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Large scale international testing of railway ground vibrations across Europe

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ABSTRACT

This paper provides new insights into the characteristics and uncertainties in railway ground-borne vibration prediction. It analyses over 1500 ground-borne vibration records, at 17 high speed rail sites, across 7 European countries. Error quantification tests reveal that existing scoping models, for at-grade tracks, are subject to a mean error of approximately ±4.5 VdB. Furthermore, it is found that seemingly identical train passages are subject to a standard deviation of ±2 VdB, thus providing an indicator of the minimum error potentially achievable in detailed prediction studies. Existing vibration attenuation relationships are also benchmarked and potential new relationships proposed. Furthermore, it is found that soil material properties are the most influential parameter that effect vibration levels while the effect of train speed is low. In addition, sites with train speeds close to the 'critical velocity' are examined and it is found that their vibration characteristics differ vastly from non-critical velocity sites.

The study presents one of the most comprehensive publications of experimental ground-borne railway vibration data and comprises of datasets from Belgium, France, Spain, Portugal, Sweden, England and Italy. First, several international metrics are used to analyse the data statistically. Then the effect of train speed is investigated, with train speeds ranging from 72 to 314 km/h being considered. Next the effect of train type is analysed, with correlations presented for TGV, Eurostar, Thalys, Pendolino, InterCity, X2000, Alfa Pendular, AVE-S100 and Altaria trains. Then, vibration frequency spectrums are considered and critical speed effects analysed. Finally, an investigation into the typical standard deviation encountered in vibration prediction is undertaken.

1. Introduction

Railway ground vibrations are a growing environmental challenge. This is partly due to a rapid global growth in railway infrastructure and an increasing desire to place new lines within urban environments. It is also partly due to more aggressive railway scheduling (i.e. more frequent passages) and both heavier and faster trains.

Before the construction of a new line or the upgrading of an existing line, it is usually necessary to undertake a ground-borne noise and vibration assessment. These assessments are often expensive because the complex interactions between train, track and soil potentially require rigorous analysis. Despite this, if vibration levels are not accurately predicted, unexpected remediation measures may be required post-construction [1–3].

To obtain a high accuracy estimate of vibration levels (i.e. frequency curves), in practice a commonly used method is [4–6]. This requires the use of physical tests performed at the proposed track construction site to determine the transfer function of the surrounding soil. Then the transfer function is combined with similar track transfer functions for the train and track, resulting in an overall estimate of the ground-borne vibration characteristics.

Under certain conditions, it is impractical to use this procedure and instead an analytical or numerical approach is preferred. A large body of research is ongoing in this area, with early work being undertaken by [7, 8], to derive analytical expressions for vibration levels. More advanced analytical [9] and semi-analytical [10] models have recently been proposed, particularly for predicting vibrations from underground lines [11], however there is an increasing trend for the utilisation of numerical techniques. In particular, time domain and frequency domain finite element method (FEM) ([12–17]) approaches have been widely developed.

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A shortcoming of the FEM is that it becomes computationally expensive for large domains and requires the use of an absorbing boundary to truncate the modelling space [18]. To reduce run-times, the computational domain can been reduced to 2.5 dimensions by assuming that the track is invariant in the direction of train passage ([19, 20]). Although this considerably reduces computational times, the invariant track assumption makes it challenging to model discrete components (e.g. sleepers), thus leading to the incorporation of Floquet transforms ([21, 22]), or non-isotropic material properties ([12, 23])

Another alternative solution is to couple the FEM with the boundary element method (BEM), either using 2.5D ([24, 25]) or 3D formulations ([26]). This FE/BE approach allows for large offsets to be computed more efficiently than using only the FEM. Despite this, the contrasting nature of the FE and BE methods can be computationally challenging and fully 3D models still require long run times.

Although numerical railway modelling has advanced significantly, a persistent challenge is the acquisition of high accuracy soil material properties, for use as modelling inputs. Soil is a non-engineered material that forms naturally and thus is highly inhomogeneous. This makes it difficult to quantify its material characteristics, even using time consuming and expensive in-situ tests (e.g. Multi-channel analysis of surface waves analysis).

To overcome this, at the early stages of a vibration assessment, it is common to forego rigorous analysis in preference of a 'scoping' approach ([4, 27, 28]) using very limited site data (i.e. soil properties typically ignored). This allows for the rapid approximation of vibration levels to determine the sites where ground-borne vibration levels might exceed national limits. Then the aforementioned numerical modelling or physical testing approaches can be used to calculate the potential vibration levels at these locations with greater accuracy. To minimise project cost it is important that only the locations where vibration levels will exceed national limits are analysed in greater detail. Each site where vibration levels are over-predicted (i.e. a 'false positive'), will result in unnecessary additional project costs. Similarly, each site where vibration levels are under-predicted will result in unexpected additional project costs from abatement installations post-construction. Therefore it is imperative that the accuracy of scoping assessments is maximised.

In an attempt to perform scoping predictions of railway vibration, [29] presented a mathematical model to quickly approximate velocity levels. Results were compared to results from [30] and a positive correlation was found. Another approach was proposed by [4] which used empirical factors to adjust an experimentally defined vibration curve. This approach was built upon by [31], [27] who included soil parameter information to increase prediction accuracy.

Alternatively, [32] presented an empirical model where a basic vibration value was multiplied by factors account for conditions such as train speed, track quality and building factors. It was also able to predict more complex frequency curves in a similar manner to that proposed by [33].

To perform a scoping assessment, it is common to use a combination of historical vibration results and empirical relationships to estimate vibration levels. Therefore, to improve scoping accuracy, it is important to better understand the underlying characteristics of railway vibration. One approach to this is to analyse existing experimental results. Despite this, due to a recent surge of interest in numerical modelling, little attention has been given to the analysis of historical experimental data.

Another potential stumbling block for experimental analysis is that freely available experimental data is scarce. In an attempt to overcome this, this current work documents the combined efforts of several railway research institutions to analyse a large body of experimental results. To the author's knowledge, although such efforts have been made in the field of acoustics [34], this research is one of the most comprehensive analyses into the statistical characteristics of railway vibration. Therefore it presents a highly original and commercially valuable analysis.

This paper aims to quantify the level of error that can be expected when using scoping and detailed assessment methods, while also investigating the effect of train speed, critical velocity and train type on ground-borne vibration propagation. There is a focus on vibrations from at-grade high speed lines, due to their widespread nature, however several lower speed lines are also considered.

2. Test site information

Experimental data from a total of 17 test locations, across 7 countries was examined (Fig. 1). All sites consisted of ballasted track and key details regarding each test location are provided in Tables 1 and 2. Ground wave velocity profiles are shown in Fig. 3. 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 the track vibration signals were removed. A more detailed description of each of the test sites and experimental setups, please refer to: [25,35-44]

Further considerations included:

- At some sites, three component vibration signals were recorded, however to maximise compatibility this study only considers vertical component vibrations.
- Although the datasets were recorded by several different research institutions and using different types of recording equipment, all methodologies were broadly in-line with the recommendations detailed in [45]. A selection of the measurement sites are shown in Fig. 2.
- Vibration velocities were solely analysed in this investigation. Therefore, where necessary, acceleration time histories were converted into their equivalent velocity components.
- The majority of datasets included full time history vibration records. Despite this, only instantaneous vibration data (velocity decibels – Eq. (1)) was available for the test sites described by [35]

3. Vibration metrics

Three internationally used metrics were used to assess vibration levels. As the aim of this research was to analyse a wide range of vibration signals for scoping assessment purposes, absolute vibration measurements were desirable, rather than frequency curves. The most commonly used metric for scoping assessment is VdB, as described by [4]. VdB is calculated using a logarithmic scale as:

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

where v_{rms} is the moving root mean square amplitude (rms slow, 1 s) and v_0 is a reference level for background vibration (chosen as 2.54×10^{-6} m/s).

In addition to VdB, peak particle velocity (PPV) and $\mathrm{KB}_{\mathrm{fmax}}$ were also used to assess vibration levels. PPV [46] was calculated as:

$$PPV = max|v(t)| \tag{2}$$

where $v(t)$ is the velocity time history. Similarly, $\mathrm{KB}_{\mathrm{Fmax}}$ [47] was calculated by taking the maximum amplitude of:

$$KB_f(t) = \sqrt{\frac{1}{\tau}\int_0^t KB^2(\xi)e^{\frac{-t-\varepsilon}{\tau}}d\xi} \tag{3}$$

where $\tau = 0.125$ seconds (rms fast), and KB(ξ) was the velocity time history. It should be noted that KB(ξ) was first transferred into the frequency domain, giving KB(f), filtered according to Eq. (4), and