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# Comparison of maximum versus peak-hold train vibration spectra for ground-borne noise assessments


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## ABSTRACT

When ground-borne noise from trains cannot be measured directly, it can be estimated from train vibration spectra using appropriate adjustments. Representative train vibration spectra may be measured directly, modelled or derived from measurements elsewhere and adjusted to suit new conditions. The accuracy of train vibration spectra is an important 'stepping stone' towards obtaining accurate estimates of ground-borne noise. This paper investigates differences when analysing in-situ measurement data using peak-hold vibration spectra versus spectra when the unweighted or A-weighted overall vibration levels are a maximum. The potential differences on the outcomes of predicted ground-borne noise are studied based on four large data sets of train vibration measurements.


## 1 INTRODUCTION

The International Standard ISO 14837-1 Mechanical vibration – Ground-borne noise and vibration arising from rail systems states the following (where *r.m.s.* and *FFT* stand for root mean square and Fast Fourier Transformation, respectively):

> *Rail system vibration events are transient and time varying. There is no single definition of the frequency content for such signals. The form of frequency analysis used [(e.g. running r.m.s., FFT analysis, running r.m.s. with "max hold") can have a significant impact on the frequency spectra identified)]. The form of analysis should be carefully considered and recorded.*

As train vibration propagates from the trackbed to receivers, its characteristics are frequency and amplitude shifted due to geometric spreading, damping losses, coupling losses at interfaces and foundations and localised amplification effects at receivers (FTA 2018; ANC Guideline; ISO 14837; Nelson 1987; Dawn et al, 1979). Often, the existence of multiple propagation paths further divorces receiver vibration from trackbed vibration during a train passby. During the passage of a train there may also be a pronounced dependence of the frequency content on the position of the axles relative to the measurement location (Duschlbauer et al, 2008).

These effects, amongst others, introduce uncertainty in the prediction of ground-borne noise and it is not always clear which frequencies will be governing the assessment of ground-borne noise. This paper examines how different post-processing techniques of train passby vibration can impact on the assessment outcomes of ground-borne noise.

### 1.1 Peak-hold versus Maximum

In the context of environmental assessments during the design of new rail lines, it is often advisable to plan for conservative assessment outcomes. This is due to the degree of uncertainty typically involved in the prediction of ground-borne noise and because the retrofitting of mitigation can be relatively difficult and costly. It may therefore be appropriate to define source vibration levels in terms of peak-hold (or "max hold") one-third octave spectra which provides a conservative snapshot of a passby. A peak-hold one-third octave spectrum is the maximum level in each one-third octave band measured during a passby. Peak-hold spectra capture all transient peaks across the frequency range of interest, regardless of whether they are time coincident.

Contrary to peak-hold spectra, the use of maximum spectra may also be considered. A maximum spectrum is a one-third octave spectrum at a defined time during a train passby. Preferably, for the assessment of ground-borne noise, the definition of that time results in the highest predicted levels of ground-borne noise at a receiver.

In this study, two different maximum spectra are considered:

- When the overall unweighted slow response vibration velocity is at its maximum during a passby.
- When the overall A-weighted slow response vibration velocity is at its maximum during a passby.

This paper investigates the potential degree of conservatism associated with the use of peak-hold one-third octave spectra versus one-third octave spectra when either of the two definitions listed above are used.

The use of unweighted maximum or A-weighted maximum spectra are only two possible snapshots in terms of frequency weighting as the addition of track to receiver transfer functions (such as floor amplification, coupling losses, geometric attenuation, damping, etc, refer to FTA, 2018; ANC Guideline; ISO 14837; Nelson 1987; Dawn et al, 1979) change the relative contribution of each one-third octave band to the overall ground-borne noise levels at a receiver.

## 2 POST PROCESSING

All train passby vibration spectra presented in this paper are ‘slow response’ spectra (ie integration time of 1 second). The use of slow response, one-third octave spectra coincides with the preferred metric for the assessment of ground-borne noise in Australia (eg EPA 2013; Duschlbauer et al, 2024). The qualifying terms ‘one-third octave’ and ‘slow response’ are omitted going forward as all spectra presented and discussed are slow response one-third octave spectra. All vibration velocities are presented in units of decibels relative to a reference level of 1 nm/s.

### 2.1 Datasets

Train vibration data from four different sites are used for this study (refer to Duschlbauer et al, 2024, for supporting information). Table 1 provides a summary of the four sites. At each site, vibration acceleration in vertical direction was recorded (5 days at Site 1 and 24 hour periods at Sites 2, 3 and 4). At all sites individual train passbys were identified and saved in individual files for further analyses.

Table 1: Dataset overview

| Site | Train Type | Trackform | Dataset Size | Measurement Location |
|---|---|---|---|---|
| 1 | Freighters and XPTs | Ballasted track, concrete sleepers | 129 passbys | Surface, 15m from track |
| 2 | Metro | Direct fixation, stiff pads | 316 passbys | Tunnel invert |
| 3 | Heavy rail | Direct fixation, highly compliant pads | 164 passbys | Tunnel invert |
| 4 | Metro | Floating slab track | 316 passbys | Tunnel invert |

### 2.2 Analysis of an Individual Train

For each passby, the following calculation steps were undertaken:

- Bandpass filtering (third order Butterworth) the measured acceleration using corner frequencies of 8 Hz and 355 Hz.
- Calculation of unweighted velocities by integrating the acceleration to velocities in the time domain after application of a 5 Hz high pass filter and detrending of the bandpass filtered accelerations.
- Calculation of A-weighted velocities by A-weighting the unweighted velocities in the time domain.
- Calculating the overall time-weighted vibration level for the unweighted and A-weighted velocities using a 1 s exponential time constant or slow response.
- Calculation of slow response one-third octave spectra:
  - “Peak-hold” spectrum of the unweighted velocity trace, which is the highest level in each one-third octave band recorded during the passby. The peak-hold one-third octave levels have not necessarily registered at the same point in time.
  - “Unweighted maximum” is the unweighted spectrum at the time when the overall, slow response of the unweighted velocities is maximum.
  - “A-weighted maximum” is the unweighted spectrum at the time when the overall, slow response of the A-weighted velocities is maximum.

Time weighting and A-weighting was applied as per AS IEC 61672.1, 2019. Figure 1 presents an example train taken from the Site 2 dataset. In this particular case the maximum of the unweighted overall velocity occurs at 23.4 s, while the maximum of the A-weighted overall velocity occurs at 21.5 s.

The unweighted and A-weighted maximum velocity spectra are shown in red triangle down and salmon triangle up, respectively. The corresponding peak-hold velocity spectrum is presented in blue circles in Figure 1.

The unweighted maximum spectrum is 5 dB to 12 dB lower than the peak-hold spectrum at bands 40 Hz and lower. The A-weighted maximum spectrum is 5 dB to 12 dB lower than the peak-hold spectrum at bands 100 Hz and lower.

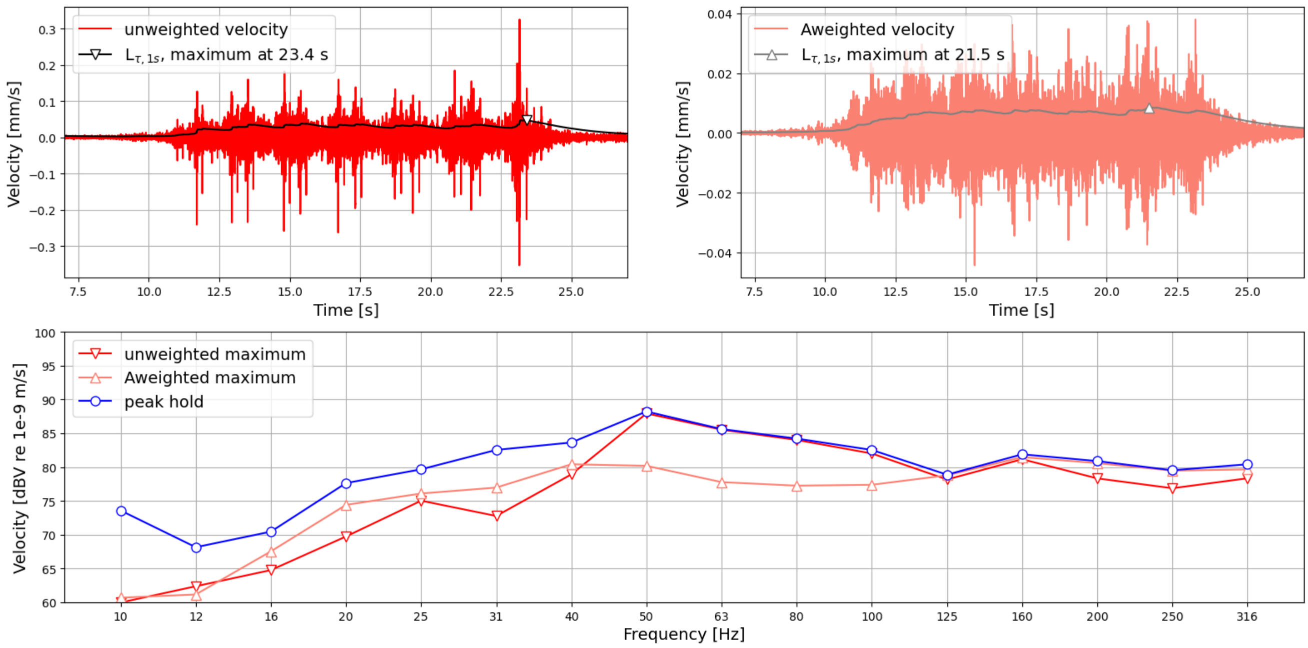


Figure 1: Example train measured at Site 2.

### 2.3 Statistical Analysis

Statistical 95th percentile results have been calculated to determine representative spectra for each dataset (peak-hold, unweighted maximum and A-weighted maximum). For this purpose, the decibel levels in each one-third octave band of all trains in each dataset are sorted and the 95th percentile band level is then selected. If the number of trains multiplied by the percentile (ie 0.95) is a non-integer, then this number is rounded up.

The differences between peak-hold and maximum spectra were also evaluated for each individual train and the linear average of the decibel differences for all trains in each dataset were calculated in each one-third octave band.

## 3 RESULTS

The statistical 95th percentile result spectra are presented in Figure 2 for all four sites. The 95th percentile of the peak-hold spectra are represented by blue circles and the 95th percentile of the A-weighted and unweighted maximum spectra are represented by salmon triangles up and red triangles down, respectively.

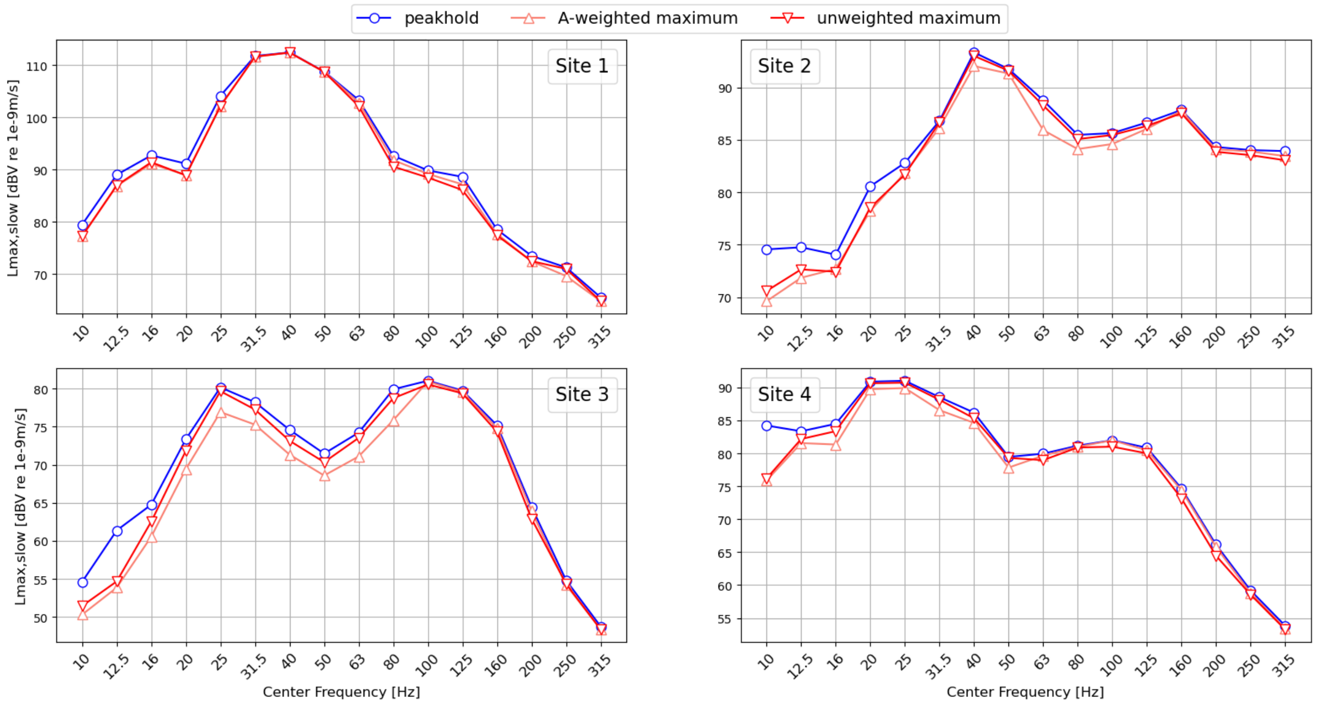


Figure 2: 95th percentile peak-hold (circles) and maximum (squares and diamond) $L_{max,slow}$ spectra.

For clearer visualisation, the difference between the peak and maximum spectra are shown in Figure 3 and Figure 4 for the unweighted maximum and A-weighted maximum, respectively. Figure 3 and Figure 4 show:

- The difference of the 95th percentile peak-hold and maximum spectra as red curves with triangle markers.
- The differences of individual train peak-hold and maximum spectra as grey curves.
- The difference of the linear average peak-hold and maximum spectra as black curves with square markers.

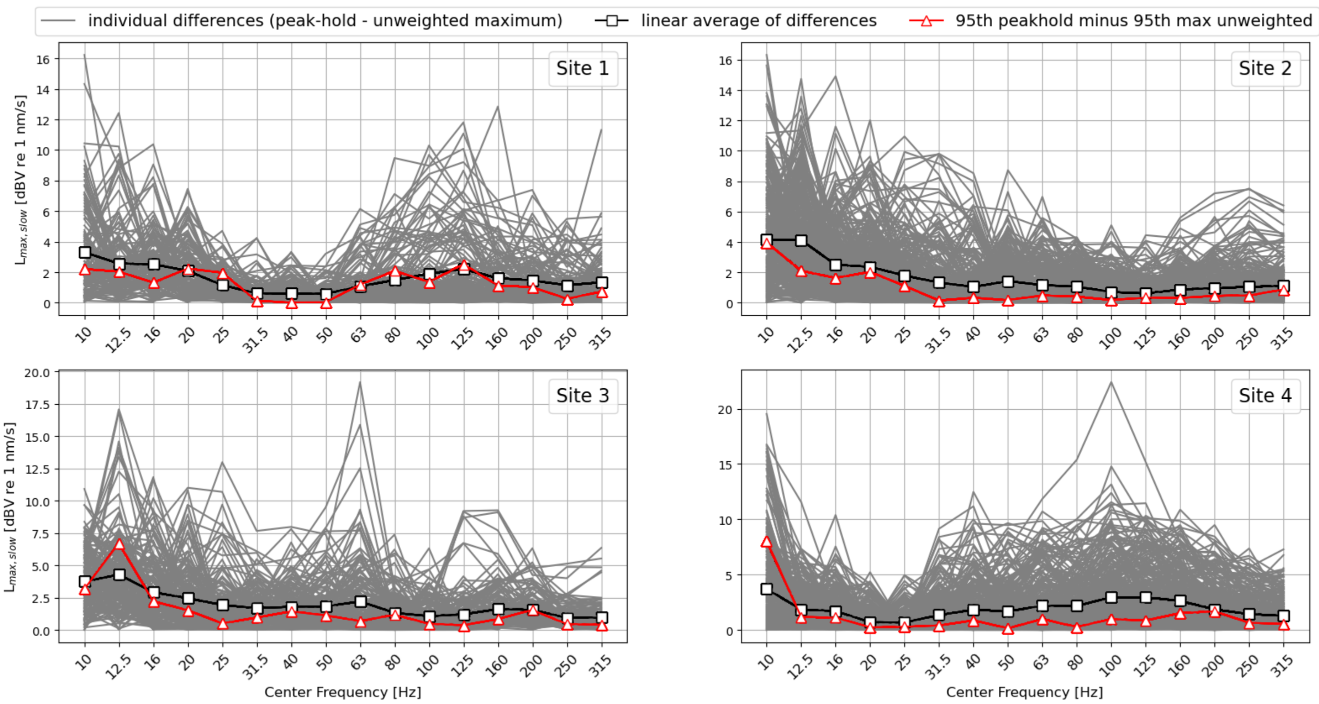


Figure 3: Result summary for peak-hold and unweighted spectra.

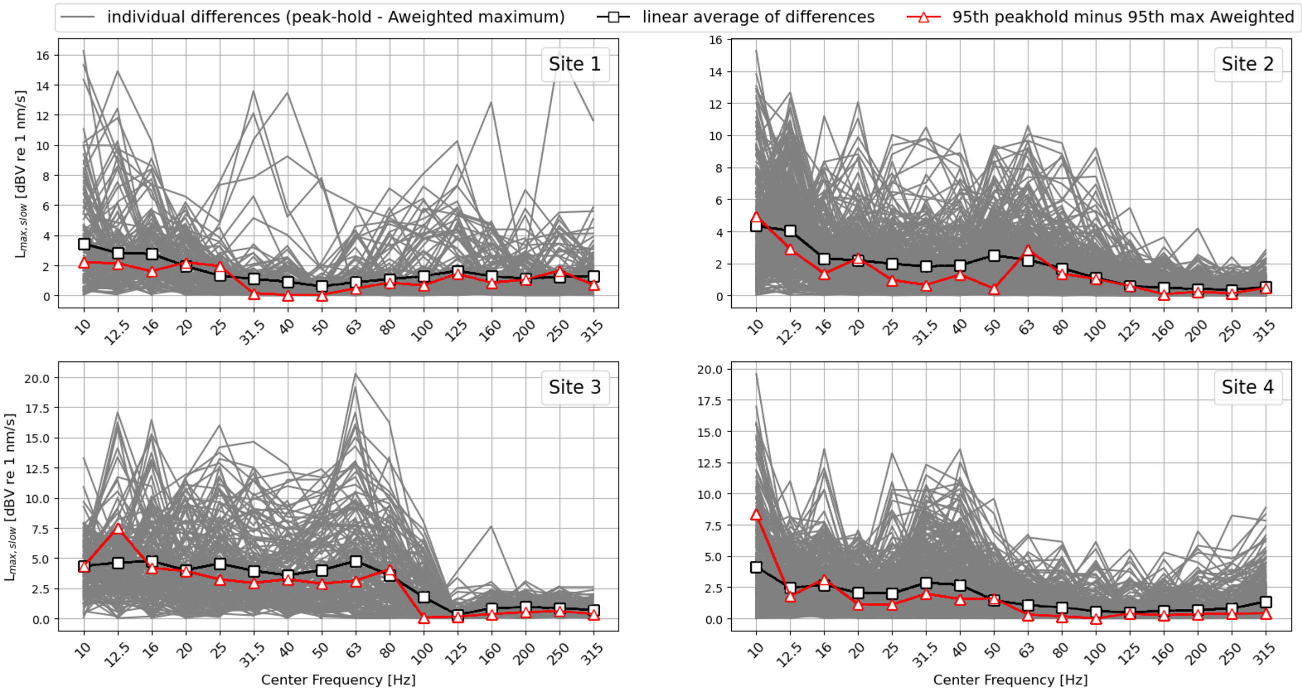


Figure 4: Result summary for peak-hold and A-weighted spectra.

The calculated results show:

- The four datasets exhibit varied characteristics in the difference between peak-hold and maximum spectra, particularly at low frequencies (red curves).
- The individual differences indicate numerous outliers at all four sites where the one-third octave band level difference of an individual train is greater than 10 dBV (grey curves).
- The linear average of the differences between peak-hold and maximum spectra are observed to be generally higher than the corresponding differences between the 95th percentile peak-hold and maximum spectra.

For a comparison of the effect of using maximum versus peak-hold measured train vibration spectra to determine the representative spectrum for a dataset, the use of relative difference in 95$^{th}$ percentile spectra is recommended. This is because the difference in 95$^{th}$ percentile levels is influenced by trains with high overall levels, while the linear average of individual train differences are influenced by trains with a high difference which may not necessarily have high absolute vibration levels. Further, 95$^{th}$ percentile levels correspond with the statistical evaluation metric commonly used for the evaluation of ground-borne noise. Considering frequencies at 20 Hz and higher, which are generally most relevant to ground-borne train noise, the peak-hold method results in one-third octave levels typically 0 to 3 dB higher than those based on the two considered maximum spectra.

## 4 CONCLUSIONS

The degree of conservatism associated with working with peak-hold one-third octave spectra rather than the two considered maximum spectra (evaluated when the unweighted and A-weighted overall vibration velocity levels are greatest) is frequency dependent. Considering one-third octave frequencies greater than 20 Hz, the differences in 95$^{th}$ percentile levels for the evaluated datasets are typically less than 3 dB.

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