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Assessing Railway Vibration Modelling Accuracy via Experimental Testing Across Seven Countries

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This work presents an experimental analysis of ground-borne vibrations collected on high speed lines across 7 European countries. 1500 ground-borne vibration records, at 17 high speed rail sites are analysed with the aim of quantifying the errors associated with ground-borne vibration prediction models. It represents one of the most comprehensive analyses of experimental ground borne vibration data undertaken and comprises of datasets from Belgium, France, Spain, Portugal, Sweden, England and Italy.

Firstly, a variety of vibration metrics are considered and best fit relationships for each are calculated. Furthermore, the suitability of several mathematical vibration relationships are considered to describe the attenuation of vibration with distance. Then a variety of high speed train speed passages are analysed, up to 300km/h and the effect of train velocity on vibration levels is investigated. Next, 1/3 frequency octave bands are investigated to determine the effect of critical velocity on vibration propagation. Finally, a statistical analysis is undertaken to determine the typical error encountered when modelling high speed rail vibrations. To do so, train passages of similar trains and similar speeds are analysed to determine the unquantifiable error between each. The results present valuable findings for the design of new high speed railways, particularly close to urban environments.

1. Introduction

Ground-borne vibrations from railway lines in urban environments are an increasing environmental concern. This is due to a growth in railway infrastructure, including high speed rail, underground lines and increased freight movements.

Before new railway infrastructure is constructed it is common to perform a ground-borne noise and vibration assessment. The most widely used approach is to predict vibrations using a scoping model. Such scoping studies are used to predict vibrations quickly and ignore many of the complexities associated with ground vibration modelling (eg. soil material properties). The aim of a scoping model is to obtain a quick approximation of the anticipated vibration levels, and to identify potential areas which may require further investigations.

Several attempts have been made to develop numerical models for scoping purposes. For example, [1] outlined an analytical model that predicted vibration levels in terms of velocity decibels. Alternatively, an empirical model [2] is defined in American standards and is commonly used in practise. This approach uses empirical factors to adjust a reference vibration curve. A challenge with this approach was that it could not account for soil properties, and thus [3], [4] built upon this methodology and soil material input parameters were used to improve accuracy.

In contrast, [5] developed a scoping model where factors accounting for variables such as train speed and track quality were used to adjust an average base vibration curve.

Scoping prediction methods (e.g. the previously described approaches) are based upon using a combination of experimental datasets and empirical relationships to approximate vibration levels. To minimise the costs of both prediction and mitigation of ground-borne vibration, it is imperative that the accuracy of scoping models is maximised.

With this in mind, this paper analyses large ground vibration datasets from across Europe to assess the accuracy of current prediction relationships. Next, the effect of train speed on vibration response is assessed, and then 1/3 octave frequency bands are compared. The potential of critical velocity to amplify low frequency content is investigated, and finally recommendations are made regarding the typical accuracy and repeatability of vibration predictions.

2. Test site information

Experimental data from 17 test locations, across 7 countries was analysed (Figure 1). All sites consisted of ballasted track and key details regarding each test location are provided in Table 1. It should be noted that some datasets contained a mix of ground vibration and track vibration data. For the purposes of this (far-field) study, track vibration signals were removed.

Figure 1 – A selection of test site locations

The datasets were recorded across Belgium, France, Spain, Portugal, Sweden, England and Italy. Detailed descriptions of the experimental campaigns are described in: [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], and [16].

Site number	Details
1	At grade
2	Embankment
3	Cutting
4	Over-pass
5	At grade
6	At grade
7	At grade
8	At grade
9	At grade
10	At grade
11	At grade
12	At grade
13	Curve
14	At grade
15	At grade
16	Curve
17	Embankment

Table 1 - Test site details – general description

3. Experimental analysis

3.1 Analysis of existing mathematical VdB attenuation relationships

When performing a detailed vibration assessment it is typical to analyse the frequency content of vibrations, however for initial scoping studies it is more common to use instantaneous vibration indicators. One of the most commonly used instantaneous metrics is the logarithmic based Vibration Decibels (VdB). It is calculated as:

$$VdB = 20 \times \log_{10}\left(\frac{v_{rms}}{v_0}\right) \tag{1}$$

Where v_0 is the background vibration levels and v_{rms} is the moving root mean square amplitude.

A variety of relationships have been proposed to describe the relationship between VdB and distance from railway lines. To examine these, a selection were fitted to the field data to determine their suitability. The relationships (as outlined in [17], [18], [19] and [2] respectively) were:

$$VdB(d) = -20 \times \log_{10}(d) + c \tag{2}$$

$$VdB(d) = -10 \times \log_{10}(d) + (a \times d) + c \tag{3}$$

$$VdB(d) = a \times d^b \tag{4}$$

$$VdB(d) = -20 \times \log_{10}(1 + d) + (a \times d) + c \tag{5}$$

where a, b and c were fitted variables and d was track offset.

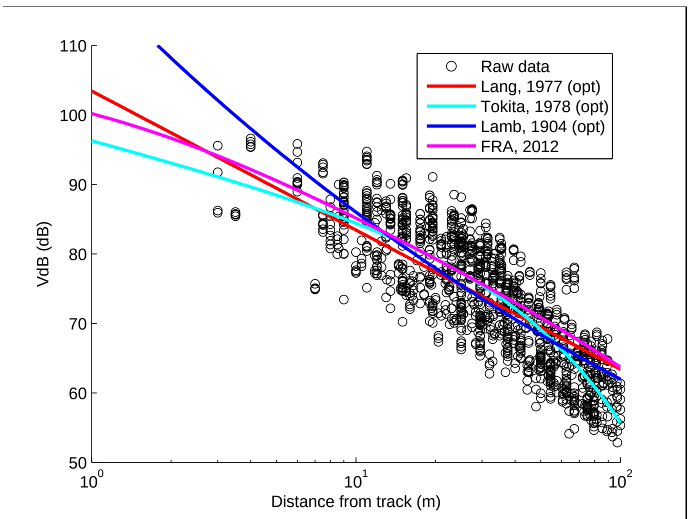

Figure 2 – Best fit relationships for VdB data

Figure 2 shows the four relationships plotted against the raw experimental VdB data. It was found that in the 30-40m track offset range, all relationships offered similar performance. Despite this, for scoping studies, larger distances (e.g. 30-100m) are of greater interest, and in this range performance differences were more pronounced. The most accurate relationship was found to be that proposed by [18] and gave a mean error of ±4.5dB and a maximum error of 13.75dB.

Reference	**Equation**	**Best fit values (all distances)**		
		a	**b**	**c**
Lang, 1977	$VdB(d) = -20 \times \log_{10}(d) + c$	-	-	103.42
Tokita, 1978	$VdB(d) = -10 \times \log_{10}(d) + (a \times d) + c$	-	0.208	96.47
Lamb, 1904	$VdB(d) = a \times d^b$	0.142	-	119.37
FRA, 2012 (standard)	$VdB(d) = -20 \times \log_{10}(1 + d) + (a \times d) + c$	0.024	-	106.21

Table 2 – Optimised best fit coefficients for vibration propagation

3.2 Speed effects

Figure 3 shows the effect of train speed on vibration levels. The dashed red line signifies the base curve as described by [2], which is unadjusted for train speed. Alternatively, the dotted blue line is based on the same curve, however it has been adjusted for train speed as suggested by [2], using:

$$VdB_{speed\ adjusted} = VdB_{base\ curve} + 20\log_{10}\left(\frac{train\ speed\ (km/h)}{reference\ speed}\right) \quad (6)$$

where the reference speed was 241.403 km/h.

Figure 3 shows that there was a low correlation between train speed and VdB levels. For example, the vibration level generated by one train at 72 km/h, was higher than the vibration generated by some of the greater train speeds at 300 km/h. Although some of this scatter was likely due to differences in track conditions and soil properties [20], [21], the overall low correlation indicated that train speed did not have a major effect on vibration levels. To better estimate the correlation between these variables, a best fit line was also plotted on Figure 3. As expected, only a low (but positive) correlation was found.

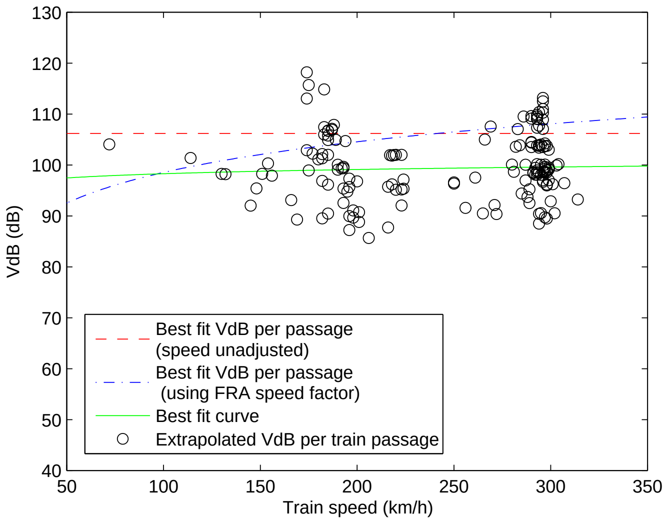

Figure 3 – The effect of train speed on VdB

3.3 Frequency content effects

Railway vibrations are generated at the wheel-rail contact points [22]. The nature of their generation and propagation depends on train, track and soil characteristics [23]. At locations near the track the primary excitation mechanisms are the wheel, axle and bogie passages. These are low frequency and are typically modelled as quasi-static. In comparison, locations further from the track are dominated by higher frequency dynamic excitation caused by rail unevenness and vehicle unsprung mass.

The frequency content of each test site at a distance of 25m from the track is shown in Figure 4, in terms of 1/3 octave bands. As expected, the dominant frequency range was 20-40Hz, which is caused by soil layering characteristics. Despite this, for site 7 there were elevated low frequency components in the 2-10Hz range. This indicated that the vehicle passage frequencies had been magnified, a characteristic associated with critical velocity effects [24]. Therefore, to investigate this further, the critical velocity was calculated for each at-grade test site via the procedure described in [25]. This involved the calculation of both the track and soil dispersion curves [26], and identifying their intersection. This intersection point has been shown to approximate the critical velocity within 3% of the true value [25].

Site number	Ratio (mean train speed/critical velocity)
1	0.57
5	0.51
6	0.46
7	0.75
8	0.45
9	0.57

Table 3 shows the calculated critical velocity ratios (where 0=stationary train, and 1=train moving at critical velocity). For site 7, the train speed was equivalent to 0.75 of the critical velocity. In comparison to the other sites, this was much closer to the critical velocity. This is significant because at speeds greater than 50% of the critical velocity, vibration amplitude increases significantly [27], [28], [29].

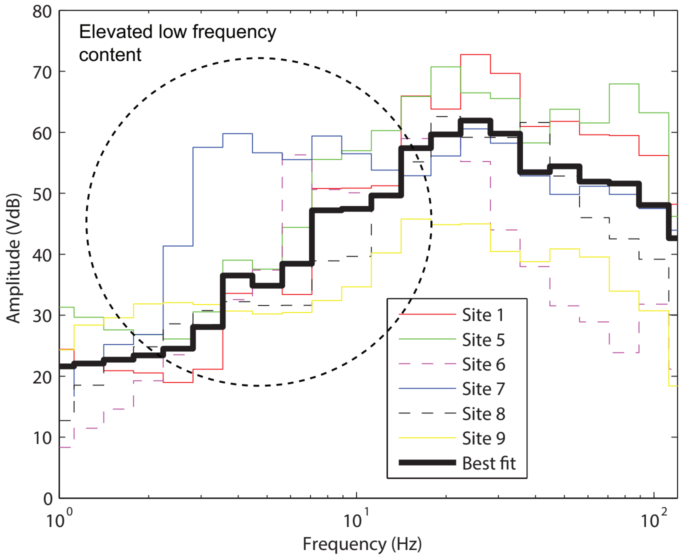

Figure 4 - One third octave bands (25m offset from track)

Site number	Ratio (mean train speed/critical velocity)
1	0.57
5	0.51
6	0.46
7	0.75
8	0.45
9	0.57

Table 3 – Critical velocity calculations

3.4 Sources of discrepancy

The accurate numerical modelling of railway vibrations is challenging due to the uncertainties in input variables. These variables can be divided into two types: site specific variables (e.g. soil material properties), and non-site specific variables (e.g. train loads, wheel irregularities and train speed).

During experimental field testing on railway lines, the only variables that are subject to change are non-site specific variables. Therefore, this means that any discrepancies between successive (nearly identical) train passages are generated due to non-site specific variables. To quantify the effect of these variables for trains running on the same network with similar mechanical characteristics, the discrepancies between successive train passages was calculated. Such discrepancies are due to non-site specific effects that are difficult to quantify and thus difficult to simulate within a vibration prediction model. The resulting calculations showed that the standard deviation was ±2dB. This is important because it indicates that the highest likely accuracy obtainable from a detailed vibration study is ±2dB (if soil properties etc are modelled exactly).

In addition to calculating the average standard deviation at each site, the standard deviation was also compared against track offset. It was found that there was a relatively constant relationship with distance, for offsets greater than 20m. For distances in this range the standard deviation was typically below 5 VdB. For distances closer to the track, there were several data points with higher standard deviation levels (max 13.3 VdB). It was postulated that the standard deviations in the near field were due to discrepancies between quasi-static train loads (e.g passenger effects), whereas the standard deviations in the far field were due to discrepancies in dynamic excitation such as wheel defects.

4 Conclusion

1500 vibration records, across 7 countries were analysed to obtain new insights into the nature of ground-borne vibration and critical velocity, on at-grade tracks. Existing scoping prediction methodologies were benchmarked and optimised to determine their suitability to model ground vibration attenuation. Investigations were also undertaken to assess the effect of train speed and critical velocity on ground vibrations. Furthermore, insights were made into the typical errors associated with scoping and detailed vibration prediction models.

The key findings were:

- Train speed had only a very minor effect on ground-borne vibration levels. Furthermore, existing relationships used to describe the effect of speed on vibration levels were found to be overly conservative.
- Current vibration attenuation relationships had a mean error of ±4.5 VdB. Additionally, for similar trains, at similar speeds, a mean standard deviation of ±2 VdB was found. This gives an indication of the maximum potential prediction accuracy.
- Critical velocity effects magnify low frequency quasi-static excitation which can propagate to elevated distances from the track, thus also effecting ground-borne vibration characteristics.

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