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Analysis of methods proposed by International Standard ISO 2631 for evaluating the human exposure to whole–body vibration

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Systematic Review

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Abstract

In order to evaluate human exposure whole-body vibration and shock the ISO 2631 is the most common used standard. The human body presents different sensitivity of the body in different axes. ISO 2631 offers different frequency weightings and multiplying factors to predict discomfort. [DOI:10.12866/J.PIVAA.2016.19] [1]

Keywords: International Standard, Whole–body vibration

Contents

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1 Introduction

The International Standard ISO 2631 defines reasonable procedures for quantifying the severity of the complex vibration and shocks to which people are exposed. The International Standard ISO 2631 concerns all forms of multi–axis, multi–frequency, random, stationary and non–stationary vibration and repeated shock in the frequency range 0.5–80 Hz ISO [1997]. Annexes of the ISO 2631 provide guidance on the interpretation of the measurements.

The paper seeks to identify the aspects of the measurement, evaluation and assessment of exposures to vibration and shock. We analyze several aspects: time–dependency, crest–factor limitation, frequency weighting, number of axes, the summation methods over axes, the evaluation of discomfort and the vibration limits. In addition, the discussion evaluates the apparent inadequacies in the International Standards ISO 2631.

2 Duration of measurement

The International Standard ISO 2631 affirms that

> *The duration of measurement shall be sufficient to ensure reasonable statistical precision and to ensure that the vibration is typical of the exposures which are being assessed. The duration of measurement shall be reported.*

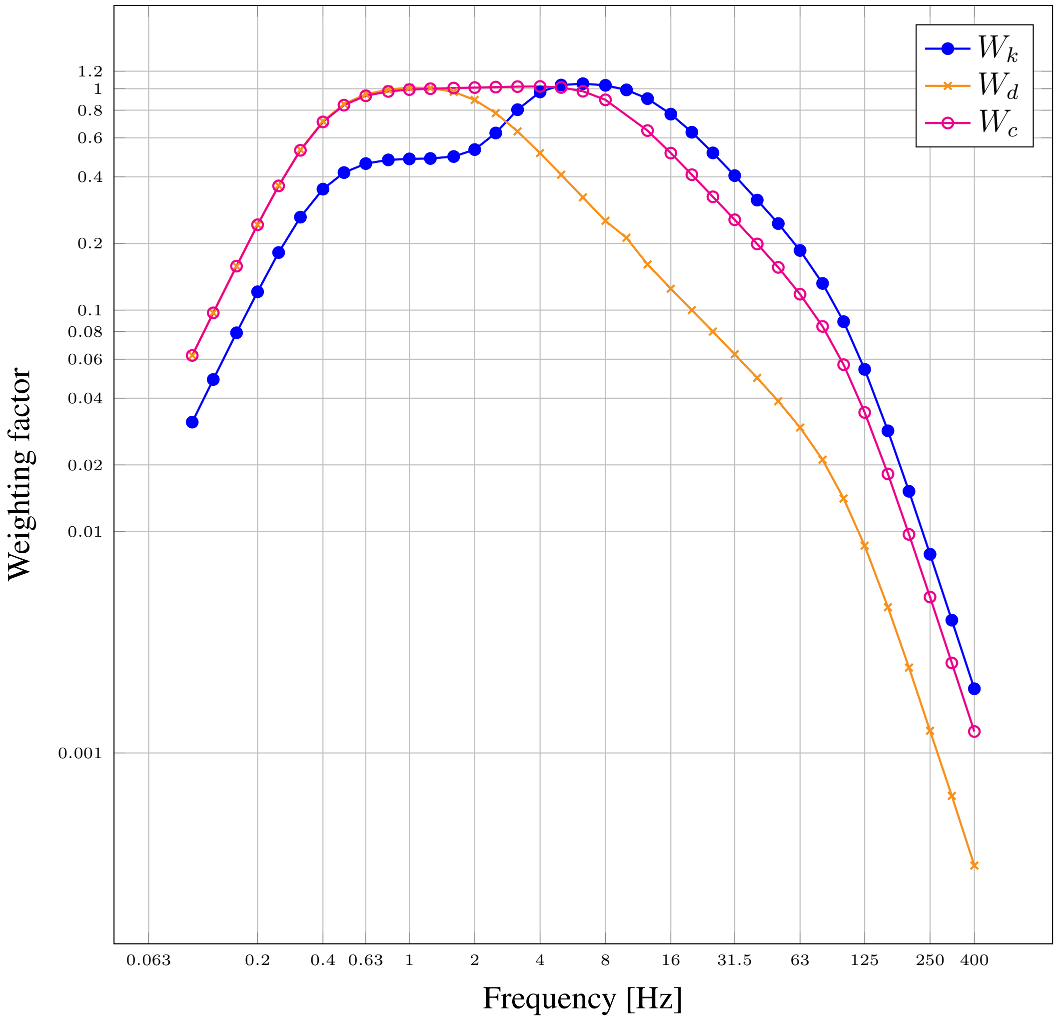

Figure 1: Frequency weighting curves for principal weightings ISO 2631

> *Where complete exposure consists of period of different characteristics, separate analysis of the various periods may be required.*

In contrast to the standard, common experience suggests that human responses are dependent on duration of exposure below 4 mins [Griffin, 1998, p.896].

A note in the standard suggests that for statistical reasons the minimum measurement duration will be 227 s (assuming a lower limiting frequency of 0.5 Hz). The measurement duration will be representative of the vibration exposure.

The standard should have identified how to measure and evaluate all possible exposures, either: (i) from a measurement over the full period of exposure (however short), or, (ii) by calculating a value using one or more measurements obtained over shorter periods [Griffin, 1998, p.901].

3 Frequency weightings

The frequency range, considered in ISO 2631, is divided into following fields:

- ✓ 0.1 to 0.5 Hz for motion sickness;

Location	Axis	Weighting	Multiplying factor
Seat	x	W_d	1.4
	y	W_d	1.4
	z	W_k	1.0
Backrest	x	W_c	0.8

Table 1: Frequency weightings and multiplying factors as specified in International Standard 2361 for seated persons

✓ 0.5 to 80 Hz for health, comfort and perception.

ISO 2631 suggests that vibration is measured in the three translational axes on the seat pan. The frequency weightings and multiplying factors are defined in ISO 2631 (Table 1) for axes x, y and z and for different locations.

The ISO defines contours for each axis over the 1–80 Hz frequency range. One contour is defined limits for z–axis vibration and another one is defined limits for both x- and y–axis vibration.

We can remark the following aspects:

- The weighting W_k indicates greatest sensitivity to vibration acceleration between 4 and 8 Hz. The acceleration limits increases in proportion to frequency at frequencies above 8 Hz. The z–axis acceleration limits advances in inverse proportion to the square root of the frequency below 4 Hz.
- The weighting W_d gives greatest sensitivity to vibration acceleration between 0.63 and 2.0 Hz. The acceleration limits increases in proportion to frequency from 2–80 Hz.
- The weighting W_c attributes greatest sensitivity to vibration acceleration between 1.0 and 6.3 Hz.

4 Axes vibration

International Standard ISO 2631 requires the measurement of vibration in three translational axes on the supporting seat. ISO 2631 does not propose rules about the rotational vibration of the seat, on the translational vibration at the back or at the feet. The assessments, evaluated by International Standard 2631, is based on the axis giving the greatest frequency–weighted acceleration on the seat pan. If no dominant axis of vibration exists, ISO 2631 requires the use of multiplying factors for the horizontal axes. The x–and y–axes frequency–weighted values have to be multiplied by 1.4 for the comparison with the z–axis frequency–weighted value (Table1).

The value of acceleration should be the root–sums–of–squares of the weighted values obtained in each axis. The purpose is to develop the comparison between the vector sums and acceleration of different motions. The text of ISO 2631 is ambiguous because the vector sum should be used to compare measurements with the exposure limits for health and safety, indicated in the International Standard ISO 2631.

International Standard ISO 2631 affirms that

> *The vibration total value or vector sum have also been proposed for evaluation with respect to health and safety if no dominant axis of vibration exists.*

The evaluations for health and safety is developed by the comparison between acceleration of dominant axis and acceleration of the exposure limits.

If measurements in the x– and y–axes are multiplied by a factor of 1.4, measurements in the different axes could be compared with each other. However, the International Standard ISO 2631 does not offer any notation or justification about the multiplying factor 1.4.

The International Standard ISO 2631, in Section 7.2.3, addresses partial attention to x–axis on backrest:

> *. . . Measurements in the x-axis on the backrest . . . are encouraged. However, . . . not included in the assessment of the vibration severity . . .*

On one hand we are encouraged to acquire accelerations in the x–axis on the backrest, on the other hand the measurements are not considered in the assessment of the vibration.

The International Standard ISO 2631 is equivocal on the axes to be assessed, how they may be combined and what relationship should be chosen. In the Section 7.2.2 the International Standard ISO 2631 asseverates that

> *The assessment of the effect of a vibration on health shall be made independently along each axis. The assessment of the vibration shall be made with respect to the highest frequency–weighted acceleration determined in any axis on the seat pan.*

In Section 7.2.2 Note, the International Standard adds:

> *When vibration in two or more axes is comparable, the vector sum is sometimes used to estimate health risk.*

The term *sometimes* can not be a criterion to evaluate human exposure to whole–body vibration.

5 Vibration evaluation

The standard proposes a basic evaluation method or the calculation of the r.m.s. value. The basic evaluation method is suitable for vibration with crest factors below or equal to 9.

> *If the basic evaluation method may underestimate the effects of vibration (high crest factors, occasional shocks, transient vibration, . . .*

the standard defines the following additional or alternative methods: the running r.m.s. method and the fourth power vibration dose method.

- **Crest factors**. The crest factor is defined as the modulus of the ratio of the maximum istantaneous peak value of the frequency weighted acceleration to its r.m.s. value.

  The ISO 2631 affirms that the crest factor does not necessarily indicate the severity of vibration. The ISO 2631 method was originally limited to a crest factor of 3. It is clear that this was set arbitrarily without knowledge of the crest factor.

  If the measurements are made for longer periods and under true operational conditions, very much higher crest factors often occur. If the vibrations contains shocks and if the crest factor is not greater than 9, the crest factor may miscalculate the severity with respect to discomfort ISO [1997].

- **The weighted r.m.s. acceleration**. The running r.m.s. method considers irregular shock and transient vibration by use of a short integration time constant. The running r.m.s. method is defined in two alternative ways: linear and exponential averaging. The linear averaging offers the following relation of running r.m.s. at $t = t_0$

$$a_w\left(t_0\right) = \frac{1}{\tau}\left[\int_{t_0-\tau}^{t_0} a_w\left(t\right)^2 dt\right]^{1/2} \qquad \left[m \cdot s^{-2}\right]. \tag{1}$$

where

  - $a_w\left(t\right)$ is the instantaneous frequency weighted acceleration;
  - τ is the integration time for running averaging;
  - t is the time integration variable;
  - t_0 is the time of observation.

The exponential averaging is the the following relation of running r.m.s. at $t = t_0$

$$a_w\left(t_0\right) = \frac{1}{\tau}\left[\int_{t_0-\tau}^{t_0} a_w\left(t\right)^2 exp\left(\frac{t-t_0}{\tau}\right) dt\right]^{1/2} \qquad \left[m \cdot s^{-2}\right]. \tag{2}$$

The exponential function Eq.(2) of time, of a specified time constant, weights the square of the instantaneous weighted accelerations. The standard affirms that the difference between the two methods, defined by Eqs.(1)-(2), may be up to 30% for some motions.

The standard recommends the use of the integration time $\tau = 1$ s. If other integration times are used to calculate the running r.m.s. values, different values of running r.m.s. can be obtained.

It follows that the vibration total value of weighted r.m.s. acceleration, determined from vibration in orthogonal coordinates is calculated by following relation

$$a_w = \left(k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2\right)^{1/2}. \tag{3}$$

where

  - a_{wx}, a_{wy} and a_{wz} are the weighted r.m.s. accelerations with respect to the orthogonal axes x, y, z;
  - k_x, k_y and k_z are multiplying factors.

- **Vibration dose values.** The VDV gives a measure of the total exposure to vibration, taking account of the magnitude, frequency and exposure duration. VDVs are estimated using apposite frequency weightings and axis multiplying factors:

$$\text{VDV} = \left[\int_0^T a_w\left(t\right)^4 dt\right]^{1/4} \qquad \left[m \cdot s^{-1.75}\right]. \tag{4}$$

where

  - $a_w\left(t\right)$ is the frequency–weighted acceleration time history, in m/s^2, at the input to the body;
  - T is the duration of measurement.

According to International Standard ISO 2631, the total vibration dose value VDV_{total} is the fourth root of the sum of the fourth powers of the VDVs in each axis of vibration. VDV_{total} is calculated over the measurement period, t seconds (e.g., 60 s)

$$VDV_{total} = \left(VDV_{xs}^4 + VDV_{ys}^4 + VDV_{zs}^4\right)^{1/4}. \tag{5}$$

where

- VDV_{xs} is vibration dose value computed in the x–axis on the seat;
- VDV_{ys} is vibration dose value computed in the y–axis on the seat;
- VDV_{zs} is vibration dose value computed in the z–axis on the seat.

- **Estimated vibration dose value.** The vibration dose value can be calculated from the r.m.s. acceleration using the estimated vibration dose value, eVDV,

$$eVDV = \left[\left(1.4 \cdot a_{rms}^4\right) \cdot t\right]^{1/4}. \tag{6}$$

where a_{rms} is the frequency–weighted r.m.s. value, and t is the duration (in s). There are two important remarks:

1. *This estimate is only valid for signals with low crest factors (i.e., < 6).* [Mansfield, 2005, p.129]
2. *. . . The empirically determined correction factor of 1.4 is said to be obtained from typical vibration environments having low crest factors (below about 6.0) but, of course, will not work when the crest factor is high (or very low). The standard says that where there is any doubt or difference between true and estimated vibration dose values the true values according to equation (4) should be used.* [Griffin, 2004, p.897]

- **Maximum transient vibration value.** A quantity called the maximum transient vibration value, MTVV is defined as the highest magnitude of the running r.m.s. .

The section 6.3.3 of the standard affirms that:

> *Experience suggests that the use of the additional methods will be important for the judgement of the effects of vibration on human beings when the following ratios are exceeded (depending on which additional method is being used) for evaluating health or comfort:*
>
> $$\frac{MTVV}{a_w} = 1.5 \tag{7}$$
>
> and
>
> $$\frac{VDV}{a_w} = 1.75 \tag{8}$$
>
> *The basic evaluation method shall be used for the evaluation of the vibration. In cases where one of the additional methods is also used, both the basic evaluation value and the additional value shall be reported.*

6 Criteria in time domain for evaluating duration in exceed

The health guidance zones, quoted in International Standard ISO 2631, are represented in Fig.2. Two zones are provided as they are derived from r.m.s. and VDV approaches.

The standard states that

> *For exposures below the zone, health effects have not been clearly documented and/or objectively observed; in the zone, caution with respect to potential health risks is indicated and above the zone health risks are likely.*

Dashed and solid red lines are the rating line that define the phase of the exposure level of health warning from 2.8 ms^{-2} to 5.6 ms^{-2}. In International Standard ISO 2631 the maximum exposure is more than 10 minutes as defined by following equation:

$$a_w = \left.\begin{array}{c} 2.8 \\ 5.6 \end{array}\right\} \sqrt{\frac{t_0}{t}} \tag{9}$$

with $t_0 = 10$ min and t exposure time. Eq.(9) approximately corresponds to the so–called fatigue-decreased proficiency limit in the old ISO 2631 for exposures between 1 and 10 minutes [Griffin, 1998, p.904].

Dashed and solid blue lines represent the VDV assessment and define warning level between 8.5 ms$^{-1.75}$ (lower VDV level) and 17 ms$^{-1.75}$ (upper VDV level). An estimated vibration dose values eVDV has been used

$$eVDV = 1.4 \cdot a_w t^{1/4} \tag{10}$$

The estimated vibration dose values correspond to 8.5 ms$^{-1.75}$ (lower VDV level) and 17 ms$^{-1.75}$ (upper VDV level). VDV assessment 17 ms$^{-1.75}$ is similar to time–dependency for z–axis, proposed in International Standard ISO 2631 (1974, 1978, 1985a–c).

Above the top line health risk is likely. We distinguish caution with respect to health risks between upper and lower VDV level. Below the bottom line health effects are not been observed.

The zones coincide for duration of about 4 to 8 h (Fig.2). The standard states that

> *The health guidance caution zones for Eqs.(9)-(10) are the same for duration from 4 h to 8 h for which most occupational observation exist.*

In the caution zone, potential health risks are very likely. The standard attests that an increment of vibration dose and of risk can be provoked by two factors: the increased duration, within the working day or daily over years, and the increased vibration intensity. Periods of rest can decrease the risk.

7 Criteria in frequency domain for evaluating duration in exceed

International Standard ISO 2631 proposes different methods to evaluate comfort for seat vibration. The guide ISO 2631 introduces limits of exposure to vertical and lateral vibration by following criteria:

1. *Exposure limit (EL)*. It regards the preservation of health or safety. The daily exposure limit has two aspects:

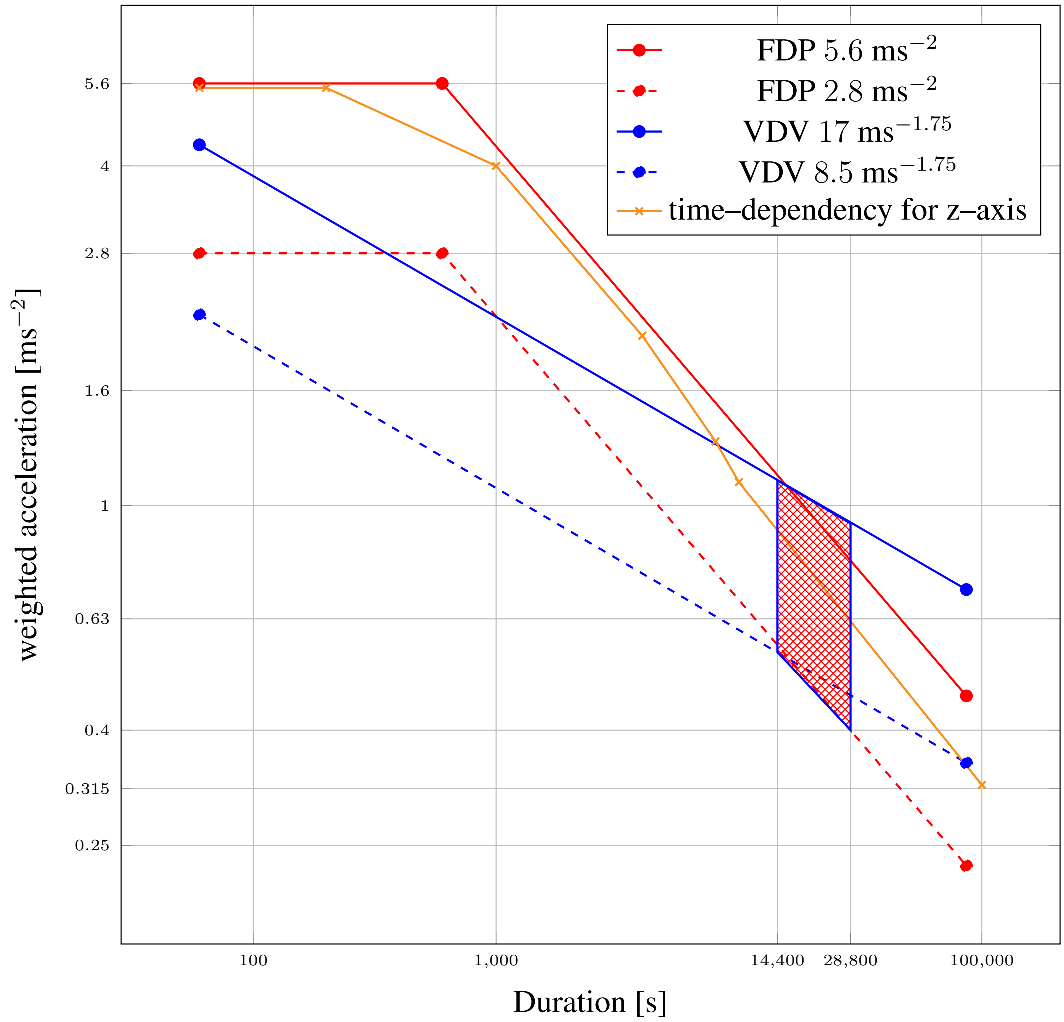

Figure 2: Health guidance caution zones given in ISO 2631

- ✓ Daily exposure limit value (ELV). It is a maximum amount of vibration to which an employee may be exposed every day. The daily exposure limit value is 1.15 m/s^2 A(8).
- ✓ Daily Exposure action value (EAV). It indicates the vibration level above which we adopt action to reduce exposure. The daily exposure action is 0.5 m/s^2 A(8).

The exposure limit is considered appropriately half the threshold of pain.

2. *Working efficiency or fatigue decreased proficiency (FDP) boundary*. It involves the preservation of working efficiency. It is defined a limit of working efficiency of many kinds of task.

3. *Reduced comfort boundary (RCB)*. It concerns the preservation of comfort. It was related to difficulties of carrying out operations as reading and writing in transport.

We consider the 1 min and 24 exposure limits, fatigue–decreased proficiency boundaries and reduced comfort boundaries (Fig.3). If we consider the disturbance of activities, the fatigue decreased proficiency limits would be recommended for drivers and operators, the reduced–comfort boundaries for passengers.

The vibration limit appropriate to a system is not entirely determined by the frequency, magnitude, direction and duration of the vibration. The vibration limit for preserving performance must depend on the activities to be performed. The limit for preserving health depends on degree of allowable risk.

The relationship of limits corresponding to the three criteria for any vibration frequency, axis or duration is the following relation

$$\mathrm{EL} = 2 \cdot \mathrm{FDP} \qquad \mathrm{RCB} = \frac{\mathrm{FDP}}{3.15} \tag{11}$$

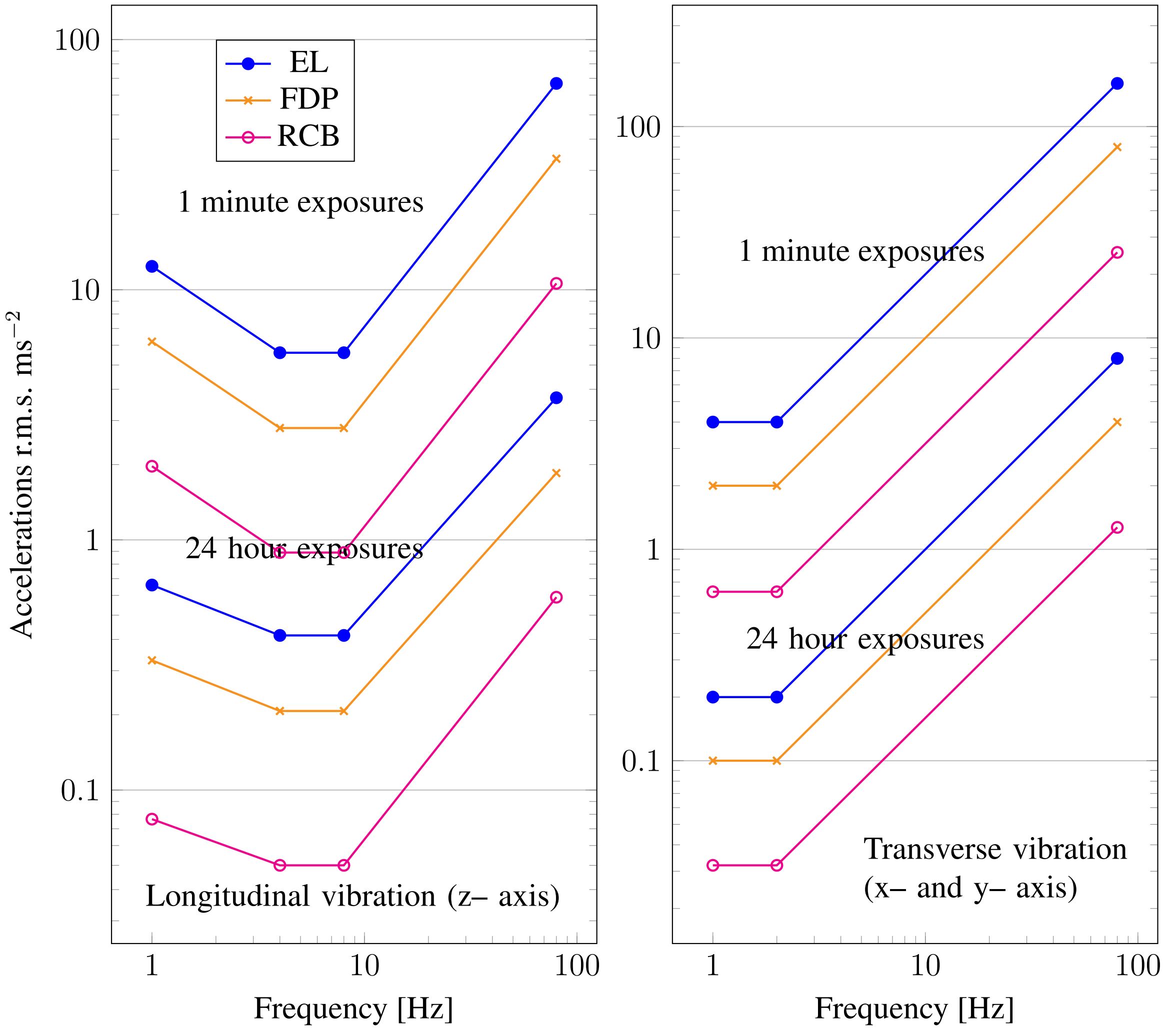

Figure 3: The exposure limits, fatigue–decreased proficiency boundaries and reduced comfort boundaries for 1 min and 24 h exposures to whole–body vibration as given in ISO 2631

8 Comfort reactions to vibration environments

The International Standard ISO 2631 propose 5 vibration environments and 5 comfort reactions. The International Standard ISO 2631 affirms that

Vibration environments	Comfort reactions
Less than 0.315 m/s^2	not uncomfortable
0.5 to 1	a little uncomfortable
0.8 to 1.6	uncomfortable
1.25 to 2.5	very uncomfortable
Greater than 2.0	extremely uncomfortable

Table 2: Comfort reactions to vibration environments according to International Standard ISO 2631

> *Acceptable values of vibration magnitude for comfort depend on many factors which vary with each application. Therefore, a limit is not defined in this part of ISO* 2631. *The following values give approximate indications of likely reactions to various magnitudes of overall vibration total values in public transport.*
>
> *However, as stated before, the reactions at various magnitudes depend on passengers expectations with regard to trip duration and the type of activities passengers expect to accomplish (e.g. reading, eating, writing, etc.) and many other factors.*

The scale, proposed in International Standard ISO 2631, evaluates the discomfort for seat vibration (Table 2), but the ISO 2631 declares that there is no definitive demonstration to sustain a universal time dependence of vibration effects on comfort.

The International Standard ISO 2631 considers continued exposure to vibration and it affirms that

> *It generally takes several years for health changes caused by whole–body vibration to occur. It is therefore important that exposure measurements are representative of the whole exposure period.*

9 Discussion

The performance of a driver might be compromised by vibrations at seat backrest, at head and at footrests.

> *If a person is exposed to a sinusoidal signal that gradually increases in frequency (swept sine), then different parts of the body will resonate in turn. Many body parts will resonate at about* 5 *Hz (e.g., the head and abdomen, . . .)* [Mansfield, 2005, p.170].

The International Standard ISO 2631 encourages the measurement of fore–and–aft vibration on a backrest. The measurement on seat backrest, on head and on footrests are not included in the assessment of vibration severity. A complete frequency weighting should provide a model of the response of a person to all kinds of vibration.

The International Standard ISO 2631 warns against using the zones for shorter duration. If exposure time is between about 5 and 30 min (Fig.2), it is possible to exceed the limits of the zone according to one method and not reach the zone for the other [Mansfield, 2005, p.170].

With reference to Fig.2, a doubling of r.m.s. acceleration magnitude originates a reduction of exposure time:

- by a factor of 16 for VDV methods;
- by a factor of 4 for fatigue–decreased proficiency limit.

There are doubts about the use of MTVV [Griffin, 2004, p.905].

> *ISO* 2631 *(1997) does not indicate what measures should be compared against the r.m.s. health guidance caution zone. Users might use either of the two caution zones to assess the significance of overall r.m.s. measures. Vibration dose values will normally be compared with the vibration dose value caution zone. It is not clear how MTVV values can be compared with either health guidance caution zone without yielding unlikely conclusions.*

There is no equivalent zone for MTVV.

Criteria in frequency domain are articulated in relation to measured effective accelerations (r.m.s.). Three different levels of human discomfort are proposed:

- □ the reduced comfort boundary is applied to the threshold at which activities such as eating, reading or writing are disturbed
- □ the fatigue decreased proficiency boundary is implemented to the vibration level that causes fatigue to working personnel. The fatigue reduces efficiency at work. The decrease of ecciciency occurs at about three times reduced comfort boundary.
- □ the exposure limit defines the maximum tolerable vibration with respect to health and safety. It is at about six times the reduced comfort boundary.

Figure 4 shows the flow chart the measurement, evaluation and assessment method defined in ISO 2631. The flow chart remarks the complex procedure for International Standard ISO 2631.

10 Conclusions

The International Standard ISO 2631 proposes methods to analyze the complex reality of human responses to whole–body vibration. A series of frequency weightings are defined in the International Standard ISO 2631. It is used to quantify horizontal and vertical vibration with respect to its effects on activities. Weighted values of r.m.s. acceleration in the x– y– and z–axes determined with respect to the fatigue–decreased proficiency limits in ISO 2631. The analysis is restricted to quantifying vibration between 1 and 80 Hz. Some aspects of International Standard ISO 2631 are not satisfactory.

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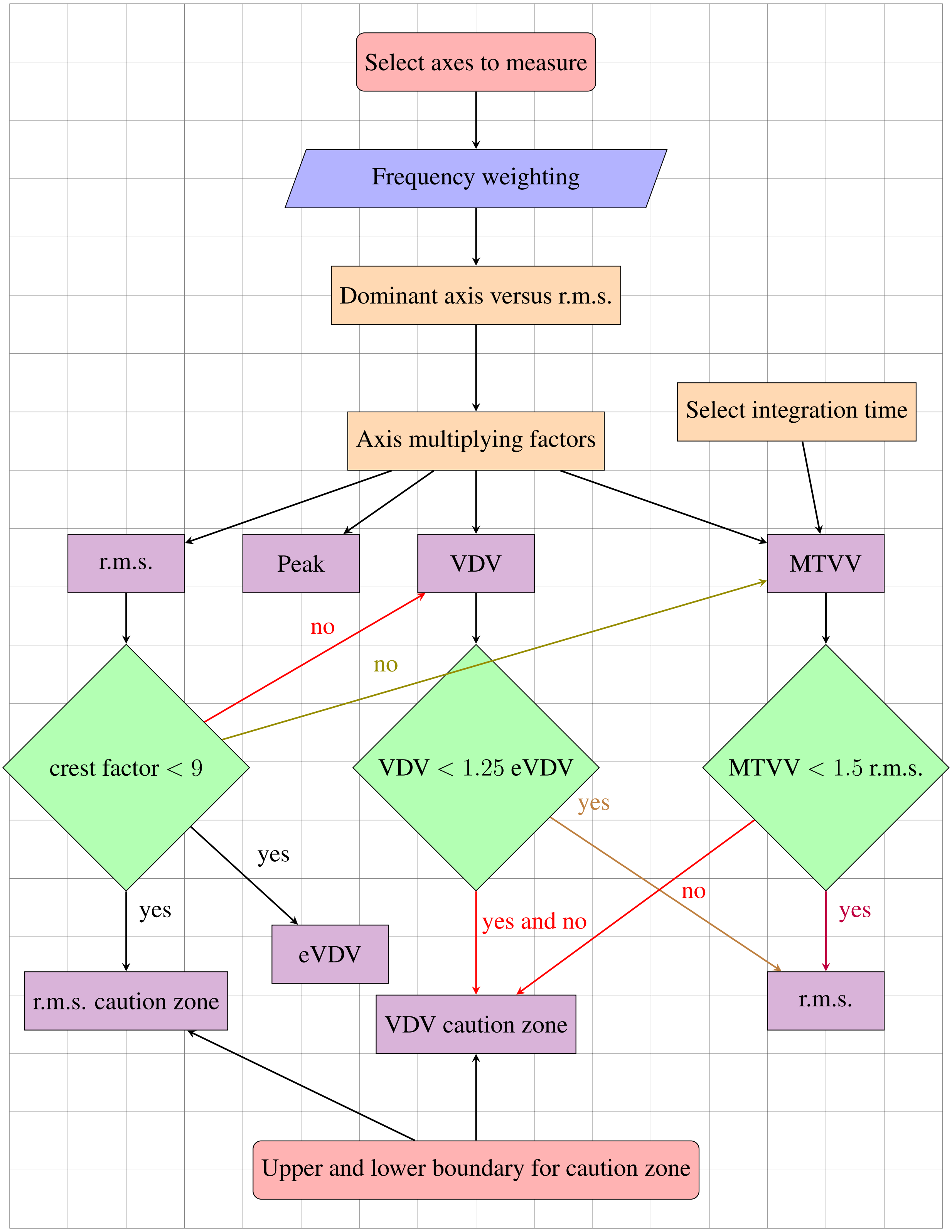

Figure 4: Methods of evaluation and assessment defined in ISO 2631