How many indicators for vibration exposure are needed?

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Summary
From the overviews of studies on the effects on vibration it seems that almost every researcher uses its own method to assess the vibration exposure. This makes it very difficult to compare results or use the outcomes in different settings. As it does not seem that one indicator is clearly to be preferred over any other, some way to select a harmonised indicator is needed.
When discussing the harmonisation of vibration indicators, a set of criteria is required to able to select from the likely candidates. The criteria for indicators depend not only on scientific validity, but also on how that indicator will be used in practice and applied in the legislation. In the paper the criteria will be discussed as well as how well present indicators meet the criteria. And is there a chance that one best indicator can be found?.

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1. Introduction

From the overviews of studies on the effects on vibration it seems that almost every researcher uses its own method to assess the vibration exposure. This makes it very difficult to compare results or use the outcomes in different settings. As it does not seem that one indicator is clearly to be preferred over any other, some way to select a harmonised indicator is needed.
When discussing the harmonisation of vibration indicators, a set of criteria is required to able to select from the likely candidates. The criteria for indicators depend not only on scientific validity, but also on how that indicator will be used in practice and applied in the legislation. The following set of criteria was formulated by the Dutch Health Council [1] and the European Commission[2]:
- validity: relationship with effects.
What effects have be to taken into consideration is largely a political question. In most European countries noise regulations are mainly aimed at the avoidance of considerable annoyance, complaints and disturbance, as well as health effects. A large number of possible effects can be derived from the scientific literature. However, a quantitative relationship has been established for just a few of these: i.e. speech interference, annoyance, sleep disturbance (to some extent: for sleep related annoyance a relationship could be established, but the relationship with physical factors, like waking up, is still open to debate), and the risk of an increase in cardiac disease (weak).

- practical applicability:
ease of calculation from available data, or measurement using available equipment. Most importantly, it must offer the authorities a reliable basis on which to make decisions about noise reduction measures.

- transparency:
easy to explain, intuitive, as simple as possible, relationship with physical units, small number of indicators - preferably one.

- enforceability:
use of indicator in assessing changes or when set limits are exceeded. One example is the use of a long term average: if the indicator is based on a year mean, a different approach is needed to demonstrate that a set limit has been exceeded than where an instant maximum level is used which may never be exceeded.

- consistency:
as little difference as possible with current practice. In view of the widespread use of indicators, it is should be recommended to switch to indicators which belong to a totally different class only if they can be demonstrated to have significant advantages over existing ones.

2. How to make an indicator

The quest for a single, simple indicator is complicated by the fact that the criteria which are seen to be the most important can lead to different, even opposed, conclusions. From the point of view of transparency, the simplest indicator for vibration would be the non-weighted linear averaged acceleration. But this would be inconsistent with the criteria consistency and practical applicability, while the validity may be hard to prove. Furthermore, the relative importance given to each may differ for different end users.

This approach was carried out by the European Commission [2] to select the Lden and Lnight harmonised noise indicators, but for vibrations this has not be done yet. Passchier-Vermeer [3, 4, 5] made an attempt to select the best indicator for annoyance, but did not look at the other criteria.

The first step in selecting an indicator is to draw up sets of possible indicator variants. The variants can then be given a score, after which a ranking can be made.

The first criteria asks that the indicator is a valid predictor for effects. In the public health area critical effects from vibration are annoyance and sleep disturbance. There is not much evidence for other effects like blood pressure and cardiovascular effects. Instantaneous effects may be important if acute damage can be expected (like hearing damage for noise), but for vibrations no such acute damage on humans exists. Damage on property may very well occur of course, but a separate indicator and limit value will be needed for that anyway.
It is not easy to assess for vibrations the indicator that is best associated with effects, because the data base is limited and high correlations are found between possible indicators. In the RIVAS [6] and CARGOVIBES [7] recommendations are given which are mainly based on the existing methods and standards, but the question of how an indicator of vibration should ideally look like is not raised.
Based on the theoretical model developed by Miedema[8], the elements that compose an indicator can be defined and studied. The basis of this model is the hierarchical power sum, which is obtained by the repeated application of the power sum rule:

$$B=[\sum k\ (b_k x_k)^a]^{1/a} \qquad (1)$$

This model has been the basis for the choice of the Lden [1].
In Passchier-Vermeer [3] this model is applied to vibration measurements and vibration nuisance. A separate step to consider is the weighting over directions. The next discussion is based on [3], but with variations and extensions by the author.
This 5 steps can be distinguished:
1. Frequency Weighting./Direction weighting
2. Weighting within an event. Most vibration indicators use a the maximum, but a time-weighted step is more logical.
3. Weighting of events over a period.
4. Weighting of periods over a day. It is logical to assume that vibrations are annoying in the evening and (more) at night. The weighting factors of 5 and 10 are for vibration difficult to prove, as a default, but can be adopted.
5. Weighting over a year. In noise research a (small) weekly and seasonal variations can be demonstrated. Although there is evidence of a higher weighting factor for the weekends and the summer the evidence for this is still meager.

Ad 1. Frequency and direction Weighting.
All measurements are taken into account. Vibration is based on the vibration intensity in a particular direction as the quantification by frequency-time combination. For vibration the equivalent of the A-weighting is either the DIN or the ISO 2631-2 weighing curve. This is calculated as follows:

$$IF=[\sum_j (F_j I_j)^2]^{1/2} \qquad (2)$$

where I_j are the vibration intensities at a given time and F_j are the frequency weights for a specific direction. In formula (2) the frequency weights are according to ISO 2613.
Also the direction is outside the time domain, there is no objection to apply the power sum also to these values. There is no principal reason to do this before or after the other weightings. The current practice is to establish the highest value

per direction and then proceed with the other steps. ISO 2631 formally defines an rms weighted sum for multi-axes accelerations:

$a=(1{,}4a_x^2 + 1{,}4a_y^2 + a_z^2)^{1/2}$

ad 2. weighting in an event.
Of the possible quantifications of vibration events per single axle there are 3 different options specified: the maximum per direction of vibration [a], the root-mean-square [b], and the 4th square root of the fourth powers of the intensities [c].
Let IF (t) indicate the intensity value at time t in a certain direction.

$$IF_{max} = \max\{T, IF(t)\} \qquad [3a]$$

$$IF_X = [\sum t\ [IF(t)]^2]^{1/2} \qquad [3b]$$

$$IF_Q = [\sum t\ [IF(t)]^4]^{1/4} \qquad [3c]$$

ad 3. weighting in a period.
The combination of the IF values into values per period, step 3, is done in an analogous manner, as follows:

$$IP_{eff} = [\sum i\ 1/n[IF_{max}(i)]^2]^{1/2} \qquad [3a,a]$$

$$IP = [\sum i\ [IF_{max}(i)]^2]^{1/2} \qquad [3a,b]$$

$$IF_{XX} = [\sum i\ [IF_X(i)]^2]^{1/2} \qquad [3b,b]$$

$$IF_{QQ} = [\sum i\ [IF_Q(i)]^4]^{1/4} \qquad [3c,c]$$

[a,b] means that first a max-value is determined, and these max values are then RMS-combined, etc.
ad 4. weighting of periods to obtain a long term (eg year) average
Analogous, the day, evening, night or 24 hr periods can be combined. This is not often made explicit, and the same weightings are used as for the periods. Sometimes the duration of the time over which the indicator must be assessed is left to the operator.

ad 5. Weightings for day, evening and night.
If day evening and night were kept separated, they may now be combined in an overall value. The current vibration indicators make no distinction in for the evening. The values indicated in Table 1 are derived from the different limit values for day and evening. Actually the values are not combined.

The different vibration indicators now in use are summarized in table 1. The last column gives the corresponding values for Lden for comparison

Table 1. Weightings for vibration indicators

	ISO	BS	DIN/SBR	Lden
1.frequency	a=1 b=ISO	a=1 b=ISO	a=1 b=DIN	a=1 b=ISO
1b direction	a=2	a->∞	a->∞	NA
2. Event	a=2 b=1	a=4 b=1	a->∞ (Vmax) a=2 (Vper) b=1	a=1 b=1
3. Within daily period	a=2 b=1	a=4 b=1	a->∞ (Vmax) a=2 (Vper) b=1	a=1 b=1
4. Within a year	a->∞ b=1	a->∞ b=1	a->∞ b=1	a=1 b=1
5. Day/evening/night	a=1 NA	a=1 b=1;NA;2	a=1 b=1;NA; 1.5	a=1 b=1; 3.16; 10

Now in principal for each effect the best fitting set of parameters can be found by analysing available data. For vibration annoyance there is not much empirical evidence to support (or contradict) the values in table 1. For noise there is more evidence. Thus the important steps 3 (the trade-off factor) and 5 (evening and night penalty) were examined by (Miedema, 2000)[9]. For vibration Howarth and Griffin[concluded on the base of a very limited laboratory experiment that annoyance is associated with ~ the fourth power of the number of trains and that a second power is worse. This was not supported by the CARGOVIBES[6] study in which the VDV did not show any advantage over Vmax or RMS

For regulation this relationship is of great importance, given the role of the standstill principle. The trade-off factors of RMS (power 2) and of the VDV (power 4) lead to relative increases of the values which are very different. If the number of trains increases from 2 per day to 100 per day, the RMS increases by 700%, the VDV by 260%. This means that over a wide range of events a substantial change in number of trains is not reflected well in the indicator.

Although the uncertainties are large, from noise research it appears that very different weighting factors away from the equivalent indicators leads to poorer correlations between indicator and effect. A good example is the study of aviation noise in Frankfurt [11].

Because the correlations between related indicators are high, it is to be not expected that an analysis of the data quickly produces a "best" indicator, given the relatively limited data for vibration and in general the weak correlations between exposure and effects.

3. Recommendations for vibration indicators

On the basis of general principles and available knowledge, the range of possible indicators could already be limited.
From the theoretical point of view, the most used standards come close to the desired structure, but fail at some point or another (table 1). The RMS used by CARGOVIBES to explore the relation with annoyance is "well-behaved", but has no weights for evening and night. To make the indicator more future resistant it would perhaps be better to separate the RMS in a day/evening/night part. For the moment they can then be combined in a RMS24hr without weights or experimentally the weights could be used as can be derived from [12]. From that information it looks like the b-weights would be 10 for the evening and 50 for the night time. Rather more than the weights in Lden, but there are indications that the effect for vibrations at night is more pronounced[7]. A further advantage is an RMS-night is available for use in - much wanted - studies into the relation between sleep and vibration.
Howarth and Griffin [10] propose an integrated noise/vibration indicator on the basis of laboratory tests. The general form is:
$A= \alpha L +\beta V + \gamma$
Where A is the annoyance, L is the noise level and V is vibration level. This expresses nicely that annoyance is caused by as well noise as vibration.

Such a relationship would of course be very useful. In this way it can be avoided for example that measures against (small) vibrations are taken in noisy situations where the noise is dominant. It opens also the possibility to simply extend noise regulations with a correction for vibrations.

4. Conclusions

The vibration standards and methods currently in use were born from a focus on complaints and avoiding physical damage. While that is still important, the focus is now shifting to public health issue, much like the noise focus shifted from hearing damage to public health. With this in mind the main indicators currently in use were analysed from a theoretical and practical point of view. It was found that although recent proposals to improve the indicators are a major step in the right direction, refinements may make the proposed indicator more future resistant.
The answer to the question appears to be 2.

5. References

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