Building vibrations induced by railways

Kouroussis, Georges; Connolly, David; Florentin, Juliette; Conti, Calogero; Verlinden, Olivier

Published in:
Proceedings of the 21st International Congress on Sound and Vibration

Publication date:
2014

Citation for published version (APA):
Kouroussis, G., Connolly, D., Florentin, J., Conti, C., & Verlinden, O. (2014). Building vibrations induced by railways: An analysis of commonly used evaluation standards. In Proceedings of the 21st International Congress on Sound and Vibration. (pp. 1-8)

ICSV 21
13-17 July, 2014, Beijing/China

The 21st International Congress on Sound and Vibration

13-17 July, 2014, Beijing/China

BUILDING VIBRATIONS INDUCED BY RAILWAYS: AN ANALYSIS OF COMMONLY USED EVALUATION STANDARDS

Georges Kouroussis, Juliette Florentin, Calogero Conti, Olivier Verlinden
Université de Mons – UMONS, Faculty of Engineering, 7000 Mons, Belgium
e-mail: georges.kouroussis@umons.ac.be

David P. Connolly
Heriot-Watt University, School of the Built Environment, Edinburgh EH14 4AS, Scotland

Whole-body-vibrations and vibrations in buildings strongly depend on internal and external sources acting on the studied structures. In addition to the comparison of vibrations with fixed limits, this paper focuses on relevant indicators defined according to selected guidelines. Various standards (or directives similar to standards) exist and and the choice of a relevant indicator is a complex exercise. The most important and the most used ones, for ground vibrations induced to buildings or for human exposure inside buildings, are presented. A first step is based on the comparison of harmonic signals with well-defined and well-known limits. Next, complex vibrations generated by railway traffic are used in order to present a relevant analysis of severity of each norm. The knowledge of these standards allows the use of suitable indicators and the studied criteria noticeably vary from one reference to another. It is shown that the thresholds are different for each standard.

1. Introduction

Railway induced ground vibrations can cause negative effects on local communities situated near rail lines. Although the current field of research is steadily advancing, the problem and its solutions are still not fully understood. This is because the propagation of railway vibrations (particularly in urban areas) is complex, due to the different transmission paths within a medium that is fundamentally inhomogeneous and infinite in three directions. Moreover, unlike noise, vibrations are described by various indicators.

In a growing number of situations, the influence of vibrations on structural damage in buildings and on people inside buildings can no longer be neglected. Among all the difficulties associated with the measurement of vibrations, the choice of a relevant indicator is critical, and is often made by relying on standards, especially in the context of building design or diagnosis. This includes the impact of vibration on people inside buildings located in the vicinity of external sources of vibration. The transmission path of possible external sources is complex due to soil/structure interaction and to effective means for vibration isolation. If various sources exist, they do not act in the same way, the generated level depends on the type of source (rail and road traffic, underground traffic, soil compaction, blasts, . . .), the soil configuration (surface geometry, presence of a rigid layer, water saturation of soils), the principal mode of propagation (body and surface waves), and obviously the distance from the source.

Two problems are commonly examined, most often within a single study: the human perception and the damages on buildings. In the case of people residing in buildings, they receive vibrations passively and this plays a role on health and comfort. Vibrations also affect the integrity of structures by imposing dynamic loads sufficient to cause structural fatigue (cracks are often the first visual impact of excessive stresses). The interest of engineers in problems of impact of vibrations on buildings is understandable. Consequently, they must evaluate the possible damage caused by their processes and ensure that the level of generated vibrations in buildings will not jeopardize the necessary comfort of people. To assist hem, several standards exist, which define adequate procedures and assessments. The most important ones are:

- the international standards ISO [1, 2], which are often considered as a reference for comfort evaluation,
- the recommendations [3] of the United States Department of Transportation (USDT) on the assessment of potential vibration impacts resulting from high-speed train lines,
- the German standards DIN 4150-2 [4] and DIN 4150-3 [5] used in Germany, in Belgium and other European countries,
- the Swiss standards SN 640 312a [6] for the building damages only.

All these baselines represent the most used assessment guidelines for measurement and interpretational methodologies.

Research on recognizing the influence of vibrations and definition of criteria abounds on literature (see for example [7–10]). The perception of threshold for specific situations is often analysed [11, 12]. However, reflections about the retained primary vibration indicator are scarce, which is unfortunate, as when an indicator is retained, it masks important information. For example, an effective value gives an overview of the motion level but may hide short-term and transient vibrations. Different methods are associated to these working documents and proposed evaluations are based on different indicators with, at first glance, any correlation.

The purpose of this paper is to compare the aforementioned guidelines, to analyse the associated criteria and to present the most interesting vibration indicators, based on the authors' experience. Such an analysis outlines the limit of these guidelines. Our first step is to introduce the methodology. Two kinds of signal are then chosen for this study: simple harmonic motions and railway-induced ground vibrations. It is important, in discussing the obtained results, i.e. the effects of vibration on humans or on building, to define exactly the methodology of assessment of the influence of transport vibrations on people inside existing buildings and on buildings themself.

2. Passenger comfort and assessment of ground vibrations

One of the main issues in vehicle design is the improvement of passenger comfort. Vibrations generated by wheel/rail contact are transmitted into the vehicle itself. Similarly to stability, suspension dynamic properties are designed with the aim to reduce the vibration transmission in a high frequency range, with the aim of health, comfort, and positive effects on the passengers.

In order to accomplish this, the ISO standard [1] is dedicated to vibrations felt inside vehicles, and serves the purpose of reducing them. In 1997, the evaluation procedure was changed with the definition of frequency-dependent filters related to activity, human position (standing, sitting or sleeping) and direction of vibrations. These filters take into account the human perception in the frequency range $1–80\,\mathrm{Hz}$, with special attention dedicated to the range $4–8\,\mathrm{Hz}$ where a resonance of the content of abdominal and thoracic cavities may occur (a loss of focus is also possible at $30–80\,\mathrm{Hz}$). The weighted acceleration a_w is derived from the time history of the measured acceleration $a(t)$ (the British standard [13] is analogous to this ISO standard, but presents some minor differences on slant curves). The old version of ISO 2631-1 (1985 version) was based on a comparison of the frequency signal to a third-octave band limit curve. The various guidelines for comfort and health were defined by a multiplication factor. The latest standards represent a radical change. A root-mean squared (rms) value is calculated and used to describe the steady vibration amplitude, assuming that the human body responds to an average vibration amplitude during a recorded time of $0 \leq t \leq T$

$$\langle a_w \rangle = \sqrt{\frac{1}{T}\int_0^T a_w^2(t)\,\mathrm{d}t} \,. \tag{1}$$

A guide on the effect of vibration on comfort and perception is provided with valuable limits defining the grades of various magnitudes of reaction to vibrations. The effects on health are, however, less well described. Only two bounds are given (a probable risk if above the upper limit, an improbable risk if below the lower limit), without any further explanation in case the calculated value lies within the intermediate region. The time duration of vibration is only vital for further health assessments.

This interpretation is entirely different from the one related to vibrations in buildings and their transfer to the people inside them. In the case of evaluations inside buildings [2], it is noteworthy that only a single filter is defined, independent of the direction of measurement and human position, which focuses on the frequency range 1-$20\,\mathrm{Hz}$. Alternatively, as vibration is often non-stationary, the DIN 4150-2 standard [4] proposes the use of a running, root-mean square applied to the velocity signal. A weighted, time-averaged signal is defined by:

$$KB_F(t) = \sqrt{\frac{1}{\tau}\int_0^t KB^2(\xi)\, e^{-\frac{t-\xi}{\tau}}\,\mathrm{d}\xi} \tag{2}$$

where the weighted velocity signal $KB(t)$ is obtained by passing the original velocity signal $v(t)$ through the high-pass filter

$$H_{KB}(f) = \frac{1}{\sqrt{1+(5.6/f)^2}} \,. \tag{3}$$

The filter is a function of the frequency f. The assimilation time τ is typically equal to $0.125\,\mathrm{s}$, which takes into account transient phenomena, such as impacts or shocks, that would otherwise be masked if a simple rms operation was performed. Although no unit is specified in the standards, the associated unit is clearly $\mathrm{m/s}$ (or more usually $\mathrm{mm/s}$). The only comfort that can then be assessed is by comparing the maximum level $KB_{F,\max}$ with three guideline limits denoted by A_u, A_o and A_r, used both for an entire evaluation and for the short-term frequency vibrations as well. Part 3 of DIN 4150-3 [5] is entirely dedicated to vibration effects on structures. The peak particle velocity PPV, which is defined as the maximum absolute amplitude of the velocity time signal, is calculated and compared to other limits, depending on the dominant signal frequency. If multiple directions are measured, the maximum of the three components (x, y or z) is

$$PPV = \max(|v_x|, |v_y|, |v_z|) \,. \tag{4}$$

By taking into account velocity as a primary indicator, it is possible to evaluate both human comfort and building damage from a single signal. The Swiss standard [6] is similar to its German counterpart DIN 4150-3 because it also uses a PPV, which is defined as the norm of the vector velocity $\underline{\mathbf{v}}(t)$:

$$PPV = \sqrt{v_x^2 + v_y^2 + v_z^2} \,. \tag{5}$$

If one direction is dominant in terms of amplitude, then both definitions are equivalent. The guidelines are also different when an excitation frequency is introduced (occasional, frequent or continuous excitation) with limits being the function of the dominant signal frequency.

Taking into account that vibrations consist of rapidly fluctuating motions, a decibel scale was adopted by the U.S. Department of Transportation in order to evaluate the vibrational impact of a passing high-speed train [3]. As for the description of noise, this scale is intended to compress the range of numbers required to describe the vibration velocity level, and is defined as:

$$V_{dB} = 20\log_{10}\frac{v_{rms}}{5\,10^{-8}} \tag{6}$$

where v_{rms} is the root mean square amplitude of the velocity time history. Notice that no weighting is applied to the signal, which is contrary to ISO standards. An equivalent standardized weighted vibration level VL_{dB} has been used in Japan to evaluate human response to vibration. For frequencies greater than $8\,\mathrm{Hz}$, the following relationship exists [3]

$$VL_{dB} = V_{dB} - 21\;. \tag{7}$$

Typical levels of ground-borne vibrations are also provided in [3].

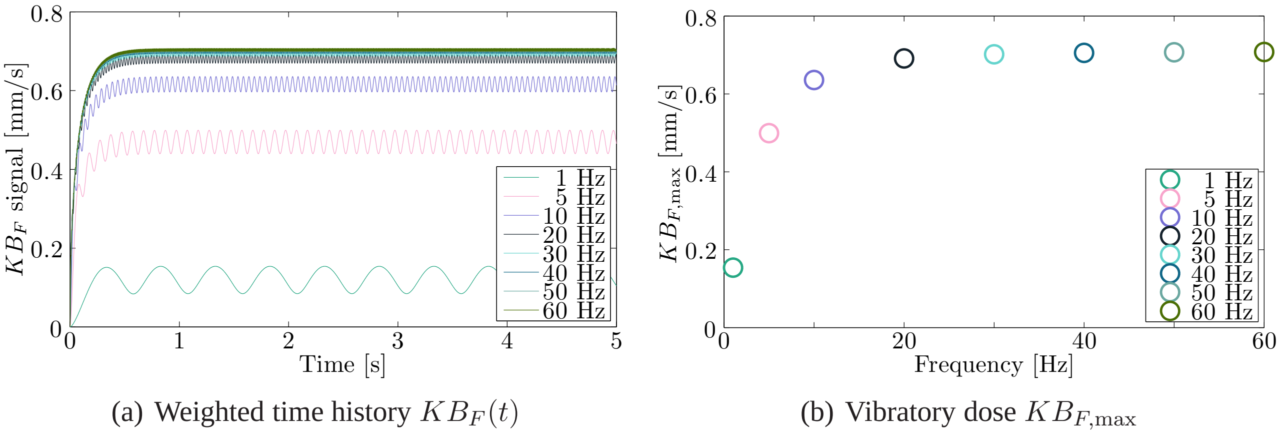
3. Harmonic excitation analysis

A harmonic signal is certainly the simplest vibration record. It can be encountered in practice when the vibration is dominated by an important resonance mode and/or when the excitation is clearly mono-frequency. To be concise, the vibration amplitude is imposed so as to define a vibratory motion by

$$v(t) = A\sin(2\pi f t) \tag{8}$$

where the amplitude A is constant and the frequency f can vary from 1 to $100\,\mathrm{Hz}$.

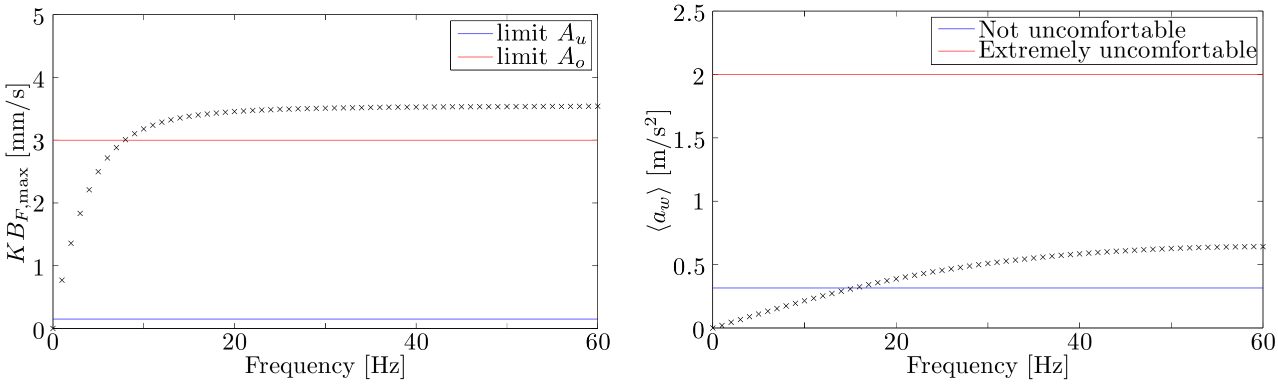
An initial analysis was used to evaluate human exposure, based on the $KB_F(t)$ indicator because it uses “non-usual” operations compared to the other guidelines. Figure 1 presents this indicator as a function of the frequency f, showing its time history (Fig. 1(a)) as well as its maximum value (vibratory dose — Fig. 1(b)). The level clearly tends to the effective value of $0.707\,A$, showing the effect of the running rms operation.



(a) Weighted time history $KB_F(t)$ (b) Vibratory dose $KB_{F,\max}$

Figure 1. DIN 4150-2 standards putting into practice on harmonic signals

Including the limits proposed by these baselines allows the comparison in terms of comfort evaluation. Figure 2 shows the results with a harmonic signal of amplitude $A = 5\,\mathrm{mm/s}$, sufficiently high to exceed the proposed limits, and an increasing signal frequency (note that an increase of amplitude translates the calculated curves vertically). Several comments can be made on the results. The limit is exceeded at 8 Hz, according to DIN, and at 15 Hz according to ISO. Notice that the definitions are different: for the DIN standards, limit A_o represents the borderline case from which the annoyance is confirmed for any event. A_u represents the limit below which the annoyance is not detected. The number of events only plays a role if the vibration level is comprised between A_u and A_o (the supplementary limit A_r is used in this case). In a different spirit, the ISO standard defines various grades of annoyance. This means that a harmonic vibration signal can be assumed strong for the DIN standard and low for the ISO one if the frequency lies between 8 Hz and 15 Hz.

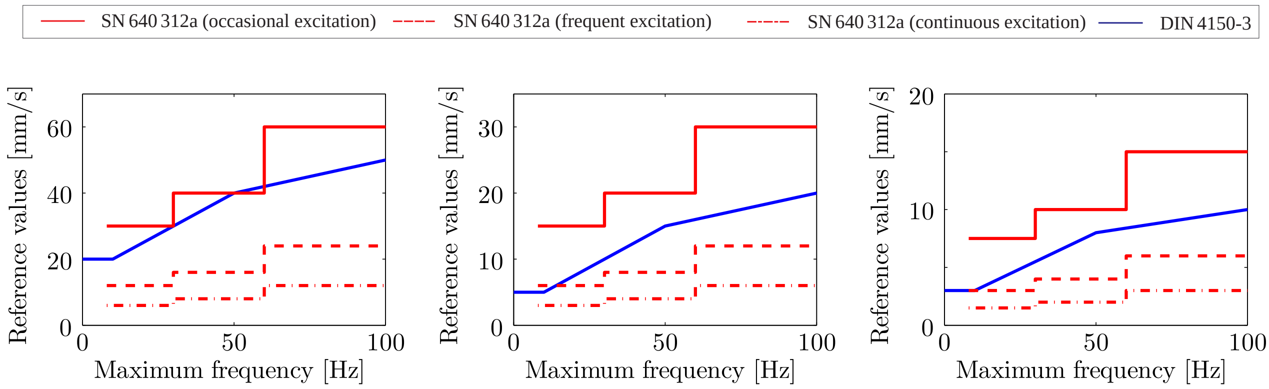


(a) Assessment according to the DIN 4150-2

(b) Assessment according to the ISO 2631-2

Figure 2. Comparison between standards DIN 4150-2 and ISO 2631-2 for harmonic signals

The second analysis is the effect on buildings. Only the German and Swiss standards give assessment methods, correlating the PPV to the structural stress. Figure 3 displays the associated limits, showing that they are close to each other. The Swiss standard presents the undeniable advantage to consider explicitly the frequency of events. It is also observable that the DIN limits are approximately to the SN limits for frequent to continuous excitations.



(a) Industrial buildings

(b) Standard buildings

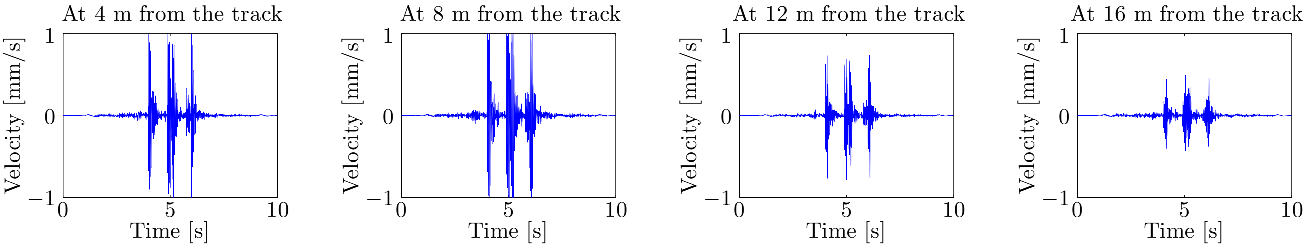
(c) Sensitive buildings

Figure 3. Comparison between DIN 4150-3 and SN 640 312a for the effects on building according to the type of structure

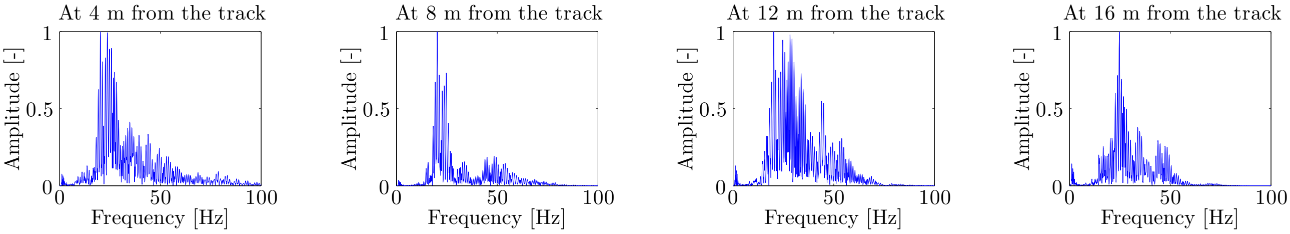
4. Analysis with railway-induced ground vibration signals

The effect of train passages on ground vibrations is interesting and has been mainly treated in the past. The purpose of this analyse is to quantify the ground vibration levels with respect to the aforementioned indicators. An application is proposed based on the T2000 tram. Ground vibrations problems are often developed in urban areas where (*1*) the distance between the source and the receiver is close and (*2*) singular rail surface defects are numerous and can significantly affect the ground vibration levels. The application of built environment is clearly a problem in urban area, more common than those from high-speed trains. To propose relevant and sufficient results, a numerical model was developed by Kouroussis et al. [14] and validated in several cases. This prediction scheme is based on a two-step approach, separating the vehicle/track and the soil dynamics calculations, in order to focus on detailed models of vehicles.

Figure 4 shows results from such a numerical model which describes the passage of a tram on a singular rail surface defect. They are based on the calculation of vibrations in the vicitiny of the building [15] placed at a distance of $4\,\mathrm{m}$ from the track (the vibrations in the ground floor surface of the house is described between 4 and $11\,\mathrm{m}$). It presents some time histories of the vertical velocity at the ground surface at various distances from the track and for a vehicle speed of $30\,\mathrm{km/h}$. The corresponding frequency spectra are also included, showing that the main response frequency is around $20\,\mathrm{Hz}$ (a mean of $21.1\,\mathrm{Hz}$ is calculated for all the distance between 2 and $20\,\mathrm{m}$). These results are typical of important wheel/rail interactions where the vehicle dynamics is clearly visible in the ground-borne vibrations [16, 17].



(a) Time histories



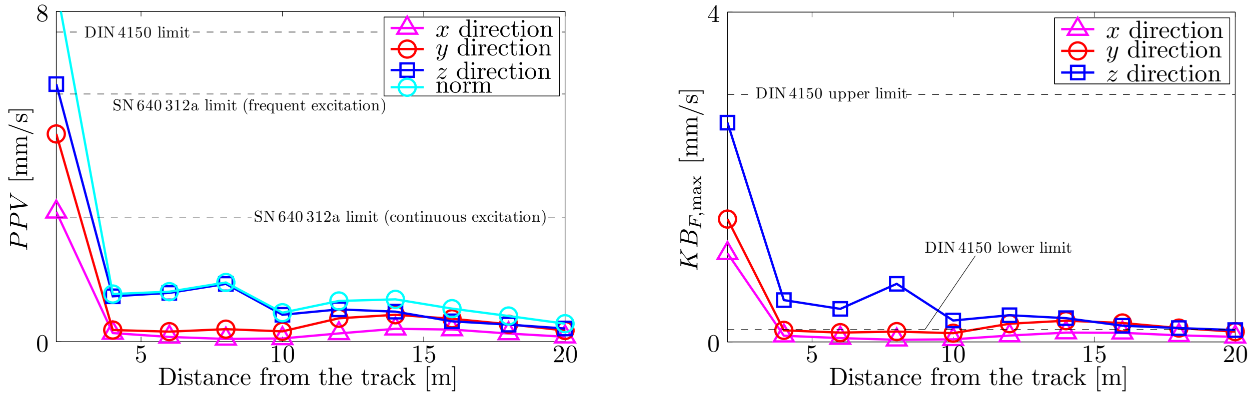
(b) Frequency contents

Figure 4. Predicted results for vertical ground velocities due to the passage of a tram over a singular rail surface defect in the vicitiny of a building

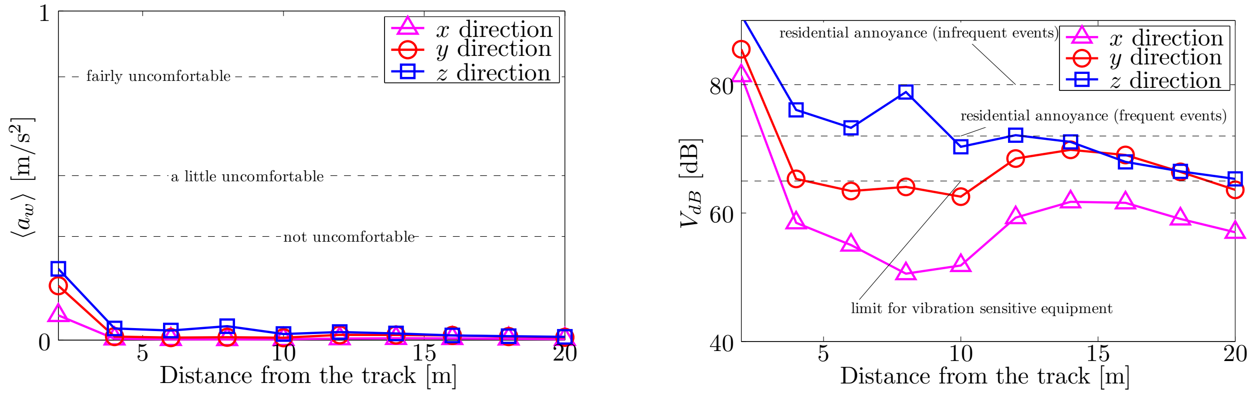
Figure 5 shows the corresponding indicators based on the aforementioned guidelines. The three directions are analysed (x, y or z for horizontal parallel to the track, horizontal perpendicular to the track or vertical, respectively). While the vibration level in the vertical direction is the greatest, the horizontal vibrations cannot be ignored. This statement confirms the good practice rules observed in experimental assessments to always record the three directional components of vibratory nuisances. The four indicators, namely the peak particle velocity, the maximum weighted acceleration, the vibration velocity level and the maximum weighted velocity dose, present the same tendency: a strong decrease in level in the near field (up to $5\,\mathrm{m}$) and a weak reduction above $10\,\mathrm{m}$ from which the y and z direction amplitudes tend to the same values. For the PPV graph, the norm of the velocity vector is calculated to facilitate the comparison with the SN 640 312a standard.

Adding the guideline limits to each plot reveals different observations for human exposure:

- For the ISO 2631 standard, vibratory nuisance is avoided for any distance from the track.



(a) Peak particle velocity (b) Maximum weighted velocity dose



(c) Maximum weighted acceleration (d) Vibration velocity level

Figure 5. Calculated indicators associated to the passage of a tram over a singular rail surface defect and as a function of the distance from the track

- For the DIN 4150, no direct conclusion can be drawn. The number of events must be taken into account.

- The recommendation of USDT clearly shows that infrequent events are tolerated for vibrations at distances beyond $8\,\mathrm{m}$. This statement is close to the ISO recommendations.

Regarding the effects on buildings, the observations are also different depending on which recommendation is considered. For DIN 4150, structural damages cannot appear at any distance from the track. For the SN 640 312a standard, the worst case appears at distances smaller than $7\,\mathrm{m}$ and only for continuous vibrations.

5. Concluding remarks

Common standards for the evaluation of vibration annoyance were reviewed in this work. This paper also presented practical results based on mono-frequency excitation and railway-induced ground vibrations. It appears that the assessment problem is complex, since contradictory recommendations are provided by the guidelines, both for human exposition and for the effects on structures. Additional research is required to provide a definitive assessment of the effects of vibrations.

REFERENCES

[1] International Organization for Standardization. *ISO 2631-1: Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 1: General requirements*, 1997.

[2] International Organization for Standardization. *ISO 2631-2: Mechanical vibration and shock — Evaluation of human exposure to whole-body vibration — Part 2: Vibration in buildings (1 Hz to 80 Hz)*, 2003.

[3] U. S. Department of Transportation (Federal Railroad Administration). High-speed ground transportation. Noise and vibration impact assessment. Technical Report 293630–1, Office of Railroad Development Washington, 1998.

[4] Deutsches Institut für Normung. *DIN 4150-2: Structural vibrations — Part 2: Human exposure to vibration in buildings*, 1999.

[5] Deutsches Institut für Normung. *DIN 4150-3: Structural vibrations — Part 3: Effects of vibration on structures*, 1999.

[6] Schweizerische Normen-Vereinigung. *SN-640312a: Les ébranlements — Effet des ébranlements sur les constructions (Swiss Standard on vibration effects on buildings)*, 1992.

[7] M. G. R. Toward and M. J. Griffin. The transmission of vertical vibration through seats: Influence of the characteristics of the human body. *Journal of Sound and Vibration*, 330:6526–6543, 2011.

[8] M. J. Griffin, editor. *Handbook of human vibration*. Elsevier, London (UK), 2nd edition, 1996.

[9] K. Vogiatzis. Protection of the cultural heritage from underground metro vibration and ground-borne noise in Athens centre: The case of the Kerameikos archaeological museum and Gazi cultural centre. *International Journal of Acoustics and Vibration*, 17:59–72, 2012.

[10] D. P. Connolly, G. Kouroussis, A. Giannopoulos, O. Verlinden, P. K. Woodward, and M. C. Forde. Assessment of railway vibrations using an efficient scoping model. *Soil Dynamics and Earthquake Engineering*, 58:37–47, 2014.

[11] M. J. Griffin. A comparison of standardized methods for predicting the hazards of whole body vibration and repeated shock. *Journal of Sound and Vibration*, 104(3):803–914, 1998.

[12] M. J. Griffin. Minimum health and safety requirements for workers exposed to hand-transmitted vibration and whole-body vibration in the european union; a review. *Occupational and Environmental Medicine*, 61(5):387–397, 2004.

[13] British Standard. *BS 6841: Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock*, 1987.

[14] G. Kouroussis, O. Verlinden, and C. Conti. A two–step time simulation of ground vibrations induced by the railway traffic. *Journal of Mechanical Engineering Science*, 226(2):454–472, 2012.

[15] G. Kouroussis, L. Van Parys, C. Conti, and O. Verlinden. Prediction of ground vibrations induced by urban railway traffic: an analysis of the coupling assumptions between vehicle, track, soil, and buildings. *International Journal of Acoustics and Vibration*, 18(4):163–172, 2013.

[16] G. Kouroussis, O. Verlinden, and C. Conti. Efficiency of resilient wheels on the alleviation of railway ground vibrations. *Proc. IMechE, Part F: J. Rail and Rapid Transit*, 226(4):381–396, 2012.

[17] G. Kouroussis, N. Pauwels, P. Brux, C. Conti, and O. Verlinden. A numerical analysis of the influence of tram characteristics and rail profile on railway traffic ground-borne noise and vibration in the brussels region. *Science of The Total Environment*, 482-483:452–460, 2014.