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VIBRATION PREDICTION FOR HIGH SPEED TRAINS UTILISING THE PIPE IN PIPE (PIP) MODEL TO DETERMINE GROUNDBORNE NOISE LEVELS IN THE VICINITY OF DIFFERENT TUNNEL TYPES: MODEL VALIDATION

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A further iteration of validation of the Pipe in Pipe software for high speed train vibration prediction has been carried out to extend the prediction methodology to high speed trains operating on the HS2 line in the UK. Vibration measurements were carried out at a number of locations above both bored tunnels and cut and cover tunnels on the HS1 line and European high speed railways for a range of train speeds. The aim is to extend the prediction methodology to the HS2 line which when operational would operate at speeds of up to 360 kph. The paper describes the measurement and analysis methods which were employed and the extent to which the software and methods developed can be relied upon for the prediction of vibration and groundborne noise.

Keywords: groundborne noise, vibration, high-speed rail

1. Introduction

This paper extends ACCON’s work with the Pipe in Pipe software, which we have previously utilised to predict vibration from underground construction trains on the Crossrail project [1]. The paper describes the vibration measurement and prediction method utilised to develop a reliable fast vibration prediction methodology for high speed trains travelling in tunnels, building on some initial published work [2]. The aim of this work has been to further develop the software such that the model can be utilised for predictions of vibration from HS2 train pass-bys with a reasonable degree of confidence. In this way impacts related to groundborne noise and vibration can be assessed for receptors above and to the side of tunnels for a range of tunnel configurations and tunnel depths.

2. Pipe in Pipe Model

The Pipe in Pipe (PiP) [3] model developed by Hunt and Hussein determines the vertical displacement due to a moving train within a tunnel embedded in a half space. The model adopts thin shell theory for the inner pipe, representing the tunnel, and elastic continuum theory for the outer pipe that represents the surrounding soil. The displacements arising due to the forces between the wheel-rail interfaces are determined by modelling the track system as a double beam system. The track is coupled to the tunnel-soil system by utilising the frequency response function of the double beam and tunnel soil systems. The source displacement is then utilised in conjunction with Green’s function for a half space in order to allow the vertical displacement at the surface to be determined. The principal parameters of the PiP model are shown diagrammatically in Fig. 1.

The PiP model was developed to predict vibration for trains operating on floating slab track. However, for this project other track configurations (i.e. ballast and sleepers) were modelled by altering the mechanical input properties of the slab and slab bearing. The PiP model is consistent with ISO

14837-1: 2005 ‘Mechanical vibration - Ground-borne noise and vibration arising from rail systems’ [4]. The model considers the necessary parameters such as train speed, unsprung mass, mechanical properties of the rails and rail support system, together with soil conditions and tunnel depth.

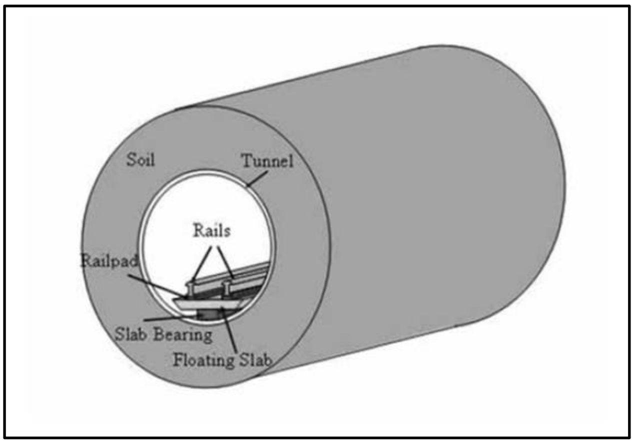

Figure 1: Pipe in Pipe Model arrangement.

The force generated by the wheel-rail interaction is dependent on the rail roughness. PiP calculates the vertical displacement using one of three rail roughness profiles representing the source excitation. The power spectral density for the track condition is calculated using the following equation developed by Frederich [5, 6]:

$$S_{in}(\omega) = \frac{1}{2\pi} \frac{av^2}{(bv + \frac{\omega}{2\pi})^3} \tag{1}$$

where v is the velocity of the train, a is the track unevenness and b is the track waviness. Values for a and b were derived by Frederich for track conditions stated as “good, average or bad”. As the rail roughness for the tracks used for the vibration measurements is unknown, an “average” rail roughness profile has been used for the model validation exercise. This approach has appeared to be realistic as the modelled and monitored vibration levels are in relatively close agreement.

3. Measurement Study

ACCON UK has conducted two measurements surveys obtaining simultaneous speed and vibration measurements above and to the side of tunnels for high speed train movements. Firstly, measurements were obtained in the UK along the High Speed 1 route between London St Pancras and Ashford International where Class 373 Eurostar trains were operating with maximum line speeds of 300 kph. The second survey was carried out on the German railway line between Munich and Nuremberg. On this line ICE2 trains operate up to 280 kph and ICE3 trains operate up to 300 kph, although the results presented here are only for ICE3 units. The measurement locations and tunnel types used in the study are summarised in Table 1, which includes the approximate depth of the tunnel below the measurement location, measured to the track bed. Three accelerometer positions were adopted at each location to capture vibration data directly above and to each side of the tunnel, offset by 10m to 20m.

Table 1: Vibration measurement locations.

HS1 survey			ICE survey		
Location	Tunnel Type	Depth	Location	Tunnel Type	Depth
H2	Cut & cover	9	I1	Cut & cover	13
H4	Cut & cover	10	I2	Bored	17
H5	Cut & cover	10	I3	Bored	14
H6	Bored	22	I4	Bored	24

3.1 Measurement methodology

The measurement system utilised for the vibration monitoring was a Rion DA-20 data recorder with high sensitivity Lance accelerometers mounted on ground spikes to a depth of 20cm. The data obtained from the measurement surveys was analysed using Prosig DATslite software to determine the vibration velocity from each pass-by.

Examples of results from the measurement locations are presented in Figs. 2 & 3 below. The results have been converted to estimated groundborne noise levels to represent estimated noise levels within dwellings constructed at the measurement locations. The groundborne noise level is determined by subtracting 27 dB from the vibration velocity in decibels, according to the formula derived by Kurzweil [7].

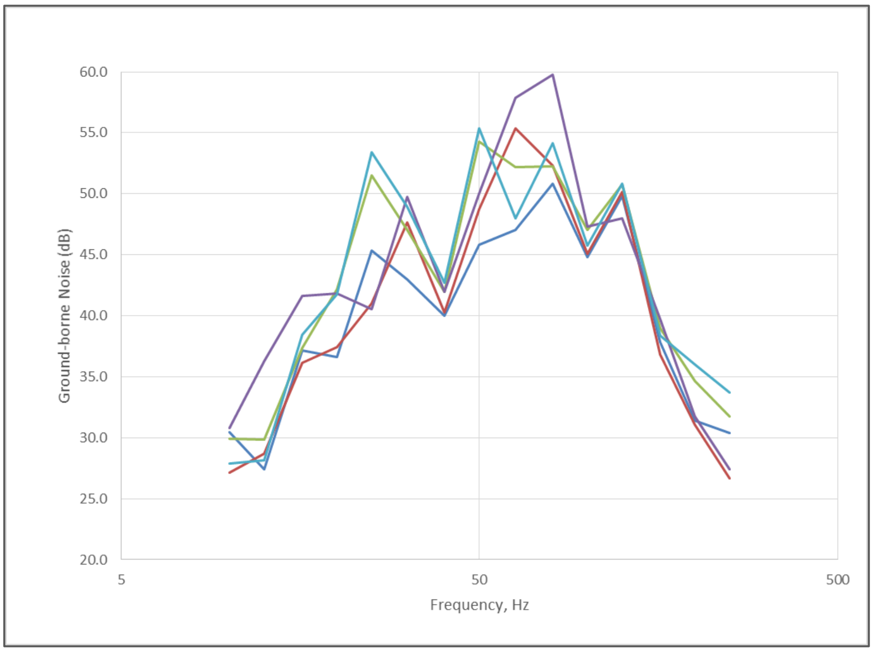

Figure 2: Measurement results - Location H6, Class 373 speeds 280-300 kph

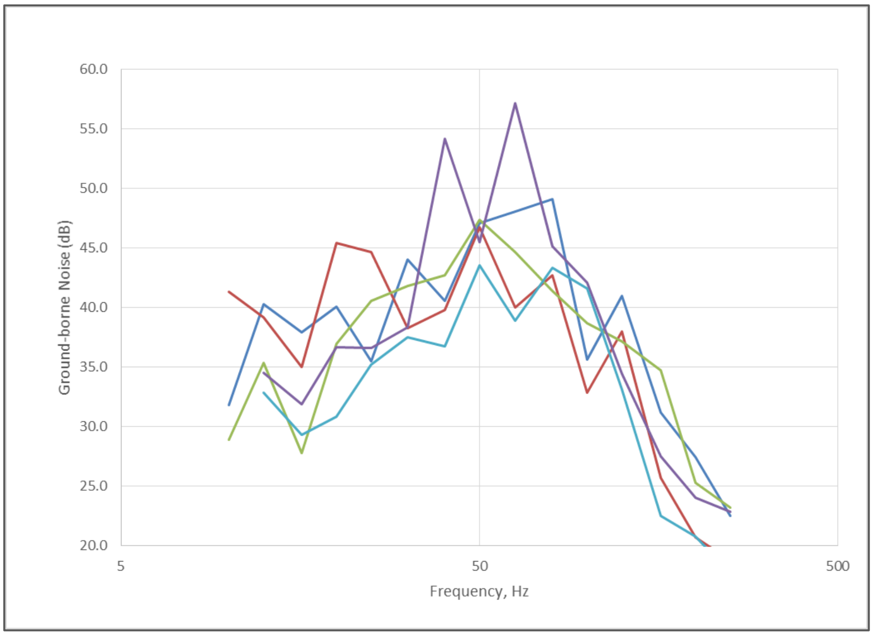

Figure 3: Measurement results - Location I2, ICE3 speeds 240-280 kph

It can be seen by reference to Figs. 2 & 3 that reasonably repeatable vibration signatures were obtained, although these varied between measurement locations and the position of the accelerometer with respect to the tunnel, i.e. above the centre-line or offset.

4. Predictions using Pipe in Pipe

The Pipe in Pipe software has been employed to predict groundborne noise levels from trains passing through tunnels corresponding to the various sets of measurements. Sample results are displayed in Figs. 4 to 6. Each graph gives a set of measured data averaged from a number of similar train events and the corresponding predicted groundborne noise levels obtained from the PiP model. It should be noted that the calibration factors derived from the model validation, as described in Section 4.1 have been applied to the predicted values.

It can be seen from Fig. 4 that there is relatively close agreement between the predictions and measurements for location H6 which corresponds to Eurostar Class 373 trains operating in a bored tunnel of 22m depth. The differences between predicted and measured values are generally in the range 5–10 dB. In Fig. 5 the agreement is less pronounced for Class 373 trains operating in a cut and cover tunnel only 10m deep. As a cut and cover tunnel will behave less like a circular pipe, the poorer agreement is not unexpected. With reference to Fig.6, it can be seen that for ICE3 trains running within a 17m deep bored tunnel, the agreement between predictions and measurements is within a 5-15 dB margin across the main frequency range of interest. Although, the agreement is not as good as for the HS1 bored tunnel, it still represents a reasonable level of agreement for this type of model, given the inherent assumptions and uncertainties. It may be possible to achieve closer agreement for ICE3 trains with further refinement of the model inputs relating to the properties of the track mounting system and other input variables. It is also expected that the shallower the tunnel, the greater that any inhomogeneity in the soil may influence the differences between measured and predicted levels of vibration. This factor may have contributed to the variability in the results for both the HS1 cut and cover tunnel (Location H2) and the ICE3 bored tunnel (Location I2).

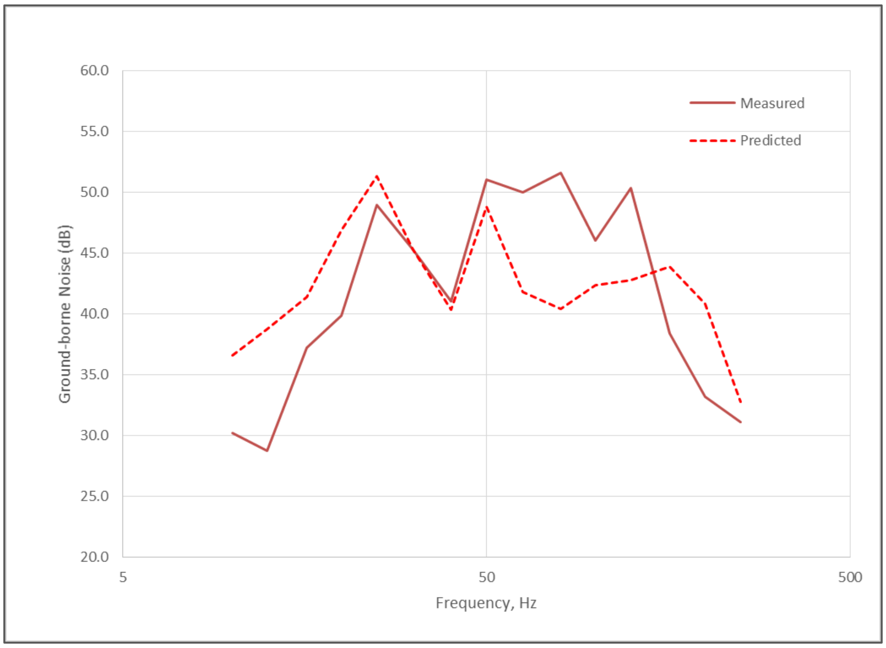

Figure 4: Model results - Location H6, Class 373 speed 280 kph.

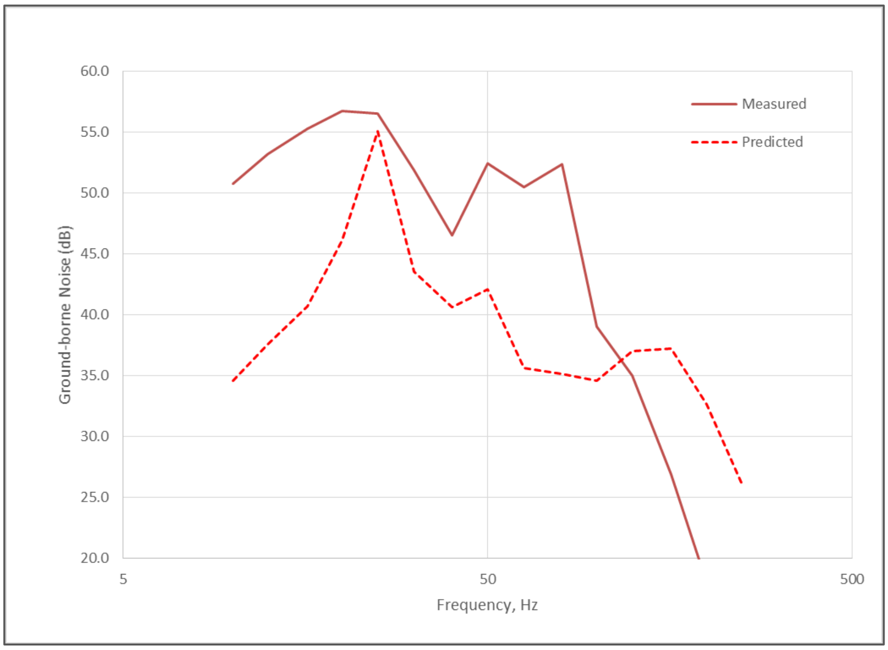

Figure 5: Model results - Location H2, Class 373 speed 290 kph.

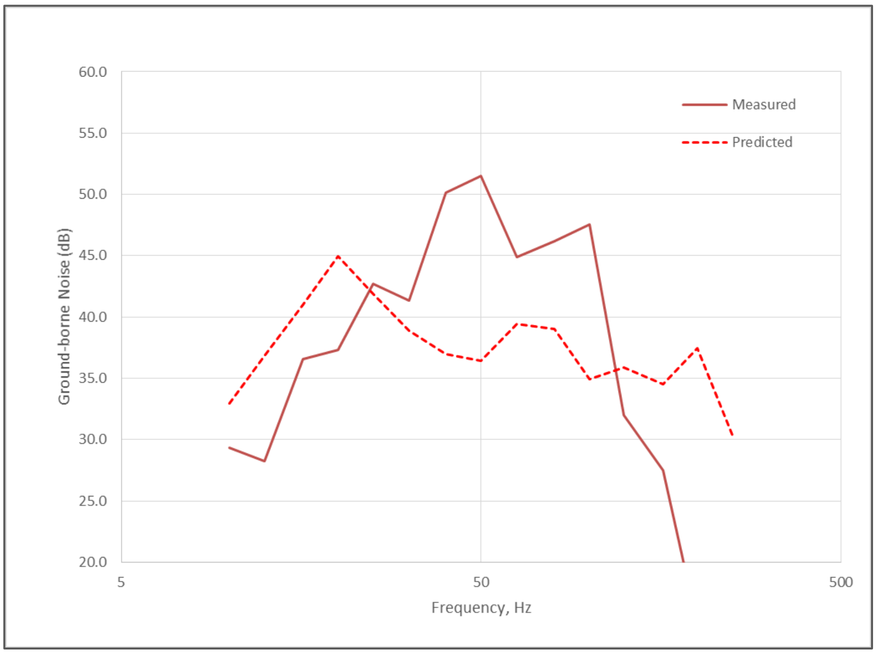

Figure 6: Model results - Location I2, ICE3 speed 270 kph.

4.1 Validation of the model

The calibration and validation of the model was carried out in line with requirements of ISO 14837-1. This involved the following steps:

a) Taking a set of vibration measurements at the ground surface above various high speed train lines;
b) Using the model to predict groundborne noise levels for corresponding scenarios to the measured data in terms of A-weighted noise levels;

c) Determining average differences between measured and predicted levels;
d) Using average differences to derive calibration factors for the model;
e) Carrying out a second set of calibrated model predictions; and
f) Performing a set of regression analyses of the predictions versus measured data.

Model predictions were carried out for each of the monitoring locations given in Table 1 (apart from location I1) for a range of train speeds corresponding to the speeds measured at the tunnel portal for the measured train events. The measurement results were grouped into speed bands with a range of approximately 10% in order to limit the number of PiP model runs.

An analysis of the average differences observed between the measured and predicted groundborne noise levels was used to derive calibration factors for the model applying to each speed, tunnel configuration and reception point. These calibration factors were then utilised to correct the predicted groundborne noise levels used in the regression analysis. The application of these calibration factors takes into account sources of uncertainty such as track condition, wheel condition and any inhomogeneity within the soil.

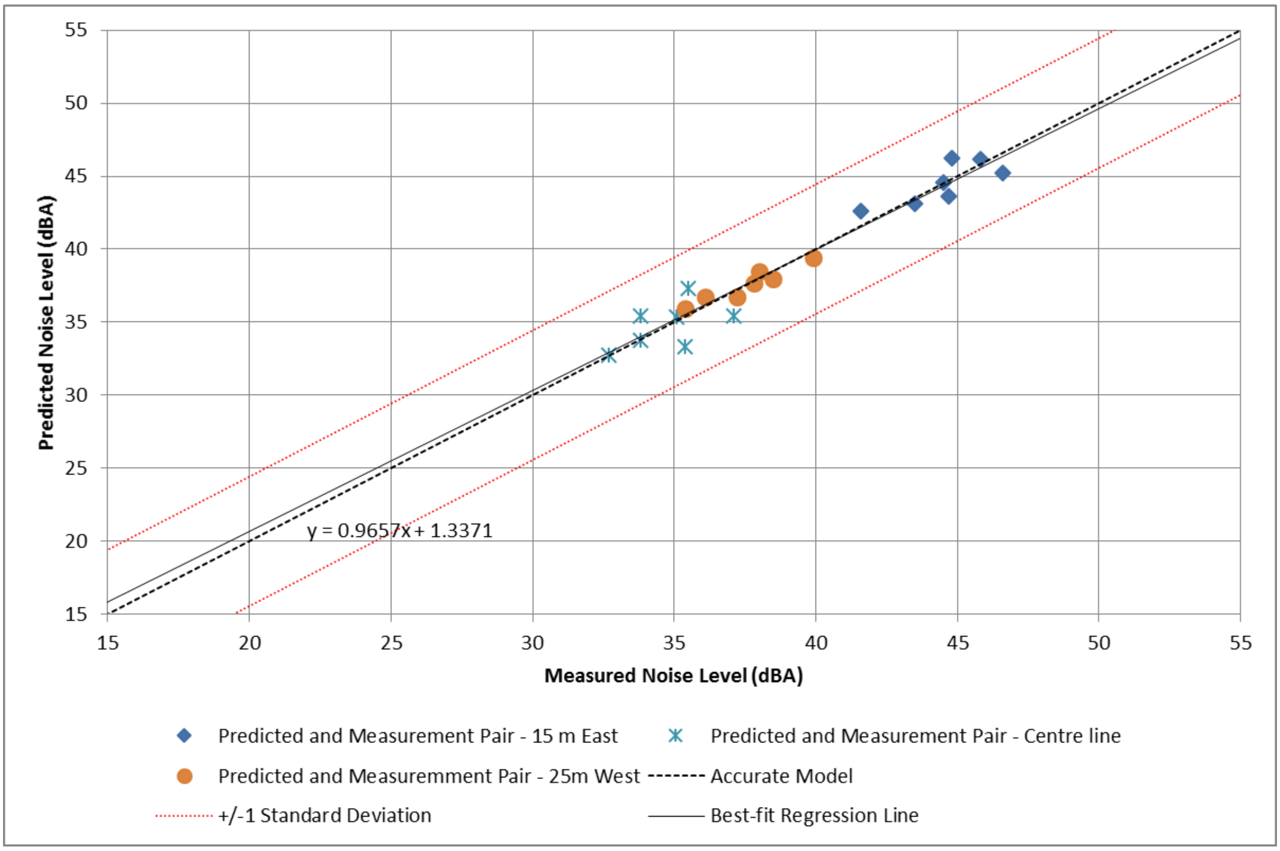

Figure 7: Model validation analysis – HS2 bored tunnel

Graphs showing the model validation regression analyses on the calibrated model results are given in Figs. 7, 8 and 9 and the resulting validation data is summarised in Table 2.

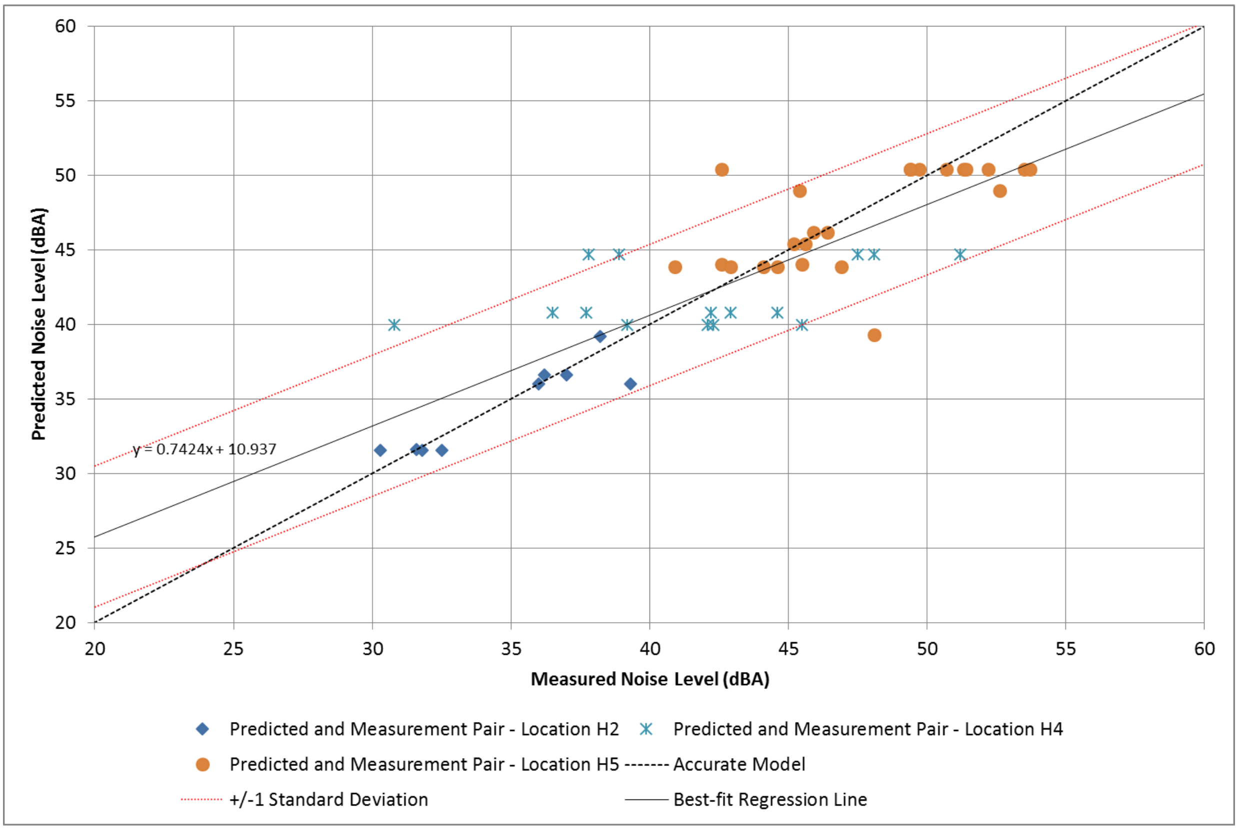

Figure 8: Model validation analysis – HS2 cut and cover tunnel

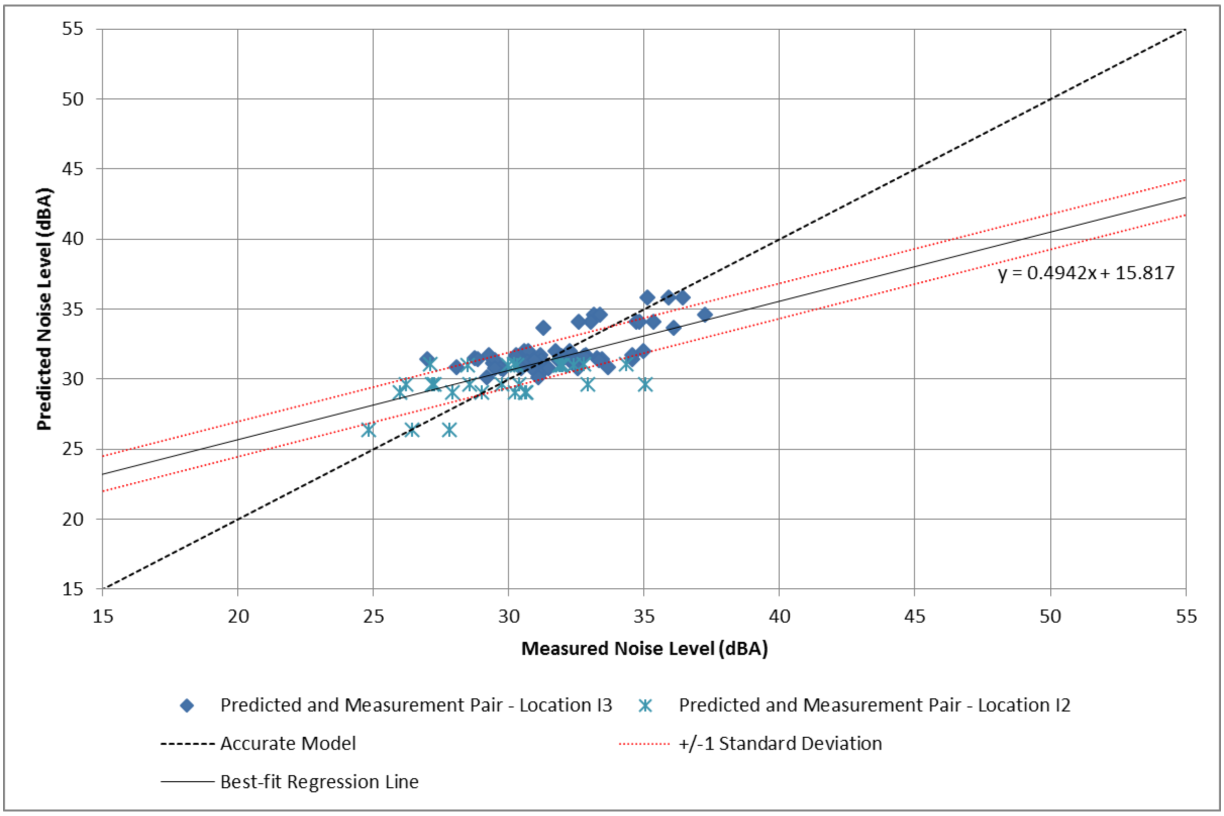

Figure 9: Model validation analysis – ICE3 bored tunnel

Table 2: ISO 14837-1 validation data

Data	HS1 Bored Tunnel	HS1 Cut & Cover	ICE Bored Tunnel[1]
Gradient	0.97	0.74	0.49
Standard Deviation	4.4	6.4	2.5
Offset	+ 1.3	+10.9	+15.8
Random Error	+/- 4.4	+/- 6.4	+/- 2.5

1. Only shallow bored tunnel locations used: I2 (14m) and I3 (17m).

The results in Table 2 confirm the indications observed from the graphs of measured versus predicted groundborne noise levels. The systematic error of the model is represented by the difference between the best fit regression line and the “accurate model” line; and the random error by the range between the +/-1 standard deviation lines. It can therefore be seen that the PiP modelling for the HS1 bored tunnel shows the closest agreement with measurement results, from a combination of a gradient of the best-fit regression line approaching unity and a random error of +/- 4.4 dB. The combination of the gradients of the regression lines, offsets and standard deviations for the other two validations show lesser levels of agreement. The likely reasons behind the varying levels of agreement between the calibrated PiP results and the measured data are discussed above in Section 4.

5. Conclusions

The findings of this study show that predictions of vibration or groundborne noise from different high speed train types operating at speeds in the range 200-300 kph can be obtained using the PiP model with a reasonable level of accuracy. The closest agreement between predictions and measurements were obtained for measurements above a section of HS1 bored tunnel approximately 22m deep. The modelling required adjustment of the PiP input parameters as the PiP model is currently only configured for tunnels with floating slab track. It is noted that the combined influence of the various mechanical properties of the train, soil, tunnel, track and track mounting have a larger influence on the predicted levels of vibration than the speed of the train. Based on this and the results obtained from the study, there are no reasons why employing these techniques to model groundborne noise from trains operating at speeds above 300 kph would prove less accurate. On this basis, the adjusted PiP model could be employed to predict groundborne noise from trains operating on HS2 at speeds of up to 360 kph.

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