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GROUNDBORNE NOISE AND VIBRATION FROM RAILWAYS: THE PITFALLS

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1. INTRODUCTION

The accurate prediction of wayside noise and vibration is a critical component of the environmental assessment of proposed railways. Whilst there are now many national standards and guidelines for predicting airborne noise from rail bound vehicles, the prediction of groundborne noise and vibration remains something of a "black-science". Predictive methodologies, both empirical and theoretical, have been proposed but in most cases their validation is limited either to a particular classification of rail system (eg light-rail, mass-transit) or to a limited range of operational conditions. This makes choosing a predictive methodology for a new scheme problematic. Moreover, these complications can mean that, without care and experience, the application of an inappropriate methodology may result in substantial inaccuracies in any predictions undertaken.

This paper considers the potential pitfalls associated with selecting an appropriate predictive methodology in respect of two issues: the effect of train speed and the prediction of kurtosis based measurement indices (root mean quad, rmq, or VDV) such as those used in UK standards to assess the subjective response to perceptible vibration.

2. THE EFFECT OF TRAIN SPEED ON GROUNDBORNE VIBRATION

By analogy with airborne noise it is often assumed that levels of groundborne noise and vibration have a simple relationship with train speed. The first part of this paper shows that such assumptions are not always realistic. More complicated relationships between vibration and speed can and do exist. The reasons for this are discussed in the following section as is the potential inaccuracy associated with assuming simpler relationships.

Background

Some published research [eg 1,2] suggests that there may be a linear relationship between groundborne vibration and train speed. The majority of this work, however, relates to low or medium speed rail systems. Conversely, the limited research so far published in respect of wayside vibration from high speed lines suggests that the levels of vibration generated at high speeds are relatively independent of speed [3,4]. These different conclusions suggest either that the research is inconsistent or that the underlying phenomena are more complicated than can be considered using simple relationships.

Wayside vibration is generated by the interaction of forces occurring at the wheel/rail interface. These forces are, in turn, dominated by two phenomena:

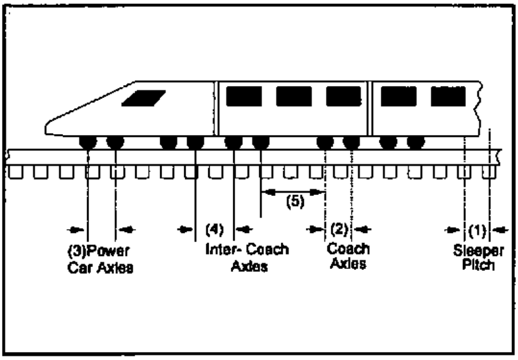

FIGURE 1: TRAIN/TRACK CONFIGURATION

Quasi-Static Loading: The force at any given point on the rail head will vary from zero to a maximum and back to zero again, each time a wheel passes. The way in which this force is transferred to the underlying ground is the affected by the following:

i) Rail Support Non-Uniformity: When a track system does not have continuous rail support, each tie/sleeper behaves like an individual vibration source. These discrete sources are switched on/off at a frequency determined by the train speed and the spacing of the supports. This is known as sleeper passage frequency (Figures 1 and 2).

ii) Axle Spacing: As with the non-uniform rail support, the periodic spacing of the axles along a train results in axle passage frequencies (Figures 1 and 2).

Wheel/Rail Surface Roughness: Such roughness results either from production tolerances or from wear and results in a random levels of excitation as the wheel tyre moves over the rail.

The Speed Relationship - Its Theoretical Description

Some researchers [5] have proposed mathematical descriptions for the aforementioned components from first principals. The approach adopted in this research, however, was to provided a mathematical description for the *effect* of each component. The vertical vibration velocity level at a point in the ground, $L_{Vrms}(v,f)$, can be described as:

$$L_{Vrms}(v,f) = 10 \times \mathrm{Log}_{10}\left[10^{\frac{L_{Roughness}(v,f)}{10}} + \sum_{N=1}^{n} 10^{\frac{L_{Passage\ Freq,N}(v,f)}{10}}\right]$$

Where:

$$L_{Roughness}(v,f) = A(f) + B(f)\times Log_{10}\left(\frac{v}{100}\right)$$

$$L_{Passage\ Freq,N}(v,f) = \frac{W(f,N)\times C(f,N) - [v-3.6\times f\times \delta(N)]^2}{W(f,N)}$$

and, v = train speed [km/h]; N = N^{th} passage frequency; f = ⅓ octave band centre frequency [Hz]; A,B,C,W = components for particular type of track system which are principally determined by its acoustic transmissibility and wheel/rail roughness; and δ(N) = characteristic spacing - wavelength - of the N^{th} passage frequency (eg sleeper pitch, axle spacing).

Figure 2 shows diagrammatically the principle components of the procedure in relation to the 12.5 Hz ⅓ octave band for one train/track system. Complicated speed relationships occur due to the interaction between the narrow band excitation components that "sweep" through the frequency range with increasing speed and the natural frequencies of the train/track system. Figure 3 presents the predicted relationship between train speed and groundborne vibration for a German ICE. The Figure shows that, because of the interactions between the excitation and the train/track system, it is possible for groundborne vibration to be strongly dependant on speed at low speeds with a lesser dependence at high speeds. This Figure also demonstrates the magnitude of the potential over estimation that could occur if a simple linear dependence on log speed was extrapolated from lower speed ranges. Figure 4 shows how the methodology predicts, for increasing speed, the way in which the different passage frequencies "sweep" through the frequency range and the resonances that occur as a consequence.

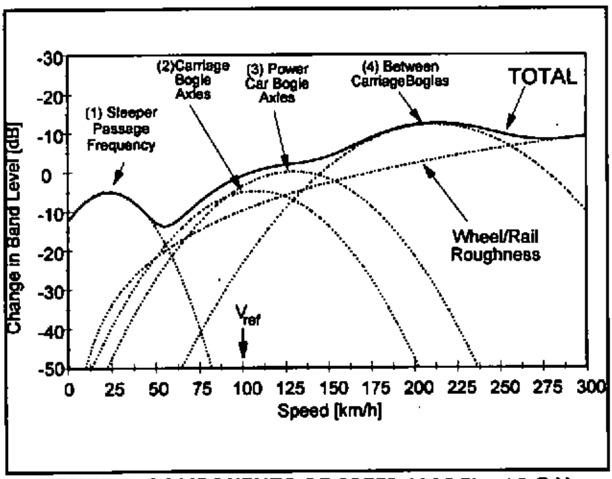

FIGURE 2: COMPONENTS OF SPEED MODEL - 12.5 Hz 1/3 OCTAVE BAND (SEE ALSO FIGURE 1)

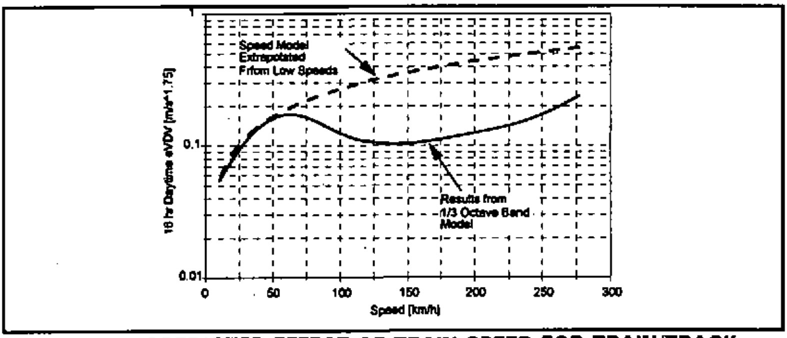

FIGURE 3: PREDICTED EFFECT OF TRAIN SPEED FOR TRAIN/TRACK SYSTEM WITH A PRIMARY NATURAL FREQUENCY AT 30Hz

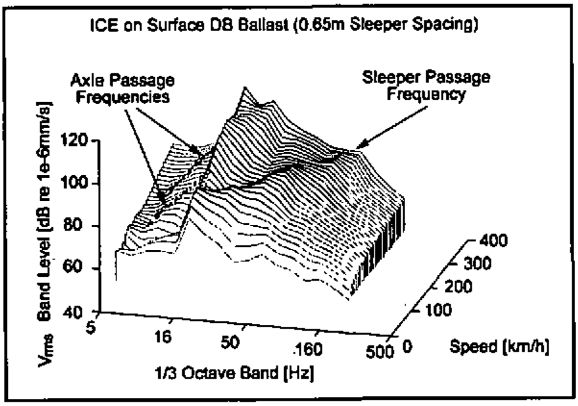

FIGURE 4: PREDICTED EFFECT OF TRAIN SPEED

3. THE PREDICTION OF RMQ BASED MEASUREMENT INDICES

Background

In the UK, the potential impacts of vibration on people in buildings are assessed using the British Standard BS 6472 [6]. This standard advises that, for intermittent and or "impulsive" vibration signals, the exposure should be quantified using a measurement index called the Vibration Dose Value (VDV). The VDV is based upon Kurtosis (or fourth power) averaging with time and, for a signal lasting τ seconds, may be evaluated using:

$$VDV = \left[\int_0^{\tau} a_w^{\,4}(t)\,dt\right]^{\frac{1}{4}}$$

Where a_w = weighted acceleration [m/s^2] using weighting W_g from BS 6841 [7].

BS6472 describes a procedure for estimating VDVs (denoted as eVDV) from the overall rms, weighted acceleration evaluated over the period τ. The basic form of the estimation is:

$$eVDV = K \times a_{Wrms} \times \tau^{\frac{1}{4}}$$

where: eVDV = Estimated VDV [m/s$^{1.75}$]; K = Constant (BS6472 defines K = 1.4); a_{Wrms} = RMS of weighted acceleration evaluated over period τ [s].

For frequencies between 8 and 80 Hz the weighting applied means that weighted acceleration, a_W, is equal to scaled velocity. This equivalence starts at 8 Hz and hence the scalar required is 50.3 (ie $2.\pi.8 = 50.3$). A nominal weighting function is still required, however, for frequencies between 1 and 6.3 Hz, represented W_v in the following equations.

It follows that the eVDV may now be described in terms of RMS velocity. Moreover, the RMS velocity can be evaluated from the logarithmic sum of its ⅓ octave band components. The eVDV can therefore be evaluated using:

$$eVDV = K \times 50.3 \times \left[\sum_{f=1}^{80Hz} (V_{rms,f} \times W_V)^2\right]^{\frac{1}{2}} \times \tau^{\frac{1}{4}}$$

To confirm the appropriate value of K, vibration measurements taken over several railway tunnels described in Reference 8 were analysed in terms of both the "real" VDV and the eVDV. The results showed that for the majority of situations K = 1.4 (standard error of 0.1). *[It should be noted that the VDV is in fact based upon the root mean quad (rmq) of the time history and not the rms. The rmq will place higher weighting on occasional peaks within the vibration signal and hence the relationship between the rmq and rms will vary, dependant on the character of the signal under consideration. This means that the method of estimating VDVs described herein should always be extended to new situations with care.]*

Methodologies for Predicting VDVs .

To provide rapid assessments of new railways, or to scale measurements from one site to another, the simplest approach to predicting VDVs is to have a methodology in the form:

$$VDV = VDV_{ref} \times TF_{speed} \times TF_{track} \times TF_{propagation} \times TF_{building}$$

This approach is often adequate provided that there are no substantial differences (in terms of speed or distance for example) between the reference data and the situation under consideration. Figure 5 shows a test of the accuracy of just such a simple methodology developed to predict the groundborne vibration arising from the operation of underground railways. The methodology is based upon source data which relates to trains operating over ballast track. The Figure shows that the methodology is effective in modelling the VDVs recorded over tunnels which also contain ballast track. Conversely, the methodology results in substantial over-estimations when applied to tunnels that contain non-ballast track-forms. This lack of transportability occurs because the frequency content of the vibration generated by the two different trackforms is very different and this difference cannot be accounted for using overall correction factors.

Figure 6 shows the same data but modelled using a predictive methodology which predicts eVDVs using ⅓ octave band vibration levels. Comparing Figures 5 and 6 it is clear that this type of methodology is more adept at modelling the vibration from a range of different railways than its simpler counterpart. Another example of where problems can occur using a simple overall VDV methodology, is predicting the VDV on a floor of a proposed property based upon measurements obtained from the site before development.

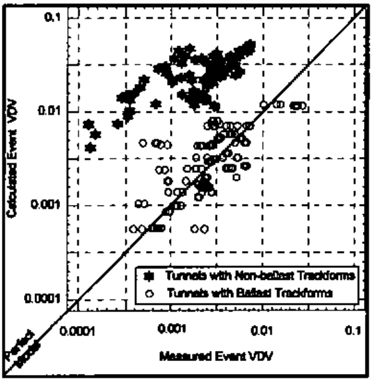

FIGURE 5: ACCURACY OF SIMPLE MODEL (eVDVs NOT NORMALISED FOR TRAIN LENGTH)

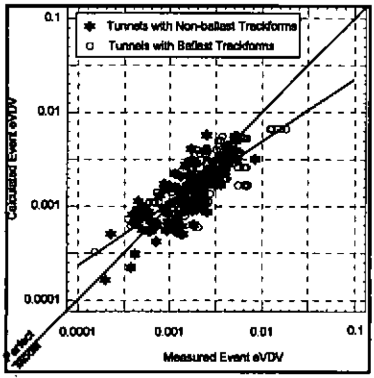

FIGURE 6: ACCURACY OF 1/3 OCTAVE MODEL (VDVs NORMALISED FOR TRAIN LENGTH)

4. CONCLUSIONS

The prediction of groundborne vibration from railways remains a "black science". As a result care should be exercised in selecting an appropriate methodology when predicting the potential vibration for a new or revised railway scheme.

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