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# Examining the use of eVDVs for rail vibration in NSW

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**ABSTRACT**
In NSW, vibrations from train passbys that result in human comfort concerns are assessed in terms of Vibration Dose Values (VDVs). Measuring VDVs requires the use of instrumentation that can either measure VDVs directly or record waveforms that enable VDVs to be calculated through post-processing. However, when rail vibration is measured within buildings, ground-borne noise is often of primary concern with human comfort vibration relegated to being a secondary concern or an afterthought. Ground-borne noise is often measured in terms of one-third octave band vibration spectra and VDVs or waveforms are not recorded in many cases; in these instances, VDVs can only be calculated using the eVDV method detailed within BS 6472. It is not clear how much error/conservatism may be introduced with this approach with respect to rail vibration. This paper compares the estimated VDVs (eVDVs) calculated from one-third octave band acceleration spectra, from total root-mean-square (RMS) acceleration and from Peak Particle Velocities (PPVs) with the VDVs calculated from velocity waveforms recorded on the same device simultaneously. The comparison considers results collected from two locations in the Sydney metropolitan rail network. Different methods for calculating eVDVs are examined as well as the influence of different weighting functions.

## 1 INTRODUCTION

In NSW, vibration for human comfort from train passbys is assessed in accordance with the NSW Department of Environment and Conservation guideline "Assessing Vibration: a Technical Guideline" (abbreviated as AVaTG in this paper, DEC2006). This Guideline is based on British Standard 6472:1992 Evaluation of human exposure to vibration in buildings (1 Hz to 80 Hz) and classifies railway trains of intermittent type which should be assessed in terms of Vibration Dose Values (VDVs).

The British Standard 6472:1992 was superseded in 2008 with BS 6472-1:2008 and the 1992 version of the Standard was withdrawn. The new Standard contains some significant differences to the older 1992 version, including a change of the vertical frequency weighting function (Allan et al, 2010). AVaTG has not been updated to reflect the changes associated with the revision of BS 6472 and still states that it "*can be considered as interim until the revision* [of BS 6472] *is published*".

## 2 VDVs and eVDVs

The VDV of a transient signal can be calculated as the fourth root of the time integral of the fourth power of the frequency weighted acceleration (Eq. (1)). In Eq. (1), $a_w$ is the frequency weighted acceleration and $T$ is the duration over which the VDV is calculated.

$$\mathrm{VDV} = \sqrt[4]{\int_0^T {a_w}^4(t)dt} \tag{1}$$

VDVs are cumulative and only increase with increasing exposure duration. In this paper, VDVs are calculated using both $W_g$ weighting functions endorsed in AVaTG (and the superseded BS 6472:1992) and $W_b$ weighting functions endorsed in BS 6472:2008. The weighting functions are defined in BS 6841:1987 "Guide to measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock".

The precise mathematical evaluation of VDVs requires knowledge of the actual acceleration signal, sampled at sufficiently high frequencies with appropriate bandpass filters. In cases where vibration was recorded in terms of velocities or displacements, differentiation and double-differentiation need to be applied, respectively, to obtain accelerations.

Often, continuous vibration signals are not recorded and data is saved in a condensed format due to limitations of the hardware or simply to limit the data size. In this case, VDVs can be estimated and such quantities are referred to as eVDVs which stands for "estimated Vibration Dose Value".

AVaTG provides guidance on how to estimate VDVs based on either weighted RMS acceleration levels or RMS velocity levels. The relationship for RMS acceleration is shown in Eq. (2), where $a_{w,RMS}$ is the weighted RMS acceleration, $k$ is nominally 1.4 for crest factors below 6 and $t$ is the cumulative time (over which the weighted RMS acceleration was calculated).

$$\mathrm{eVDV} = k \times a_{w,RMS} \times t^{0.25} \quad (2)$$

AVaTG also provides an equation that utilises unweighted velocities which is shown in Eq. (3), where the RMS velocity ($v_{RMS}$) is in units of mm/s. The scaling factor $k$=0.07 is consistent with $W_g$-weighting of accelerations. This paper also explores $W_b$-weighting and for that purpose the scaling factor was doubled ($k$=0.14) which reasonably approximates the $W_b/W_g$ ratio at frequencies greater than 20 Hz.

$$\mathrm{eVDV} = k \times v_{RMS} \times t^{0.25} \quad (3)$$

Inherent to Eqs. (2) and (3) are a number of assumptions and simplifications and one goal of this paper is to investigate the difference of VDVs and eVDVs for the case of rail vibration. It is not clear how the '$k$' factor of 1.4 has been derived as BS 6472 (both the 1992 and 2008 versions) only notes that this "*has been determined empirically from typical vibration environments having low crest factors*". However, supporting data has not been found in the literature within the Bibliography of BS 6472 that was available to the Authors. The '$k$' factor of 1.4 was found to be suitable for rail vibration and had a standard error of 0.1 in another trial (Greer et al 2005), so it is therefore expected that the eVDVs will be representative of the VDVs, however this does not appear to have been validated for trains in NSW.

## 3 PRACTICAL MEASUREMENT OF VDVs and eVDVs

Only a small minority of vibration loggers or sound level meters allow for measuring VDVs directly. More often, acceleration or velocity traces are continuously recorded and VDVs are subsequently calculated. The latter option is considered the most versatile approach and more readily allows for extraneous data to be reviewed and filtered accordingly.

The assessment of vibration and noise from surface trains usually is driven by the effects of airborne noise, while tactile vibration and the effects of ground-borne noise (also referred to as 'structure-borne noise' or 'regenerated noise' describing vibrations travelling from the trackbed through the ground and into a building structure where they are re-radiated as noise) are of less immediate concern. On underground railways where the effects of airborne noise are negligible, it is often found that compliance with ground-borne noise criteria are more difficult to achieve than compliance with tactile vibration criteria.

Therefore in practice, VDVs are generally not the main measurement metric of interest and the type of logger is determined based on other considerations such as ground-borne noise. The Authors have also found that loggers designed to measure PPVs to enable comparison to structural damage criteria (such as those contained within BS 7385 or DIN 4150) are also used in practice to determine eVDVs; such loggers are commonplace and are used either as an afterthought to satisfy the assessment of tactile vibration or to address concerns in relation to damage.

In these scenarios, eVDVs may be calculated depending on the type of metric saved by the deployed instrument. For example, many sound level meters allow for saving vibration spectra at one second intervals, while monitors for structural damage save PPVs at regular intervals. Where it is necessary to calculate eVDVs, the accuracy of the estimates will depend on the measurement metric saved.

## 4 MEASUREMENTS

Measurements have been undertaken at two locations in the Sydney metropolitan area in buildings above rail tunnels. The primary objective of the monitoring was to quantify ground-borne noise levels. A Brüel & Kjær 2270 was used in two-channel configuration measuring both noise and vibration. A Brüel & Kjær 4370 accelerometer was connected to the sound level meter via a Brüel & Kjær 2635 charge amplifier which integrated acceleration to velocity, incorporating a band-pass filter between 1 Hz and 3 kHz. One second one-third octave band velocity spectra were saved as well as continuous wave files which were recorded at a sampling frequency of 8 kHz with anti-aliasing filters providing useable data up to 3.3 kHz. Measurements were undertaken for a period of approximately 48 hours and more than 400 passenger train passbys were captured at each site.

## 5 POST-PROCESSING

In the first post processing step, individual trains were identified and the data was saved in individual files. Only trains on the closest track (including double passbys) were considered in the analysis of each site. The start and stop times were the 10 dB down points relative to the maximum slow spectrum ($L_{ZSmax}$). The use of 10 dB down points for demarking the passby duration is recommended in Greer et al., 2005.
For each train passby the following metrics were calculated:

- VDVs: The measured raw velocity was integrated to acceleration which was then $W_b$- and $W_g$-weighted. VDVs were subsequently integrated as per Eq. (1).
- $eVDV^{a,1s}$: All slow (or 1 s) $L_{ZSmax}$ velocity spectra falling within the start and end time of a passby were converted to acceleration spectra through multiplication of the one-third octave band centre frequencies. The acceleration spectra were then $W_b$- and $W_g$-weighted. The fourth powers of the one second $eVDV^a$ were then summed and the quad-root was taken of this sum.
- $eVDV^{a,RMS}$: The RMS values of the $W_b$- and $W_g$-weighted acceleration of the whole passby were calculated based on the one-third octave band velocity spectra. The eVDV was then evaluated using Eq. (2) with $t$ being the total duration of the passby.
- $eVDV^{v,RMS}$: The RMS velocity of the passby was estimated by division of the PPV by the crest factor. A crest factor of 5 has been used for all passbys (FTA, 2018). The eVDV was then computed using Eq. (3) with $t$ being the total duration of the passby.

A velocity spectra based metric $eVDV^{v,1s}$ was also investigated as part of the study and the results were found to be essentially identical to $eVDV^{a,1s}$. The negligible differences are due to the imperfect match of unweighted velocities and weighted accelerations integrated to velocities at low frequencies (less than 8 Hz and 16 Hz). Given the dominant frequencies at both sites were above 40 Hz, the differences between the $eVDV^{v,1s}$ and $eVDV^{a,1s}$ metrics were found to be, for practical reasons, inconsequential and only $eVDV^{a,1s}$ results are presented.

## 6 RESULTS

The average RMS overall velocities (up to 500 Hz) are 0.043 mm/s and 0.077 mm/s at Site 1 and Site 2, respectively. At Site 1 the dominant one-third octave bands are the 63 Hz and 80 Hz bands, while at Site 2 the dominant one-third octave bands are 40 Hz, 50 Hz and 63 Hz. The overall levels and spectra are fairly typical for the specifics of each site (ie the offset from the track, the type of fastener).

Histograms of the $W_b$- and $W_g$-weighted VDVs for Site 1 and Site 2 are presented in Figure 1. $W_b$-weighted VDVs are typically twice as high as $W_g$-weighted VDVs, consistent with the weighting curves and the dominant frequencies for train vibration. The spread of VDVs is approximately a factor of 2 between the train with the highest and lowest VDVs. For Site 1 the average $W_b$ and $W_g$-weighted VDVs are 0.009 $m/s^{1.75}$ and 0.004 $m/s^{1.75}$, respectively. For Site 2 the average $W_b$- and $W_g$-weighted VDVs are 0.02 $m/s^{1.75}$ and 0.01 $m/s^{1.75}$, respectively. The standard deviation at Site 1 is 1/6 of the mean while on Site 2 it is 1/10 of the mean (independent of the frequency weighting).

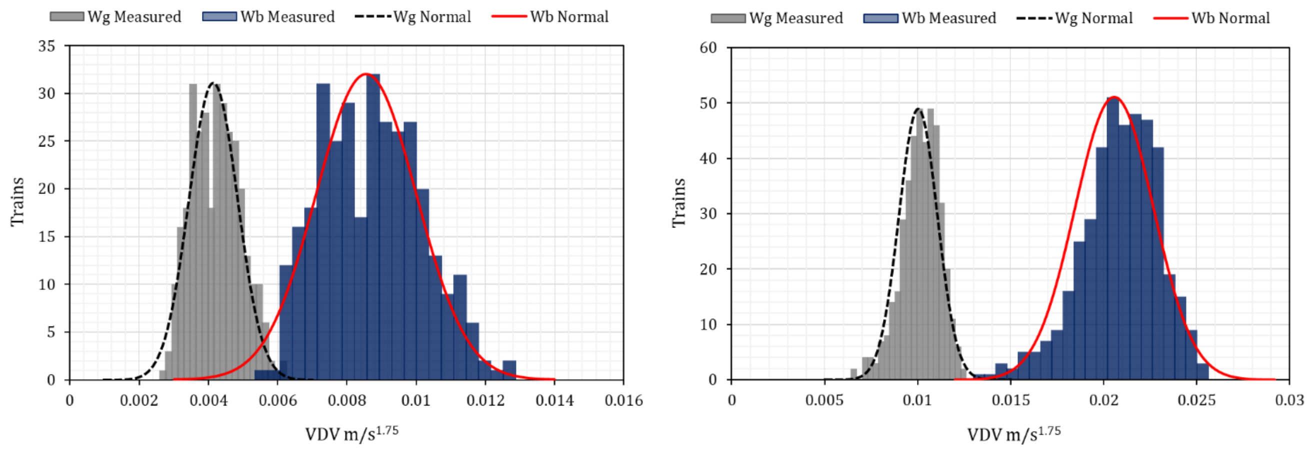


Figure 1: Wg-weighted (grey) and Wb-weighted (blue) VDVs for Site 1 (left) and Site 2 (right).

### 6.1 eVDVs v VDVs

In Figure 2 and Figure 3 the considered eVDV metrics are plotted against the exact VDVs. The eVDVs of points falling on the solid black lines equal the exact VDV. The dashed lines demark the ±10% and ±20% zones; the eVDVs within this range are not expected to be noticeably different from the actual VDV, based on commentary provided in Willford et al (2006). The observations made for both sites are very consistent and can be summarised as follows:

- The $eVDV^{v,RMS}$ metric exhibits the largest variance. It tends to overpredict based on $W_g$-weighting and underpredict on $W_b$-weighting.
- The $eVDV^{a,1s}$ values are greater than $eVDV^{a,RMS}$ values. This, however, is dependent on the underlying duration over which the overall RMS acceleration is calculated and may therefore vary depending on measurement subject.
- For $W_g$-weighting the $eVDV^{a,1s}$ provides the best fit while for $W_b$-weighting the $eVDV^{a,RMS}$ provides the best fit.
- Both the $eVDV^{a,1s}$ and $eVDV^{a,RMS}$ metric generally fall within the ±10% zone.

The crest factors at both sites ranged from 3 to 8 with the majority of passbys having crest factors of perhaps 4. The eVDVs, when plotted against the actual crest factors, did not exhibit a noticeable correlation with the crest factors.

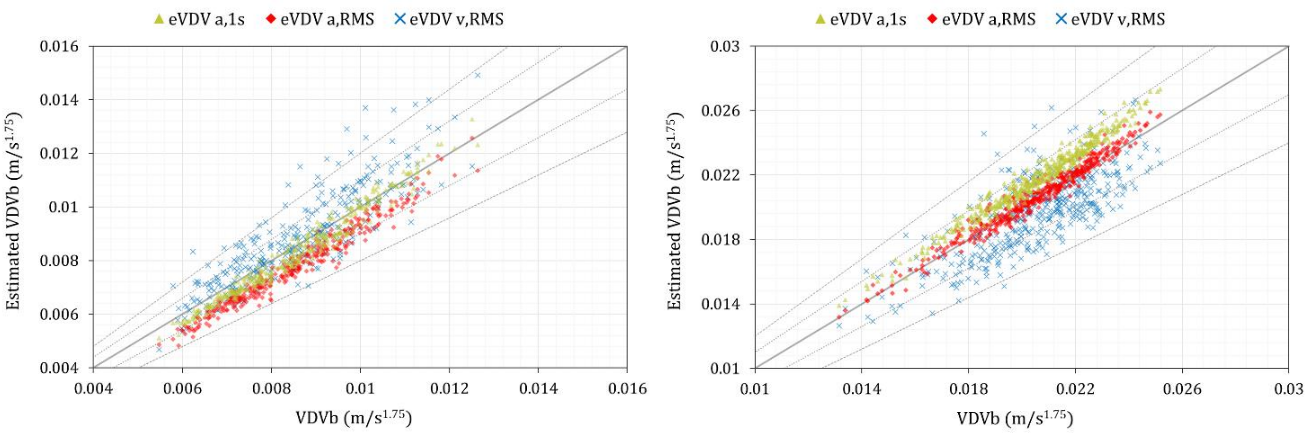


Figure 2: Site 1 – VDV vs eVDV Plots –Wg Weighting (left), Wb Weighting (right).

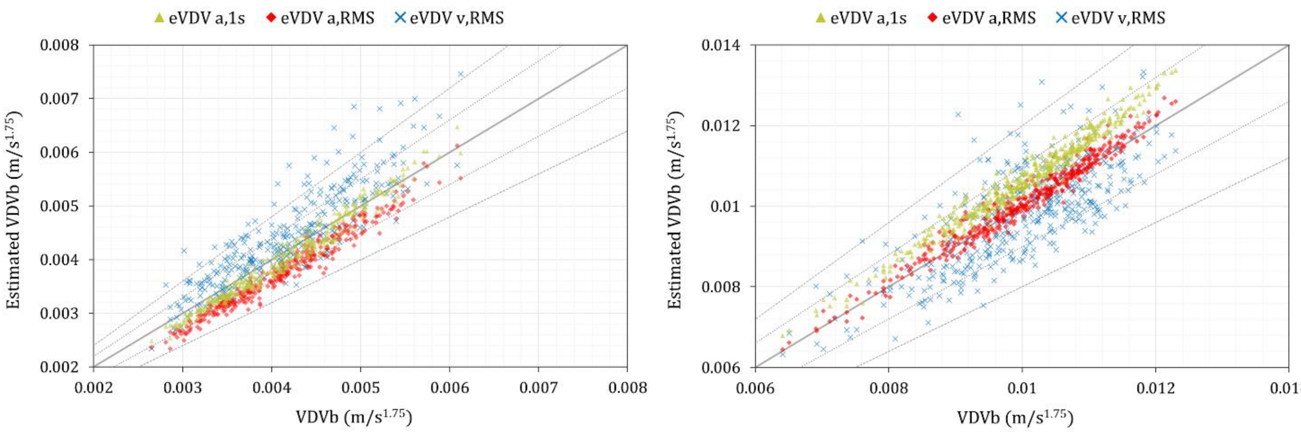


Figure 3: Site 2 – VDV vs eVDV Plots –Wg Weighting (left), Wb Weighting (right).

## 7 CONCLUSIONS

In this paper the relationship between VDVs and various mathematical implementations of eVDVs was studied. The study focused on train vibration and its conclusions apply to train vibration only, more specifically to Electrical Multiple Units used on underground tracks in metropolitan Sydney. The Authors plan to validate the use of eVDVs for freight and light rail as part of future studies. Two different eVDV metrics based on acceleration were studied; one using a series of spectra recorded at one second intervals and the other using the overall RMS acceleration of a passby defined by the 10 dB down points. Both eVDV metrics are generally within ±10% of the exact VDV. This is excellent agreement and shows that these acceleration based eVDVs are suitable for screening assessments or even more detailed assessments. The PPV based eVDV metric showed a larger variance than the considered acceleration based eVDVs. The chosen nominal crest factor of 5 resulted in good agreement, although the mismatches of more than 20% were regularly observed. The actual crest factors ranged from 3 to 8, which likely contributed to the scatter.

## REFERENCES

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