PREDICTING GROUNDBORNE RAILWAY NOISE AND VIBRATION IN BUILDINGS: A COMPARISON OF MEASUREMENTS AND METHODS

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1 INTRODUCTION

Noise and vibration from railways are well known to affect nearby buildings and their occupants, causing sleep disturbance, work interference and annoyance[1]. Where trains run in tunnels, the main consideration is groundborne noise, and, to a lesser extent, feelable vibration. However, it is very difficult to predict such levels of noise and vibration accurately due to the many different physical mechanisms involved (see Fig. 1), and the wide variations in building types.

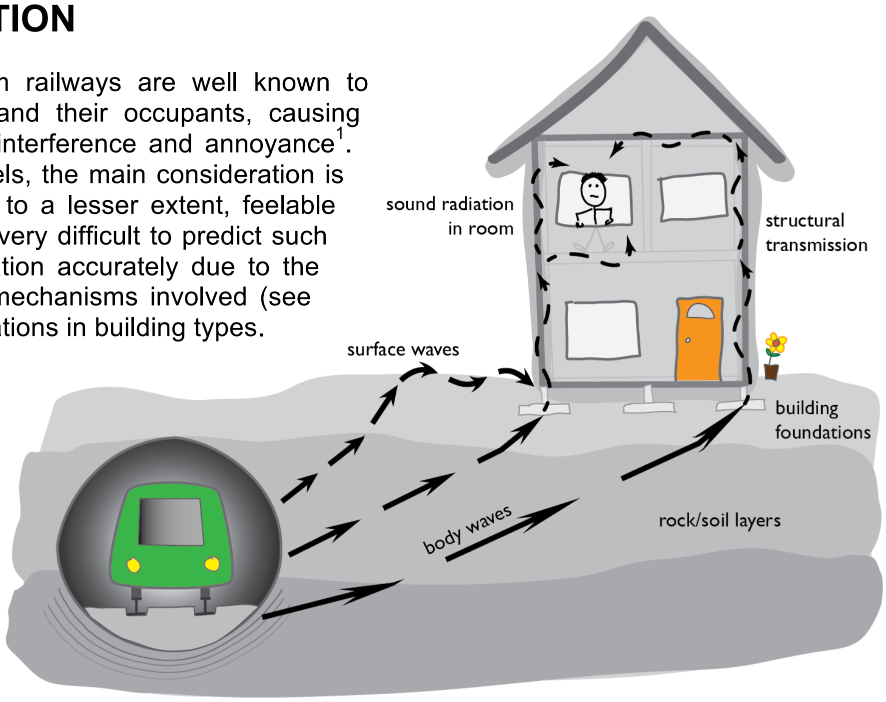


Figure 1. Sketch representation of groundborne noise and vibration propagation

Whilst some empirical guidance is available[2,3], predictions are nevertheless subject to a large uncertainty, which limit their usefulness. In addition, there is very little guidance on how design changes to buildings might improve or worsen the situation. This usually results in overdesign of mitigation measures such as track or building isolation systems.

The problem has been approached through the development of 3D finite element (FE) models for detailed study of the influence of structural parameters on vibration levels[4]. However, measurement data for individual buildings is usually limited to a small number of locations, which makes model updating unrealistic. Therefore, measured data from a number of different buildings has been collated and their general trends and variability is studied. These results are used for comparison with the results of the prediction models. The opportunity has also been taken to compare the predicted data to other, simpler models.

2 PREDICTION APPROACH BACKGROUND

2.1 Empirical Models

The primary reference for predicting groundborne railway noise and vibration in buildings is Chapter 16 of the Transportation Noise Reference Book (TNRB)[2]. This advises that the range of attenuation per storey in a building is frequency dependent, typically 2 to 6 dB (16 to 250 Hz, see Fig. 2); mid-span floor amplification may be up to around 14 dB (see Fig. 3).

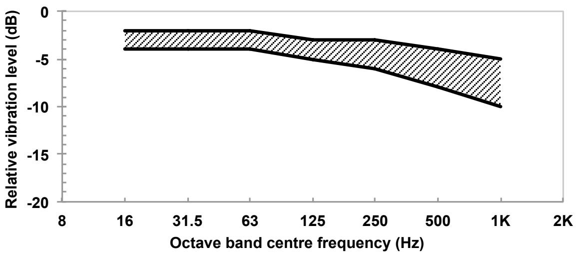


Figure 2. TNRB inter-storey attenuation

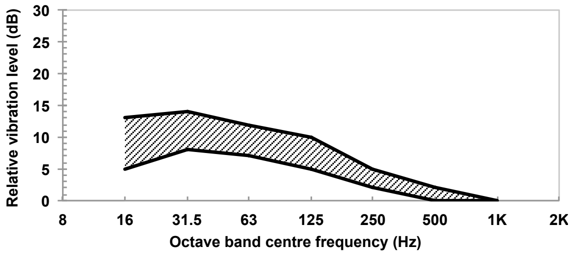


Figure 3. TNRB mid-span amplification

The Federal Transit Administration (FTA) guidelines for noise and vibration impact assessment[3] advise that 2 dB of vibration attenuation should be expected per storey for the first five floors, and 1 dB of attenuation for upper storeys. It is also suggested that amplification of around 6 dB may be expected near the resonance frequencies for building elements such as floors and walls.

2.2 Mathematical Models

Suitable mathematical models typically comprise either analytical or numerical methods. Analytical approaches use equations to describe the dynamics of the whole system albeit with a number of assumptions and approximations necessary for simplification. Analytical approaches are fast to run and imply a good understanding of the underlying physical principles involved. Because of the complexity of the equations required, analytical approaches are, however, best suited to simple structures and scenarios.

For more complex structures, numerical solutions are sought, usually through FE techniques. This involves discretisation of the structure into a mesh, with the dynamic system solved in terms of its mass and stiffness matrices. In all mathematical modelling approaches, assumptions are required about the boundary conditions, as well as any connection restraints. In addition, the material properties must be correctly specified.

3 MEASUREMENT DATA

For assessment of prediction accuracy, it is necessary to compare any predictions against measured data. It is reasonable that the accuracy of predictions should be assessed for a number of storeys up the building.

Historical data from a number of measurements has been collated for several concrete frame buildings in London, UK. Measurements were undertaken mostly within the last few years, with the exception of one building for which measurements were undertaken in 1991. In all cases, the sources for the vibration measurements were existing underground railways. Data was analysed by splitting the time domain recordings into train pass-bys, and performing 1/3 octave band analysis (with a slow time weighting) on each resulting waveform.

The measured vibration levels at basement level are given in Figure 4 for twelve buildings, along with the calculated (arithmetic) average. These are given as vertical velocity levels in decibels, relative to 10^{-9} m/s. It is seen that the various sites exhibit a similar shape in the frequency spectrum, with broad peaks at around 10 Hz and 63 Hz. The upper peak is understood to be a feature of the coupled wheel/track resonance. The 10 Hz peak is deemed to coincide with an anti-resonance of the vehicle primary suspension[5].

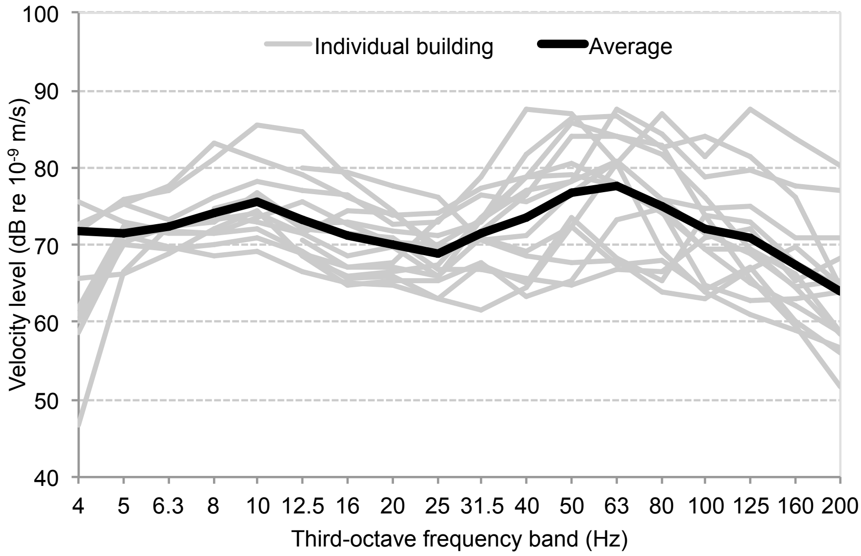


Figure 4. Measured basement vibration levels from twelve buildings

A-weighted vertical velocity levels at the middle of a floor span are understood to correlate with measured noise levels within affected rooms[6-8]. This comes from the understanding that the radiated sound power from a vibrating surface is related to the vibration velocity and radiation efficiency of the surface, as given by Equation 1. When the radiation efficiency is assumed to be constant with frequency, the A-weighted velocity level is therefore directly related to the A-weighted sound pressure level.

$$W_{\mathrm{rad}} = \rho_0 c_0 \sigma S \langle \overline{v^2} \rangle \qquad \text{(Equation 1)}$$

where:

W_{rad} is the radiated sound power, in Watts;
ρ_0 is the density of air, in kgm^{-3};
c_0 is the speed of sound in air, in ms^{-1};
σ is the radiation efficiency of the plate;
S is the surface area of the plate, in m^2;
$\langle \overline{v^2} \rangle$ is the spatially averaged mean-square velocity of the plate, in ms^{-1}.

Figure 5 gives the mid-span A-weighted vibration data relative to the basement at each storey for each of the buildings. An average of the relative values over the first six storeys is also given. Note that the average is calculated from the frequency data rather than directly from overall A-weighted levels, and assumes that the vibration at basement level is given by the average spectrum given in Fig. 4. There is a significant spread in the measured data, particularly in the transition between basement and ground floor, probably due to the influence of special floor constructions at basement and ground floor levels. The average A-weighted levels are seen to exhibit an attenuation of approximately 1 dB per storey.

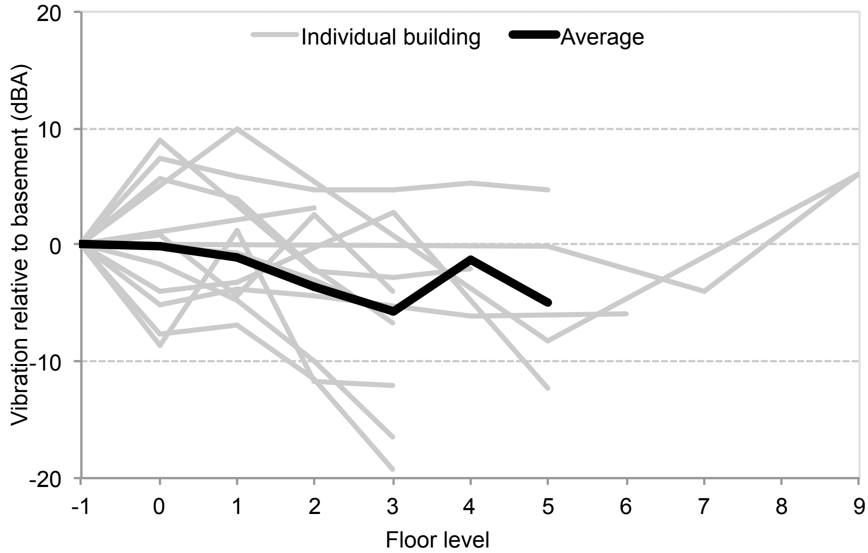


Figure 5. Measured vibration relative to basement, mid-span expressed as overall A-weighted level

The mid-span vibration levels at 3rd floor are given in Figure 6, relative to basement vibration. The peaks noted in the measured spectra in the 6.3 to 16 Hz region are due to natural frequencies of the floor slabs, and it should be noted that the averaging procedure excludes these effects to a considerable degree, which would be an important factor when considering the assessment of perceptible vibration.

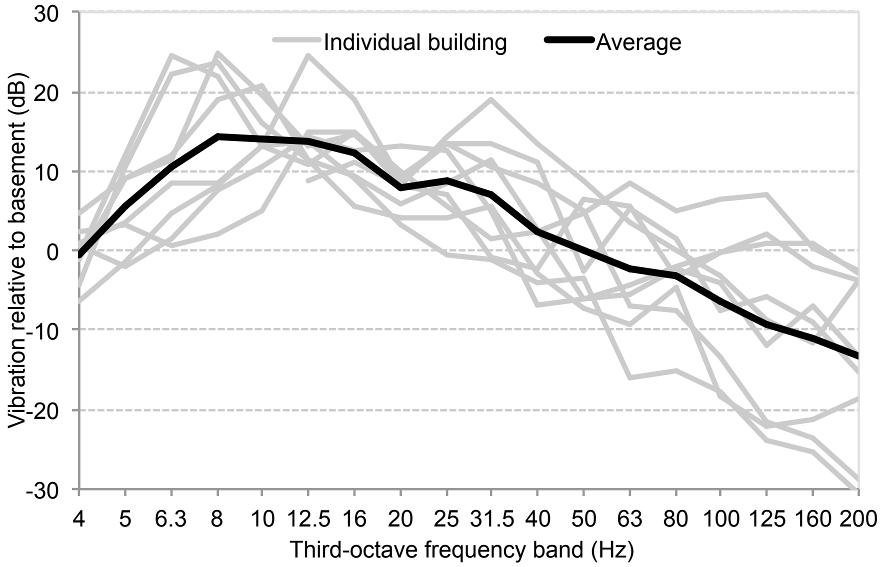


Figure 6. Measured 3rd floor vibration relative to basement, mid-span

4 COMPARATIVE MODELLING RESULTS

4.1 Model Parameters

For comparison of various modelling approaches, a portal frame is assumed for a generic building with the parameters as given in Table 1. For each model, vertical velocity was evaluated for the floor surfaces near all columns and at all mid-span positions, converted to 1/3 octave band values, and averaged (where applicable) for each storey. The ground is not included, but the building is excited by a known force over its base (with a vertical magnitude twice that of the horizontal directions) and the results are expressed as transmissibility from basement to other storeys. Each model was solved for 1301 frequency points from 3 to 200 Hz, spaced to give finer resolution at the lower frequencies.

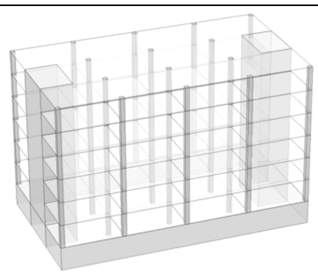
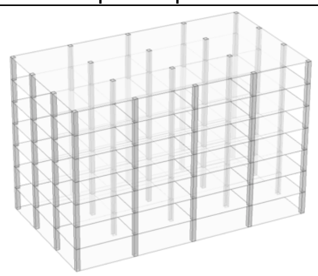
Table 1. Generic building model portal frame parameters

Parameter	Value
Number of storeys	Six, plus a basement
Column	Square cross section, side length 0.5 m
Floor slab dimensions	8 x 6 x 0.27 m
Ceiling height	3 m
Number of floor slabs per storey	4 x 3
Young's modulus of concrete	27 GPa
Density of concrete	2300 kgm^{-3}
Material damping (loss factor)	0.05

4.2 3D FE Models

Prediction of building dynamics using 3D FE techniques is the most computationally intensive approach considered, but given appropriate input parameters should provide the most accurate prediction. Three models with differing levels of complexity are considered as shown in Table 2. For reference, the number of degrees of freedom (DoF) and calculation time are also given.

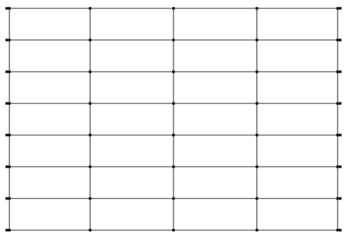
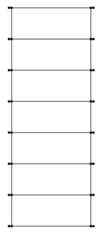
Table 2. 3D FE model description

Full model with structural shafts	Full simplified portal frame	Single 1 x 1 portal frame
		
DoF: 224,250 Calculation time: ~18 hours	DoF: 245,910 Calculation time: ~24 hours	DoF: 21,642 Calculation time: 2 hours

FE modelling was performed using COMSOL Multiphysics running on a high specification desktop computer (Intel i7 3.1 GHz quad-core processor with 16GB RAM). For each model, the columns were modelled as solids (tetrahedral mesh) and the walls and floor were modelled as shells (triangular mesh). Quadratic elements were used, with a maximum size of 1.5 m, sufficient to account for bending wavelengths in the frequency range of interest (up to 200 Hz)[9]. The edges were assigned free boundary conditions.

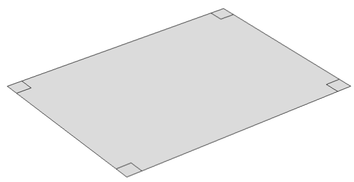
4.3 2D FE Models

2D FE analysis is considerably less computationally intensive than its 3D counterpart, due to the reduced number of degrees of freedom required. Table 3 shows the 2D models considered. The frames are modelled with beam elements, with appropriate cross-sectional parameters. Each of the models assumes a span of 8 m for each floor.

Table 3. 2D FE model description	
4-bay model	Single bay model
	
DoF: 1011 Calculation time: ~ 1 min	DoF: 612 Calculation time: 1 min

4.4 1D FE Models

A simple 1D FE analysis is also considered in which the building is represented by a sequence of point masses representing the floors, connected by rods representing the columns. This model does not allow for the inclusion of any amplification at mid-span locations. This has been accounted for by assuming weak coupling between the 1D model and a simply supported plate, thereby applying the calculated mid-span amplification to the results at each point mass. Whilst this approach has been performed using FE methods, it would be straightforward to implement through an analytical approach.

Table 4. 1D FE model description	
1D model	Weak coupled 3D plate model
	
DoF: 87 Calculation time: ~ 15 s	DoF: 2910 Calculation time: ~ 25 min

4.5 Empirical Models

For comparison, the empirical method given in TNRB[2] is also included, taking the midpoints of the ranges of values suggested therein.

4.6 Results

The predicted vibration levels from each of the models have been calculated relative to the basement, in 1/3 octave bands. Overall A-weighted levels were also calculated, by normalising the vibration values in the basement to the average measured frequency spectrum given in Figure 4 and then these are expressed as relative levels compared with the basement.

Figure 7 shows the resulting predicted relative vibration level at mid-span locations. 1/3 octave band results for the 3rd floor are shown in Figure 8. It is clear that the average building response is best represented by the 2D and 3D FE prediction models although there are differences in the frequency spectra.

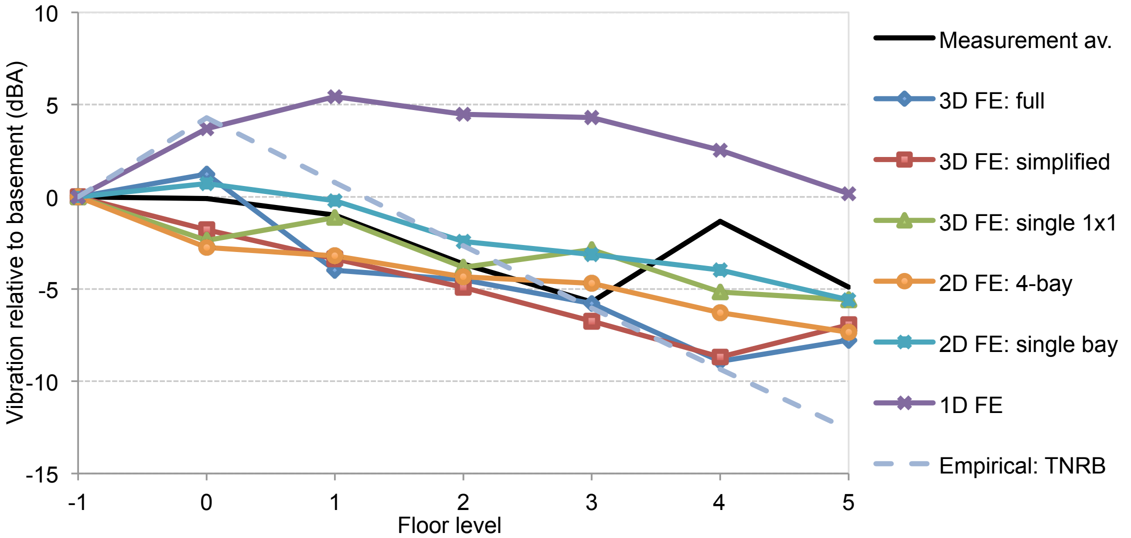


Figure 7. Predicted vibration relative to basement, mid-span

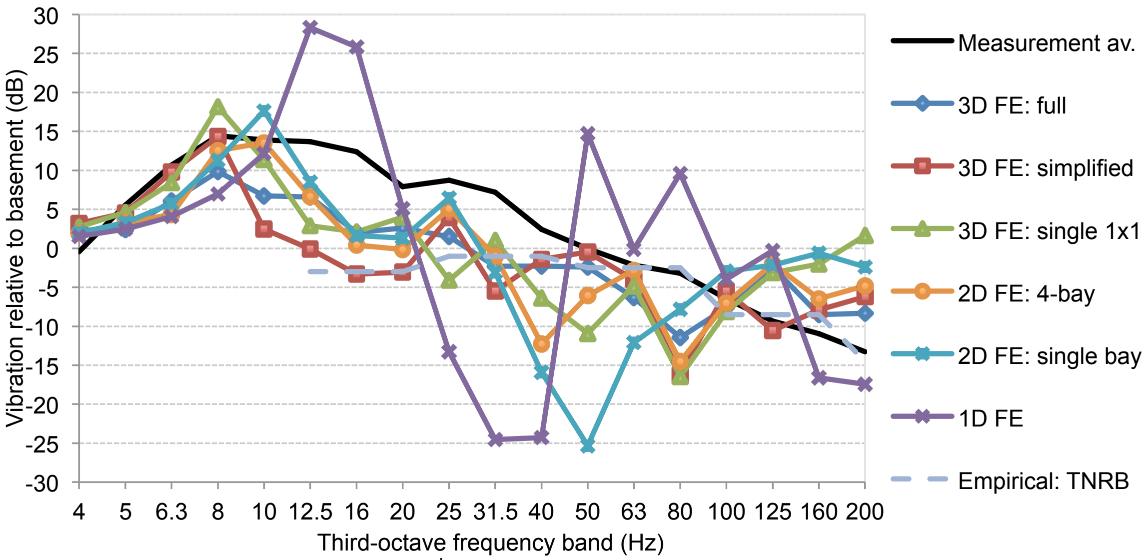


Figure 8. Predicted 3rd floor vibration relative to basement, mid-span

4.7 Discussion

The results shown in Fig. 7 indicate that for the A-weighted vibration levels, the 2D and 3D FE models give similar results, and show trends similar to the average measured results with an approximate attenuation of around 1 dBA per storey. The 1D FE and empirical predictions give results that show somewhat less agreement with the trend observed for average measurements.

When considering the frequency band data shown for 3rd floor in Fig. 8, the 2D and 3D FE models again give similar results, although the peaks in these results around 8 to 10 Hz (due to floor natural frequencies) are much more pronounced than seen in the average measurement results. In addition, the peaks for the larger FE models also appear to be less prominent compared to those with only a single floor span in the horizontal plane. This is due to averaging of results from different positions over a given storey for the larger models, where the dynamic response of floor slabs depends on the boundary conditions at their edges.

In general the 2D and 3D FE models show close enough agreement to the average measurement trends. They can therefore be considered suitable for parametric study in order to investigate the effect of structural parameters on vibration levels.

5 CONCLUSIONS

A study comparing the results of a number of groundborne railway noise and vibration measurements with several prediction models has been undertaken, with a focus on reinforced concrete frame buildings in London, UK.

The measured results show a significant amount of variability, particularly between basement and ground floor, but the average A-weighted vibration undergoes attenuation with each storey of about one decibel.

In the comparison of the various prediction models, for the A-weighted vibration the 2D and 3D FE models give results closest to the measured average, and when considering individual frequency bands, there appears to be benefit in using full 3D FE models.

The research has also brought to light the variability in measured and model data, particularly at low frequencies and even within the same storey. This occurs due to the variation in floor slab dynamic response, which depends on boundary conditions. However, when averaging over different buildings, and/or over many different locations on a given storey, the significance of these natural frequencies tends to be suppressed in the results, and as such, results based on averaged data should be interpreted with care.

6 REFERENCES

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