Insights from long-term wayside monitoring of rail vibration

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ABSTRACT
Over a year's vibration data was collected from a monitor located adjacent to the rail corridor in Sydney. The results allow detailed analysis of long-term vibration trends by train type and track. The results also provide insight into the repeatability of short-term vibration monitoring, such as the common approach of attended measurements of around 20 trains.

1 INTRODUCTION

This report describes results and insights gained through analysis of almost a year of train vibration data collected at a location adjacent to the Sydney Trains network. Train vibration monitoring in New South Wales is commonly undertaken using attended measurements with simultaneous observation of train type, track, train speed etc. Since rail vibration criteria are often based on a 95th percentile vibration level, a minimum of 20 train passby events is typically collected to characterise the vibration levels at any particular location of interest. The dataset collected in this study is considerably larger, enabling examination of the repeatability of short-term vibration monitoring, and detailed analysis of long-term vibration trends by train type and track.

2 MONITORING DETAILS

In August of 2020, long-term vibration monitoring commenced at a location adjacent to railway tracks in Sydney. Various changes in track configuration in the area have occurred or are proposed to facilitate construction of a new metro rail project. The nearest track to the monitoring location (the Sydney Trains UP track, carrying trains towards Central Station) is within 10 m of the neighbouring residences. At the commencement of the monitoring in this study, the Sydney Trains DOWN track (trains travelling outbound from Central) was operating immediately adjacent to the UP track as shown in Figure 1. In March of 2021 DOWN traffic was relocated to the opposite side of the corridor from the residences, outside the future metro tracks. The monitoring location was approximately 8 m horizontally from the UP track centreline, with the transducer mounted on a noise barrier constructed at the top of a retaining wall, with the railway tracks below grade in a cutting.

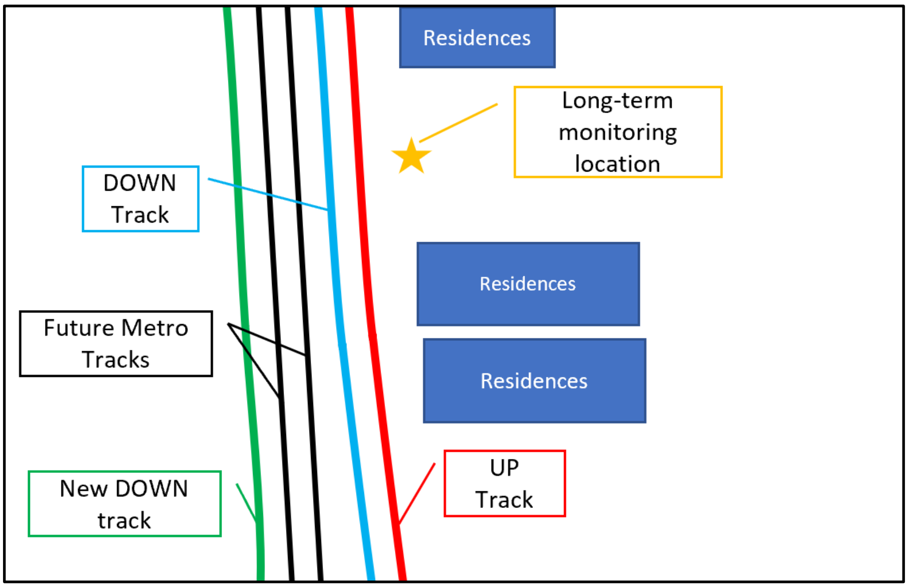

Figure 1: Monitoring location and track configuration. DOWN track relocated to new location in March 2021.

2.1 Equipment

The vibration monitoring equipment setup is shown in Figure 2, and consists of:

- A Convergence Instruments VSEW mk2 vibration logger (s/n ANtWJ90Q+Xc9ihtS76p5lD), magnet mounted to an angle bracket that is epoxied to the noise barrier. This sensor is secluded behind foliage and covered with cloth tape to help prevent vandalism and protect from the elements.
- An equipment case containing 2 x 38Ah lead acid batteries (replaced every 5 weeks), a 12V-5V DC-DC converter, and a Telstra 4G hotspot.

Figure 2: Monitoring equipment

The Convergence Instruments logger records vibration from each passing train in triggered mode at 1000Hz sample rate. Both vertical and lateral (perpendicular to the tracks) raw data are recorded. These two vibration axes were selected for long term monitoring after short-term measurements at the site indicated that vibration in both these axes are significant at this site, with lateral vibration along the axis of the track being considerably lower in magnitude.

2.2 Data processing

The raw vibration signals are uploaded to the cloud, and analysed using bespoke code written in Python. Results are then uploaded to a remotely accessible portal. The corresponding train ID is also extracted from the NSW Government live data feed (NSW Government, 2021) and this metadata is associated with the vibration results.

Some data cleaning was required prior to analysis of vibration trends. Since collection of vibration data is triggered based on vibration level, some vibration events are likely to have been triggered by sources other than trains. Events without an associated train and track identification have been excluded from the analysis to minimise the potential influence of vibration from other sources. In some cases, two or three vibration records were triggered and matched to the same individual train passby event. In this case, the single highest vibration record of the set was retained and assumed to be attributable to the corresponding train event, with additional triggered records discarded. In this way, multiple triggered records for the same train do not erroneously identify more train passby events than actually occurred.

3 OVERVIEW OF MEASURED VIBRATION

Figure 3 shows an overview of the vertical vibration data collected in the form of the slow response maximum vibration level (Lmax,S) during each identified train passby event, overlaid with the rolling 95th percentile vertical vibration level assessed over 1000 trains (representing approximately 5 days of traffic). The relocation of the Sydney Trains DOWN traffic to the western edge of the rail corridor (i.e. further from the vibration monitor) in March 2021 is clearly evident in the approximately 7dB reduction of vibration at the bottom end of the dataset. Note however, that the 95th percentile is not significantly impacted, indicating that this metric is controlled by the vibration from trains on the closer UP track. The three longest gaps in the data set are periods when data was not collected due to brief equipment outages. Shorter periods without train passby events can also be seen in the data, these correspond to periods of trackwork when no trains were operating.

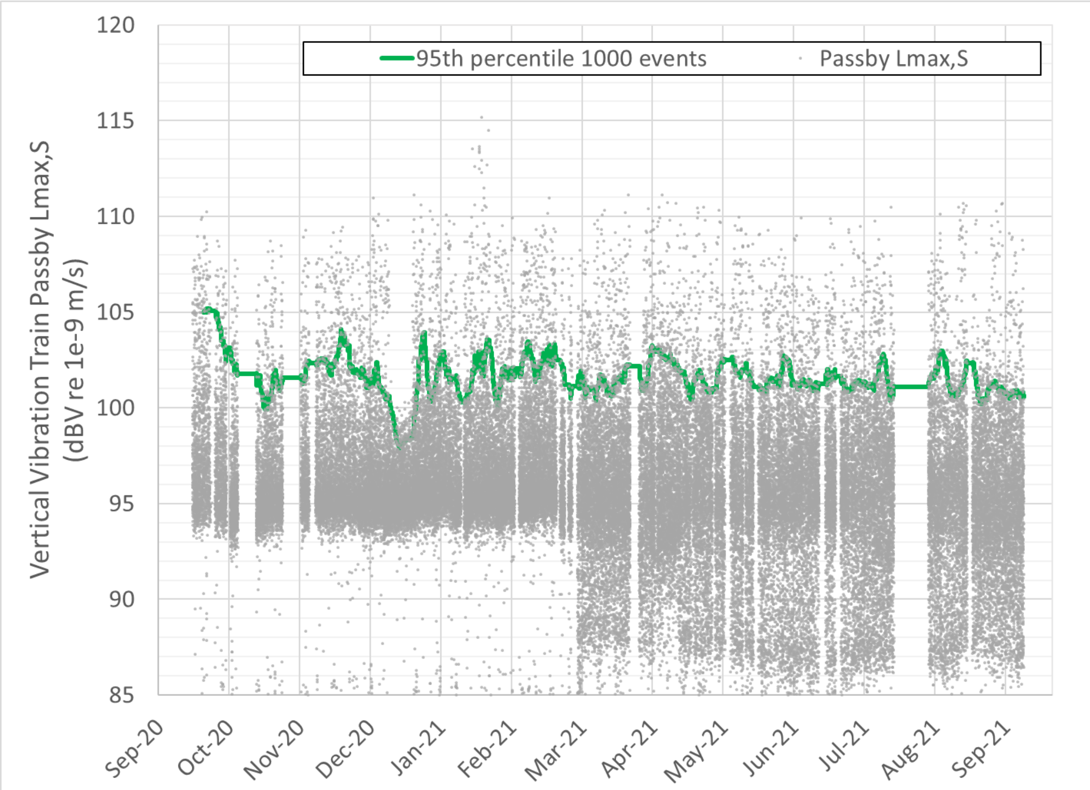

Figure 3: Vertical train passby vibration dataset with individual events and 95th percentile levels

The noticeable drop of about 5 dB in the 95th percentile vertical vibration level in early January corresponds to a period of trackwork elsewhere on the network from January 1st to 10th 2021. This required operation of a reduced timetable of shuttle services past the monitoring location, with shuttle services operated by Waratah trains exclusively. Observed differences in vibration between different train types are discussed in Section 4.

Another feature that is noteworthy in the overall dataset is that 95th percentile vibration level (assessed over 1000 events) was 3-4 dB higher at the commencement of monitoring than typically observed later in the year. These initially higher vibration levels have been linked to a period when increased numbers of train wheels were known to have rolling surface defects due to a maintenance issue.

Over the year considering the full dataset collected, the 95th percentile $L_{max,S}$ passby vibration level at the monitoring location was 101.6 dBV in the vertical direction and 110.9 dBV in the lateral direction.

4 OBSERVATIONS AND ANALYSIS

The data collected over the year has been reviewed to identify trends in vibration level over time, and differences in vibration level between tracks and train types. Train speeds have not been identified for specific events, however the designated track speeds are 75 km/h on the UP track and 70 km/h on the DOWN track (Railsafe, 2021). Sydney Trains services operate on average every three minutes during peak times, and approximately 250 trains a day travel past the monitoring location.

4.1 Summary of measured vibration levels for common train types

Table 1 summarises the arithmetic mean measured vibration levels across the three tracks, in both vertical and lateral directions and for the two most common train types operating on the Sydney Trains network, 8-car A-Set (Waratah trains) and T-Set (Tangara trains). The standard deviation of events for each category is also shown.

Table 1: Summary of measured train vibration levels

Track	Train type	No. Events	Vertical		Lateral	
			Mean Lmax,S dBV re 1e-9 m/s	Standard Deviation	Mean Lmax,S dBV re 1e-9 m/s	Standard Deviation
DOWN	A-set	14723	95.4	2.3	103.0	3.5
	T-set	2655	97.4	2.3	106.3	3.7
NEW DOWN	A-set	16213	91.8	3.8	97.0	4.8
	T-set	3907	94.4	2.6	99.9	3.8
UP	A-set	33129	96.5	2.4	103.4	3.7
	T-set	6034	101.4	3.8	109.8	5.3

As expected, vibration levels were typically highest from traffic on the nearest track to the vibration logger (the UP track), and lowest on the furthest track (the new DOWN track). The relocation of train traffic to the new DOWN track approximately 3 times further away from the vibration monitor resulted in a 6 dB reduction in average vibration levels from trains travelling northbound. Figure 4 summarises the data in terms of the vibration level mean and quartile distribution across the three tracks, excluding outliers.

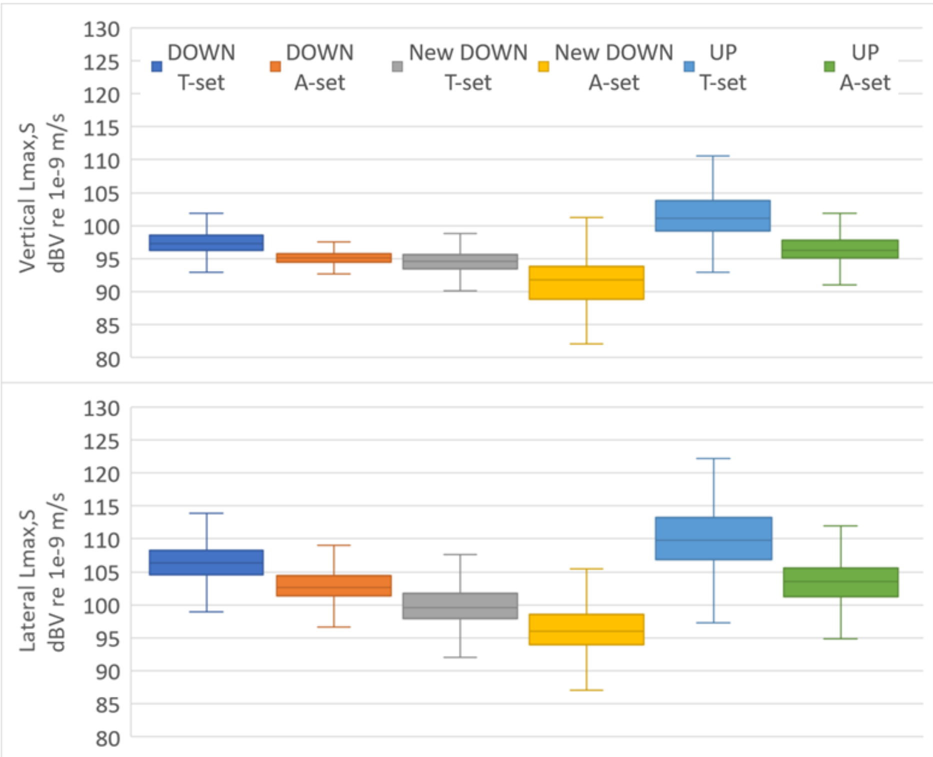

Figure 4: Vibration mean and quartile distribution by axis, track and train type. Outlier results not shown.

Lateral vibration levels measured perpendicular to the track at this location were typically greater than vertical vibration, by 5 dB to 9 dB on average as shown in Table 1. Although the fundamental excitation of the ground via the wheel/rail contact is in the vertical direction, the greatest energy transmission through the ground particularly extending over longer distances is usually due to Rayleigh wave propagation along the surface (Thompson, 2009). This involves a combination of shear and compressional wave effects resulting in a combination of vertical and horizontal motion. The geometry of the site, with the vibration logger mounted on the wall at the top of the cutting, is also likely to be a factor in the relatively high lateral vibration levels. The notably higher lateral vibration levels at this site emphasise that it is important not to disregard lateral vibration effects due to rail traffic when measuring and assessing vibration impacts.

As can be seen in both Figure 4 and Table 1, vibration levels generated by Tangara (T-set) trains were typically higher than vibration levels due to Waratah (A-set) trains. The difference was most notable on the UP track, nearest to the vibration monitor, with Tangara vertical vibration 5 dB higher on average than the Waratahs, and lateral vibration 6 dB higher. As noted in relation to Figure 3, an approximate 5 dB reduction in vertical 95th percentile vibration levels was also observed in a ten day period of reduced service with no Tangara trains operating.

The observation of higher Tangara vibration levels relative to Waratah trains could be due to fundamental design differences, or typically worse wheel condition for this train type, or a combination of these factors. Inherently higher vibration due to vehicle type could be due to design geometry / mass; material / metallurgical properties resulting in different wheel condition; or different maintenance practices linked to vehicle type, noting that the train types are maintained in different depots.

The standard deviation values (Table 1) do not indicate a clear trend of greater vibration variability for either train type, which might be expected if one type has more variability in wheel condition (a greater difference between the typical best and worst wheels). This suggests that the higher Tangara vibration levels are somehow inherent to the vehicle type or to maintenance practices specific to this vehicle type.

The European Union research project Railway Induced Vibration Abatement Solutions (RIVAS) investigated rolling stock factors that contribute to vibration (RIVAS Project, 2013). The project investigated design elements such as unsprung mass, suspension stiffness and axle spacing, and how these influence ground-borne vibration. The effects of wheel defects and out-of-round wheels were also quantified in relation to other vibration excitation mechanisms. The RIVAS vehicle studies (Nielsen et al, 2013) concluded that unsprung mass and wheel out-of-roundness (OOR) are the key vehicle parameters influencing vibration. In this context, wheel OOR includes both discrete surface defects such as wheel flats, and periodic irregularities around the wheel circumference such as eccentricity, ovality, and polygonisation. Primary suspension stiffness was also found to be important, however modification of suspension stiffness mostly caused a narrow-band frequency shift rather than changes in vibration magnitude.

Reducing unsprung mass was found to have a broadband effect in reducing vibration (Nielsen et al, 2013). A potential vibration reduction of 1-2 dB was identifed for a 25% reduction in unsprung mass, a 2-4 dB reduction for a 35% unsprung mass reduction, and up to a 6 dB vibration reduction might be achieved if a 50% reduction in unsprung mass could feasibly be acheived. The unsprung mass is largely controlled by the geometry and mass of the wheelset. Reducing wheel OOR on passenger vehicles was found to reduce vibration by up to 5 dB.

The unsprung masses of the Waratah train are 4216 kg for the motor cars and 3100 kg for the trailer cars. Tangara wheels are about 50 kg heavier than the Waratah wheels, the motor axles are about 60 kg heavier and trailer axles are about 90 kg heavier (TfNSW, 2021). Assuming similar motor and brake masses indicates that the unsprung mass of the Tangara trains is about 8-11% higher than the Waratah trains. With reference to the RIVAS project findings, the difference in unsprung mass may be a small factor explaining perhaps 1 dB of the observed 5-6 dB difference in vibration levels. Since unsprung mass is unlikely to fully explain the difference in vibration generation, systemic differences in wheel OOR between vehicle types are likely.

4.2 Typical vibration spectra for common train types

Figure 5 shows the average measured vibration level spectrum across the three tracks, in both vertical and lateral directions and for the Waratah and Tangara train types. Waratah trains show a similar spectrum shape to the Tangaras, but at a lesser level. The dominant vertical vibration frequency bands are 63-80 Hz for trains travelling on the UP track, and 25-40 Hz for trains on both DOWN tracks. Lateral vibration on all tracks tends to be dominated by frequency components around 40 Hz.

The shape of these average spectra do not indicate clear differences between the two train types. The main difference in spectral shape is evident between the different tracks for vertical vibration, with traffic on the UP track producing higher frequency vibration. This could be a function of the higher line speed limit, but the posted speed differences are relatively small and unlikely to explain a doubling in frequency of dominant vertical vibration. Another possible explanation is excitation of a vertical track resonance around 63 Hz, with an UP track posted line speed of 75 km/h corresponding to an excitation wavelength around 0.3m, which is a harmonic of the sleeper passing frequency.

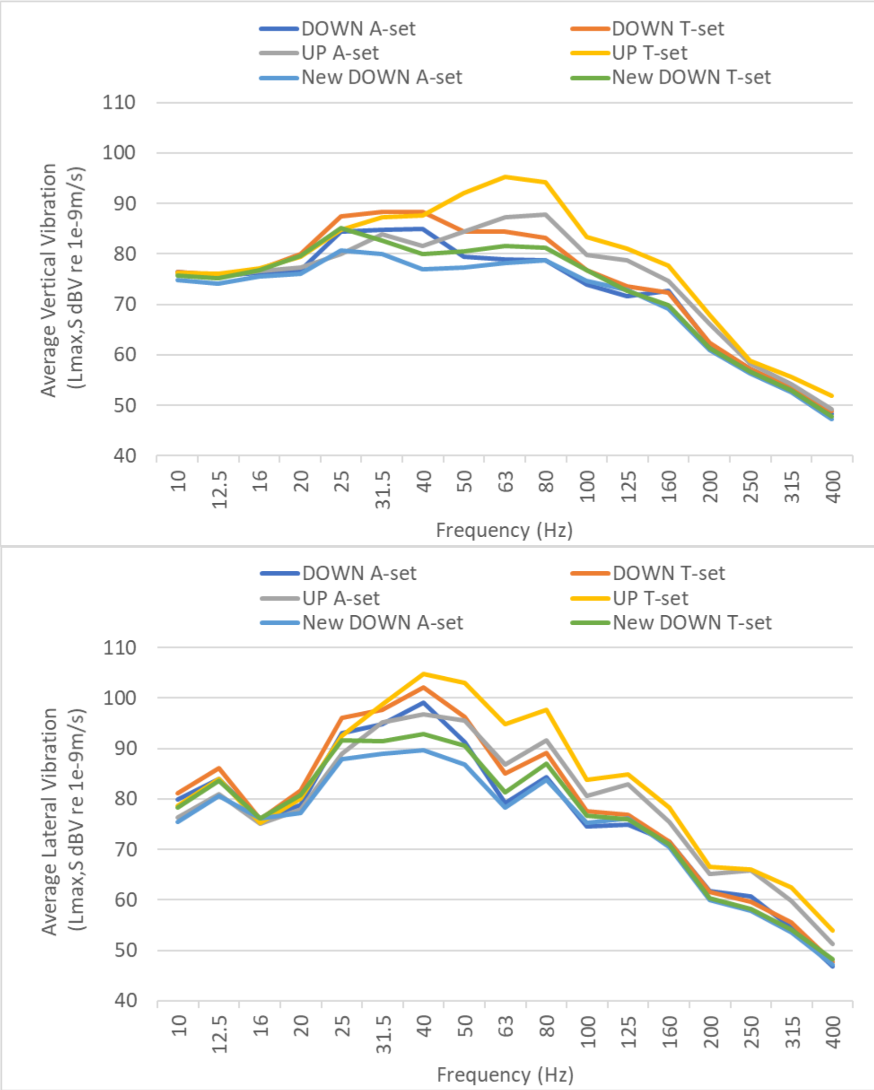

Figure 5: Arithmetic average vibration spectrum by axis, track and train type

5 HOW REPRESENTATIVE IS A 20 TRAIN SAMPLE?

Rail vibration and associated ground-borne noise criteria are often based on a 95th percentile level, meaning that one train passby event in 20 is permitted to exceed the nominated criterion. This approach to setting criteria reflects the inherent variability in train passby events, and the potential for isolated events to have unusually high vibration levels for example due to trains with wheelflats, which require a certain amount of time to be identified and before the train can be removed from service for maintenance.

A 95th percentile criterion suggests that a minimum of 20 train passby events should be collected to characterise the vibration levels at any particular location of interest. The larger data set collected in this study provides an opportunity to review the differences in assessment outcomes that could arise from measuring different numbers of passby events.

Figure 6 shows a randomly selected single day of passby vibration data, from 26th April 2021. Lateral vibration levels are shown as an indicative example. On this day, measurement of the vibration from 20 train passby events over an hour or so up to 1 pm would lead to an identified 95th percentile vibration level around 107 dB. Measurement of around 20 events up to 11 am would give a considerably higher result, a 95th percentile vibration level around 114 dB. Also shown in Figure 6 is the rolling 95th percentile level obtained from 250 events (approximately a full day of traffic) and from 1000 events. Both these results are similar indicating an overall population 95th percentile vibration level around 113 dB.

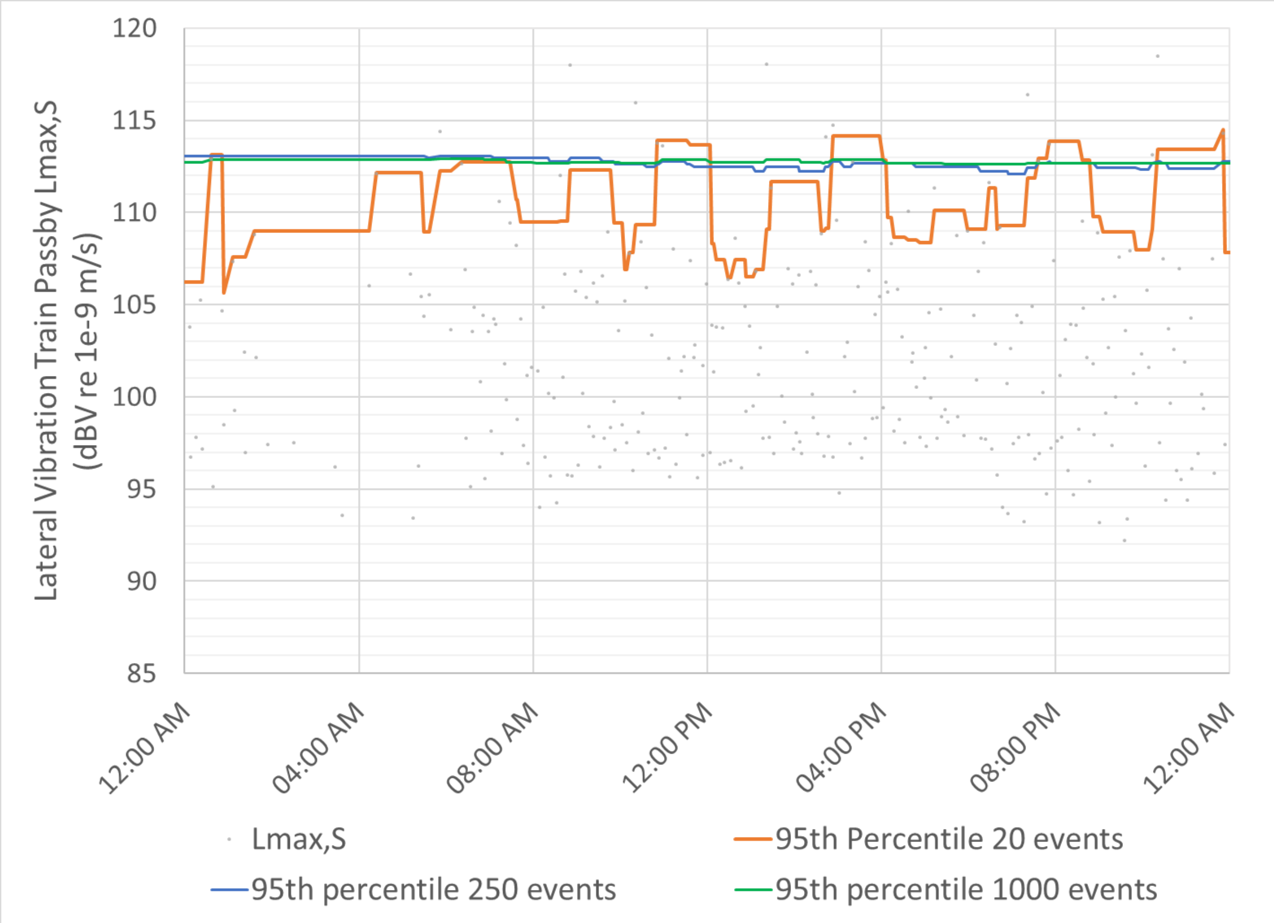

Figure 6: One day example (April 26th 2021) showing variability in 95th percentile vibration level from 20 events

This example indicates that attended monitoring for a relatively short duration (e.g. several hours or only 20 passby events) may not provide results that are representative of the vibration environment at this location. Normal distribution is assumed on the basis of the symmetry of the box plots in Figure 4. With normal distribution, the sample size *n* required to give 95% confidence that the sampled 95th percentile vibration level will be within a certain percentage margin of error is given by Equation (1) (Walpole et al, 2011):

$$n = \left(\frac{1.960}{\%\,error}\right)^2 \times 0.05 \times (1 - 0.05) \qquad (1)$$

If a 5% error is acceptable, then the number of train passby sample events required to assess vibration compliance with 95% confidence to the criterion is 73. If only 2% error is acceptable with the same confidence, then 457 events should be measured. As demonstrated by the example, a measurement of only 20 train passby events is not a convincing demonstration of compliance (or exceedance) of a 95th percentile vibration criteria.

6 CONCLUSIONS

Vibration data was collected from train passby events over the course of a year, with the train type and track identified automatically for each event. The results allow detailed analysis of long-term vibration trends and provide insight into the repeatability of short-term vibration monitoring.

Some refinements can be made to the automatic triggering and identification of events to remove the possibility that multiple vibration events will be associated with the same train passby event and to automate the data cleaning steps implemented for this study.

The effect of a major change in source vibration level such as the shift in DOWN traffic from one track to another was clearly evident in the measured data. Overall, the study demonstrates the potential use of long-term low cost vibration monitoring systems to understand overall trends and relative differences between tracks and train types. The key conclusions drawn from the analysis of long-term vibration data at this site are as follows:

1. Lateral vibration in the direction perpendicular to the track can be higher in magnitude than vertical vibration. The geometry of the site in cutting with the transducer mounted on the retaining wall may be a factor in this finding. However, when planning rail vibration monitoring campaigns it should not be assumed that vertical vibration will be dominant.

2. Tangara trains were observed to generate higher vibration levels than Waratah trains. Tangara trains made up approximately 16% of the total traffic, but were responsible for over 70% of events above the overall population 95th percentile vibration level. The difference between train types was most notable on the UP track nearest the monitor, with Tangara trains producing vertical and lateral vibration levels at least 5 dB higher on average than Waratahs. Only a small part of this difference (about 1 dB) is thought to be attributable to the higher unsprung mass of the Tangara trains. It is possible there are systemic differences in wheel out-of-roundness (discrete defects and/or periodic irregularities) between the two train types.

3. The shape of the average measured vibration spectra do not indicate clear differences between train types. A noticeable difference in spectrum shape was observed on the UP track relative to the two DOWN tracks, and may be associated with the higher UP track line speed coinciding with a track resonance at a harmonic of the sleeper passing frequency.

4. It was observed that a measurement of only 20 train passby events is not a convincing demonstration of compliance (or exceedance) of a 95th percentile vibration criteria. On the same day, measurement of 20 trains just a few hours apart could give a 7 dB difference in the identified 95th percentile vibration level. Considerably larger sample sizes are required to be confident in assessing compliance to the criterion.

7 RECOMMENDATIONS FOR FUTURE WORK

The observed trend of higher vibration levels from Tangara trains indicates a potential opportunity to reduce 95th percentile vibration levels around the Sydney network by about 5 dB, if the root cause of the higher Tangara vibration levels can be identified and addressed. Further investigations could include cross-referencing vibration measurements with vehicle maintenance records and examining data from wheel impact load detectors around the network, to understand if the higher vibration levels are due to increased incidence of wheel flats or periodic out-of-roundness.

The observation that the vibration standard deviation is similar between train types suggests that all the Tangaras may have higher out-of-roundness than all the Waratahs, even freshly turned wheels. To understand this, wheel metallurgy, maintenance equipment and practices should be investigated to identify any systemic differences. For example, if Waratah wheels are machined on the axles but Tangara wheels are removed from the axles for machining this could lead to a systemic out-of-roundness issue.

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