DEVELOPING PREDICTION MODEL FOR GROUND-BORNE NOISE AND VIBRATION FROM HIGH SPEED TRAINS RUNNING AT SPEEDS IN EXCESS OF 300KM/H

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The UK Government believes that a new north-south rail link will revitalise Britain’s rail network. The Government has created HS2 Ltd, which is developing a Y-shaped high-speed railway to provide capacity and connectivity to populated urban areas at speeds up to 360km/h. A key concern for many is the environmental impact of the scheme, including the potential impact of ground-borne noise and vibration. The ground vibration generated by a train is expected to increase with speed hence methods for predicting ground vibrations at high speed are essential for a robust impact assessment. Currently there is limited published ground vibration data for trains travelling at speeds of more than 300km/h to validate existing ground-borne vibration models. However, there is a significant amount of data for trains travelling at lower speeds and the mechanisms that result in vibration generation at these speeds are well understood. This paper presents a model for predicting train vibration at speeds of up to 360km/h. The model is a development of an existing validated prediction model for ground vibration from the UK’s High Speed 1 railway which operates trains at speeds of up to 300km/h. This paper focuses on the part of the model that enables a measured train vibration spectrum to be scaled for train speed. The development has sought to improve the accuracy of the extrapolation to higher speeds by ensuring that the mechanisms that generate ground-borne vibration, such as wheel and rail roughness, are appropriate for the required speed range and by maximising the goodness of fit of the model with the available data at lower speeds.

1. Introduction

High Speed 2 (HS2) is a proposed north-south high-speed railway to connect populated urban areas in the UK. A key concern for many is the environmental impact of the scheme. This is because vibration generated at the wheel-rail interface during the passage of a train is transmitted through the track and into the trackbed where it becomes ground-borne. The vibration is then transmitted through the ground into nearby buildings where it can be felt as vibration (0.5Hz to 80Hz) or heard as ground-borne noise (25Hz to 250Hz). The mechanisms that result in ground-borne vibration from trains are well understood and are documented in international standards for the prediction of ground-borne noise and vibration from trains. One prediction model is that used to
predict ground vibration from the UK’s High Speed 1 railway operating on the surface and in bored tunnels \( \frac{2}{3} \). This empirical methodology was developed from thousands of measurements of train vibration and has been validated for a range of train types and speeds up to 300km/h. An overview of the HS1 prediction method is shown in Fig. 1.

| 1. Identify ground conditions at study location | 5. Correction for different track system |
| 2. Measured vibration emission source term | 6. Propagation of vibration away from source |
| 3. Correction for different train speed | 7. Response of building to ground vibration |
| 4. Correction for different train unsprung mass | 8. Predicted ground-borne noise and vibration inside building |

**Figure 1.** The modules of the HS1 ground-borne noise and vibration prediction method \(^2\).

This paper describes development and validation of the part of the method that corrects the train vibration emission term for speed. Trains on HS2 are specified to operate at a maximum speed of 360km/h. The ground vibration generated by a train is expected to increase with speed hence methods for predicting ground vibrations at high speed are essential for a robust impact assessment. Currently there is limited published ground vibration data for trains travelling at speeds of more than 300km/h to validate existing ground-borne vibration models. However there is a significant amount of data for trains travelling at lower speeds. This paper presents a method for speed scaling measured vibration spectra. Section 2 presents the revised speed correction, introducing the concept of effective roughness. The new method has sought to maximise the accuracy the extrapolation to higher speeds by ensuring that the mechanisms that generate ground-borne vibration, such as wheel and rail roughness, are appropriate for the required speed range and by maximising the goodness of fit of the model with the available data at lower speeds. In Section 3 the revised speed correction is validated against measured ground vibration data from Deutsche Bahn (DB) trains at a test site near Muehlberg, Germany and TGV trains at a site near Vendome, France. Its accuracy for predicting noise and vibration indicators appropriate for environmental impact assessment is also established. Section 4 includes a short discussion on the method.

## 2. Concept for speed scaling measured train vibration emission terms

### 2.1 Vibration emission term

The HS1 model \(^2\) uses a measured vibration emission source term as the input. The term \( L_{\text{rms}}(f) \) is the route mean square (rms) vibration velocity level measured at ten metres from the track centreline, evaluated over the train pass-by period and expressed in one-third octave bands between 6.3Hz and 250Hz. The speed scaling method presented here assumes that the term can be expressed according to Eq. (1):

\[
L_{\text{rms}}(f) = R_{\text{eff}}(\lambda, v) + F - IL(f) + G(f),
\]

where \( R_{\text{eff}}(\lambda) \) is the ‘effective roughness’ (described in detail in Section 2.2) which represents the displacement amplitude at the wheel-rail interface that results from wheel-rail interaction. The amplitude affects not only the displacement of the wheel and rail, but the frequency spectrum of the vibration input to the track below. For a given train speed \( v \) (m·s\(^{-1}\)) a roughness wavelength of \( \lambda \) (m)
The frequency track, $K -$rm is plotted with a blue dashed-log $B^4$. Here, the first three terms to the left of Equation 1 are the equivalent of the

$$L_K(\lambda) = R(\delta_K) + A - \left( \log_{10} \frac{\lambda}{\delta_K} \right)^2,$$

condition at the site and transfer mobility are used to derive the vibration forces of a train independently of the

2.2 Effective Roughness

The effective roughness term of Eq. (1) is intended to describe the magnitude and frequency content of the vibrational forces generated by the passage of the train. ISO-14837 defines some of the excitation mechanisms for ground vibration from trains. Those appropriate to high speed rail for the frequency range of interest include: Excitation caused by wheel/rail roughness – the irregularities of the rail and wheel contact surfaces, and parametric excitation – the excitation caused by passing wheels interacting with discrete elements of the track support system such as sleepers (The speed of the vehicle, and sleeper spacing defines the sleeper passage frequency). Similarly other harmonic components arise due to axle spacing and bogie spacing.

Both mechanisms are accounted for in $R_{eff}$ which is plotted for an experimental ICE-V train in Fig. 2. The figure shows how $R_{eff}$ (red solid line) is derived from the combination of a wheel/rail roughness spectrum (blue dashed line) and parabolic terms representing the parametric excitation from sleeper and axle passage frequencies (green dotted lines).

Wheel/rail roughness - Wheel and rail roughness data corresponding to the vibration emission terms of the HS1 prediction method are not publicly available. Therefore, for HS2’s prediction method a typical roughness spectrum has been derived from published data. Typically wheel and rail roughness data is measured for the purposes of airborne rolling noise assessment and is presented in the wavelength range 0.003m to 0.25m$^2$. Wavelengths that lead to low frequency ground-borne vibration require a definition which includes data to much longer wavelengths. The vibration emission terms for the HS1 prediction method are defined down to 6.3Hz. For a train speed 360km/h (100 m·s$^{-1}$) $R_{eff}$ must include wavelengths as long as 16m to include sufficient information to describe this frequency.

In the wavelength range 0.02m to 2m a roughness known to be representative of the combined wheel/rail roughness of disc-braked wheels and the average UK rail roughness in the 1990s has been used to describe $R_{eff}$. In the wavelength range 2m to 16m an approximation of data from good quality ballast track measured with a corrugation analysis trolley and a track recording car near Stevenage, UK has been used. The full wheel/rail roughness term is plotted with a blue dashed line in Fig. 2.

Parametric excitation - parabolic functions have been used to model the displacements generated by the sleeper and axle passage frequencies. The definition of these functions (Eq. (2)) ensures that the sleeper and axles pitches (spacings) correspond to the vertex of the parabola:

$$L_K(\lambda) = R(\delta_K) + A - \left( \log_{10} \frac{\lambda}{\delta_K} \right)^2.$$
where \( L_K(\lambda) \) is the vibration level due to the \( K^{th} \) sleeper and axle passage frequency, \( R \) is the wheel/rail roughness amplitude, \( \delta_K \) is the \( K^{th} \) sleeper or axle pitch, \( A \) and \( B \) are constants defining the amplitude and width of the parabolic term. The parabolic functions are plotted by dashed lines in Fig. 2. In Fig. 2 the sleeper pitch corresponds to 0.55m which is equal to the sleeper pitch at the test site in Muelberg, Germany (See section 3). Axle pitch 1, 2 and 3 are defined in Table 1 and refer to the ICE bogie wheel base, the intra-carriage axle spacing and the intra-bogie axle spacing respectively.

An effective roughness spectrum \( R_{\text{eff}}(\lambda) \) is then modelled as the combination of the wheel/rail roughness \( R(\lambda) \) and parametric excitation \( L_K(\lambda) \) according to Eq. (3):

\[
R_{\text{eff}}(\lambda) = 10 \log_{10} \left[ 10^{R(\lambda)/10} + \sum_K 10^{L_K(\lambda)/10} \right].
\] (3)

In Fig 2, the amplitude \( A \) and width \( B \) constants for the sleeper and axle passage terms (Eq. 2) has been fixed to 5dB and 0.05m respectively as these values were found to provide best fit with measured data.

### 2.3 Speed scaling process

Assuming that only the effective roughness term is speed dependent, a measured vibration spectrum of a train travelling at the speed \( v_1 \), \( L_{v_1 \text{rms}} \), can be scaled to estimate the vibration spectrum at speed \( v_2 \), according to Eq. (4):

\[
L_{v_2 \text{rms}}(f) = L_{v_1 \text{rms}}(f) + R_{\text{eff}}(f, v_2) - R_{\text{eff}}(f, v_1).
\] (4)

The result of scaling a vibration emission term measured at 160km/h to a speed of 280km/h is shown in Fig. 3. The change in \( R_{\text{eff}} \) plotted against frequency is also shown. As speed increases \( R_{\text{eff}} \) is shifted towards higher frequencies. The terms \( IL(f) \) and \( G(f) \) are inherent in the measured vibration emission term therefore the speed scaling is valid at the site where the vibration emission term was measured or at sites where \( IL(f) \) and \( G(f) \) are equivalent to the measurement site. Changes to the track or the local ground conditions could be modelled by changing these terms, however the effect of changing these parameters is not considered in this paper.
Figure 2. Effective roughness for an ICE train. $R_{eff}$; ..., wheel/rail roughness term; ..., parametric excitation terms.

Figure 3. Predicted ICE train vibration spectra: —, 160km/h; ---, 280km/h. $R_{eff}(f)$: ..., 160km/h; ●●, 280km/h.

3. Comparison with measurement data

The speed-scaling method defined above has been tested using measurements of ground vibration generated by ICE trains near Muehlberg7, Germany and TGV trains near Vendome8. The dataset includes trains operating at speeds between 100 and 304 km/h. At each site the speed scaling function defined in Eq. 4 has been applied to measurements of trains operating at approximately 100km/h to predict the vibration spectrum of trains running at higher speeds. At each site $R_{eff}$ defined in Eq. 3 is defined using the known train-track characteristics shown in Table 1.
The site vibration spectrum. Both prediction of a new scheme in the UK. The predictions are in very good agreement with the measured vibration at each location and predicted spectra from measurements made in 100km/h. The predictions are in very good agreement with the measured data in all frequencies and at all train speeds.

Figure 5 compares the measured vibration spectra for speeds between 270 and 296 km/h at 113 km/h. The track was supported by ballast and typical SNCF sleepers over chalk lithology. The predictions are in reasonable agreement with the measured data in some frequencies. However the difference in certain frequency bands can be up to 10dB.

3.2 Accuracy of the speed scaling method for environmental impact assessment

ISO14837-1 provides a method to assess the accuracy of a ground-borne vibration prediction model. To predict the environmental impact of a new scheme in the UK, predictions of the overall maximum A-weighted ground-borne noise level with a ‘slow’ time weighting and ground-borne vibration level with the Vibration Dose Value (VDV)\(^9\) are necessary.

In this section the accuracy of the speed-scaling method for predicting ground-borne noise has been evaluated by comparing predictions of the ground-borne noise level inside a building and the pseudo-measured ground-borne noise level. In each case the ground-borne noise level has been calculated by A-weighting and summing the predicted or measured ground vibration band levels and then subtracting 28dB from the result to represent the transfer function between the ground-vibration and the sound pressure level measured inside a building\(^10\).

The accuracy of the speed-scaling method for predicting the free-field \(w_{10}\)-weighted VDV for a single train event has been evaluated by comparing the measured VDV at each location and predicting the estimated Vibration Dose Value (eVDV) from the speed-scaled vibration spectrum. Both sites have been plotted on the same graphs in Fig. 6. To increase the data sample, all the measurement positions and speeds have been considered. The predictions have been made from the train vibration spectra with the lowest speed measured at each location and the speed scaling function defined in Eq. (4).

It can be seen that the speed scaling method defined here can be used to predict the pseudo measured ground-borne noise level with a standard error (1 standard deviation) of 1.81dB. The VDV can be predicted with a standard error of 40%.

<table>
<thead>
<tr>
<th>Train</th>
<th>Sleeper pitch</th>
<th>Axle1 pitch</th>
<th>Axle2 pitch</th>
<th>Axle3 pitch</th>
<th>Train length</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE/V</td>
<td>0.6m</td>
<td>2.5m</td>
<td>3m</td>
<td>4.9m</td>
<td>113m</td>
</tr>
<tr>
<td>TGV-A</td>
<td>0.55m</td>
<td>3.0m</td>
<td>3.6m</td>
<td>n/a</td>
<td>240m</td>
</tr>
</tbody>
</table>
**Figure 4.** Comparison of measured (**-**•) and predicted (**••**) vibration spectra at Muehlberg for various train speeds, at 8m from the nearest track.
4. Discussion and conclusions

A model for predicting ground-borne noise and vibration from high speed trains has been introduced. The model is a development of an existing validated prediction model for ground vibration from the UK’s High Speed 1 railway. This paper focuses on developments for scaling a measured train vibration spectrum for train speed using the concept of effective roughness. The concept of effective roughness has been defined so that it includes information for wavelengths sufficient to scale vibration measurements in the frequency range 6.3Hz to 250Hz to speeds of 360km/h. The term has been used to predict the ground vibration spectra measured along two European high speed lines. At Muehlberg, the predicted and measured vibration spectra are in very good agreement. The agreement is less at the Vendome site. It is likely that some of the error is a result of using a generic term to represent wheel/rail roughness. However it should be noted that the aim of this study is to
develop a model for predicting ground-borne noise and vibration for proposed railways for which detailed information about the train and track are not available. A generic wheel/rail roughness term is therefore considered appropriate for this purpose.

The accuracy of the speed scaling method for predicting the $L_{A\max}$ and the VDV indicators has been tested. The results show that the speed scaling method provides a very good fit with measured data. Therefore, it is considered that the model developments presented here provide a good basis for predicting train ground-borne noise and vibration speeds of up to 360km/h.

![Figure 6. Comparison of measured and predicted groundborne sound and vibration levels for Muehlberg (○) and Vendome (□), all speeds and locations.](image)

REFERENCES