39 mm/s. Above 0.4 mm/s, it is higher than 61 %. These results could be compared with the limit values set for railway-induced vibration in Sweden (see section 2.2.1).

1.3 Low-frequency noise

Low-frequency sound ranges approximately between 10/20 Hz and 200/250 Hz, as generally accepted (Table 1.5). It would be rather arbitrary to set sharper lower and upper limits (Leventhall, 2009). The hearing sensitivity of human ear declines at low frequencies and the subjective quality of the sound also changes. The value of 20 Hz is often hold as the limit of audibility. But highly-sensitive persons can hear sounds at frequencies below 20 Hz (Møller and Pedersen, 2004).

Table 1.5 Sound frequency spectrum

Frequency	**0 Hz**	**10 Hz**	**20 Hz**	**200/250 Hz**	**20 kHz**
Sound	Infrasound with body resonance	Infrasound	Low-frequency sound	Non-low frequency audible sound	Ultrasound

[1] The reason for this reduction is that, for a vibrating plane surface, the near-field sound pressure is related to the surface velocity by the specific impedance ρc of the fluid (air) where ρ is the mass density of air and c is the sound speed.

ISO 226:2003 standardizes the hearing thresholds above 20 Hz (Figure 1.6). Møller and Pedersen (2004) propose normal hearing thresholds below 20 Hz (Figure 1.7).

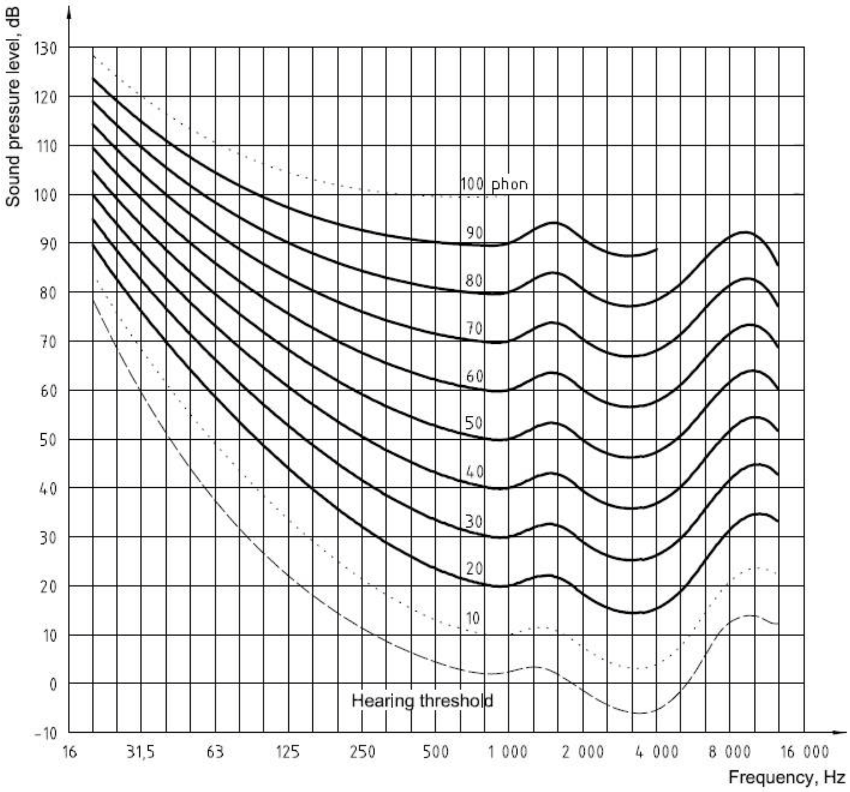


Figure 1.6 Normal equal-loudness-level contours for pure tones
(binaural free-field listening, frontal incidence) – Source: ISO 226:2004.

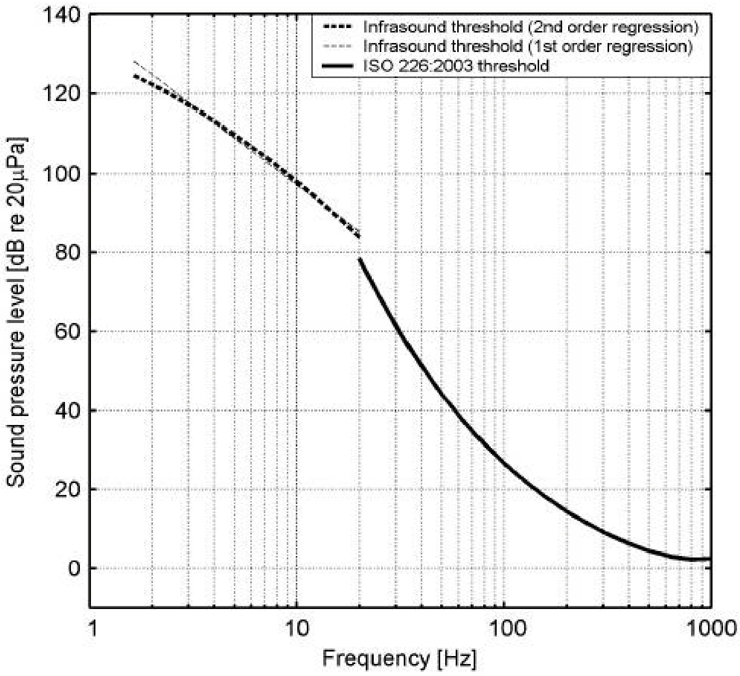


Figure 1.7 Proposed normal hearing thresholds below 20 Hz
Source: Møller and Pedersen (2004).

There are many sources of low-frequency noise (technical equipment, aircrafts, heavy vehicles, rail traffic, blasting, quarrying...) which can cause annoyance and disturbance. Low frequency noise can be more noticeable indoors. Outdoors it may be completely or partially masked by higher-frequency noise such as traffic. Indoors, mid and high frequency noise from outside is reduced because of the insulating effect of the building. The same change towards low frequencies occurs when the receiver is far from the noise source because high frequencies are much attenuated by air or ground.

A- and C-weightings are the two most common frequency weightings for sound level (Figure 1.8). They are based upon the frequency responses of the 40-phon and approx. 100-phon equal-loudness contour levels, respectively. The widely used A-weighting clearly devaluates sounds below 200 Hz (Figure 1.8). As a result, it underestimates annoyance for frequencies below that level (Persson and Björkman, 1988; Leventhall, 2004). It is inappropriate when prominent low-frequency components are present (Berglund *et al.*, 1999).

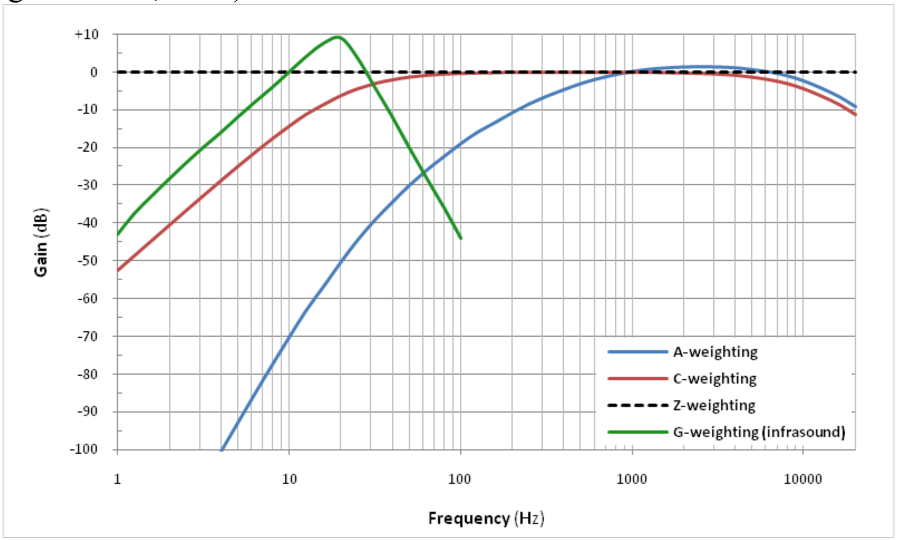


Figure 1.8 Frequency weightings for sound levels
Source: EN 61672-1:2003

Leventhall *et al.* (2003) reviewed research on low-frequency noise and its effects for DEFRA[1]. They concluded that the difference between C- and A-weightings can be used as an indicator (not a predictor) of possible annoyance; when it exceeds 20 dB, further investigation will be necessary.
Two kinds of criterion limits are set for low-frequency noise: weighted sound levels or limit curves for frequency analysis. In Denmark a A-weighted sound level $L_{pA,LF}$ over 10-160 Hz is recommended (Miljøstyrelsen, 1997) with limit values 5-15 dB lower (with a 5 dB penalty for impulsive noise) than usual L_{pA} targets.
The use of single number values hides annoying frequency characteristics of noise. Some countries defined limit (hearing) curves for one-third octave band frequency analysis (Figure 1.9). However, they differ in the frequency range and the acceptable values (see also section 3.2). Besides, relaxations may be applied, as in Moorhouse (2005a, 2005b) at day-time or for steady noise.

[1] Department for Environment, Food and Rural Affairs.

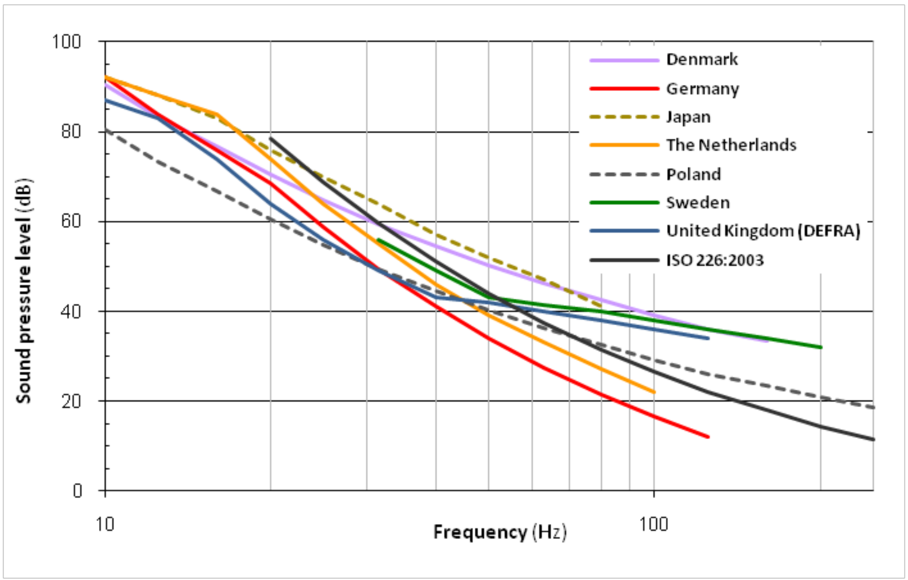


Figure 1.9 Limit curves for low-frequency noise

Field surveys on annoyance from structure-borne noise are rare. Aasvang *et al.* (2007) studied annoyance and self-reported sleep disturbance inside 313 dwellings exposed to radiated noise from railway rock-tunnels. They found that annoyance and sleep disturbance were significantly related to sound level L_{pAFmax}. Their results give support to the 32 dB limit value set for sound class C dwellings in the Norwegian NS 8175 standard (see section 3.2.1). At this level 20 % of the exposed population is annoyed (Figure 1.10), as expected. The study confirms that some factors affect the degree of annoyance: the number of train passages and the facade insulation (windows and walls), as in Vadillo *et al.* (1996).

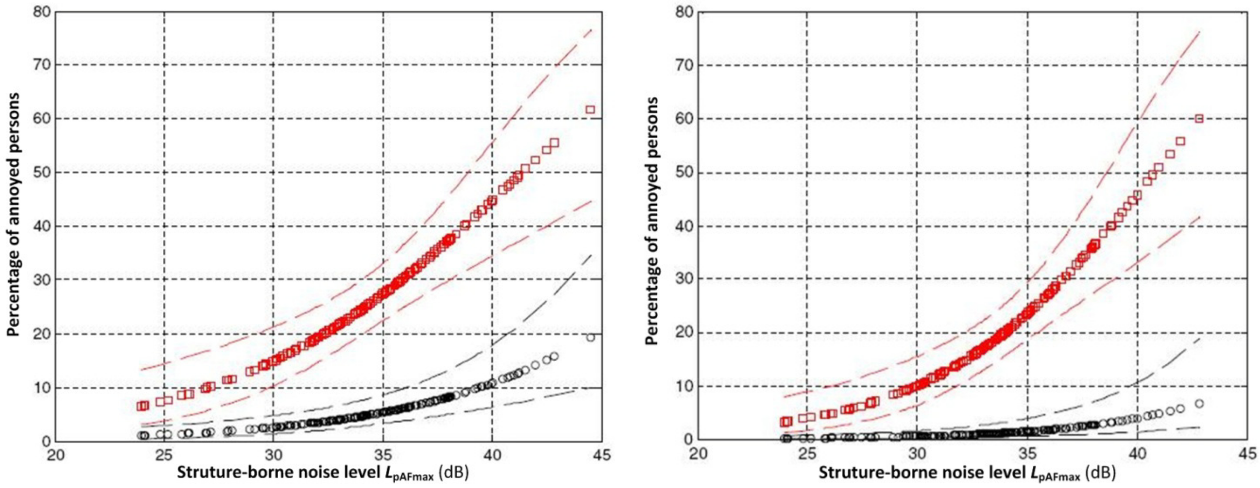


Figure 1.10 Exposure-effect of structure-borne noise from railway tunnels: overall day (left) **and night-time** (right)
□ Slightly + moderately + very + extremely annoyed; O Moderately + very + extremely annoyed; dashed lines: 95 % confidence interval.
Source: Aasvang *et al.* (2007).

When a room is excited by a noise source, the sound waves reflect from surfaces. At particular frequencies (resonant frequencies) it will result in room modes (a.k.a. standing waves) in the room. Consequently, sound pressure is irregularly distributed within the room and may vary 10-20 dB. The spatial variations and time fluctuations are particularly problematic at low-frequencies (below 200 Hz). And factors such as the nature of walls, dimensions and absorption (furniture, coverings, etc.) affect the situation. Thus the assessment of annoyance from low-frequency noise must be based on appropriate measurements at adequate locations that represent the actual exposure of annoyed people, rather than some room average level (the latter however being more reproducible).

Pedersen *et al.* (2007) compared the performance of the Swedish and Danish methods for the indoor measurement of low-frequency noise. Because sound pressure level in rooms varies very much at low frequencies, it cannot be described adequately by measurement in a single position. They propose a measurement in four randomly-selected three-dimensional (3D) corners (except near noise sources) with a maximum 0.1 m distance to the room boundaries. For the assessment of annoyance in high-level areas, a L_{10} target (not an average level) might be a "*rational and objective target*". Nevertheless, random measurement locations may be meaningless when assessing annoyance of residents.

At ISO level (ISO TC43/SC2/WG18 – Building acoustics) a work is in progress for measurement of low-frequency noise (below 100 Hz, that is to say the frequency range of vibration-induced noise) in buildings and in small rooms (about 10 m^2 or less) like bedrooms. A draft standard recommends measurements near room centre with additional corner measurements.

2. VIBRATION

2.1 Standards and guidelines

2.1.1 Overview of reference documents

Several international and national standards define the measurement and assessment procedures for vibration in buildings. In Table 2.1 below are summarized the key features of documents that are not only used in their own country. Some may be also referred to in other European countries and beyond. The definitions of the quantities used in the different standards and guidelines are given in Annex A.

Table 2.1 Standards and guidelines

Key feature	International standards[1] ISO 2631-1:1997, ISO 2631-2:2003	Austria ÖNORM S 9012:2010	Germany[2] DIN 4150-2:1999
Scope	Whole-body vibration: continuous and shock-induced vibration in buildings	Land-based transport vibration in buildings (vibration and structure-borne noise)	Effects of vibrations on people in buildings
Frequency range	1-80 Hz	1-80 Hz	1-80 Hz
Frequency weighting	W_m (recommended)	W_m	Close to W_m (DIN 45669-1)
Time constant	Slow (1 s) recommended	Slow (1 s)	Fast (0.125 s)
Measured quantity	Acceleration	Acceleration	Velocity
Indicator	• r.m.s. weighted value • Maximum transient vibration value (running r.m.s.) • Vibration dose value	• Maximum acceleration E_{max} • Mean equivalent acceleration E_r	• Maximum weighted vibration strength KB_{Fmax} • Mean vibration strength KB_{FTr}
Measurement	In the direction of the highest amplitude	Where the amplitude is the highest (usually on floor at mid-span) In bedrooms near the bed	Three directions (*x*, *y*, *z*) Floor where the highest amplitude can be observed

Note 1. As far as human response to railway-induced vibrations in buildings is concerned, the mentioned features are found in the general Part 1 and/or in the specific Part 2 of ISO 2631 as well as in ISO 8041:2005 (and its 2007 corrigendum). ISO 14837-1:2005 gives no further precision.
Note 2. The Swiss directive BEKS:1999 (Assessment of vibration and structure-borne noise from railway traffic) also refers to DIN 4150-2.

Key feature	Italy[1] UNI 9614:1990	Japan[2] Vibration regulation law	The Netherlands SBR Richtlijn – Deel B (2002)
Scope	Vibrations and shocks: comfort in buildings	Environmental vibration	Guidelines for the measurement and the assessment of vibrations: nuisance for people in buildings
Frequency range	1-80 Hz	1-80 Hz	1-80 Hz
Frequency weighting	W_m	Vertical (W_k) and horizontal (W_d)	DIN 45669-1:1995 (close to W_m)
Time constant	Slow (1 s)	0.63 s	Fast (0.125 s)
Measured quantity	Acceleration	Ground acceleration	Velocity
Indicator	Maximum weighted r.m.s. acceleration value or level (dB re 10^{-6} m/s²)	acceleration level L_V (running weighted r.m.s. value): $L_V = 20 \lg a/a_0$ re 10^{-5} m/s²	• Statistical (95-percentile) maximum vibration strength V_{max} • Mean vibration strength V_{per}
Measurement	Where the amplitude is the highest (usually on floor at mid-span)		Three directions (*x*, *y*, *z*) with horizontal x- and y-axes parallel to walls as much as possible

Note 1. See also ISO 2631-2:1989.
Note 2. See also JIS C 1510:1995 and comments.

Key feature	Norway NS 8176:2005	Spain Real Decreto 1307/2007	Sweden[1] SS 460 48 61:1992
Scope	Land-based transport: comfort in buildings	Noise regulation (zoning, quality and emissions)	Vibrations and shocks: evaluation of comfort in buildings
Frequency range	0.5-160 Hz	1-80 Hz	1-80 Hz
Frequency weighting	W_m	W_m	W_m
Time constant	Slow (1 s)	Slow (1 s)	Slow (1 s)
Measured quantity	Velocity or acceleration	Acceleration	Acceleration or velocity
Indicator	Statistical 95-percentile weighted velocity $v_{w,95}$ or acceleration $a_{w,95}$	Maximum weighted r.m.s. acceleration level L_{aw}: $L_{aw} = 20 \lg a_w / a_0$ re 10^{-6} m/s²	Maximum weighted r.m.s. value (acceleration or velocity level): $L_{aw} = 20 \lg a_w / a_0$ re 10^{-6} m/s² $L_{vw} = 20 \lg v_w / v_0$ re 10^{-9} m/s
Measurement	Where the amplitude is the highest (usually on floor at mid-span)	Where the vibration is most annoying in the dominant direction if identified; otherwise in all directions for the total resultant vibration value	Three directions (x, y, z) or if known, in the direction of maximum amplitude (often at mid-span of the longest-span floor)
Note 1. See also Dnr.S02-4235/SA60 and Nordtest method NT ACOU 082.			

Key feature	United Kingdom[1] BS 6472-1:2008	USA FRA (2005), FTA (2006)
Scope	Human exposure to vibration in buildings (sources other than blasting)	Guidance manuals on noise and vibration impact assessment (transit and high-speed rail projects)
Frequency range	0.5-80 Hz	
Frequency weighting	W_b (vertical motion) or W_d (horizontal motion)	None
Time constant		Slow (1 s)
Measured quantity	Acceleration	Velocity
Indicator	Vibration dose value	• *General Assessment*: maximum running r.m.s. velocity level L_v (VdB) $L_v = 20 \lg v_w / v_{ref}$ re 10^{-6} in/s • *Detailed Analysis*: maximum velocity level in one-third octave bands
Measurement	Highest expected level Central part of the floor (one or two measurements)	Near the centre of a floor span where the vibration amplitude are the highest
Note 1. See also BS 6841:1987.		

The German guideline VDI 2057:2002 (Human exposure to mechanical vibrations) should also be mentioned. Neither the international and European standards nor the EC Machinery Directive 2006/42/EC use the German quantity *KB*, but rather the frequency-weighted acceleration a_w as a parameter for the evaluation of vibration exposure. Thus VDI 2057:2002 aims at harmonizing the German standardization with the corresponding supranational codes. Its Part 1 deals with whole-body vibration.

2.1.2 Comparative analysis

Basic quantities

The three basic vibration quantities used in the standards are those given in ISO 2631-1:1997:

– the r.m.s. (equivalent) value;
– the maximum running r.m.s. value;
– the fourth-power vibration dose value.

One generally agrees on measuring the vibration amplitude at locations where it is the highest: most often in the vertical direction on floors at mid-span (notwithstanding some reported cases of close vertical and horizontal amplitudes). However, measurement faces uncertainty (especially reproducibility[1]). The French transport operator RATP[2] are aware of this problem: they used to measure a more reproducible (but lower) floor vibration close to load-bearing walls. The relation between the floor velocities nearby load-bearing walls and at mid-span must then be estimated since only levels at mid-span are relevant for annoyance from vibration. Such a relation depends on the type of floor and its span, as well as on the presence of partition walls. Vibration measurement is further discussed in Chapter 4.

The following differences appear between the reviewed standards.
Acceleration or velocity
The vibration amplitude can be expressed in terms of acceleration, velocity or displacement. It is straightforward to calculate the time history of one quantity from the time (signal) history of the other, and conversely. Let us remember that the relationship between acceleration, velocity and displacement is also frequency-dependent[3], which implies the frequency spectrum to be known.

The acceleration is the "primary quantity of vibration magnitude" in the ISO standards[4]. Nevertheless, the vibration amplitude presently used varies between the examined countries: acceleration in Austria, Italy, Spain and the UK, velocity in Germany, France, Switzerland and the USA, and either in Norway and Sweden.
In structural engineering, acceleration and displacement are related to the stress in the building components (design at ultimate and serviceability limit states, damage prevention and assessment). In acoustics, the sound power radiated by a vibrating surface (floor, wall) is an energy-based parameter directly linked to the surface-averaged velocity.

Frequency weighting
The frequency weighting W_m which is defined in ISO 2631-2:2003 and ISO 2631-1:1997/ISO 8041:2005 (only for acceleration) is widely used, except in the UK and Japan where specific weightings are used for vertical and horizontal vibration. Figure 2.1 illustrates the frequency weightings which ISO, DIN, BS and JIS standards refer to. The KB-weighting is very similar to the W_m-weighting. The British W_b (vertical) weighting (BS 6841:2008) as well as both Japanese vertical and horizontal weightings (JIS C 1510:1995) differ to some extent from the respective international W_k (vertical) and W_d (horizontal) weightings (ISO 2631-1:1997). When the descriptor is velocity (*e.g.* in the Norwegian standard NS 8176), its weighting is consistent with the acceleration W_m-weighting. Turunen-Rise *et al.* (2003) give the relation between velocity and acceleration: $v_w = a_w/35.7$.

[1] In the GUM (modelling) approach (JCGM 100:2008), the *uncertainty in the measurement* of a quantity of interest (the *measurand*) reflects the lack of exact knowledge of the value of the measurand. It is determined by two quantities: reproducibility and repeatability. The *reproducibility* is "the closeness of the agreement between the results of measurements of the same measurand carried out under changed conditions of measurement". By contrast the *repeatability* is closeness of the agreement between the results of successive measurements of the same measurand carried out under the same conditions of measurement. Thus the accuracy of measurement is the closeness of the agreement between the result of a measurement and a true value of the measurand.
The ISO 5725-2:1994 (empirical) approach is quite different. It uses two terms (trueness and precision) to describe the *accuracy of a measurement method*. *Trueness* refers to the closeness of agreement between the average value obtained from a large number of test results and the accepted reference value, while *precision* refers to the closeness of agreement between independent test results obtained under stipulated conditions.
[2] Régie Autonome des Transports Parisiens.
[3] The acceleration a (m/s²), the velocity v (m/s) and the displacement d (m) are related to each other:
$$a = 2\pi f v = \omega \cdot v \text{ and } d = a/(2\pi f)^2$$
where
f is the frequency (Hz);
ω is the angular (radian) frequency (rad/s).
[4] But ISO 2631-1:1997 (§ 5.1) adds that "in case of very low frequencies and low vibration magnitudes, *e.g.* in buildings and ships, velocity measurements may be made and translated into accelerations".

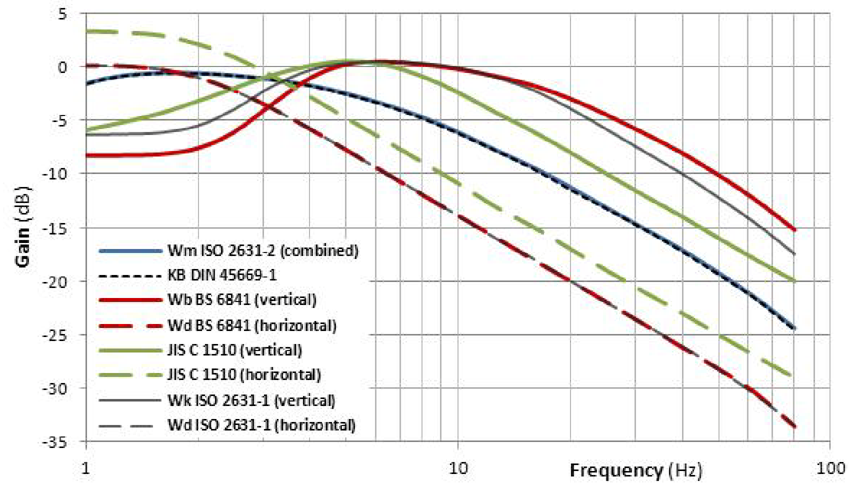


Figure 2.1 Human exposure to vibration in buildings – Frequency weightings
Note The KB weighting is given for acceleration in the figure.

T*ime constant* (running r.m.s. value)
A time constant Slow (1 s) is widely used, apart from Germany and countries referring to DIN 4150-2 (with Fast 0.125 s) as well as Japan with an intermediate time constant of 0.63 s. Degen *et al.* (2006) remark that the German KB_{Fast} value is about 1.6 times as high as the KB_{Slow} value.

Units of measurement
Quantities (acceleration or velocity) and related indicators are most commonly expressed in the basic units of measurement (metric or Imperial units). When stating vibration in decibels, the reference values of ISO 1683:2008 are widely used:

– for acceleration levels: 10^{-6} m/s² (100 dB = 0.1 m/s²), except in Japan with 10^{-5} m/² (100 dB = 1 m/s²)[1];

– for velocity levels: 10^{-9} m/s (100 dB = 0.1 mm/s) or $5{\cdot}10^{-8}$ m/s (100 dB = 5 mm/s). But the value of 10^{-6} in/s is chosen in the USA (100 dB = 2.54 mm/s).

By contrast with sound, there is no universal reference value for vibration levels and the selected values do not match any vibration perception threshold.

Metrics and descriptors
The assessment of exposure to vibrations is based upon two types of descriptors in the standards: maximum values of time-dependent running r.m.s. quantities and/or mean energy-based (or dose-based) values. See further comments in section 2.2.2 (Comparative limits) and chapter 4 (Critical analysis).

Most standards determine the maximum level as the highest value among the measured indicators for all vibration events. But in Norway (NS 8176:1999) and, afterwards, in the Netherlands (SBR-Part B:2002) the maximum value is derived statistically from the sample of measures (number and distribution of observations) as the 95-percentile (95 % confidence level) of the vibration amplitude.

Traffic-oriented descriptors
Traffic-oriented descriptors are not used in some countries (Sweden, Norway and Spain for example), where only a maximum value is considered as important (see next section).

[1] The difference between acceleration levels is 20 dB: for instance, 5 mm/s² (resp. 10 mm/s²) corresponds to 54 dB re 10^{-6} m/s (resp. 60 dB) and 74 dB re 10^{-5} mm/s² (resp. 80 dB).

When used for assessment, traffic-oriented descriptors are calculated depending on the quantity used:

– vibration dose value: the VDV of each episode of various durations t_n during the evaluation period (day or night) are summed according to $VDV_{b/d,day/night} = \left(\sum_{n=1}^{N} VDV_{b/d,tn}^4\right)^{1/4}$. VDV is more strongly influenced by vibration magnitude than by duration;

– r.m.s. (equivalent) value: an energy time weighted mean value is calculated according to: $D^2 = \frac{1}{Tr}\sum_j Te_j . D_j^2$ where D is the used r.m.s. descriptor, T_r is the evaluation period, T_{ej} *is* the duration of each episode j and D_j is the descriptor value for each episode.

The criteria can also account for the frequency of events (see next section): the American FTA manual sets different limit values for vibration and groundborne noise with regard to the frequency of transit trains (less than 30, 30-70 and more than 70 events/day).

2.2 Comfort requirements

2.2.1 Criteria and limit values

International standards

The guidance curves that were set in the 1989 version of ISO 2631-2 (Figure 1.1) are no longer present in the 2003 version. However, they may be still used in a few countries, for instance in Sweden, in the USA (at the stage Detailed Analysis) or in France (where neither national standard nor specific regulation exists for the assessment of vibration and structure-borne noise exposure of occupants within buildings[1]).

No adverse comment is expected for values (acceleration or velocity) below the 1989 base curves of ISO 2631-2. Combined-direction base curves are used in association with multiplying factors which define acceptable vibration levels regarding the considered building place (Table 2.2).

Table 2.2 Ranges of multiplying factors for building vibration with respect to human response in buildings[1]

Place	Continuous or intermittent vibration		Transient vibration excitation with several occurrences per day	
	Day	Night	Day	Night
Critical working areas	1		1	
Residential	2 to 4	1.4	30 to 90	1.4 to 20
Office	4		60 to 128	
Workshop	8		90 to 128	
Note 1. Low probability of adverse comment below such magnitudes of vibration. Structure-borne noise is not considered.				

Source: ISO 2631-2:1989.

Austria

The ÖNORM S 9012 standard prescribes two sets of requirements (satisfactory and good protection) for railway (and road) vibrations, depending on the urban area and the time period. Upper limits are given for two criteria (see Tables 2.3 A and B)

– a maximum acceleration E_{max} of any type of train (long distance, local and freight);

– a mean equivalent acceleration E_r for the whole railway traffic.

The Austrian descriptors are based on acceleration (see Annex A):

– E_{max}: maximum value derived from a running r.m.s. quantity (time constant Slow);

– E_r: time-weighted mean quantity depending on traffic.

[1] See Elias *et al.* (2007).

Table 2.3A Reference values for the maximum acceleration E_{max} (mm/s²)

Area category	Description	Satisfactory protection		Good protection	
		Day 6h-22h	Night 22h-6h	Day 6h-22h	Night 22h-6h
1	Rest areas, cure areas, hospitals	188	18.8	94	9.4
2	Dwellings in suburban and country areas, schools	250	18.8	125	9.4
3	Dwellings in urban areas, areas for forestry and agriculture buildings with dwellings	250	18.8	125	9.4
4	Central areas, areas for not-inducing vibration and noise business activities	310	25.0	188	12.5
5	Areas for low vibration- and noise-inducing business activities[1]	380		250	
6	Goods manufacturers and service companies[1]	500		380	

Note 1. However, regarding identified rest spaces, a classification in category 4 should be aimed for.

Source: ÖNORM S 9012:2010.

Table 2.3B Reference values for the mean equivalent acceleration E_r (mm/s²)

Area category	Description	Satisfactory protection		Good protection	
		Day 6h-22h	Night 22h-6h	Day 6h-22h	Night 22h-6h
1	Rest areas, cure areas, hospitals	1.65	1.59	0.85	0.84
2	Dwellings in suburban and country areas, schools	2.2	1.59	1.12	0.84
3	Dwellings in urban areas, areas for forestry and agriculture buildings with dwellings	2.2	1.59	1.12	0.84
4	Central areas, areas for not-inducing vibration and noise business activities	2.7	2.1	1.65	1.09
5	Areas for low vibration- and noise-inducing business activities[1]	3.2		2.2	
6	Goods manufacturers and service companies[1]	5.0		3.2	

Note 1. However, regarding identified rest spaces, a classification in category 4 should be aimed for.

Source: ÖNORM S 9012:2010.

It is worth noting that the new ÖNORM S 9012 is based on the latest ISO 2631 standard (Parts 1 and 2) as well as the VDI 2057 Part 1 Guidelines. The assessment quantities E_{max} and E_r have superseded the former quantities $K_{B,R}$ and $K_{B,R,max}$, derived from the German vibration strength KB. Steinhauser and Steinhauser (2010) mention a proportional relationship between the W_m-weighted vibration acceleration a_w (mm/s²) and KB (dimensionless): $KB = 0.028 \cdot a_w$ (Note the time constant Slow for a_w, respectively Fast for KB).

Germany

The vibration assessment is based on both criteria KB_{Fmax} and KB_{FTr}. The related reference values A_u, A_0 and A_r (see Table 2.4) depend on the building area and the assessment period (day or night). The assessment procedure consists of two steps:

– step 1: if $KB_{Fmax} \leq A_u$ the condition is satisfied. Conversely when $KB_{Fmax} > A_u$ the condition is not achieved;

– step 2: with $KB_{Fmax} < A_0$ the condition is achieved only if $KB_{FTr} \leq A_r$.

The German descriptors are based on velocity (see Annex A):

– *KB_{Fmax}: maximum value derived from a running r.m.s. quantity (time constant Fast);*

– *KB_{FTr}: time-weighted mean quantity depending on traffic.*

Table 2.4 Reference values for the assessment of vibrations in dwellings and similar buildings

Building area	Day (6h-22h)			Night (22h-6h)		
	A_u	A_o	A_r	A_u	A_o	A_r
Industrial area	0.4	6	0.2	0.3	0.6	0.15
Predominantly commercial area	0.3	6	0.15	0.2	0.4	0.1
Neither commercial nor residential predominantly area	0.2	5	0.1	0.15	0.3	0.07
Mainly residential area	0.15	3	0.07	0.1	0.2	0.05
Special areas (e.g. hospitals) or health buildings	0.1	3	0.05	0.1	0.15	0.05
Note. The above values apply to railway (underground and "new" surface tracks) and road traffics. The values A_u and A_r are multiplied by 1.5 for surface urban transport (tram, etc.).						

Source: DIN 4150-2:1999.

Steinhauser and Steinhauser (2010) give on the one hand the correspondence between the acceleration a_w and the quantity *KB*[1], on the other hand the relationship of both descriptors with thresholds of perception (Table 2.5).

Table 2.5 Perception of vibration according to DIN and ÖNORM S 9012

W_m-weighted acceleration (mm/s²)	Weighted vibration value *KB*	Perception
3.57	0.1	Threshold of perception: Not noticeable / Just noticeable
7.14	0.2	
		Weakly noticeable
14.3	0.4	
28.6	0.8	Awakening threshold: Noticeable / Clearly noticeable
57.1	1.6	
113	3.15	Strongly noticeable
228	6.3	
446	12.5	
893	25	
1,790	50	Very strongly noticeable
3,570	100	

Source: Steinhauser and Steinhauser (2010).

Other countries also refer to DIN 4150: Belgium, Switzerland.

The guideline VDI 3837 complements ISO 14837-1 on prediction of vibration due to surface rail traffic (excl. structure-borne noise). It describes the procedure to obtain a spectral forecast for vibration in the range of 4 Hz to 80 Hz. The data input is the kinematic excitation of vibrations at the track. The method gives estimates of the assessment quantity KB_{FTm} according to DIN 4150-2.

Italy

The Italian standard UNI 9614 sets limit values of the weighted acceleration in the vertical and horizontal directions according to the type of building. It distinguishes the time period (daytime or night-time) for residential buildings (Table 2.6)

The Italian descriptor a_w is derived from a running r.m.s. weighted acceleration (time constant Slow).

[1] See also annex D of ÖNORM S 9012:1996.

Table 2.6 Limit values of weighted acceleration according to UNI 9614

Building use		Vertical direction (*z*-axis)		Horizontal direction (*x*- and *y*-axes)	
		a_w (mm/s²)	L_{aw} (dB re 10^{-6} m/s²)	a_w (mm/s²)	L_{aw} (dB re 10^{-6} m/s²)
Critical area		5.0	74	3.6	71
Residential[1]	night-time	7.0	77	5.0	74
	daytime	10.0	80	7.2	77
Office		20.0	86	14.4	83
Industrial		40.0	92	28.8	89

Note 1. Night-time: 22h-7h; daytime: 7h-22h.

Source: UNI 9614:1990.

The Italian criteria refer to multiplying factors given in ISO 2631-2:1989. UNI 9614 also mentioned the weighted value of 3.6 mm/s² as a perception threshold for horizontal acceleration (as ISO 1631-2:1989), respectively 5.0 mm/s² for vertical acceleration.

Japan

The Japanese Vibration Regulation Law (Ministry of the Environment) sets environmental criteria for ground vibration from factories and road traffic (Table 2.7). Local governments (prefectures and municipalities) are empowered to implement the law by regulation, planning, monitoring and inspection.

The Japanese descriptor L_v is derived from a running r.m.s. weighted acceleration (time constant 0.63 s). The vibration level refers to hourly L_{10} value for road traffic.

Table 2.7 Criteria (dB re 10^{-5} m/s²) **for environmental ground vibration**

Land use area		Specified factories[1]		Road traffic[1]	
		Day[2] (7h-20h)	Night[2] (20h-7h)	Day[2] (7h-20h)	Night[2] (20h-7h)
I	Areas where maintaining quietness is particularly needed to preserve a good living environment and where quiet is called for as they are used for residential purposes[3]	60-65 (1.0-1.8 cm/s²)	55-60 (0.56-1.0 cm/s²)	65 (1.8 cm/s²)	60 (1.0 cm/s²)
II	Areas used for commercial and industrial as well as residential purposes where there is a need to preserve the living environment of local inhabitants and areas mainly serving industrial purposes which are in need of measures to prevent the living environment of local residents from deteriorating	65-70 (1.8-3.2 cm/s²)	60-65 (1.0-1.8 cm/s²)	70 (3.2 cm/s²)	65 (1.8 cm/s²)

Note 1. Ground vibration is measured at the boundary line of the factory site/road.
Note 2. Local governments may set different daytime and night-time periods.
Note 3. As well as areas within 50 m from schools, hospitals, libraries and sanatoria in areas of type II.

Source: Vibration regulation law.

A specific regulation exists for mitigation measures in the areas where vibration from Shinkansen (high-speed) railway traffic exceeds 70 dB [31.6 mm/s²] (where the vibration level L_{max} is the arithmetic mean of the upper half of twenty or more successive train pass-by measurements, *e.g.* the mean of the ten highest values out of 20 measurements).
There is no regulation for indoor vibration. A 5 dB increase (+78 %) is usually taken for the vertical vibration level inside wooden-structure houses (most common dwellings in Japan[1]). And a 55-60 dB vibration level (0.56-1.0 cm/s²) is regarded as a threshold.
Common railroad projects (new lines or large-scale development of existing lines) are subject to Environmental Impact Assessments (EIAs) according to the National EIA Law or local EIA Ordinances. But, no criteria more stringent than the national limit values seem to exist at a local level for railway traffic.

[1] In 2008 about 58 percent of 49.3 million dwellings were detached and terraced houses in Japan. And 59 percent of all dwellings (chiefly houses) have a wooden structure (Ministry of Internal Affairs and Communications (MIC) – Statistics Bureau: 2008 Housing and Land Survey).

The Architectural Institute of Japan (AIJ) issued an Environmental Standard which aimed at the design of building designers and developers: the AIJ guidelines for the evaluation of habitability to building vibration. The 2004 version (AIJES:2004) was thoroughly revised. Because the vibration regulation only considers ground vibration, the AIJES standard defines evaluation curves for maximum vertical (V) and horizontal (H) vibration (r.m.s. acceleration) from traffic, which correspond to different "perception probabilities": 10, 30, 50, 70 and 90 (Figure 2.2).

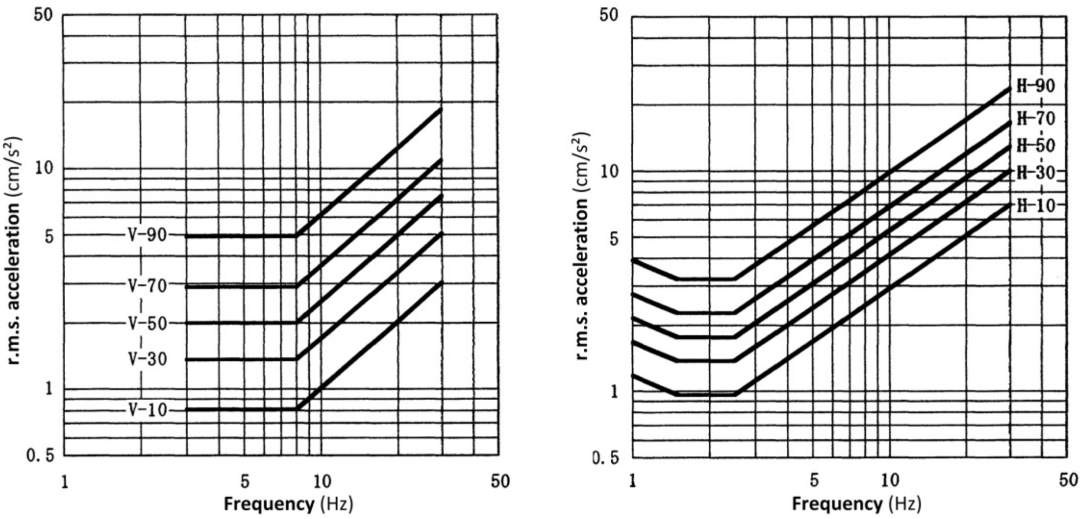


Figure 2.2 Evaluation curves for floor vibration from traffic
Vertical (left) and horizontal (right) directions
Source: AIJES-V001-2004.

The V-10 curve is slightly higher than the ISO 2631-2:1989 basic curve; the V-30 and V-70 curves are close to the ISO curves for the multiplying factors respectively 2 and 4; the V-90 is like the Canadian (CSA S16.1-1989) annoyance criterion for continuous vibration[1].

The Netherlands

The Dutch assessment procedure has been issued by the Building Research Foundation (NSG). It is very similar to the German one. It is based on both criteria V_{max} and V_{per} (somewhat analogous to KB_{Fmax} and KB_{FTr} respectively). The three related target values A_1, A_2 and A_3 (see Table 2.8) depend on the building use and the time period (day and evening, or night). The assessment procedure consists of two steps:

– step 1: when $V_{max} < A_1$ the condition is satisfied. Conversely when $V_{max} \geq A_2$ the condition is not achieved;

– step 2: with $V_{max} < A_2$ the condition is achieved only when $V_{per} < A_3$.

The Dutch descriptors are based on velocity (see Annex A):

– *V_{max}: statistical 95-percentile derived from a running r.m.s. quantity (time constant Fast);*

– *V_{per}: time-weighted mean quantity based on 30-s intervals over the measurement period.*

[1] Figures 3.1 and 3.2 in AIJES-V001-2004 (page 51) give a graphical comparison for curves from various references (research findings and standards).

Table 2.8 Reference values for the assessment of vibrations in dwellings and similar buildings

a. Road and railway traffic: new situation

Building category	Day and evening			Night		
	A_1	A_2	A_3	A_1	A_2	A_3
Health care, residential	0.1	0.4	0.05	0.1	0.2	0.05
Education, office and public assembly	0.15	0.6	0.07	0.15	0.6	0.07
Critical work areas	0.1	0.1	–	0.1	0.1	
Note. Periods of assessment: day (7h-19h), evening (19h-23h) or night (23h-7h). These values also apply to underground railway traffic, whichever situation (new or existing) may be.						

b. Road and railway traffic: existing situation

Building category	Day and evening			Night		
	A_1	A_2	A_3	A_1	A_2	A_3
Health care, residential	0.2	0.8	0.1	0.2	0.4	0.1
Education, office and public assembly	0.3	1.2	0.15	0.3	1.2	0.15
Critical working environment	0.1	0.1	–	0.1	0.1	
Note. Periods of assessment: day (7h-19h), evening (19h-23h) or night (23h-7h).						

Source: SBR (2002), Deel B.

Notice that the statistical value $V_{\max}$ is determined as a 95 % confidence upper bound. The annex 5 of SBR (2002) indicates the annoyance level according to $V_{\max}$ for road and railway traffic (see Table 2.9).

Table 2.9 Annoyance level for maximum vibration strength $V_{\max}$ for road and railway traffic

$V_{\max}$	Level of annoyance
< 0.1	Not annoyed
0.1 – 0.2	A little annoyed
0.2 – 0.8	Moderately annoyed (existing situation)
0.8 – 3.2	Annoyed
> 3.2	Significantly annoyed

Source: SBR (2002), Deel B.

Norway

In its informative annex B the Norwegian standard NS 8176 specifies four classes of comfort for dwellings that are exposed to vibration from land-based transport (Table 2.10). Those classes are based on the degree of annoyance at various vibration levels (see also Turunen-Rise *et al.*, 2003):

– Class A: very good conditions, where people will only perceive vibration as an exception (the occupants of such dwellings are not expected to notice vibration);

– Class B: good conditions (the occupants of such dwellings are expected to be disturbed by vibration to some extent);

– Class C: limit value recommended for vibration within new residential buildings and in connection with the planning and construction of new transport infrastructures (about 15 % of the affected occupants of such dwellings can be expected to be disturbed by vibration);

– Class D: conditions that should be achieved in existing residential buildings (about 25 % of the affected occupants of such dwellings are expected to be disturbed by vibration), when cost-benefit considerations make it unreasonable to require class C.

The Norwegian descriptors are based on velocity or acceleration (see Annex A):

– $v_{w,95}$, $a_{w,95}$*: statistical 95-percentiles derived from running r.m.s. quantities (time constant Slow)*

Table 2.10 Guidance classification of dwellings according to vibration exposure from land-based traffic

Type of vibration value	Class A	Class B	Class C	Class D
Statistical maximum value for weighted velocity $v_{w,95}$	0.1	0.15	0.3	0.6
Statistical maximum value for weighted velocity $a_{w,95}$	3.6	5.4	11	21
Note. The above values of $v_{w,95}$ (mm/s) and $a_{w,95}$ (mm/s²) are the upper limits for each class of comfort.				

Source: NS 8176:2005.

Spain

The Spanish law (Royal Decree 1367/2007) states mandatory requirements in order to prevent people within buildings from annoyance caused by rail and road traffic (Table 2.11). Limit values are set out with respect to the building use. For new and upgraded (double capacity or more) national railway lines, adequate measures should be taken in case their operation results in exceeding those vibration levels.

The Spanish vibration level L_{aw} is from a maximum running r.m.s. quantity (time constant Slow).

Table 2.11 Limit vibration level L_{aw} (dB) within buildings

Building use	Vibration level L_{aw}	
	dB re 10^{-6} m/s²	mm/s²
Dwellings or residential use	75	5.6
Hospitals	72	4.0
Education and culture	72	4.0

Source: Real Decreto 1367/2007.

The same decree details how compliance with the regulation should be monitored. The inspection procedure distinguishes between stationary and transitory vibration (traffic). In the former case no measurement should exceed the limit level L_{aw} under scrutiny. In the latter case, for instance when different trains (vehicle, speed) pass by on the same route, the limit values may be exceeded for only a few events under the following conditions:

– each assessment period (day [7h-23h] and night [23h-7h]) is examined;
– the limit value ought not be exceeded over the night-time period;
– when permitted, the limit value should not be exceeded by more than 5 dB;
– the number of excess events cannot be greater than 9. A measure exceeding by at most 3 dB is counted as one event, otherwise it is counted as three events.

Sweden

In its annex B the Swedish standard SS 460 48 61 presents three ranges of guideline values for new buildings and developments according to the vibration values given in Table 2.12:

– Under Moderate Disturbance: few people will experience disturbance from vibration;
– Moderate Disturbance: people may complain in some cases;
– Probable Disturbance: most people will be disturbed by noticeable vibration.

The Swedish descriptors are derived from running r.m.s. weighted quantities (time constant Slow).

Table 2.12 Guideline values for the evaluation of comfort in buildings

Type of vibration value	Moderate disturbance	Probable disturbance
Maximum weighted r.m.s. velocity (mm/s)	0.4 – 1.0	> 1
Maximum weighted r.m.s. acceleration (mm/s²)	14.4 – 36.0	> 36

Source: SS 460 48 61:1992.

These guidelines apply first to dwellings at night-time period and less strictly to office buildings.

If a frequency dominates in the weighted vibration value (which can be the case when it is close to the natural frequency of floors or buildings, creating resonance) the frequency-dependent r.m.s. value can replace it and be directly compared to the frequency curves given in Figure 2.3.

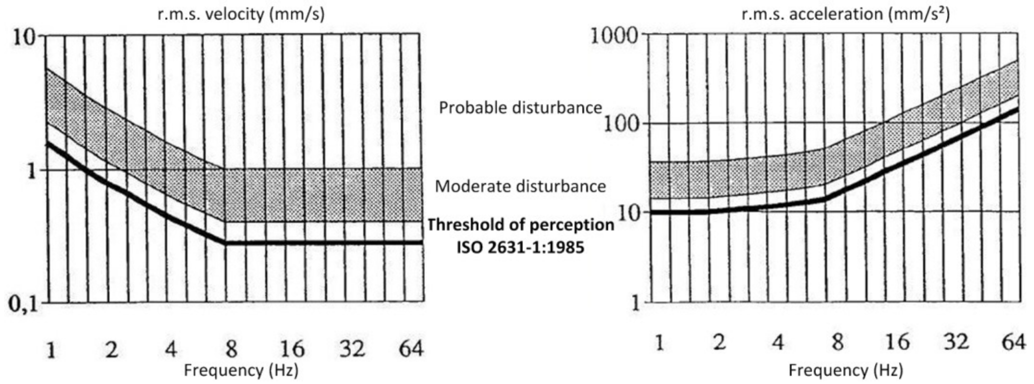


Figure 2.3 Frequency-dependent vibration value (SS 460 48 61)

Banverket[1] (now Trafikverket[2]) and Naturvårdsverket[3] issued guidelines for noise and vibration from rail traffic. They set out guideline values (velocity or acceleration) based on SS 460 48 61 (Banverket, Naturvårdsverket, 2006). The guideline values (velocity) are seen as long-term targets while the limit values should not be exceeded (Table 2.13).

Table 2.13 Guideline values for buildings near rail tracks

Type of railway works	Velocity (mm/s)	Acceleration (mm/s²)
New construction[1]	0.4[4]	14
Important refurbishment[2]	0.4[5]	14
Existing environnement[3]	1.0[6]	36
Note 1. Values for permanent dwellings, leisure housing and care premises. Note 2. Values for bedrooms in permanent dwellings, leisure housing and care premises at night-time (22h-6h). Note 3. Values for bedrooms in permanent dwellings at night-time (22h-6h). Note 4. Limit (highest acceptable) value in bedrooms at night-time: 0.7 mm/s. Note 5. Limit (highest acceptable) value in bedrooms at night-time: 1.0 mm/s. Note 6. Limit (highest acceptable) value in bedrooms at night-time: 2.5 mm/s.		

Source: Banverket, Naturvårdsverket (2006).

Switzerland

The Swiss directive of the Federal Office for the Environment (BEKS 1999) refers to DIN 4150-2:1999 for the evaluation of vibration induced by railway traffic. The standard applies to new railway construction as well as to refurbishment, alteration and change in the operating conditions if the vibration exposure is expected to increase by 40 % (about + 3 dB) from the existing situation.

A draft Federal Ordinance on Vibration Abatement is being discussed (Meloni, 2011). Regulatory vibration exposure limits, expressed in *KB* values, might be enforced in some years (Table 2.14 in which K_r is similar to the German KB_{FTr}).

[1] Swedish Rail Administration.

[2] Swedish Transport Administration, which is responsible for long-term planning of the transport system for all types of traffic, as well as for building, operating and maintaining public roads and railways.

[3] Swedish Environmental Protection Agency.

Table 2.14 Limit values K_r (dimensionless) for vibration (draft Swiss Federal Ordinance)

Sensitivity level[1]		Vibration level K_r	
		Day (06h-22h)	Night (22h-06h)
I	Zones with higher noise abatement requirements, especially in leisure zones	0.07	0.05
II	Zones in which operations that emit noise are not permitted, among others in residential zones and zones for public buildings and installations	0.10	0.07
III	Zones in which operations emitting a certain level of noise are permitted, especially in residential and industrial zones (mixed zones) and agricultural zones	0.15	0.10
IV	Zones in which operations emitting a high level of noise are permitted, especially in industrial zones	0.20	0.15
Note 1. See Noise Abatement Ordinance (Art. 43).			

Source: Federal Office for the Environment.

An additional directive should detail monitoring of the compliance with the applicable requirements of the ordinance.

United Kingdom

The British BS 6472-1:2008 gives vibration criteria for the relevant time periods (16 h daytime and 8 h night-time) and buildings (Table 2.15).

The British descriptor is based on acceleration (see Annex A):
– vibration dose value: derived from a frequency-weighted acceleration.

Table 2.15 Vibration dose value ranges ($m \cdot s^{-1.75}$) **within residential buildings**

Place	Time	Low probability of adverse comment	Adverse comment possible	Adverse comment probable
Residential buildings	Day (16 h)	0.2 to 0.4	0.4 to 0.8	0.8 to 1.6
	Night (8 h)	0.1 to 0.2	0.2 to 0.4	0.4 to 0.8
Note 1. For offices and workshops, the above values are multiplied respectively by 2 and 4 for a 16-hour day. Note 2. Time period: e.g. 7h-23h for daytime and 23h-7h for night-time.				

Source: BS 6472-1:2008.

These values are unchanged with respect to the 1992 version of the standard. They are seen as "*the best judgement currently available and may be used for both vertical and horizontal vibration, provided they are correctly weighted*".

As an example Crossrail[1] (information papers D10 and D26) sets out trigger values which lie within the BS 6472-1 ranges (Table 2.16). They will be achieved, "*in all reasonably foreseeable circumstances*", at sensitive receptors. The limits are valid for both construction and operation of railway lines.

Table 2.16 Construction and Operational Vibration Criteria

In the Absence of Appreciable Existing Levels of Vibration (VDV $ms^{-1.75}$)		**Appreciable Existing Levels of Vibration**[1, 2]
Day (7h-23h)	Night (23h-7h)	% increase in VDV
0.31	0.18	40
Note 1. Highest impact category used, daytime or night-time. Note 2. There is an appreciable existing level of vibration where daytime and night-time vibration dose values (VDVs) exceed 0.22 $ms^{-1.75}$ and 0.13 $ms^{-1.75}$ respectively.		

Source: Crossrail (2007, 2008).

In the same way the assessment criteria used by Network Rail (Table 2.17) are very similar to those adopted the Channel Tunnel Rail Link (CTRL).

[1] Crossrail Ltd (CRL) is a fully owned subsidiary of Transport for London (TfL).

Table 2.17 Construction and Operational Vibration Criteria

Impact classification	In the Absence of Appreciable Existing Levels of Vibration (VDV $ms^{-1.75}$)[1]		Appreciable Existing Levels of Vibration[1, 2]	Effect
	Day (7h-23h)	Night (23h-7h)	% increase in VDV	
Slight	> 0.22-0.31	> 0.13-0.18	25-40 %	
Moderate	> 0.31-0.44	> 0.18-0.26	40-100 %	Significant
Substantial	> 0.44-0.62	> 0.26-0.37	100-185 %	Significant
Severe	> 0.62	> 0.37	> 185 %	Significant
Note 1. Highest impact category used, daytime or night-time. Note 2. Where there is an appreciable existing level of vibration and night-time vibration dose values (VDVs) exceed 0.22 $ms^{-1.75}$ and 0.13 $ms^{-1.75}$ respectively.				

Source: .

The criteria in numerous projects (Channel Tunnel Link Rail, Thameslink, West Coast Hand Line, Jubilee Line Extension, Edinburgh Airport Air Link, Edinburgh tram lines) lie within the values given BS 6472-1 for a low probability of adverse comments.

United States of America

FRA (2005) and FTA (2006) are two guidance manuals on noise and vibration impact assessment for high-speed ground transportation (HSGT) and mass transit projects respectively. Three levels of analysis may be employed, depending on the type and scale of the project, the stage of project development, and the environmental setting:

– Screening Procedure: Identifies noise- and vibration-sensitive land uses in the vicinity of a project and whether there is likely to be impact;

– General Assessment: Identifies location and estimated severity of noise and vibration impacts in the noise and vibration study identified in the screening procedure;

– Detailed Analysis: Quantifies impacts through an in-depth analysis usually only performed for a single alternative of the project.

The criteria for acceptable groundborne vibration, as maximum running r.m.s. velocity (time constant Slow) expressed in VdB[1], are presented in Table 2.18A for the General Assessment Analysis. The criteria account for land use as well as the frequency of events. The acceptable limits are specified for three land-use categories:

– Vibration Category 1 (High sensitivity): buildings within which vibration levels that may be well below those associated with human annoyance. Concert halls and other special-use facilities[2] are covered separately in Table 2.18B;

– Vibration Category 2;

– Vibration Category 3: schools, churches, other institutions, and quiet offices that do not have vibration-sensitive equipment, but still have the potential for activity interference.

As can be seen, the FTA and FRA guidance manuals account for an inverse relationship between the number of daily events and the degree of annoyance caused by groundborne vibration. The impact threshold is 8 VdB higher if there are fewer than 30 events per day and 3 VdB higher if there are fewer than 70 events per day.

[1] The values in VdB are converted to mm/s in the table below.

Value (VdB re 10^{-6} in/s)	Converted value (mm/s)
60	0.025
65	0.045
72	0.101
75	0.143
78	0.202
80	0.254
83	0.359

[2] Out of scope of the RIVAS project.

The American descriptor is a vibration level derived from an unweighted r.m.s. acceleration.

Table 2.18A Groundborne vibration impact criteria for General Assessment

Land use category	**Impact level** (VdB re 10^{-6} in/s)		
	Frequent events[1]	Occasional events[2]	Infrequent events[3]
1. Buildings where vibration would interfere with interior operations.	65 VdB[4]	65 VdB[4]	65 VdB[4]
2. Residences and buildings where people normally sleep (such as hotels, hospitals).	72 VdB	75 VdB	80 VdB
3. Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB

Note 1. "Frequent Events" is defined as more than 70 vibration events of the same source per day. Most rapid transit projects fall into this category.
Note 2. "Occasional Events" is defined as between 30 and 70 vibration events of the same source per day. Most commuter trunk lines have this many operations.
Note 3. "Infrequent Events" is defined as fewer than 30 vibration events of the same kind per day. This category includes most commuter rail branch lines.
Note 4. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC systems and stiffened floors.

Table 2.18B Groundborne vibration impact criteria for special buildings

Type of building or room	**Impact level** (VdB re 10^{-6} in/s)	
	Frequent events[1]	Occasional or infrequent events[2]
Concert halls, TV studios, recording studios	65 VdB[4]	65 VdB[4]
Auditoriums	72 VdB	80 VdB
Theatres	72 VdB	80 VdB

Note 1. "Frequent Events" is defined as more than 70 vibration events of the same source per day. Most rapid transit projects fall into this category.
Note 2. "Occasional or Infrequent Events" is defined as fewer than 70 vibration events per day. This category includes most commuter rail branch lines.
Note 3. If the building will rarely be occupied when the trains are operating, there is no need to consider impact. As an example, consider locating a commuter rail line next to a concert hall. If no commuter trains will operate after 7 pm, it should be rare that the trains interfere with the use of the hall.

Source: FRA (2005), FTA (2006).

FTA (2006) states that "*although the perceptibility threshold is about 65 VdB* [0.045 mm/s], *human response to vibration is not usually significant unless the vibration exceeds 70 VdB* [0.080 mm/s]. *[...] If the vibration level in a residence reaches 85 VdB* [0.452 mm/s], *most people will be strongly annoyed by the vibration*".
FTA (2006) explains how to account for the existing vibration conditions. When the vibration change due to the project is higher than 5 VdB (*i.e.* a 78 % increase in the velocity value), the existing source can be ignored and the standard vibration criteria apply to the project. If the increase in vibration events or the shift of existing tracks results in a 3 VdB higher vibration level (*i.e.* a 41 % increase in the velocity value) the additional impact need being assessed.

Neither document (FTA and FRA guidance manuals) is specifically oriented to freight rail projects. The significantly greater length, weight and axle loads of freight trains make it problematic to use these impact criteria for freight rail. However, the impact criteria and general procedures have been reasonably applied to a number of freight rail and commuter rail projects. But they may be disregarded altogether in some cases (e.g. spur rail lines with very little traffic or with short trains).

More detailed criteria are used in the Detailed Analysis. They result from ISO 2631-2:1989 for the effects of vibration on people (standing) in buildings and from industry standards for vibration-sensitive equipment (out of scope of the RIVAS project). They are expressed in one-third octave band spectra (see Figure 2.4). Interpretations of the various levels are given in Table 2.19.

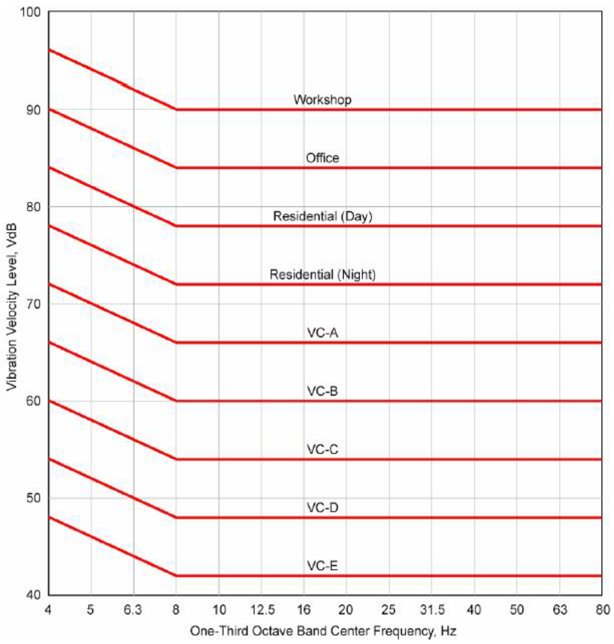


Figure 2.4 Criteria for Detailed Vibration Analysis

Note. The VC curves apply to vibration-sensitive equipment.

Criteria band levels that exceed a particular criterion curve indicate the need for mitigation and the frequency range within which the treatment needs to be effective.

Table 2.19 Interpretation of vibration criteria for Detailed Analysis

Criterion curve (see Figure 1.x)	Max L_v (VdB)[1]	Description of use
Workshop	90	Distinctly feelable vibration. Appropriate to workshops and non-sensitive areas.
Office	84	Feelable vibration. Appropriate to offices and non-sensitive areas.
Residential Day	78	Barely feelable vibration. Adequate for computer equipment and low-power optical microscopes (up to 20X).
Residential Night	72	Vibration not feelable, but groundborne noise may be audible inside quiet rooms.
Note 1. As measured in one-third octave bands of frequency over the frequency range 8-80 Hz.		

Source: FTA (2006).

The human response to vibration and groundborne noise is described in Table 2.20. Its first column is the vibration velocity level, and the next two columns are for the corresponding noise level. Note that two distinct levels are set according to whether the vibration spectrum peaks at 30 Hz or 60 Hz. The A-weighted noise level will be circa 40 dB less than the vibration velocity level if the spectrum peak is around 30 Hz, and 25 dB lower if the spectrum peak is around 60 Hz. It appears that "*achieving either the acceptable vibration or acceptable noise levels does not guarantee that the other will be acceptable*".

Table 2.20 Human response to different levels of vibration and groundborne noise

Vibration level (re 10^{-6} in/s)	Noise level		Human response
	Low frequency[1]	Mid frequency[2]	
65 VdB (0.045 mm/s)	25 dBA	40 dBA	Approximate threshold of perception for many humans. Low-frequency sound usually inaudible, mid-frequency sound excessive for quiet sleeping areas.
75 VdB (0.143 mm/s)	35 dBA	50 dBA	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find transit vibration at this level annoying. Low-frequency noise acceptable for sleeping areas, mid-frequency noise annoying in most quiet occupied areas.
85 VdB (0.452 mm/s)	45 dBA	60 dBA	Vibration acceptable only if there are an infrequent number of events per day. Low-frequency noise annoying for sleeping areas, mid-frequency noise annoying even for infrequent events with institutional land uses such as schools and churches.
Note 1. Approximate noise level when vibration spectrum peak is near 30 Hz. Note 2. Approximate noise level when vibration spectrum peak is near 60 Hz.			

Source: FRA (2005), FTA (2006).

2.2.2 Comparative analysis

ISO standards

ISO 2631-2:2003 defines the frequency weighting W_m only for acceleration (close to the 1989 one). It does not give limit values any longer.

In the former ISO 2631-2:1989, base frequency-dependent base curves were given for both acceleration and velocity, corresponding to no adverse comments. The reference vertical velocity curve was flat, corresponding to 0.1 mm/s over the range 8-80 Hz. These curves are still in use in France, Sweden and the USA for detailed frequency analysis. Acceptable vibration levels are then expressed through multiplying factors applied to the base curves with respect to the building use and the assessment period (daytime or night-time).

An informative annex of ISO 2631-2:2003 emphasizes on phenomena associated with vibration such as groundborne noise, airborne noise generated by railways (or not) and transmitted through the building façade, as well as rattle and visual effects, both usually generated by rather low-frequency vibration. Then it recommends to measure groundborne noise and to describe the other phenomena in the measurement report. However, the standard proposes neither descriptor nor measurement procedure for such an assessment.

National standards

The acceptable vibration levels defined in the national standards have the following features:

(*i*) In general, national criteria are based on subjective acceptable annoyance rather than on an absolute threshold of perception. By contrast with protection against noise, few national criteria are currently derived from exposure-effect relationships with an admissible expected proportion of (highly) annoyed people (Norway, USA) yet.

(*ii*) Quality classes regarding vibration are proposed in some countries:
- Austria: two classes (satisfactory and good);
- Norway: four classes (very good, good, moderate, probable);
- United Kingdom: three classes (low probability, possible, probable adverse comments);
- Sweden: two classes (moderate and probable disturbance).

(*iii*) Limits can be given in terms of maximum values only (as in Norway, Sweden, Spain and the USA), in terms of traffic-oriented equivalent values only (as in the UK with the vibration dose value), or in terms of both maximum and traffic-oriented equivalent values (as in Austria E_{max} and E_r). Germany along with the Netherlands and Switzerland also use maximum (A_0) and traffic-oriented (A_r) criteria; but the latter is a time-weighted mean of maximum values (not of equivalent mean values). The relevance of these two types of descriptors is discussed in chapter 4.

(*iv*) As a result, the two types of descriptors (maximum and equivalent values) should be distinguished when comparing national criteria for acceptable vibration. The following national criteria at night-time for dwellings, standing for the acceptable annoyance level in the considered countries to date, can be compared:

– Austria (ÖNORM S 9012): 'satisfactory' ($E_{max} \leq 18.8$ mm/s² and $E_r \leq 1.59$ mm/s²) and 'good' ($E_{max} \leq 9.4$ mm/s² and $E_r \leq 0.84$ mm/s²) protection;
– Germany (DIN 4150-2): $KB_{FTr} \leq 0.05$ and $KB_{Fmax} \leq 0.2$;
– Italy (UNI 9614): $a_w \leq 7$ mm/s² (z-axis);
– Norway (NS 8176): class C ($a_{w,95} < 11$ mm/s²) and class B ($a_{w,95} < 5.4$ mm/s²);
– Spain (Royal Decree 1367/2007): $a_w \leq 5.6$ mm/s²;
– Sweden (SS 460 48 61): 14 and 36 mm/s²;
– United Kingdom (BS 6472-1): VDV_{night} at 0.1 to 0.2 m.s$^{-1.75}$;
– United States of America (FTA manuals): $v \leq 7$ mm/s (72 VdB re 1 µin/s) for 'Frequent' passbys (over 70 vibration events per day);
– ISO 2631-2:1989: $v \leq 0.14$ mm/s (multiplying factor of 1.4 for residential buildings).

All criteria are converted to weighted acceleration for comparison (Table 2.21).

Table 2.21 Vibration criteria at night-time in residential buildings (W_m-weighted acceleration in mm/s²)

Country and quality class	Austria		Germany	Italy	Norway		Spain	Sweden	UK	USA	ISO 2631-2 (1989)
	Satisf.	Good			Class C	Class B					
Maximum value	18.8	9.4	7.1	7.0	11	5.4	5.6	14-36	10	3.6	5.4
Equivalent value	1.59	0.84	1.8	–	–	–	–	–	0.5	–	–

Comments:
• The relationship used between acceleration and velocity is: $a_w = 35.7\ v_w$.
• Austria: assessment with exposure corresponding to $a_{w,s} > 3{,}57$ mm/s².
• Germany:
  – time constant: Fast;
  – assessment with exposure corresponding to $KB > 0.1$ mm/s².
• Norway: the assessment quantity is the statistical 95-percentile value (a more stringent criterion than the maximum measured value).
• United Kingdom:
  – 8 occurences at night-time, each of duration $t = 10$ s;
  – $eVDV = 1.4 \times a(t)_{r.m.s.} \times t^{0.25} = 0.1$ m.s$^{-1.75}$;
  – the calculated constant value (10 mm/s²) is an average r.m.s. acceleration over a train passage, thus underestimating the actual maximum value.

The figures in Table 2.21 should be considered as provisional. As from now, the example of the British vibration-dose value illustrates that vibration criteria can have opposite meanings, depending on whether they aim at rating acceptable annoyance from single vibration events or acceptable harassment from repeated exposure to vibration.

Further investigation could be performed if time signals (measured or estimated) were available for various situations (source/ground/building foundation). The effects of mitigation measures will be evaluated for typical cases in RIVAS project. It will give the opportunity for deepening the comparison of the national descriptors and criteria (see deliverable D1.9 when issued) and for highlighting possible differences between types of railway traffic (passenger, freight, etc.).

(*v*) A 40 % variation in the existing vibration conditions (e.g. an increase in traffic) has often been considered as the minimum change that is noticeable by exposed people. Evidence from recent lab findings give support to lower difference thresholds (about 25 %). See further in chapter 4.

(*vi*) The Spanish regulation details how the compliance with the regulation should be monitored. Limit values may be exceeded in certain conditions. It does not state any tolerance interval allowing for measurement uncertainty, maybe defined elsewhere (see discussion in chapter 4).

(*vii*) Frequency analysis may be required in order to scrutinize the particular frequency ranges of vibration that have to be treated. The base curves of ISO 2631-2:1989 are still used to that end (at least in Sweden, the USA and France).

(*viii*) As is indicated in Annex A, the Austrian (E_{v}), German (KB_{FTr}) and Dutch (V_{per}) mean equivalent descriptors are calculated for signal amplitudes over a ‘perception threshold’ (3.57 mm/s^2 for acceleration and 0.1 mm/s for velocity). See further discussion in chapter 4.

3. INDOOR NOISE

3.1 Standards and guidelines

3.1.1 Overview of reference documents

In Table 3.1 below are summarized the key features of documents that are be concerned with discomfort from low-frequency noise. Some of them are specifically dedicated to structure-borne noise from railway traffic. Others deal with indoor noise in general with special provisions for low-frequency noise (mainly from technical equipment); they may sometimes be used as references for the vibration assessment of railway projects. Few features are not given (especially frequency range and measurement procedure). The definitions of the quantities used in the different standards and guidelines are given in Annex A.

Table 3.1 Standards and guidelines

Key feature	International standards ISO 14837-1:2005	Austria ÖNORM S 9012:2010	Germany TA Lärm[1]
Scope	Groundborne noise and vibration from rail systems	Land-based transport vibration in buildings (vibration and structure-borne noise)	Noise from service equipment (incl. low-frequency noise)
Frequency range	16-250 Hz	16-125 Hz	8-125 Hz
Frequency weighting	A	A	A and C
Time constant	Slow	Slow	Fast
Indicator[1]	• Maximum SPL L_{pASmax} (dB) • Equivalent SPL L_{Aeq} (per event or longer duration *e.g.* 1 h)	• Maximum SPL L_{pASmax} (dB) • Equivalent SPL L_{Aeq} (dB) for all types *i* of trains	Equivalent SPL L_{Aeq} (dB) per one-hour period.
Measurement	Near the centre of the room (also if predicted)	Measured or computed from floor vibration according to ONR 199005.	
Note 1. See also DIN 45680 and comments below (section 3.2.1 – Germany).			

Key feature	Italy D.P.C.M. 5-12-1997	The Netherlands NSG-Richtlijn (1999)	Spain Real Decreto 1307/2007
Scope	Noise regulation (technical equipment)	Low-frequency noise	Noise regulation (zoning, quality and emissions)
Frequency range	20-100 Hz	20-100 Hz	none
Frequency weighting	A	A	A and C
Time constant	Slow	Slow	Not specified
Indicator	Maximum SPL L_{ASmax} (dB)	Reference curve Equivalent SPL L_{Aeq} (dB)	Equivalent SPL $L_{d/e/n}$ (dB)
Measurement		Where the noise is most perceptible (bedroom or living room if anywhere) Otherwise in a corner at 0.2-0.5 m from both walls (without door, window or cupboard)	

Key feature	Sweden[1] SOSFS 1996:7, 2005:6	Switzerland BEKS:1999	United Kingdom Contractual guidelines
Scope	Indoor noise	Railway vibration and groundborne noise within buildings	Construction and operational groundborne noise from railway
Frequency range	31.5-200 Hz	none	none
Frequency weighting	A and C	A	A
Time constant	Fast	None	Slow
Indicator	Reference curve Maximum SPL L_{ASmax}	Equivalent SPL L_{pAeq} (day and night)	Maximum SPL L_{pASmax}
Measurement	0.5 m from room corner	No information	Where the effect is most disturbing
Note1. See also SS 25263 and SS-EN 16032.			

Key feature	USA FRA (2005), FTA (2006)
Scope	Guidance manuals on noise and vibration impact assessment (transit and high-speed rail projects)
Frequency range	none
Frequency weighting	A
Time constant	Slow
Indicator	Maximum SPL L_{ASmax}
Measurement	No information

3.1.2 Comparative analysis

Two main types of descriptors are used:

– the A-weighted maximum sound level (running r.m.s. Slow) is widely used (L_{pASmax});

Remark: C-weighting is proposed in Sweden for louder vibration-induced noise.

– distinct A-weighted equivalent sound level are used in Switzerland and Spain:

– Switzerland: L_{pAeq} (dB) at daytime (8h, 6h-22h) and night-time (1h, worst hour 22h-6h);

– Spain: $L_{pd/e/n}$ (dB) in Spain (with penalties: +5 dB in the evening and +10 dB at night).

The measurement procedures for vibration-induced noise are not always given. When they are, they differ. In ISO 14837-1:2006, sound level is measured near the room centre and, therefore, underestimated because of the strong modal behaviour of rooms (see section 1.3). In ISO 2631-2:2003 and BS 6472-1:2008, the measurement is performed where the noise effect is the most disturbing (it could be in a corner of the room). See further discussion in chapter 4.

3.2 Comfort requirements

3.2.1 Criteria and limit values

Austria

The ÖNORM S 9012 standard prescribes two sets of requirements (satisfactory and good protection) for structure-borne noise induced by railway (and road) traffics, depending on the urban area and the time period. Upper limits are given for two criteria:

– an averaged A-weighted maximum sound level L_{Amax} for the noisiest type of train (long distance, local and freight) in tables 3.2A (satisfactory protection) and 3.2B (good protection). The criterion is calculated as a maximum SPL averaged over n train passages of the same type m;

– a mean equivalent SPL L_{Aeq} for the whole railway traffic in table 3.2C.

Table 3.2A Reference values for the mean maximum A-weighted sound level L_{Amax} (dB) – Satisfactory protection

Area category	Description of the built-up area	Working day		Sunday and public holidays	
		Day (6h-19h)	Evening (19h-22h)	Day and evening (6h-22h)	Night (22h-6h)
1	Rest areas, cure areas, hospitals	40	35	35	30[1]
2	Dwellings in suburban and land areas, schools	45	40	40	35[1]
3	Dwellings in urban areas, areas for forestry and land business buildings with dwellings	45	40	40	35[1]
4	Central area, area for business activities without vibration and noise emission	50	45	45	40[1]
5	Areas for low vibration and noise emitting business activities[1]	50	50	50	50
6	Goods manufacturers and service companies[1]	65	65	65	65

Note 1. When public transport cease service four hours at night-time, the evening values may also be used as criteria for the night period.

Table 3.2B Reference values for the mean maximum A-weighted sound level L_{Amax} (dB) – Good protection

Area category	Description of the built-up area	Working day		Sunday and public holidays	
		Day (6h-19h)	Evening (19h-22h)	Day and evening (6h-22h)	Night (22h-6h)
1	Rest areas, cure areas, hospitals	35	30	30	25[1]
2	Dwellings in suburban and land areas, school	40	35	35	30[1]
3	Dwellings in urban areas, areas for forestry and land business buildings with dwellings	40	35	35	30[1]
4	Central area, area for business activities without vibration and noise emission	45	40	40	35[1]
5	Area for low vibration and noise emitting business activities[1]	45	45	45	45
6	Goods manufacturers and service companies[1]	65	65	65	65
Note 1. When public transport interrupts service four hours at night-time, the evening values may also be used as criteria for the night period.					

Table 3.2C Reference values for the A-weighted equivalent continuous sound level L_{Aeq} (dB)

Area category	Description of the built-up area	Satisfactory protection		Good protection	
		Day and evening	Night	Day and evening	Night
1	Rest areas, cure areas, hospitals	25	20	20	15
2	Dwellings in suburban and land areas, school	30	25	25	20
3	Dwellings in urban areas, areas for forestry and land business buildings with dwellings	35	30	30	25
4	Central area, area for business activities without vibration and noise emission	35	30	30	25
5	Area for low vibration and noise emitting business activities	35	35	30	30
6	Goods manufacturers and service companies	55	55	50	50

Source: ÖNORM S 9012:2010.

Germany

No clear regulation concerns structure-borne noise. But the Federal State/States Working Group for Protection against Immissions (LAI[1]) issued instructions for measurement, assessment and mitigation of vibration (*LAI-Hinweise*). They referred to two documents: the technical guide Noise (*TA Lärm* 1998) and DIN 45680:1997.

The technical guide Noise is used to apply the federal law on noise nuisance caused by various installations. Limit values are also set for low-frequency noise within buildings at large, including structural-borne noise. If the difference L_{Ceq} - L_{Aeq} exceeds 20 dB, low-frequency noise may cause disturbance. Then the criterion L_r (L_{Aeq}) should not exceed values that are 5 dB lower than regulatory (24. BImSchV) indoor sound levels (Table 3.3).

Table 3.3 Limit value L_r (dBA) for low-frequency noise

Assessment period	Sound level L_r (L_{Aeq})	
	TA Lärm 1998	24. BImSchV
Daytime (6h-22h)	35	40
Night-time (22h-6h)[1]	25	30
Note. One-hour periods within the night-time period should also be assessed.		

Source: TA Lärm 1998, 24. BImSchV.

Moreover peaks of short-time noise should not exceed these values by more than 10 dBA.

A draft of new DIN 45680 is currently under review. Its scope is the measurement and the assessment of low-frequency noise from 8 to 125 Hz, including structure-borne noise. In a

[1] Bund/Länder-Arbeitsgemeinschaft für Immssionsschutz.

preliminary investigation the sound levels L_{Ceq} and L_{Aeq} are measured. If L_{Ceq} - L_{Aeq} > 15 dB further investigation based on frequency analysis should be carried out. Then two criteria are used (Table 3.4):

– the maximum difference of the perception-exceeding one-third octave sound pressure level $\ddot{U}_{Dmax}$ and the associated limit value A_0;

– the characteristic (overall exceeding level) for low frequencies H (see Annex A Germany) and the associated limit value A_H.

Table 3.4 Reference values (dB) **for the characteristics $\ddot{U}_{Dmax}$ and H**

Assessment period	A_0 ($\ddot{U}_{Dmax}$)	A_H (H)
Day	35	30
Rest periods	30	25
Night	25	20

Source: DIN 45680:2011 (draft).

If either of the criteria is not met, substantial annoyance from low-frequency noise can be expected. Note that neither the 2010 draft state nor the current 1997 version of DIN 45680 state that railway structure-borne noise is out of its scope.

How to deal with structure-borne noise caused by railway traffic was rather controversial in the past. In the last years, regional judicial settlements pronounced that only the noise regulation (24. BImSchV) should apply to structure-borne noise from railways, giving support to Deutsche Bahn AG and railway authorities' viewpoints. However, some region-states (for instance Bavaria[1]) keep recommending the LAI instructions and the technical guidance *TÄ Larm*.

Deutsche Bahn AG developed a method to predict structure-borne noise in dwelling rooms (Said *et al.*, 2006). They recommend it for the assessment of vibration impact in their rail projects. It uses the A-weighted velocity level L_{vA} (dBA ref 10^{-5} m/s) measured at mid-span of floors. From regression analyses, an overall noise level L_{sekA} can be estimated for two types of floors (wooden and concrete floors) and two types of railways (urban light trains and transit passenger trains). Relationships are also given for one-third octave bands between 25 and 80 Hz for each floor. The method does not deal with freight trains. But it might assuming vibration dynamics similar to passenger trains. It cannot apply to special buildings (concert halls, churches, high-rise buildings, long-span floors, etc.) requiring ad hoc investigation.

Italy

The Italian regulation sets limit values for indoor sound value, including technical equipment (Table 3.5).

Table 3.5 Limit values (dB) **for indoor sound level**

Building	Passive requirements		Technical equipment	
	L_{Aeq}	L_{ASmax}	L_{Aeq} [1]	L_{Asmax} [2]
A. Dwellings and similar	35	35	25	35
B. Offices and similar	35	35		
C. Hotels and similar	35	35		
D. Hospitals, clinics, health care and similar	25	35		
E. Schools and similar	25	35		
F. Recreational or religious activities and similar	35	35		
G. Commercial activities and similar	35	35		
Note 1. Continuous functioning. Note 2. Discontinuous functioning.				

Source: D.P.C.M. 5-12-1997.

[1] See Bayerisches Landesamt für Umwelt (2007): *Schall- und Erschütterungsschutz im Planfeststellungsverfahren für Landverkehrswege.*

The requirements for technical equipment may be referred to in environment impact assessment of railway projects.

Japan

Under the Basic Environment Law (1993), the Noise Regulation Law (1998, 2000) provides criteria for environmental (outdoor) noise from road traffic (Figure 3.6). Specific limit values are also required for noise from Shinkansen railway traffic (Figure 3.7).

Table 3.6 Criteria (dB) **for environmental (outdoor) noise from road traffic in Japan**

Area[2]	Sound level[1]		
	Day	Evening Morning	Night
Areas alongside a one-lane road in Area I	55	50	45
Areas alongside a one-lane road in Area II	60	55	50
Areas alongside a two-lane road in Area I or II	70	65	55
Areas alongside a more-than-two-lane road in Area I or II	75	70	60
Areas alongside a one-lane road in Area III or IV	70	65	60
Areas alongside a two-lane road in Area III or IV	75	70	65
Areas alongside a more-than-two-lane road in Area III or IV	80	75	65

Note 2. Hourly L_{Aeq}.
Note 2. Area classification:
– Area I: area where maintaining quietness is particularly needed to preserve a good living environment;
– Area II: area where quietness is needed for as used for residential purpose;
– Area III: area used for commercial and industrial as well as residential purposes where there is a need to preserve the living environment of local residents;
– Area I: area mainly used for industrial purposes where measures are needed to prevent the living environment of local residents from deteriorating.

Source: Cabinet Order for the implementation of the Noise Regulation Law.

Table 3.7 Criteria (dB) **for environmental (outdoor) noise from Shinkansen railway traffic in Japan**

	Land use area[1]	Sound leverl[2] (6h-24h)
I	Areas used mainly for residential purpose	70
II	Other areas, including commercial and industrial areas, where the normal living conditions shall be preserved	75

Note 1. There is also an area classification (a, bA, bB and C) for existing lines with target dates for achievement.
Note 2. Energy mean value of the half highest sound levels (L_{ASmax}) of 20 successive representative train passages.

Source: Environment Agency notification no. 91 (1993).

There is no regulation for indoor noise. But, in the Environmental quality standards for noise which were notified by the Environment Agency, there are standards for indoor noise transmitted from outside: 45 dB or less at daytime, and 40 dB or less at night-time for residences exposed to road traffic.

As complaints from low-frequency noise were increasing, the Ministry of Environment issued an evaluation guide which deals with noise from stationary sources. It provides reference values for two categories of complaints: rattling in fittings and discomfort in a room (Table 3.8). It also includes a G-weighted (or default unweighted) limit value of 92 dB for discomfort.

Table 3.8 Reference values (dB) **for low-frequency noise in Japan**

Frequency (Hz)	5	6.3	8	10	12.5	16	20	25	31.5	40	50	63	80
Rattling	70	71	72	73	75	77	80	83	87	93	99	–	–
Mental and physical discomfort	–	–	–	92	88	83	76	70	64	57	52	47	41

Source: Ministry of the Environment (2004).

The Netherlands

The Dutch Foundation for Noise Nuisance (NSG) published a guideline for low-frequency noise. It aimed first to manage complaints from people annoyed by low-frequency noise. It became a basis for jurisprudence. It is currently used, among others, for the impact assessment of some railway projects. The existence of low-frequency noise is detected in the 20-100 Hz range by comparing the unweighted one-third octave sound level to an audibility threshold curve (Table 3.9). However, the NSG guideline assumes continuous low-frequency noise and does not account for short-time (less than 5 minutes) train passages.

Table 3.9 Reference curve for low-frequency noise (20-100 Hz)

Frequency (Hz)	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160	200
Reference curve[1] (dB) *D*	92	88	84	74	62	55	46	39	33	27	22	18	14	10
Measured level *G*														
G_i - D_i														
Note. The reference curve for audibility corresponds with the perception threshold of the best hearing 10 % of people aged 50-60 (the average age of complainants).														

Source: NSG (1999).

The assessment level is the A-weighted equivalent sound pressure level L_{Aeq}. It cannot exceed the limit value of 35 dB(A) at daytime. It can be diminished at night-time (-10 dB) and for tonality (-5 dB) down to 20 dB (35 - 10 - 5 dB) at the very least.

Norway

The Norwegian standard NS 8175:2008 defines the sound classification (classes A, B, C and D) of various types of buildings. The Technical Regulation (TEK 97) is achieved if the requirements for class C are met. Limit values are set out for indoor sound pressure level (Table 3.10a and 3.10b). The criteria for service equipment are valid for traffic noise from tunnels and culverts. The maximum C-weighted sound pressure level L_{pCFmax} for dwellings and health buildings is introduced to check whether the noise contains annoying low-frequency sound.

Table 3.10 Limit values (dB) **for indoor sound level**

a. From service equipment

Type of building	Type of space	Descriptor	Class A	Class B	Class C	Class D
Dwellings	Drawing rooms and bedrooms[1]	$L_{pAeq,24h}$	20	25	30	35
		L_{pAFmax}	22	27	32	37
		L_{pCFmax}	–[1]	42	47	–
Schools, teaching buildings	Classrooms, conference rooms	L_{pAFmax}	25[1]	28	32	35
	Classrooms for people with visual and hearing impairment	L_{pAFmax}	22[1]	25	30	35
	Special rooms, sound studios, etc.	L_{pAFmax}	20[1]	22[1]	25[1]	25
Kindergartens, day-care facilities for schoolchildren and first-year classrooms	Day rooms	L_{pAFmax}	25[1]	28	32	35
Hospitals and care institutions	Bedrooms, residential rooms, common rooms	L_{pAFmax}	22	27	32	35
		L_{pCFmax}	–[1]	45	50	55
Overnight accommodation	Guest rooms	L_{pAFmax}	25[1]	28	32	35
	Common areas, common drawing rooms	L_{pAFmax}	30	30	35	40
Offices	Offices, common areas, conference rooms	L_{pAFmax}	30	35	40	45
Note 1. For this class a frequency analysis of low-frequency noise by octave band is performed according to the method described in the annex A of NS 8175.						

b. From outdoor noise sources

Type of building	Type of space	Descriptor	Class A	Class B	Class C	Class D
Dwellings	Drawing rooms and bedrooms	$L_{pAeq,24h}$	20	25	30	35
	Bedrooms at night-time (23h-07h)	L_{pAFmax}	35	40	45	50
Schools, teaching buildings	Classrooms, conference rooms	$L_{pAeq,T}$	25	28	32	35
Kindergartens, day-care facilities for schoolchildren and first-year classrooms	Day rooms	$L_{pAeq,T}$	25	28	32	35
Hospitals and care institutions	Bedrooms and residential rooms	$L_{pAeq,24h}$	20	25	30	35
	As above at night-time (23h-07h)	L_{pAFmax}	35	40	45	50
Overnight accommodation	Guest rooms and common areas	$L_{pAeq,24h}$	25	30	35	40
Offices	Offices	$L_{pAeq,T}$	30	35	40	45

Source: NS 8175:2008.

The assessment method of annoying sound components (annex A of NS 8175) is based on the American standard ANSI S12.2:1995 on criteria for evaluating room noise, and its RC and NCB curves. The room criterion (RC) curves are derived from studies on HVAC noise in offices. The balanced noise criterion (NCB) curves are based on the threshold of hearing with emphasis on speech interference level and loudness level. The two sets are incompatible at low frequencies and low sound levels (Rebanek, 2005). ANSI/ASA S12.2 was revised in 2008 (see below).

Spain
The Spanish Noise Regulation (RD 1367/2007) sets out the acoustical quality levels (equivalent SPLs) that ought to be met inside buildings (Table 3.11).

Table 3.11 Criteria for indoor noise

Building use	Type of premise	Noise Level (dB)		
		L_d	L_e	L_n
Dwellings and residential use	Stay rooms	45	45	35
	Bedrooms	40	40	40
Hospitals	Stay rooms	45	45	35
	Bedrooms	40	40	30
Education and culture	Lecture rooms	40	40	40
	Reading rooms	35	35	35

Source: Real Decreto 13067/2007.

The regulation also limits environmental noise ($L_{d/e/n}$ and L_{Amax} outdoor levels) from new road, railway and airport infrastructures. For new and upgraded (double capacity or more) national railway lines, adequate measures should be taken in case their operation results in noise levels exceeding the limit values. For new and existing infrastructures within their competence, the Autonomous Communities (*Comunidades Autónomas*) sets local noise specifications.

The Spanish regulation also explains how to comply with the noise provisions. For each noise requirement ($L_{d/e/n}$ or L_{Amax}):
– the relevant criterion should never be exceeded;
– 97 % of the daily values do not exceed by 3 dB the required noise level.

Sweden
The National Board of Health and Welfare (*Socialstyrelsen*)[1] issues various recommendations (SOSFS[2]). SOSFS 2005:6 sets out limits for noise within buildings (Table 3.12).

Table 3.12 Guideline values for indoor noise[1]

Noise level	Value (dB)
Maximum sound level (L_{AFmax})	45
Equivalent sound level (L_{AeqT})[2]	30
Sound with audible tonal components (L_{AeqT})	25
Sound from music centre (L_{AeqT})	25
Note 1. Liveable rooms in dwellings and leisure homes. Note 2. *T* is the time period.	

Source: Socialstyrelsen SOSFS 2005:6.

The possible existence of low-frequency noise is detected by measuring the A- and C-weighted sound levels L_{Ceq} and L_{Aeq}. If the difference L_{Ceq} - L_{Aeq} exceeds about 15-20 dB a frequency analysis based on the SOSFS 1996:7 reference curve is performed (Table 3.13).

Table 3.13 Reference curve for low-frequency noise

Frequency band (Hz)	31,5	40	50	63	80	100	125	160	200
Sound level (dB)	56	49	43	41,5	40	38	36	34	32

Source: Socialstyrelsen SOSFS 1996:7.

[1] A government agency under the Swedish Ministry of Health and Social Affairs.
[2] SOSFS stands for *Socialstyrelsens författningssamling* (regulation of the National Board of Health and Welfare).

The Swedish guidelines for rail traffic (Banverket, Naturvårdsverket, 2006) also set out limit values (sound pressure levels $L_{Aeq,24h}$ and L_{AFmax}) for indoor and outdoor noise by type of building (Table 3.14).

Table 3.14 Guideline values for buildings near rail tracks

Type of railway works	Equivalent $L_{Aeq,24h}$ (dB)	Maximum L_{AFmax} (dB
Permanent dwellings, leisure houses and care premises		
Outdoor	60^1, 55^2	70^2
Indoor	30^6	45^3
Educational premises		
Indoor	–	45^7
Work premises		
Indoor	–	60^5
Areas with low background noise		
Recreational areas in urban context	$55^{1,4}$	–
Open air areas	$40^{1,4}$	–

Note 1. Free-field values or values corrected to free-field values.
Note 2. Patio, clearly delimited area.
Note 3. Sleep and rest rooms (bedrooms) at night-time (22h-6h) as well as other rooms (excl. hall, storage room, WC, etc.).
Note 4. Area with low background noise.
Note 5. Work premises with quiet activity.
Note 6. Liveable room (excl. hall, storage room, WC, etc.).
Note 7. Level during teaching hours.

Source: Banverket, Naturvårdsverket (2006).

There is no national reference for structure-borne noise in Sweden although it is mentioned in the guidelines for railway traffic (Banverket and Naturvårdsverket, 2006). But Environmental Impact Assessments (EIAs) of railway projects with tunnels may refer to guideline values (in operational conditions) such as the following for Västlänken project, a railway tunnel in Gothenburg (Table 3.15).

Table 3.15 Guideline values for railway-induced structure-borne noise (dB)

Type of building	Level L_{pASmax} (dB)
TV studio, sound recording studio, concert hall, opera	25-30[1]
Dwelling, care premise, hotel	30[2]
Museum, theatre, school, day nursery, church, library, conference centre	35
Office and similar daytime activities	40

Note 1. The low-frequency content and the noise sensitiveness of the premises may be assessed on a case-by-case basis.
Note 2. Frequency analysis according to SOFS 1997:7. Five-minute measurement interval including the noisiest train passages.

Source: Banverket (2006), Västlänken project.

There is a four-class sound classification of buildings (A, B, C and D) in Sweden. It is based on two standards: SS 25267 for dwellings and SS 25268 for other buildings. The regulatory requirements of the Building Code are met with Class C (BBR 18 – 7 *Bullerskydd*)[1]. The indoor criteria in dwellings exposed to noise from equipment and outside sources (traffic and others) are given in Table 3.16 (a and b).

[1] The Swedish Building Code (*Boverkets byggregler*) is managed by the National Board of Housing, Building and Planning (*Boverket*).

Table 3.16 Criteria for indoor noise – Swedish sound classification of dwellings

a. From service equipment

Space	Class A		Class B		Class C		Class D	
	L_{pAeq}	L_{pAFmax}	L_{pAeq}	L_{pAFmax}	L_{pAeq}	L_{pAFmax}	L_{pAeq}	L_{pAFmax}
Sleep, rest and daily social spaces	22[1]	27	26[2]	31	30[3]	35	30	35
Other spaces	31	36	35	40	35	40	35	40

Note 1. Also $L_{pC} \leq 42$ dB in bedrooms and rest rooms.
Note 2. Also $L_{pC} \leq 46$ dB in bedrooms and rest rooms.
Note 3. Also $L_{pC} \leq 50$ dB in bedrooms and rest rooms. Deviations are permitted without exceeding one-third octave band levels (Table 3.14).

b. From outdoor noise sources (traffic and others)

Space	Class A		Class B		Class C		Class D	
	L_{pAeq} [1]	L_{pAFmax} [2]	L_{pAeq} [1]	L_{pAFmax} [2]	L_{pAeq} [1]	L_{pAFmax} [2]	L_{pAeq} [1]	L_{pAFmax} [2]
Sleep, rest and daily social spaces	22	37	26	41	30	45	34	49
Cooking and hygiene	31	46	31	–	35	–	39	–

Note 1. Equivalent SPL LpAeq,24h for traffic.
Note 2. Maximum value at night-time (22h-6h).

Source: SS 025267:2004.

References curves are also set with respect to the dwelling class (Table 3.17).

Table 3.17 Sound level (*L_{peq}* in dB) in bedrooms and rest rooms – Swedish sound classification for dwellings

Frequency band (Hz)	**31,5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**
Class A	56	49	43	38	36	34	32	30	28
Classes B, C, D	56	49	43	41,5	40	38	36	34	32

Source: SS 025267:2004.

Switzerland

The Swiss directive BEKS (1999) also sets out guidance values for structure-borne noise according to the exposed built-up area (Table 3.18). They differ for new (planned) rail tracks and upgraded railroads. The L_{eq} level of exposure is evaluated for the overall daytime period and for the night-time period on an hourly basis.

Table 3.18 Guidance values for structure-borne indoor noise

Built-up area	**New construction**		**Maintenance**[1]	
	Day (6h-22h) L_{eq}-16 h	Night (22h-6h) L_{eq}-1 h	Day L_{eq}-16 h	Night L_{eq}-1 h
Residential areas, public interest areas of public interest (schools, hospitals)	35	25	40	30
Mixed areas, town centres, agriculture areas, residential areas already exposed	40	30	45	35

Note 1 Alteration or refurbishment of existing tracks, change in operating conditions

Source: BUWAL-BEKS (1999).

The above mentioned draft Federal Ordinance on Vibration Abatement might also enforce two limit values for structure-borne noise (Table 3.19): M_r (daytime and night-time) and, for road and rail traffic, M_{max} (Meloni, 2009). Structure-borne noise would be determined on the basis of the vibration signals $v_e(t)$ (velocity) of the single events[1] with respect TO acoustical room properties and sensitivity of human hearing. The mean A-weighted energy equivalent sound level M_r would result along with the 90-percentile sound level M_{max} of the sound events during night-time.

[1] Direct measurement of low-frequency structure-borne is possible, but often problematic.

Table 3.19 Limit values M_r and M_{max} (dBA) for structure-borne noise (draft Swiss Federal Ordinance)

Sensitivity level[1]		Structure-borne noise level		
		M_r value		M_{max} value[3]
		Day (06-22h)	Night (22h-06h)[2]	
I	Zones with higher noise abatement requirements, especially in leisure zones	35	25	43
II	Zones in which operations that emit noise are not permitted, among others in residential zones and zones for public buildings and installations	40	30	48
III	Zones in which operations emitting a certain level of noise are permitted, especially in residential and industrial zones (mixed zones) and agricultural zones	45	35	53
IV	Zones in which operations emitting a high level of noise are permitted, especially in industrial zones	50	40	58

Note 1. See Noise Abatement Ordinance (Art. 43).
Note 2. One hour with the maximum structure-borne noise event.
Note 3. Only for road and rail traffic.

Source: Federal Office for the Environment.

An additional directive should detail the monitoring of compliance with the regulatory requirements.

Regarding radiated structure-borne noise, the Swiss standard SIA 181:2006 (Protection against noise in buildings) refers to the future Vibration Ordinance and to provisions for noise from equipment (SIA 181, paragraph 4.5). The criterion L_H for building equipment is expressed as an adjusted L_{AFmax} or L_{Aeq} sound level with respect to the kind of noise (Table 3.20).

Table 3.20 Limit value L_H (dBA) for building equipment

Noise sensitivity[1]	Short duration noise (L_{AFmax})		Continuous noise (L_{Aeq})[4]
	Operating noise[2]	User's noise[3]	
Low	38	43	33
Medium	33	38	28
High	28	33	25

Note 1. The sound classification is based on the type and the use of the receiving premise (SIA 181:2006, paragraph 2.3).
Note 2. Filling and draining of sanitary appliances, toilet flushing, water supply and waste water pipework, turning on/off water valves, taps and other fittings, lifts, automatic garage doors, motorized door closers, blinds and shades, electric relays.
Note 3. Use of shower or bathtub, dropped toilet seat, objects banged on worktops, opening/closing of cupboard drawers and doors, manually operated equipment: garage doors, revolving doors, sliding doors and windows, valves, grids, cooker/oven doors, fireplace doors.
Note 4. Ventilation and air-conditioning system, dishwasher, washing machine, drier, refrigerator, freezer, fan, space heating, heat pump, whirlpool bathtub, rainwater piping.

Source: SIA 181:2006 (SN 520 181).

The Swiss Railways developed the semi-empirical prediction model VIBRA-2 of structure-borne noise (and indoor vibration) near railways for one-third octave band frequencies.

United Kingdom

No UK legislative standards or criteria define when groundborne noise becomes significant. But criteria are usually adopted in order to minimize the impact for construction and operation of the railway. Table 3.21 illustrates such performance specifications in Crossrail's Code of Construction.

Table 3.21 Construction[1] and Operational Groundborne Noise Criteria

Building	Level/Measure (L_{pASmax})
Residential buildings, offices, hotels	40 dB
Theatres, large auditorial/concert halls	25 dB
Sound recording studios	30 dB
Places of meeting for religious worship	35 dB
Courts, lecture theatres, small auditoria/halls	35 dB
Schools, colleges, hospitals, laboratories, libraries	40 dB
Note 1. Excluding the groundborne noise from the passage of the tunnel boring machine.	

Source: Crossrail (2008).

United States of America

The guidance manuals FRA (2005) and FTA (2006) define the assessment method for groundborne noise at each of the three levels of analysis (Screening Procedure, General Assessment and Detailed Analysis). The levels of acceptable groundborne noise at the stage General Assessment Analysis are given in Tables 3.22A and 3.22B for special buildings[1]) with respect to the land use category and the frequency of events. As for vibration the reference values account for an inverse relationship between the number of daily events and the degree of annoyance caused by groundborne noise. The impact threshold is 8 VdB higher if there are fewer than 30 events per day and 3 VdB higher if there are fewer than 70 events per day.

Table 3.22A Groundborne noise impact criteria for General Assessment

Land use category	Impact level (L_{pASmax})		
	Frequent events[1]	Occasional events[2]	Infrequent events[3]
1. Buildings where vibration would interfere with interior operations.	N/A[4]	N/A[4]	N/A[4]
2. Residences and buildings where people normally sleep (such as hotels, hospitals).	35 dBA	38 dBA	43 dBA
3. Institutional land uses with primarily daytime use.	40 dBA	43 dBA	48 dBA

Note 1. "Frequent Events" is defined as more than 70 vibration events of the same source per day. Most rapid transit projects fall into this category.
Note 2. "Occasional Events" is defined as between 30 and 70 vibration events of the same source per day. Most commuter trunk lines have this many operations.
Note 3. "Infrequent Events" is defined as fewer than 30 vibration events of the same kind per day. This category includes most commuter rail branch lines.
Note 4. Vibration-sensitive equipment is generally not sensitive to groundborne noise.

Table 3.20B Groundborne noise impact criteria for special buildings

Type of building or room	Impact level (L_{pASmax})	
	Frequent events[1]	Occasional or infrequent events[2]
Concert halls, TV studios, recording studios	25 dBA[4]	25 dBA[4]
Auditoriums	30 dBA	38 dBA
Theatres	35 dBA	43 dBA

Note 1. "Frequent Events" is defined as more than 70 vibration events of the same source per day. Most rapid transit projects fall into this category.
Note 2. "Occasional or Infrequent Events" is defined as fewer than 70 vibration events per day. This category includes most commuter rail branch lines.
Note 3. If the building will rarely be occupied when the trains are operating, there is no need to consider impact. As an example, consider locating a commuter rail line next to a concert hall. If no commuter trains will operate after 7 pm, it should be rare that the trains interfere with the use of the hall.

Source: FRA (2005), FTA (2006).

The new ANSI/ASA S12.2:2008 provides three primary methods for evaluating room noise: a survey method (A-weighted sound level), an engineering method (noise criterion NC), and a method for evaluating low-frequency fluctuating noise (room noise criterion RNC). Figure 3.1 shows the two noise criteria curves.

[1] Out of scope of the RIVAS project.

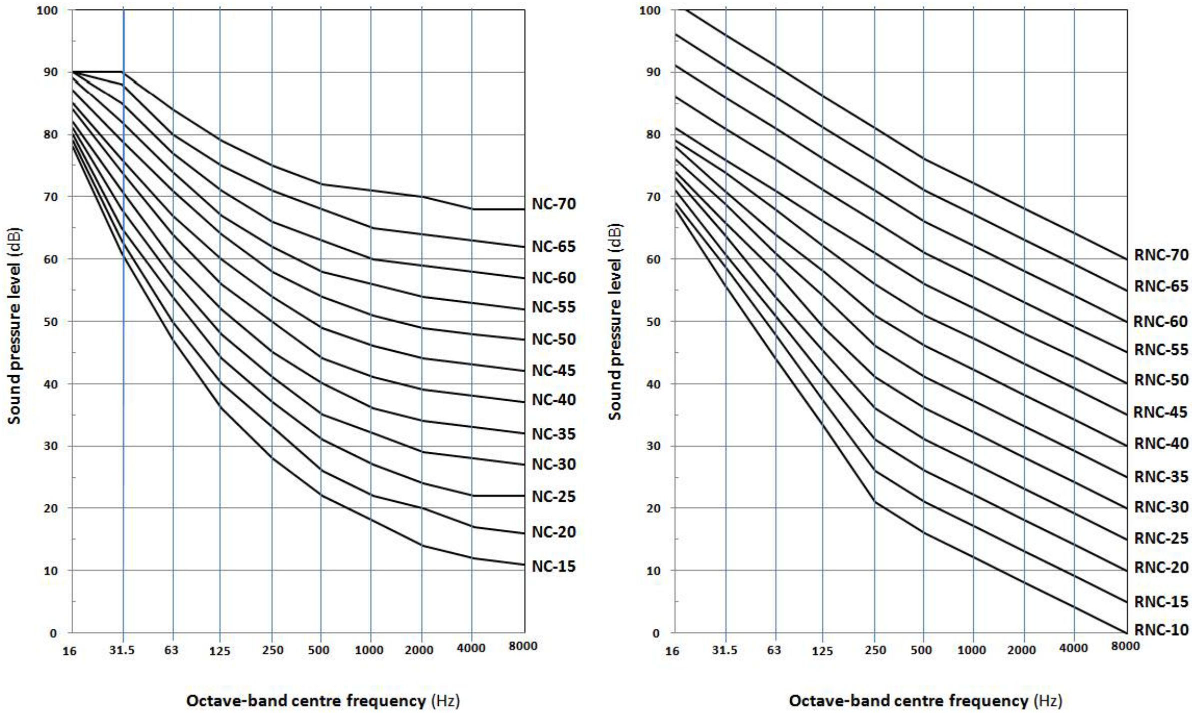


Figure 3.1 Noise criteria curves in ANSI/ASA S12.2-2008 – NC (left) **and RNC curves** (right)

Except from special buildings[1], the most stringent recommendations (25-30 curves, corresponding to 34-38 dBA) apply to bedrooms as well as lecture and classrooms (< 566 m^3), and private rooms in hospitals (Table 3.23).

Table 3.23 Octave-band SPLs (dB) **for NC and RNC criteria curves (bedrooms)**

Noise criterion	Octave-band centre frequency (Hz)				
	16	31.5	63	125	250
NC-25	80	65	54	44	37
NC-30	81	68	57	48	41
RNC-25	73	64	54	45	36
RNC-30	74	66	58	49	41

Source: ANSI/ASA S12.2:2008.

3.2.2 Comparative analysis

As for vibration, indoor noise criteria are either maximum SPLs only (as in the UK and the USA), or equivalent SPLs only (as in the Netherlands, Spain and Switzerland), or both maximum and equivalent SPLs (as in Austria, Norway and Sweden where the two criteria should be met). The relevance of these two types of descriptors is discussed in chapter 4.

The criterion values obviously relate to acceptable sound levels (dB re 20 µPa), well above a perception threshold (close to 0 dBA). A-weighting is widely used. National limits are quite different: maximum SPLs vary from 30 dB to 45 dB, and equivalent SPLs from 25 to 40 dB. The reason for so broad a range may be that some standards and guidelines focus on general indoor noise (structure-borne or airborne, low-frequency or broadband) from different sources inside or outside buildings.

The L_{pASmax} descriptor (S for Slow) is predominant, except in Norway and Sweden where the L_{pAFmax} descriptor (F for Fast) is chosen. According to ISO 14837-1:2006, L_{pAFmax} is 1 or 2 dB higher than L_{pASmax}. Among countries which use both maximum and equivalent SPLs, Austria and

[1] Concert halls, opera houses, and recital houses (15-18); large auditoriums, large dram theatres, large churches, legitimate theatres (25-30); TV and broadcast studios (15-25)

Germany agree on a 10 dB difference between them, with limits at 35 dB and 25 dB respectively. Higher limits are set in Sweden: 45 dB for L_{pAFmax} (about 43 dB L_{pASmax}) and 30 dB for L_{pAeq}. But the limit values range between 32-56 dB for low-frequency noise, depending on frequency (see Table 3.10).
When dealing with low-frequency noise (frequencies below 100 Hz), a procedure to detect low-frequency noise is proposed in several countries. The difference L_{pCeq}-L_{pAeq} between C-weighted and A-weighted sound levels is calculated; if the difference is higher than 15-20 dB, then the noise can be identified as low-frequency noise. In this case, a detailed frequency analysis of the noise, based upon a reference curve (one-third octave bands 31.5 to 200 Hz, approximate hearing threshold) which differs from one country to the other (see section 1.3). ISO 14837-1 (paragraph 6.3, note 4) also warns that A-weighted SPLs may underestimate the subjective response when low-frequency groundborne noise is predominant.

It is worth mentioning that the reproducibility for measuring noise below 50 Hz is even worse than above 50 Hz (see section 1.3). This results from the stronger modal behaviour of the room (large spatial variation). Measurement of low-frequency noise is further discussed in chapter 4.

Finally two documents (ISO 14837-1 and FRA manuals) clearly state that low-frequency noise is perceived louder than broadband noise at the same A-weighted level. For that reason proper criteria should be set for low-frequency noise, as is done in FRA manuals (Table 3.19).

3.3 Combined effects of vibration and noise

Railway traffic causes on the one hand airborne noise, on the other hand vibration and structure-borne noise. The exposure to these environmental nuisances varies in proportion with the characteristics of the source (above-, at- or below-grade rail track, variety and intensity of traffic, etc.) and of the receiver (distance and ground from rail tracks, soundproofing of the building, type of foundations and building structure, location of liveable rooms, etc.). It is crucial to know how noise and vibration combine their effects on annoyance and disturbance of exposed people. A good knowledge is needed to choose suitable mitigation measures that may appear as cooperative or trade-off solutions.

Howarth and Griffin (1990a, 1990b, 1991)[1] investigated the influence of noise and vibration and vice versa in three laboratory studies. In their 1991 experiment, twenty subjects were exposed to simulated railway vibration (VDV from 0.056 to 0.40 $\mathrm{ms}^{-1.75}$) and simultaneous noise (L_{AE} from 52.5 to 77.5 dBA). The authors reported that, "*although vibration has little effect on the judgment on noise, the assessment of vibration could be increased or decreased by noise, depending on the relative magnitudes of the vibration and noise*". They suggested a subjective equivalence of noise and vibration:

$$L_{\mathrm{AE}} = 29.3 \lg VDV + 89.2.$$

They also proposed a predicted overall annoyance approximately given by a summation of the individual effects of noise and vibration:

$$\psi = 22.7 + 0.264\,(10^{L_{\mathrm{AE}}})^{0.036} + 243\, VDV^{1.18}.$$

However, the authors stressed that further investigation was required before applying their findings to a wider range of environments (train passages of more than 29 s duration, high magnitude vibration).

Meloni and Krueger (1990) performed a laboratory study on perception and sensation of combined noise and vibration. It turned out from an experiment that the absolute perception threshold of

[1] See also Griffin (1990).

vibration was higher when noise was louder (over 64 dB) through a masking effect. In two experiments were combined four noise stimuli (L_{Aeq} 41 – background noise –, 52, 62 and 72 dB) and four vibration stimuli (no vibration, half value, single value and double value), obtained from the original signal of a tram (22 s) passing by a 5 m-distant heavy-structure building (on the first-storey floor). In a test (Figure 3.2a and 3.2b), subjects judged separately the intensity (0-9 rating) of noise and vibration stimuli. In another test (Figure 3.2c and 3.2d), 8 subjects aged between 25 and 37 rated the overall intensity of the 16 combined stimuli as a whole. From the results, the authors concluded that monosensory judgment of noise or vibration (although possible) is not a reliable measure of perception for real multisensory situations.

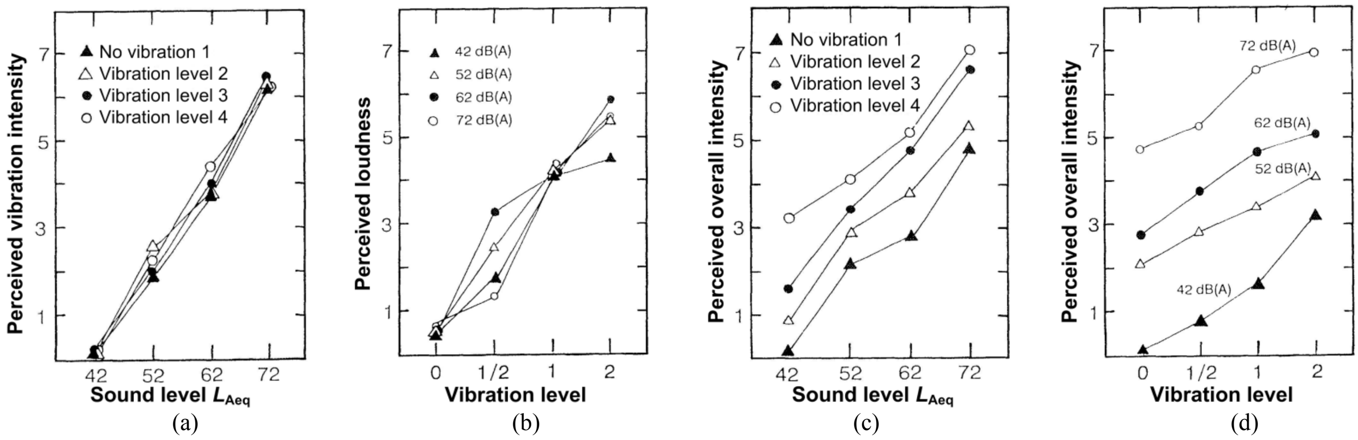


Figure 3.2 Relationships between subjective magnitudes and combined noise-vibration stimuli
(a) and (b): separate judgment of stimuli – (c) and (d): overall judgment of stimuli
Source: Meloni and Krueger (1990).

Paulsen and Kastka (1995) conducted a laboratory study to investigate the combined effects of noise and vibration on annoyance. Sixteen subjects were exposed to "tram" stimuli representing traffic (as well as industrial "hammermill" stimuli). Four target levels of vibration (r.m.s. weighted value) and noise (L_{Aeq}) were chosen: 0 (none), 1 (low: 0.05 mm/s and 34 dBA), 2 (medium: 0.11 mm/s and 45 dBA) and 3 (strong: 0.32 mm/s and 60 dBA). They rated annoyance (from vibration, from noise and overall) on a 0-9 scale (Figure 3.3).

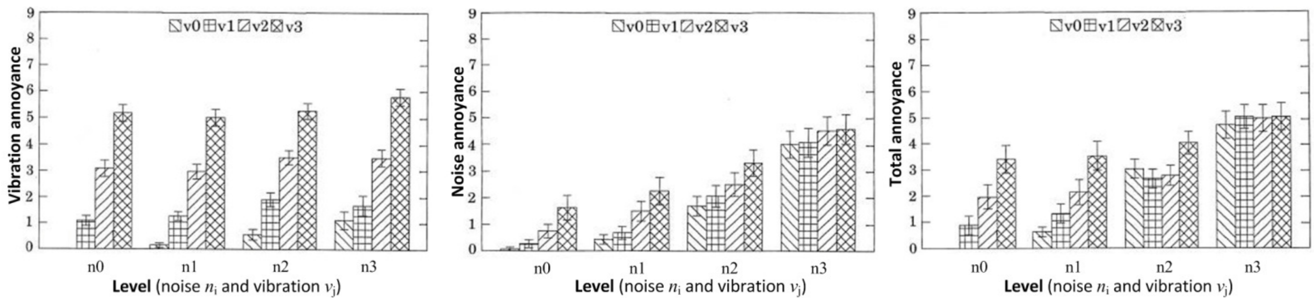


Figure 3.3 Annoyance from tram caused by vibration (left)**, noise** (centre) **and situation** (right)
Source: Paulsen and Kastka (1995).

From Figure 3.2, the stronger the vibration level, the higher the vibration annoyance (left), and the influence of simultaneous noise is negligible. By contrast (centre), vibration clearly influenced noise annoyance, especially at low noise levels (34 dB or less). As regards total annoyance (right), it is not influenced by vibration at high noise levels while it is mainly affected by vibration at low noise levels. Reducing noise exposure (*e.g.* by window insulation) makes simultaneous vibration more noticeable. Furthermore, Paulsen and Paulsen and Kastka obtained a subjective equivalence of noise (L_{Aeq}) and vibration (r.m.s. velocity), the gradient of which is half as much as in Howarth and Griffin (1991) – but the descriptor is different (velocity instead of VDV):

$$L_{\text{Aeq}} = 14.4 \lg v_{\text{m}} + 51.9.$$

Knall (1995) reviews a German field study on vibration effects in areas exposed to long-distance rail traffic. The effects of three factors as well as their possible interactions were analyzed: vibration level (KB_{Fmax} and KB_{FTm}), frequency of trains and noise level (L_{AFmax} and L_{eq}). The inhabitants of 556 houses reported that noise was more annoying than vibration. Knall found some evidence from the study that annoyance does not rise steadily, but by step, and that high noise levels can have a masking effect on annoyance from vibration.

The effects of combined exposure to noise and vibration from rail traffic were also investigated in Sweden (Öhrström and Skånberg, 1996; Öhrström, 1997). A survey covered fifteen areas. Its design included two parameters: vibration level (“none or weak” [< 1 mm/s] or “strong” [> 2 mm/s]) and the number of train passages (from less than 25 to more than 150 trains per day. The respondents (2,833 persons, mostly living in detached and terraced houses and few of them with bedroom windows facing the railway) were located between 10 m and about 300 m far from the rail track. Figure 3.4 exemplifies the fact that annoyance (percentage of rather + vey annoyed people) was higher in areas with strong ground vibrations.

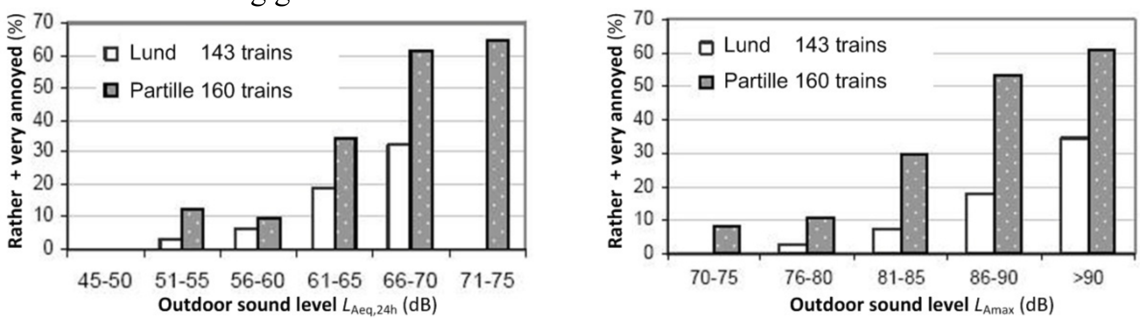
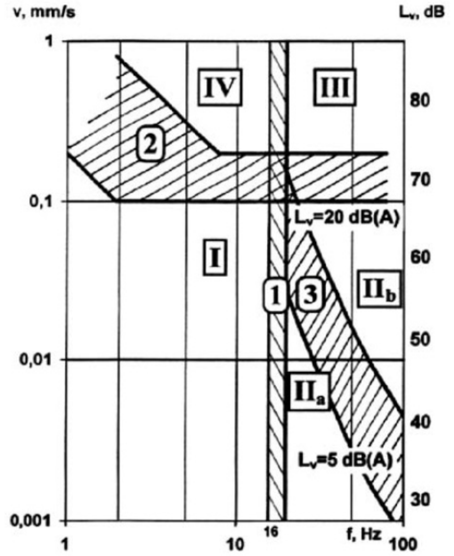


Figure 3.4 Annoyance with respect to noise levels in areas with strong (Partille area) **or weak** (Lund area) **vibrations**
Source: Öhrström and Skånberg (2006).

In areas “without” vibrations, less than 5 % of people are rather or very annoyed when exposed to railway noise below L_{Amax} 80 dB and L_{Aeq} 45 dB. In areas with strong vibrations the same degree of annoyance would be kept with noise levels cut down by 10 dB.

Findeis and Peters (2004) noticed, from road traffic vibration measurements in Brandenburg, a jump in complaints for KB_{FTm} values between 0.10 and 0.13. They find here strong evidence that noise and vibration have combined effects on the overall annoyance of residents. Only this could explain complaints though the vibration level is below the threshold of perception ($KB = 0.1$); in this case groundborne noise is present and can be annoying. They delimit zones where vibration should be felt differently, depending on frequency and magnitude (velocity). They hint that the frequency range above 20 Hz should deserve particular attention (Figure 3.5).



Boundaries:

1. Between frequency of hearing threshold and infrasound

2. Between feelable and not feelable vibration

3. Between disturbing and not disturbing structure-borne noise

Zones:

I. Not feelable vibration, structure-borne noise – not audible

IIa. Not feelable vibration, structure-borne noise – not audible or not disturbing

IIb. Not feelable vibration, structure-borne noise – disturbing

III. Feelable vibration, structure-borne noise – strongly disturbing

IV. Feelable vibration, possible infrasound

Figure 3.5 Grades for the perception of vibration in dwellings
Source: Findeis and Peters (2004).

New metrics have been recently set up for noise assessment in Japanese standards. Therefore Yokoshima *et al.* (2008) reconsider social surveys carried out in two areas along the Shinkansen railway (Kanagawa survey in 2001, Fukuoka survey in 2003). The annoyance of nearby residents was measured on a ICBEN 5-point verbal scale (Fields *et al.*, 2001). The vibration level in houses was estimated from ground vibration L_{vmax} (arithmetic mean of the highest ten out of twenty successive train pass-by measurements) at various distances from the track. The maximum-based metric L_{ASmax} rather than L_{Aeq} was found to be "universal" for assessing noise annoyance. And Figure 3.6 shows that, at noise levels of 70 dB or less, vibration has a synergetic effect on noise annoyance (Figure 3.6).

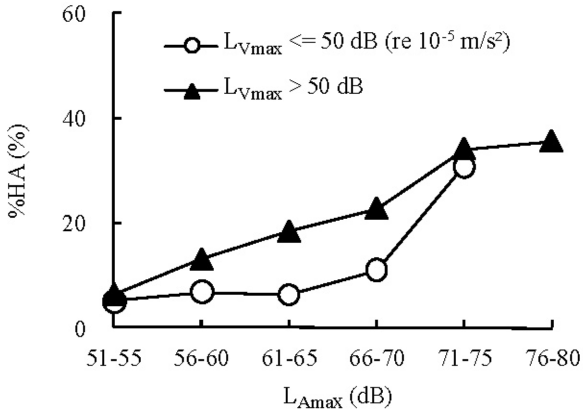


Figure 3.6 Relationship between annoyance level (% extremely annoyed) **and noise exposure** (L_{ASmax}) **for two classes of vibration level** (right)
Source: Yokoshima *et al.*, 2008.

The combined effect of noise and vibration on annoyance (comfort) and disturbance (sleep) was investigated through lab experiments and field surveys in the Swedish TVANE project. Four areas with and without strong vibrations were investigated. The results show that annoyance from noise increases when vibration also occurs (Öhrström *et al.*, 2011). The exposure-effect relationship for noise gives evidence that the proportion of people annoyed by noise from rail traffic in areas with strong vibrations (0.4 mm/s and over) is higher than in areas without vibrations (Figure 3.7). The difference in the proportion of annoyed people corresponds approximately to 5-7 dB ($L_{Aeq,24h}$). This means that, when comparing to areas without vibration, the proportion of annoyed people in areas with strong vibrations is the same if the sound level is 5-7 dB lower.

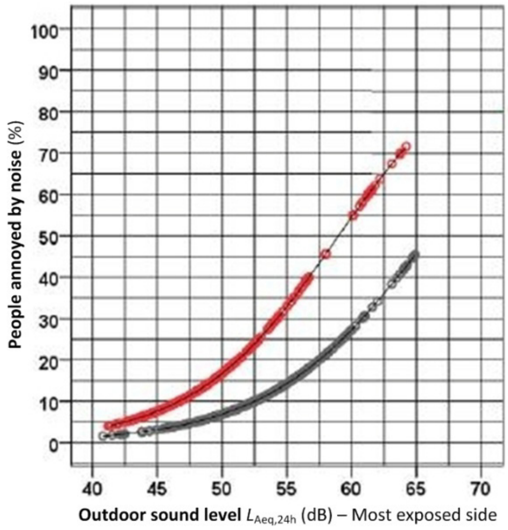


Figure 3.7 Annoyance from noise caused by railway traffic
Areas with (red) **and without** (grey) **strong vibrations**
Source: Öhrström et al., 2011.

Sleep disturbance is more frequent in noisy areas where strong vibrations also exist, and noise is more noticeable at sleep in such situations. This fact confirms the former lab study within the project (Ögren *et al.*, 2008; Öhrström *et al.*, 2008). So the authors consider that soundproofing (for instance by means of windows) might not be enough to reduce sleep disturbance when vibration exceeds 0.4 mm/s.

The Austrian standard ÖNORM S 9012 (informative annex D) accounts for the combined effects of structure-borne noise (in L_{Aeq}) and vibration (W_m-weighted vibration acceleration in mm/s²) in the evaluation of human exposure in buildings to vibration from rail and road traffic (Steinhauser, 2007). Based on past findings, is defined a region of vibration and SBN values within which further investigation would be necessary (Figure 3.8). Outside it, there exist masking effect, substitution effect, and not feelable/not audible magnitudes. It results from the Austrian criteria (maximum acceleration E_{max}) that railway traffic should not usually be concerned with this (grey) zone.

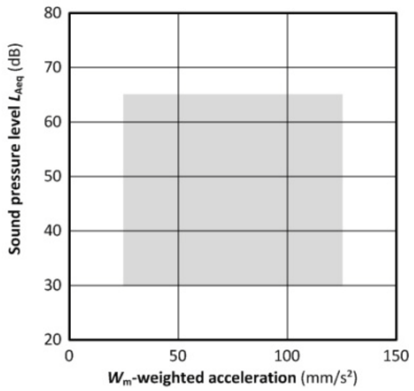


Figure 3.8 Region (in grey) of further investigation
for combined vibration and structure-borne noise
Source: Steinhauser (2007), ÖNORM S 9012:2010.

4. FINAL COMMENTS

4.1 Vibration

Human response to vibration

The basic or traffic-oriented descriptors used in the reviewed standards and guidelines are widely calculated with the combined W_m/KB frequency weighting (ISO 2631-2:2003/DIN 4150-2:1999). The only exception is the British standard with two weightings W_b (vertical motion) and W_d (horizontal motion).

Recent laboratory studies give evidence that absolute thresholds of vibration perception are rather constant for acceleration at frequencies above 8 Hz. The weightings in the current standards might underestimate human sensitivity to vibration. Thus the corresponding curves should be flatter (Figure 2.1).
Also difference thresholds (Weber ratios) are somewhat independent from the vibration magnitude and frequency. A 25 % change (circa 2 dB) in existing vibration conditions (i.e. lower than 40 % – 3 dB) appears to be significantly noticeable (as a median perceived difference threshold). What is at stake on the one hand the impact assessment of changes in traffic (frequency and duration of train passages, type of traffic), on the other hand the perceived benefit of mitigation measures at and nearby the vibration source (vehicle, wheel-track, vicinity of rail track).

Vibration classification exist for buildings in a few countries (Austria, Norway and, by analogy, the UK). Vibration criteria for classes differ by a multiplying factor of 2 (6 dB). It should be understood as a sensible strategy to supply the scope of the building market with quality-differentiated enough products. Such quality steps cannot mean lowest acceptable changes in vibration conditions.

Subjective annoyance (discomfort) and disturbance (sleep trouble) are absolutely different from perception. It turns out from the national standards that the acceptable annoyance level varies between the countries. However, quite a few criteria are based on exposure-effect relationships for setting a cutoff probability that exposed people be (highly) annoyed. This situation outstandingly contrasts with protection against noise from traffic.

As research results repeatedly show it, physical indicators will grasp partly (sometimes poorly) so multicausal a phenomenon as subjective annoyance/disturbance. In this context a lot of competing indicators (old and new) should be tested in order to select the best fitted ones.

Descriptors

Both acceleration and velocity are used in standards, regulations as well as in lab and field studies. Each quantity has a special signification regarding construction. In structural engineering, acceleration (along with displacement) is related to the stress in the building components (design at ultimate and serviceability limit states, damage prevention and assessment). In acoustics, radiated noise is related to space-averaged squared velocity (averaged over the floor surface) – and not floor velocity at mid-span.

Both metric and logarithmic units are used for vibration descriptors. By homogeneity with noise (see Italy and the USA), it may be attractive to adopt a log scale for vibration unless it badly correlates subjective annoyance of exposed individuals. The reference value might be close to an absolute threshold of perception (i.e. almost a zero level close to this threshold). However, vibration below the perception threshold can still be annoying because of the associated structural noise.

Maximum and energy equivalent quantities

Both maximum running r.m.s. quantities and energy equivalent quantities should be used (as in Austria). Indeed the former might be more relevant as far as sleep disturbance (quality of sleep) is concerned and the latter is more related to annoyance as discomfort (see section 1.2). Such a distinction is made for noise by the European Environment Agency (see section 4.2 on noise).

Measurement
There is seemingly a general agreement on the measurement of vibration amplitude: floor vibration at mid-span, often dominant in vertical direction (although cases of equally distributed horizontal and vertical vibrations have been reported). However, measurement uncertainty (especially reproducibility) and compliance with the requirements are scarcely tackled.

4.2 Indoor noise

Descriptors and criteria
Fewer descriptors are used than for vibration, mainly the A-weighted maximum SPL L_{pAmax} (frequently with the time constant Slow) and the A-weighted equivalent sound pressure level L_{pAeq} in various forms. The C-weighting is sometimes used when noise is louder (in Sweden for example) because of the different frequency weightings required for a wide range of sound levels.

As for vibration, both maximum running r.m.s. SPLs and energy equivalent SPLs should be used (as in Austria, Norway and Sweden) since the former is more related to sleep disturbance (quality of sleep) and the latter more related to annoyance (quality of life). These ideas are presented in a recent document from the European Environment Agency (EEA 2010) on good practice for noise exposure effects where both maximum and equivalent sound levels are used, the former for quality of sleep and the later for quality of life. The document even recommends common limits within Europe: on the one hand 32dB L_{pAmax}, on the other hand 42 dBA L_{pden} and L_{pnight}.

National standards or guidelines may give criteria for indoor noise in general and/or indoor low-frequency noise in particular. It is at issue whether they apply to structure-borne noise due to traffic-induced vibration.

Measurement and prediction
Low-frequency noise induced by structure vibration varies spatially in rooms. This leads to measurement uncertainty and causes complication for monitoring. The lower the frequency, the higher the uncertainty. Noise levels measured in the middle of the room are greatly underestimated and should be combined with noise levels measured in corners to have results closer to the room spatial averaged level and more reproducible.

The measured noise can be due to vibration. It may also be airborne noise transmitted through the building façade (from surface transport). Furthermore, the measurement of low-frequency noise is often tricky (room modes) So it may be preferred evaluating indoor groundborne noise levels that are derived from measured vertical vibration levels by calculation. Such prediction methods have been developed in several countries. In Germany and Switzerland empirical frequency-dependent relations correlate floor vertical velocity and SPL in the room. In Austria an energy-based relation is used through a parameter (radiation efficiency) directly linked to the spatial average velocity of the floor; an estimated relation between floor spatial average velocity and floor velocity at mid span must then be found.

Detection of low-frequency noise components
Two documents (ISO 14837-1 and FRA guidelines) clearly state that low-frequency noise is perceived louder than broadband noise at the same A-weighted level. So the frequency content of measured noise is important. A practical procedure to detect low-frequency noise is proposed in several countries. The difference L_{pCeq}-L_{pAeq} between C- and A-weighted sound levels is calculated;

if the difference is higher than 15-20 dB, then the noise can be identified as low-frequency noise. In this case, a detailed frequency analysis of the noise is performed, based upon a reference curve (one-third octave bands 31.5 to 200 Hz, approximate hearing threshold) which differs from one country to the other.

Combined effects of vibration and noise
Laboratory experiments and field surveys show that both vibration and indoor noise influence the overall annoyance of exposed people. Therefore, both quantities must be observed (measured or estimated). A summation of the individual effects of noise and vibration could have been proposed from lab tests. But there is strong evidence that the combined effect is more complex, in particular because of a masking effect when one stimulus (*e.g.* noise) dominates at high levels.
To date, no field study gives a comprehensive view on annoyance when residents are exposed to simultaneous vibration and (airborne and/or structure-borne) noise from traffic. However, the Norwegian survey, on which NS 8176 is based, was performed in areas with low traffic noise to avoid the interaction with airborne traffic noise (indoor $L_{\mathrm{pAeq,24h}}$ not exceeding 30 dB). The American survey was also mainly concerned with underground traffic. In both cases, groundborne noise was present. The recent Swedish field study (TVANE project) also provides useful results.

4.3 Towards more appropriate descriptors

This review should be useful before working out vibration and structure-borne descriptors more appropriate than the existing ones. This could be the goal of a European working group aiming at harmonizing the quite different descriptors used in Europe. Overall annoyance of exposed people results from the combined effect of vibration and, if any, noise.
Consistent metrics (log-scale levels) should be used for both, whether measured or estimated, unless their descriptors badly correlate subjective annoyance. Two types of indicators seem equally meaningful: maximum values (of running r.m.s. quantities) and traffic-oriented equivalent (r.m.s.) values. The former are more related to sleep disturbance. The latter are more related to annoyance. Vibration as well as noise are concerned. The corresponding criteria for acceptable annoyance and disturbance may have impacts which differ to some extent regarding the railway traffic (freight, passenger, light train).
Frequency weightings that are more consistent with the findings of recent studies might substitute those (international W_{m}/KB and British $W_{\mathrm{b}}/W_{\mathrm{d}}$) in the current standards. They would result in rather flat curves for acceleration instead of the present flat curves for velocity.
However, close national vibration criteria may be for ordinary buildings (excepting possible high-quality classes of buildings), they should be determined from exposure-effect relationships. Field studies should be strongly supported to this end.
Finally, there is an agreement in several countries on setting low-frequency noise criteria lower and more severe than for broadband noise. The identification of low-frequency noise can then be performed by comparing C and A weighted levels.

In RIVAS project, the effects of mitigation measures developed in different WPs will be evaluated and characterized by frequency-dependent vibration insertion losses at ground level. Typical situations (train, traffic, track, ground, building) where problems occur regularly, will be considered (sensitive “hot spots”). For each one all the mentioned descriptors (existing or improved ones) will be calculated and compared before and after mitigation: calculations will be performed from typical ground vibration time signals regarding types of train and from measured or computed ground-building transfer functions. It is an opportunity to gain better knowledge on them and to analyse their sensitivity, particularly to key traffic characteristics (type of train, frequency and duration of passages, etc.). The investigation about mitigation measures that have a noticeable impact on the annoyance level of exposed people should also contribute to efficient policies for the environmental management of railway activities. These results will be presented in deliverable D1.9.

Standards and guidelines

ISO standards

ISO 1683:2008: Acoustics – Preferred reference values for acoustical and vibratory levels.

ISO 2631-1:1997: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration. Part 1: General requirements.

ISO 2631-2:2003: Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration. Part 2: Vibration in buildings (1 Hz to 80 Hz).

ISO 4866:2010: Mechanical vibration and shock – Vibration of fixed structures – Guidelines for the measurement of vibrations and evaluation of their effects on structures.

ISO 7196:1995: Acoustics – Frequency-weighting characteristic for infrasound measurements.

ISO 8041:2005/2007: Human response to vibration – Measuring instrumentation.

ISO 8569:1996: Mechanical vibration and shock – Measurement and evaluation of shock and vibration effects on sensitive equipment in buildings.

ISO 14837-1:2005: Mechanical vibration — Groundborne noise and vibration arising from rail systems. Part 1: General guidance.

ISO 21289:2008: Mechanical vibration and shock — Parameters to be specified for the acquisition of vibration data.

ISO/TS 15666:2003: Acoustics: Assessment of noise annoyance by means of social and socio-acoustic surveys.

ISO 16032:2004: Acoustics – Measurement of sound pressure level from service equipment in buildings – Engineering method.

Joint Committee for Guides in Metrology (2008): *Evaluation of measurement data – Guide to the expression of uncertainty in measurement*, JCGM 100:2008 GUM with minor corrections, first edition, September.

ISO 5725-2:1994: Accuracy (trueness and precision) of measurements and results – Part 2: Basic method for the determination of repeatability and reproducibility of a standard method.

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Austria

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Annex A Terms and definitions

International standards

Vibration: ISO 2631-1:1997, ISO 8041:2005.

a_w	r.m.s. weighted acceleration value (m/s^2)	$a_w = \left[\frac{1}{T}\int_0^T a_w^2(\xi)d\xi\right]^{\frac{1}{2}}$ where $a_w(\xi)$ is the weighted vibration acceleration (m/s^2) as a function of the instantaneous time ξ; T is the duration of the measurement.
L_w	r.m.s. weighted acceleration level (dB)	$L_w = 20\lg\frac{a_w}{a_0}$ where a_0 is the reference acceleration (defined as 10^{-6} m/s^2 in ISO 1683).
$a_{w,\tau}(t)$	Running r.m.s. weighted acceleration	$a_{w,\tau}(t) = \left[\frac{1}{\tau}\int_{t-\tau}^{t} a_w^2(\xi)d\xi\right]^{\frac{1}{2}}$ where $a_w(\xi)$ is the frequency-weighted instantaneous vibration acceleration at time ξ; τ is the integration time of measurement (time constant); t is the instantaneous time. With exponential averaging for the running r.m.s. method, as an approximation of the linear averaging: $a_{w,\tau}(t) \cong \left[\frac{1}{\tau}\int_{-\infty}^{t} a_w^2(\xi)\cdot\exp\left(\frac{\xi-t}{\tau}\right)d\xi\right]^{\frac{1}{2}}$ where τ is the time constant.
MTV	Maximum transient vibration value	$MTTV = \max_t\left[a_{w,\tau}(t)\right]$ when the integration time is equal to 1 s.
VDV	Vibration dose value	$VDV = \left[\int_0^T a_w^4(\xi)d\xi\right]^{\frac{1}{4}}$ where T is the total period during which vibration may occurs.
a_{wv}	Vibration total value	Combined vibration from three axes of transitional vibration: $a_{wv} = \sqrt{k_x a_{wx}^2 + k_y a_{wy}^2 + k_z a_{wz}^2}$ where a_{wx}, a_{wy} and a_{wz} are the vibration values in the three orthogonal axes x, y and z; k_x, k_y and k_z are multiplying constants whose values depend on the measurement application.

Noise

L_p	Sound pressure level (SPL) (dB)	$L_p = 10\lg\frac{p^2}{p_0^2}$ where p is the r.m.s. value of the acoustic pressure (Pa); p_0 is the reference pressure (20 μPa).
L_{10}, L_{50}, L_{90}	Percentile sound levels	Sound levels that are exceeded for 10 (respectively 50, 90) percent of the measurement period (or of the sound events)
$L_{Amax,S/F}$	Maximum A-weighted sound pressure level (dB) with a time constant Slow (1 s) or Fast (0.125 s)	
L_{eq}		
$L_{eq,T}$	Equivalent continuous sound pressure level (dB)	$L_{eq,T} = 10\lg\left(\frac{1}{T}\int_0^T\frac{p(t)^2}{p_0^2}dt\right)$ where T is the duration of exposure or a sound event.
L_{dn}	Average sound pressure level over a whole (representative) day	$L_{den} = 10\lg\frac{1}{24}\left(12\cdot 10^{\frac{L_{day}}{10}} + 4\cdot 10^{\frac{L_{evening}+5}{10}} + 8\cdot 10^{\frac{L_{night}+10}{10}}\right)$
L_{den}	Average sound pressure level over all days, evenings and nights in a year	$L_{den} = 10\lg\frac{1}{24}\left(12\cdot 10^{\frac{L_{day}}{10}} + 4\cdot 10^{\frac{L_{evening}+5}{10}} + 8\cdot 10^{\frac{L_{night}+10}{10}}\right)$
D	Loudness level of sound	$D = 10\lg\frac{I}{I_0}$ where I is the intensity of the sound (W/m^2); I_0 is the intensity of a sound barely audible to the human ear.

Austria

Vibration: ÖNORM S 9012 :2010.

E_v	Mean energy-equivalent W_m-weighted acceleration for a train passage	$E_v = \sqrt{\frac{1}{t_e}\int_0^{t_e} a_w^2(t)dt}$ where $a_w(t)$ is the running r.m.s. W_m-weighted instantaneous acceleration (ISO 2631-1:1997); t_e is the period of exposure corresponding to $a_{w,s}$ > 3,57 mm/s².
$E_{max,i}$	Mean maximum acceleration for the train type i: F [long distance], N [local] or G [freight]	$E_{max,i} = \sqrt{\frac{1}{n}\sum_n a_{w,s,i}^2}$ where $a_{w,s,i}$ is the maximum running r.m.s. acceleration of a train passage; n is the number of passages for the trains of type i.
E_{max}	Highest value of $E_{max,i}$ for all types of trains	$E_{max} = \max_i[E_{max,i}]$
$a_{w,i}$	Mean energy-equivalent of the mean value of the weighted acceleration for the train type i	$a_{w,i} = \sqrt{\frac{1}{t_i}\sum_{j=1}^{m_i} E_{v,j}^2 \cdot t_{e,j}}$ with $t_i = \sum_{j=1}^{m_i} t_{e,j}$
$a_{w,eq}$	Mean energy-equivalent weighted acceleration for all types of trains within the assessment period T_r (day, evening or night)	$a_{w,eq} = \sqrt{\frac{1}{T_E}\sum_{i=1}^{n} a_{w,i}^2 \cdot \frac{t_i \cdot m_i}{n_i}}$ with $T_E = \sum_{i=1}^{n} \frac{t_i \cdot m_i}{n_i}$ where m_i is the number of trains of type i during the assessment period T_r; T_E is the exposure duration of all trains during the assessment period; n_i is the number of trains of type i during the measurement period.
E_r	Mean energy-equivalent acceleration during the assessment period T_r	$E_r = a_{w,eq}\sqrt{\frac{T_E}{T_r}}$

Structure-borne noise: ÖNORM S 9012:2010.

L_{pv}	Sound pressure level (dB) calculated from vibration measures according to ONR 199005	
L_{pA}	A-weighted sound pressure level (dB)	
$L_{A,E}$	A-weighted sound-event level (dB)	
L_{Amax}	A-weighted maximum sound pressure level	
$L_{Amax,m}$	Mean A-weighted maximum sound level for trains of type m (dB)	$L_{Amax,m} = 10\lg\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_{Amax,i}}{10}}$
$L_{A,E,m}$	Mean A-weighted sound-event level (dB)	$L_{A,E,m} = 10\lg\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{L_{A,E,i}}{10}}$ For n passages of trains where n is the number of sound events.
$L_{Aeq,i}$	A-weighted energy-equivalent permanent sound-pressure level for a type i of train (dB)	$L_{Aeq,i} = L_{A,E,m,i} + 10\lg\frac{n}{3600 T_r}$ where n is the number of passages for trains of type i during the assessment period T_r (in hours); $L_{A,E,m,i}$ is the mean A-weighted sound-event level.
L_{Aeq}	A-weighted energy-equivalent permanent sound-pressure level (dB) for all types i of trains	$L_{Aeq} = 10\lg\sum_{i=1}^{n} 10^{\frac{L_{Aeq,i}}{10}}$

Germany

Vibration: DIN 4150-2:1999.

$KB(t)$	Weighted instantaneous vibration strength (dimensionless)	Measured weighted (DI 45669) instantaneous velocity and normalised to the velocity v_0 = 1 mm/s
$KB_F(t)$	Weighted vibration strength	$KB_F(t) = \sqrt{\frac{1}{\tau}\int_{\xi=0}^{t} KB^2(\xi)\cdot\exp\left(\frac{\xi-t}{t}\right)\mathrm{d}\xi}$
KB_{FTm}	Mean 30 s-interval maximum vibration strength	$KB_{FTm} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} KB_{FTi}^2}$ where KB_{FTi} is the maximum vibration strength in the time interval i. Values of $KB_{FTi} \leq 0.1$ are taken as 0; N is the total number of time intervals (30 s).
KB_{Fmax}	Maximum weighted vibration strength (dimensionless)	$KB_{Fmax} = \max_t[KB_F(t)]$
KB_{FTr}	Assessment vibration value (dimensionless)	Exposure outside rest periods: $KB_{FTr} = \sqrt{\frac{1}{T_r}\sum_j T_{e,j} KB_{FTm,j}^2}$ or $KB_{FTr} = KB_{FTm}\sqrt{T_e/T_r}$ where T_r is the assessment period (day 16 h, night 8 h); T_e is the time of exposure outside rest periods; $T_{e,j}$ is the partial time of exposure (time interval *i*) outside rest periods; KB_{FTm} and KB_{FTmj} are the mean signal maximum vibration strengths for T_e and $T_{e,j}$ periods. Exposure with rest periods: $KB_{FTr} = \sqrt{\frac{1}{T_r}(T_{e1}\cdot KB_{FTm\,1}^2 + 2T_{e2}\cdot KB_{FTm\,2}^2)}$ where T_r is the assessment period (day 16 h, night 8 h); T_{e1} is the time of exposure outside rest periods; T_{e2} is the time of exposure inside rest periods; KB_{FTm1} and KB_{FTm2} are the signal maximum effective values outside and inside rest periods. Rest periods: – working days: 6h-7h and 19h-22h; – Sunday and public holidays: 6h-22h.

Low-frequency noise: TA Lärm 1998, DIN 45680:2011 (draft).

L_r	Assessment sound level (dB)for an assessment period (day or night) Source: TA Lärm 1998.	$L_{\mathrm{r}} = 10 \lg \left[\frac{1}{T_{\mathrm{r}}} \sum_{j=1}^{N} T_j \cdot 10^{0.1\left(L_{\mathrm{Aeq},j} - C_{\mathrm{met}} + K_{\mathrm{T},j} + K_{\mathrm{I},j} + K_{\mathrm{R},j}\right)}\right]$ where $T_{\mathrm{r}} = \sum_{j=1}^{N} T_{\mathrm{j}}$ =16 h (daytime), 1 h or 8 h (night-time); T_j is the duration of a period *i* of exposure within the assessment period; N is the total number of periods of exposure; $L_{\mathrm{Aeq},j}$ is the sound level during the T_j; C_{met} is the adjustment factor for weather conditions; $K_{\mathrm{T},j}$ is the adjustment factor for tonality and information transfer in the time period T_j; $K_{\mathrm{I},j}$ is the adjustment factor for impulsiveness in the time period T_j; $K_{\mathrm{R},j}$ is the adjustment factor (only outside buildings) for certain times of days (work days, or Sunday and public holidays) in the time period T_j.
$L_{\mathrm{TerzF}}(t)$: Z-weighted third-octave band sound pressure level with "Fast" time-weighting in a one-third octave band.		
L_{Terzmax}	Maximum third-octave band sound pressure level during the measurement: $L_{\mathrm{Terzmax}} = \max_t L_{\mathrm{TerzF}}(t)$.	
$Ü_{\mathrm{Dmax}}$	Maximum perception-exceeding sound pressure level	$Ü_{\mathrm{D},i} = \left(L_{\mathrm{TerzFmax},i} - W_{\mathrm{Terz},i}\right) \cdot D_{\mathrm{Terz},i}$ where $Ü_{\mathrm{D},i}$ is the perception-exceeding sound pressure level for the *i*-th one-third octave; $W_{\mathrm{Terz},i}$ is the perception threshold for the *i*-th one-third octave; $D_{\mathrm{Terz},i}$ is the dynamic correction factor for the *i*-th one-third octave centre frequency. $Ü_{\mathrm{Dmax}} = \max_i \left[Ü_{D,i}\right]$
$L_{\mathrm{AF}}(t)$, $L_{\mathrm{CF}}(t)$: A-weighted (resp. C-weighted) sound pressure level (dB) with "Fast" time-weighting. The reference pressure p_0 is 20 µPa.		
$L_{\mathrm{TerzF}}(t)$: Z-weighted third-octave band sound pressure level with "Fast" time-weighting in every one-third octave band.		
L_{AFmax}, L_{CFmax}	Maximum A- and C-weighted sound pressure levels during the measurement time: $L_{\mathrm{AFmax}} = \max_t L_{\mathrm{AF}}(t)$ and $L_{\mathrm{CFmax}} = \max_t L_{\mathrm{CF}}(t)$.	
L_{Aeq}, L_{Ceq}	Equivalent continuous sound pressure levels during the measurement period T_{M} of low-frequency noise	
$Ü_{\mathrm{L},i}$	Perception-exceeding level for the *i*-th one-third octave	$Ü_{\mathrm{L},i} = G_i - W_{\mathrm{Terz},i}$ where G_i is the loudness spectrum; $W_{\mathrm{Terz},i}$ is the perception threshold for the *i*-th one-third octave. Values less than 0 are not considered.
$Ü_{\mathrm{G},i}$	Weighted exception-exceeding level for the *i*-th one-third octave	$Ü_{\mathrm{G},i} = Ü_{\mathrm{L},i} \cdot D_{\mathrm{Terz},i}$ where $D_{\mathrm{Terz},i}$ is the dynamic correction factor for the *i*-th one-third octave centre frequency.
H	Characteristic for low frequencies	$H = 10 \lg \sum_i 10^{0.1 \cdot Ü_{\mathrm{G},i}}$

The Netherlands

Vibration: SBR (2002), Deel B.

$v_{\mathrm{eff}}(t)$	Running r.m.s. weighted velocity	$v_{\mathrm{eff}}(t)=\sqrt{\frac{1}{\tau}\int_{\xi=0}^{t} v^2(t-\xi)\cdot\exp(-\xi/t)\mathrm{d}\xi}$ where τ is the time constant (0.125 s).
$v_{\mathrm{eff,max}}$	Maximum value of $v_{\mathrm{eff}}(t)$ over the measurement period (*worst case*)	
$v_{\mathrm{eff,max,30,i}}$	Maximum value of $v_{\mathrm{eff}}(t)$ within a 30-second interval *i*	
$v_{\mathrm{eff,max,stat}}$	Statistical maximum effective value (95-percentile) (*shorter duration of measurement*)	$v_{\mathrm{eff,max,stat}}=\mu\cdot\exp(\beta\sigma/\mu)$ where μ is the mean of up to the 15 highest values (equal or larger than half of $v_{\mathrm{eff,max}}$) of $v_{\mathrm{eff,max,stat,i}}$; β is a factor as a decreasing function of the number *n* of measurements ($2 \le n \le 15$) for determining the mean μ; σ is the standard deviation of the mean μ: $\sigma=\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(v_{\mathrm{eff,max,30,i}}-\mu\right)^2}$.
$V_{\max}$	Maximum vibration strength	$v_{\mathrm{eff,max}}$ or $v_{\mathrm{eff,max,stat}}$ according to the duration of measurement
V_{per}	Mean vibration strength over the assessment period (day, evening or night)	$V_{\mathrm{per}}=v_{\mathrm{per,meet}}\cdot\sqrt{\frac{T_{\mathrm{b}}}{T_0}}$ where $v_{\mathrm{per,meet}}=\sqrt{\frac{1}{n}\sum_{i=1}^{n}v_{\mathrm{eff,max,30,i}}^2}$ with the total number of 30-second intervals over the measurement period, and $v_{\mathrm{eff,max,30,i}}$ being taken as 0 if its value is equal or less than 0.1; T_{b} is the total time of exposure to vibration during the assessment period T_0; T_0 is the total time of the assessment period.

Norway

Vibration

$\overline{v_{\mathrm{w,max}}}$ or $\overline{a_{\mathrm{w,max}}}$	Mean value of the maximum weighted velocity (resp. acceleration) from *N* (at least 15) passages	$\overline{v_{\mathrm{w,max}}}=\frac{\sum_{j=1}^{N}v_{\mathrm{w,max,j}}}{N}$ where $v_{\mathrm{w,max,j}}$ (resp. $a_{\mathrm{w,max,j}}$) is the maximum running r.m.s. weighted velocity (resp. acceleration) for a single passage *j*.
$v_{\mathrm{w,95}}$	Statistical maximum weighted r.m.s. velocity (95-percentile)	$v_{\mathrm{w,95}}=\overline{v_{\mathrm{w,max}}}+1.8\times\sigma$ with the standard deviation of the maximum weighted velocity $\sigma=\sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(v_{\mathrm{w,max,j}}-\overline{v_{\mathrm{w,max}}}\right)^2}$ (based on a log-normal distribution with a coefficient of variation less than 1.0)

Spain

Structure-borne noise: Noise regulation RD 1367/2007.

$L_{\mathrm{Aeq},T}$, $L_{\mathrm{Ceq},T}$	A-weighted (resp. C-weighted) equivalent continuous sound pressure level (dB) for a period *T* (s) where *T* is *d* (day: 7h-19h), *e* (evening: 19h-23h) or *n* (night: 23h-7h).	
L_{Amax}	Maximum value of the A-weighted sound pressure level (with time constant Slow) over the assessment period.	
$L_{\mathrm{Keq},T}$	A-weighted equivalent continuous sound pressure level, adjusted for tonal, low-frequency and impulse components (dB)	$L_{\mathrm{Keq},T}=L_{\mathrm{Aeq},T}+K_{\mathrm{t}}+K_{\mathrm{f}}+K_{\mathrm{i}}$ where K_{t} is the adjustment factor for possible tonal components; K_{f} is the adjustment factor for possible low-frequency components; K_{i} is the adjustment factor for possible impulse components; *T* (d/e/n) is the considered assessment period (day/evening/night). The total adjustment factor $K_{\mathrm{t}}+K_{\mathrm{f}}+K_{\mathrm{i}}$ cannot exceed 9 dB.
L_{f}	Sound difference (dB)	$L_{\mathrm{f}}=L_{\mathrm{Ceq},Ti}-L_{\mathrm{Aeq},Ti}$ where $L_{\mathrm{Ceq},Ti}$ (resp. $L_{\mathrm{Aeq},Ti}$) is the C-weighted (resp. A-weighted) equivalent sound pressure level for the assessment period *Ti*. **Exceedance L_{f}** — **Adjustment factor K_{f}** $L_{\mathrm{f}}\le 10$ — 0 dB $10 < L_{\mathrm{f}} \le 15$ — 3 dB $L_{\mathrm{f}} > 15$ — 6 dB

Switzerland

Groundborne noise: SIA 181:2006.

<table>
<tr>
<td>$L_{H,tot}$</td>
<td>Overall sound level for building equipment</td>
<td>
$L_{H,tot} = L_{r,H} + C_V$
where C_V is the adjustment factor for the volume of the receiving room.
<table>
<tr><th>Volume V (m^3)</th><th>Adjustment factor C_V</th></tr>
<tr><td>V < 200</td><td>0 dB</td></tr>
<tr><td>200 ≤ V < 300</td><td>2 dB</td></tr>
<tr><td>300 ≤ V < 500</td><td>3 dB</td></tr>
<tr><td>500 ≤ V < 800</td><td>4 dB</td></tr>
<tr><td>V ≥ 800</td><td>5 dB</td></tr>
</table>
</td>
</tr>
<tr>
<td>$L_{r,H}$</td>
<td>A-weighted sound level for building equipment</td>
<td>
• Short-duration noise from equipment
$L_{r,H} = L_{AF} + K_1 + K_4$
where
L_{AF} is the maximum sound pressure level;
K_1 is the adjustment factor for room absorption;
K_4 is the adjustment factor (from -5 dB to -12 dB) for sound level regarding the use of equipment (see Table 12 in SIA 181).

• Continuous noise from equipment
$L_{r,H} = L_{Aeq} + K_1 + K_2 + K_3$
where
L_{Aeq} is the equivalent sound pressure level;
K_1 is the adjustment factor for room absorption;
K_2 is the adjustment factor for possible tonal components;
K_4 is the adjustment factor for possible impulse components.
<table>
<tr><th>Room absorption</th><th>Adjustment factor K_1</th></tr>
<tr><td>High</td><td>0 dB</td></tr>
<tr><td>Medium</td><td>-2 dB</td></tr>
<tr><td>No absorbing material</td><td>-4 dB</td></tr>
</table>
<table>
<tr><th>Tonal component</th><th>Adjustment factor K_2</th></tr>
<tr><td>No tonal component</td><td>0 dB</td></tr>
<tr><td>Slightly audible tonal component</td><td>2 dB</td></tr>
<tr><td>Clearly audible tonal component</td><td>4 dB</td></tr>
<tr><td>Highly audible tonal component</td><td>6 dB</td></tr>
</table>
<table>
<tr><th>Impulsive component</th><th>Adjustment factor K_3</th></tr>
<tr><td>No impulsive component</td><td>0 dB</td></tr>
<tr><td>Slightly audible impulsive component</td><td>2 dB</td></tr>
<tr><td>Clearly audible impulsive component</td><td>4 dB</td></tr>
<tr><td>Highly audible impulsive component</td><td>6 dB</td></tr>
</table>
</td>
</tr>
</table>

United Kingdom

Vibration: BS 6472-1:2008.

VDV	Vibration dose value	$VDV_{\mathrm{b/d,day/night}} = \left[\int_0^T a^4(t)\mathrm{d}t\right]^{0.25}$ (1) where $VDV_{\mathrm{b/d,day/night}}$ is the vibration dose value for daytime or night-time period; $a(t)$ is the frequency-weighted acceleration, using W_b or W_d as appropriate; T is the total period of the day or night during which vibration can occur. When the vibration conditions are constant or repeated regularly, only one representative sample, of duration τ seconds, needs to be measured. Then the total vibration dose value is given by equation 2: $VDV_{\mathrm{b/d,day}} = \left(\frac{t_{\mathrm{day}}}{t_\tau}\right)^{0.25} \cdot VDV_{\mathrm{b/d},\tau}$ (2) where t_{day} is the duration of exposure per day (s). If, during any assessment period, there is a total of N vibration episodes of t_i, each with a vibration dose value of $VDV_{\mathrm{b/d},ti}$, the total vibration dose value for the assessment period is given by equation 3: $VDV_{\mathrm{b/d,day/night}} = \left(\sum_{i=1}^N VDV^4_{\mathrm{b/d},ti}\right)^{0.25}$ (3)
eVDV	Estimated vibration dose value	$eVDV_{\mathrm{g/b/d,day/night}} = 1.4 \cdot a(t)_{\mathrm{r.m.s.}} \cdot t^{0.25}$ where $eVDV_{\mathrm{g/b/d,day/night}}$ is the estimated vibration dose value for daytime or night-time period; $a(t)$ is the r.m.s. value of the frequency-weighted acceleration (m/s²), using W_g, W_b or W_d as appropriate; t is the total duration (s) of vibration exposure. The *eVDV* provides a useful approximation to the true *VDV* for continuous vibration which is not time-varying in magnitude and which has a crest factor below about six. The *eVDV* tends to be higher than the *VDV* for very low crest factors and lower than the *VDV* for high crest factors. The use of *eVDV* is not appropriate for the assessment of shocks and other time-varying conditions.

United States of America

Vibration and groundborne noise prediction (Detailed Analysis)

L_v	One-third octave band r.m.s. vibration velocity level (dB re 1 µin/s)	The predicted floor velocity level $L_v = L_F + TM_{\mathrm{line}} + C_{\mathrm{build}}$ where L_F is the force density for a line vibration source such as a train; TM_{line} is the line-source transfer mobility from the tracks to the sensitive site; C_{build} is the adjustment to account for ground-building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings.
L_A	One-third octave band A-weighted groundborne noise level (dBA) for	The level L_A of groundborne noise is estimated from the projected floor vibration L_v: $L_A = L_v + K_{\mathrm{rad}} + K_{\mathrm{A-wt}}$ where L_v is the one-third octave band r.m.s. vibration velocity level; K_{rad} is the adjustment to account for conversion from vibration to sound pressure level including accounting for the amount of acoustical absorption inside the room (A value of zero can be used for K_{rad} for typical residential rooms when the decibel reference value for L_v is 1 µin/s); $K_{\mathrm{A-wt}}$ is the A-weighting adjustment at the one-third octave band centre frequency. For typical rooms: $L_A \approx L_v$. Hence the A-weighted velocity level (VdB) and the sound level (dBA) are similar.