The influence of the vehicle body on the sound radiation from the rail

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Abstract. Numerical models and vibro-acoustic measurements are used to assess the effect of reflections from the underside of a railway vehicle on the sound radiation from the rail. A 2D boundary element model is used in which the rail vibrates uniformly in either vertical or lateral directions; various different shapes of vehicle body are introduced into the model. Measurements are performed on a 1:5 scale model and on a full-size track with and without a metro vehicle. The presence of the vehicle primarily affects the sound pressure from the vertical vibration of the rail, with negligible effect for the lateral vibration. The vehicle body reflects the sound back down towards the track where it is partly absorbed by the ballast, reducing the sound power. Nevertheless, the sound pressure at the trackside is increased by 0-5 dB and in some frequency bands by up to 9 dB. Finally, it is shown that the sound radiation in the presence of the vehicle can be approximated reasonably well with simple line source formulae.

Keywords: Rolling Noise, Sound Radiation, Reflections, Boundary Element.

1 Introduction

Generally, in modelling rolling noise, which is radiated by vibration of the wheels and track [1], the presence of the vehicle on the sound radiation is neglected. In practice, the sound radiated by the rail is reflected and scattered by the train body located above it. As a result, the radiated sound may be altered to some extent, depending on the geometry and the type of track. Moreover, measurement methods to separate wheel and track noise are being developed in which it is desirable to measure the track vibro-acoustic transfer functions without the vehicle present [2, 3]. Corrections may therefore be needed to allow for the effect of the vehicle.

The aim of this work is to quantify the influence of the vehicle body on the vibro-acoustic transfer functions for different situations, including various generic train bodies and typical tracks. The findings can be used to support suitable adjustments for the prediction or measurement of track noise without the need for the vehicle to be present.

2 Numerical model

The two-dimensional (2D) boundary element method (BEM) is used, making use of an in-house software WANDS (wave number domain software). The rail is assumed to vibrate uniformly over its cross-section; a unit velocity is applied in either the vertical or lateral direction. An engineering approach is used to account for the acoustic effect of the periodic support of a ballasted track [4]. This separates the cases of the rail 'above ballast' and 'attached to sleeper' into two 2D calculations. These are then combined, based on a weighted average of the results from the two cases. The absorptive effect of the ballast is simulated by applying an impedance to the boundary elements based on the Delany-Bazley model. The further effect of reflections from the ground adjacent to the track is taken into account by adding the pressure at an image receiver. The track geometry used is shown in Fig. 1.

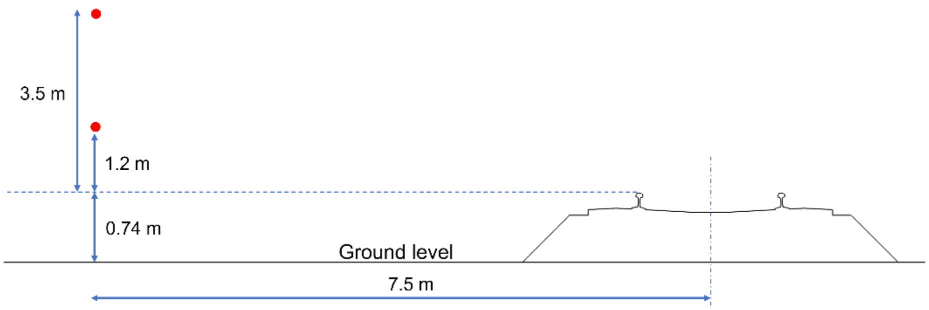


Fig. 1. Geometry used for BEM model of track.

Fig. 2 shows the sound pressure level for a unit vertical or lateral velocity, with or without a rigid ground. Compared with typical results for a point source, the effect of the ground is reduced by shielding at the ballast shoulder and tends to zero at high frequency. This 2D model will be used below in combination with various vehicles.

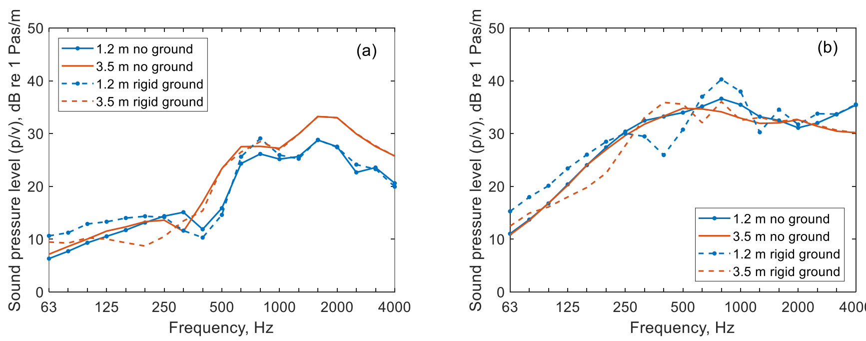
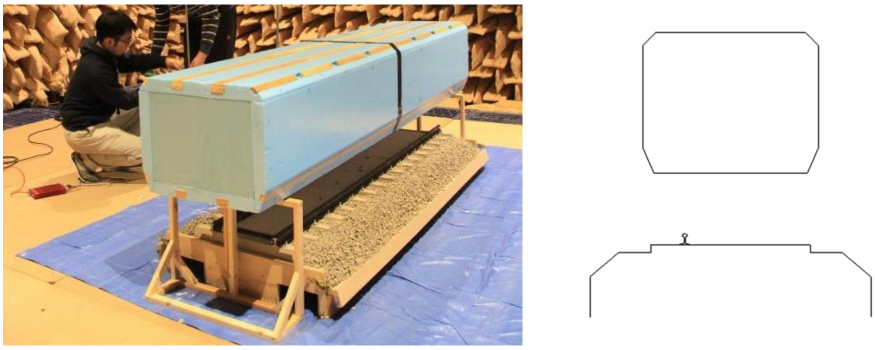


Fig. 2. Sound pressure from the rail for unit velocity at 7.5 m from track centreline and different heights, with and without rigid ground. (a) Vertical rail vibration; (b) lateral rail vibration.

3 Comparison with measured results

3.1 Scale model tests

Laboratory measurements have been carried out on a 1:5 scale model of a ballasted track with a mock-up of a vehicle body (see Fig. 3). A reciprocal method is used to determine the transfer function from a point force on the rail to the sound pressure at the scaled positions shown in Fig. 1 [6]. The results are presented as the level difference (or insertion loss) of these transfer functions, with and without the vehicle present.



(a) (b)

Fig. 3. Scale models studied in the measurements. (a) Ballasted track and vehicle body; (b) cross-section of model for normal vehicle height.

In Fig. 4 the measured results are compared with predictions from the BEM model and plotted against frequencies corresponding to full scale. For the lateral direction the vehicle has negligible effect on the sound pressure level in both the measured and predicted results. For the vertical direction it gives a slight increase above 500 Hz and there is a stronger increase around 300 Hz in the predictions. The measurements are not shown at low frequencies as they were affected by background noise.

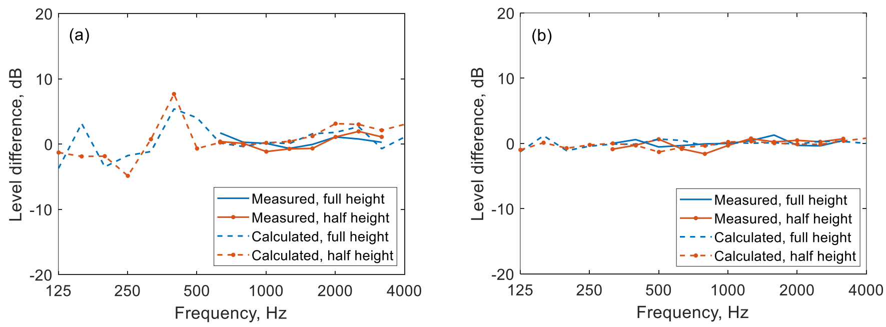


Fig. 4. Level differences due to presence of the vehicle from measurements and BEM calculations for 1:5 scale model metro train (near rail) at the receiver position of (1.5, 0.24) m; frequencies shown are for full scale. (a) Vertical vibration; (b) lateral vibration.

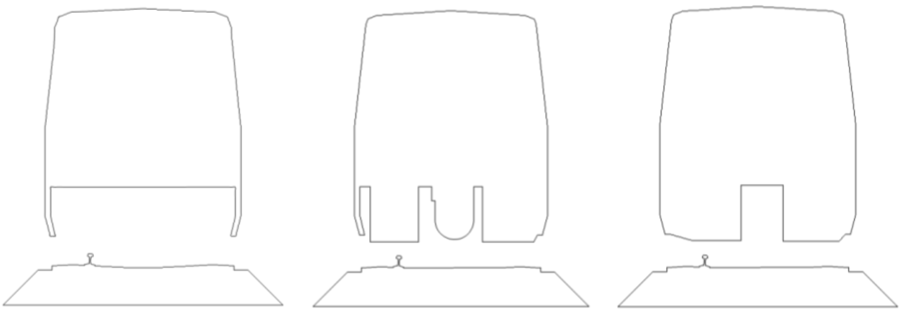
3.2 Full scale tests

Transfer function measurements were carried out at Metro de Madrid (MdM) [5] using both direct and reciprocal methods. In the direct method the track was excited with an impact hammer (Fig. 5(a)) and the force on the rail and resulting sound pressure at the trackside were measured. In the reciprocal method an omnidirectional sound source with known volume velocity was used at the trackside and the rail response was measured with an accelerometer. Two sound sources, shown in Fig. 5(b), were used to cover low and high frequency ranges.

(a) (b)

Fig. 5. Photos of the static measurements at MdM. (a) Impact hammer; (b) high frequency (left) and low frequency (right) sound sources exciting the track with train in position.

As the vehicle geometry is not invariant along its length, several different cross-sections of the vehicle are introduced above the ground in the BEM model, as shown in Fig. 6.



(a) (b) (c)

Fig. 6. Vehicle models used to represent MdM vehicle in the 2D BE model. (a) Section A, with fairings and no equipment; (b) Section B, with equipment; (c) Section C, with equipment.

Fig. 7 compares the measured and predicted level differences for the microphone position at 7.5 m from the track and 1.2 m height above the rail. Three measurements are included, one direct measurement and two reciprocal ones at different positions. BEM calculations are shown for the three different cross-sections of the vehicle shown in Fig. 6 but these produce similar results.

For the lateral rail vibration, the predicted results are again close to 0 dB and the measurements above 300 Hz are between 0 and +2 dB. For the vertical direction there is more variation with frequency and between the different measurements. The predicted sound pressure is increased in most frequency bands by 0-5 dB, but this tendency is not seen for the measurements. Instead, the measured sound pressure in some frequency bands can be reduced by 5 dB or more or increased by up to 9 dB.

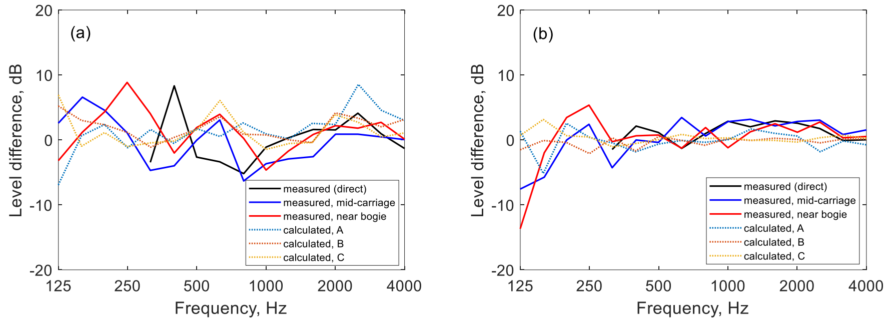


Fig. 7. The level differences due to presence of vehicle from the measurements and BEM calculations for a metro train (near rail) at the receiver position of (7.5, 1.2) m. (a) Vertical vibration; (b) lateral vibration.

3.3 Different vehicle shapes

Results have been calculated for full-size models with different train geometries, including those shown in Fig. 3 ('Model'), Fig. 6 (A, B and C), a high-speed train with a lower floor profile (HS) and two other models [5] (here labelled D and E). It should be noted that in each case in this section the sleeper spacing is set to 0.6 m, whereas it is set to 1 m in the previous section, as in the measurements. The effect of the different vehicle profiles on the sound power radiated from the rail is shown in Fig. 8. The sound power radiated from the rail is calculated by integrating the sound intensity at a radius of 15 m from the centre of the track for angles spaced 5° apart. For the vertical direction a consistent reduction of 2-6 dB is found above 200 Hz which can be attributed to the reflection of sound downwards towards the ballast. For the lateral direction the reduction in sound power level is 0-2 dB.

Fig. 9(a) shows the level difference in sound pressure due to the introduction of the vehicle for vertical vibration with no ground (or highly absorptive ground). Despite the reduction in sound power, there is an increase in the sound pressure level, at most frequencies by 0-5 dB and in some frequency bands by up to 10 dB; in other bands below 300 Hz there are reductions. The largest increases occur in the vicinity of the dip in the spectrum without the train, around 250 to 500 Hz (see Fig. 2(a)). There are differences between the various train designs but they each have the same trend. The train body makes little difference to the radiation from the lateral rail vibration (not shown).

The corresponding results in the presence of a rigid ground are shown in Fig. 9(b). The ground is located 0.74 m below the top of rail. As seen in Fig. 2, for the case without the train, the introduction of the ground leads to only small changes in the sound pressure due to vertical rail vibration. However, in the presence of the train the sound pressure level is increased as sound is reflected first from the underside of the train and then from the ground to the receiver. For the lateral direction the introduction of the train body again has little effect (not shown).

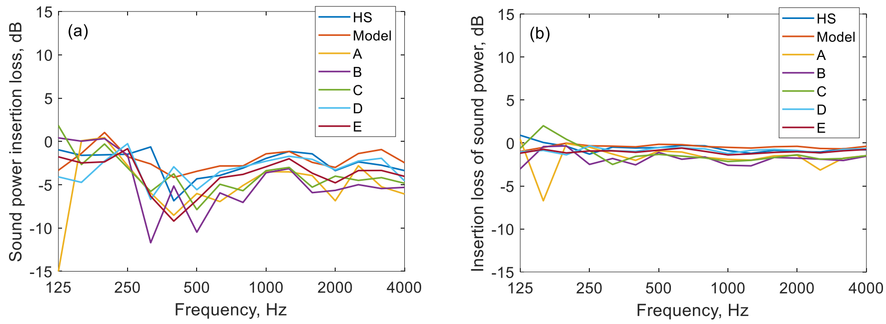


Fig. 8. Change in sound power level due to presence of vehicle calculated using BEM for different train profiles for (a) vertical rail vibration; (b) lateral rail vibration.

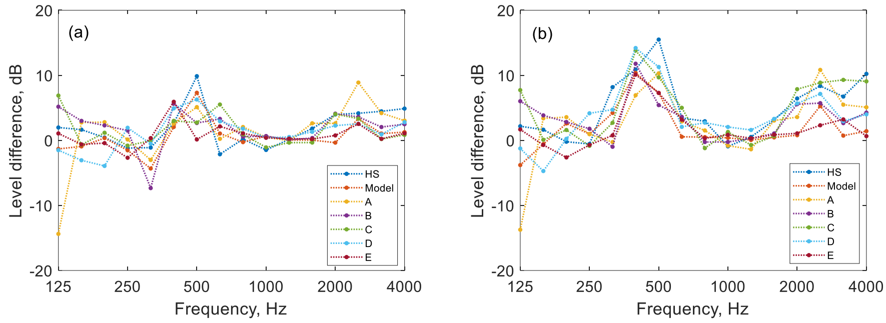


Fig. 9. Level differences due to presence of vehicle calculated using BEM for different train profiles for vertical vibration of near rail at the receiver position of (7.5, 1.2) m. (a) Without ground; (b) with rigid ground.

3.4 Comparison with line source formulae

For the vibration in the vertical direction, it is expected from [7] that the rail radiates approximately as a line monopole. This gives

$$L_p = L_{W'} - 10\log_{10} r - 8, \tag{1}$$

where L_p is the sound pressure level in dB re 20 μPa, $L_{W'}$ is the sound power level (per unit length) in dB re 10^{-12} W/m and r is the distance from the rail to the receiver in m. For the lateral direction a line dipole behaviour is expected [7]. This gives

$$L_p = L_{W'} - 10\log_{10} r - 8 + 10\log_{10}(2\cos^2\theta), \tag{2}$$

where θ is the angle to the horizontal. Fig. 10 shows the sound pressure level at 7.5 m, for the case without the ground, normalised by the corresponding line source estimate for vertical and lateral vibration of the rail (Eqs (1, 2)). Compared with the result with no train, shown as the solid line, inclusion of the train has the effect of bringing the result closer to 0 dB in the mid and high frequency regions. Consequently, the line source estimates can be used reliably in the presence of the vehicle. Although the level at the mid frequency dip is increased, it remains at around –5 dB. For the lateral direction, the train has very little effect and the result remains close to 0 dB.

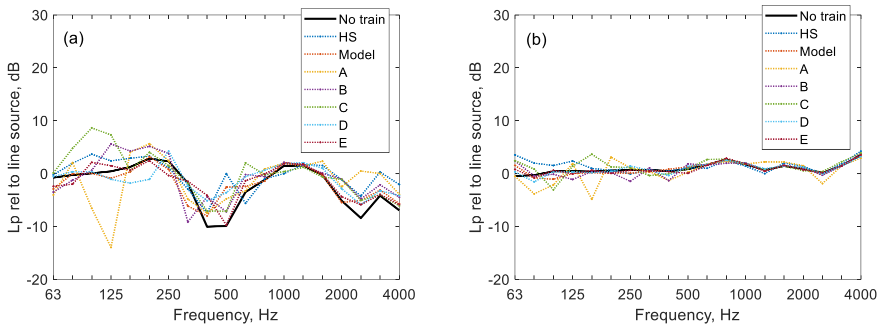


Fig. 10. Sound pressure from the rail, at 7.5 m from track centreline, normalised by sound calculated for line source – with no ground. (a) Vertical vibration; (b) lateral vibration.

Fig. 11 shows the corresponding results with a rigid ground. For the vertical direction the changes due to inclusion of the ground are small, but for frequencies above 250 Hz they nevertheless have the effect of bringing the estimates closer to 0 dB. For the lateral direction, the effect of the ground reflection can be seen in the peaks and dips but these are not affected by the presence of the vehicle.

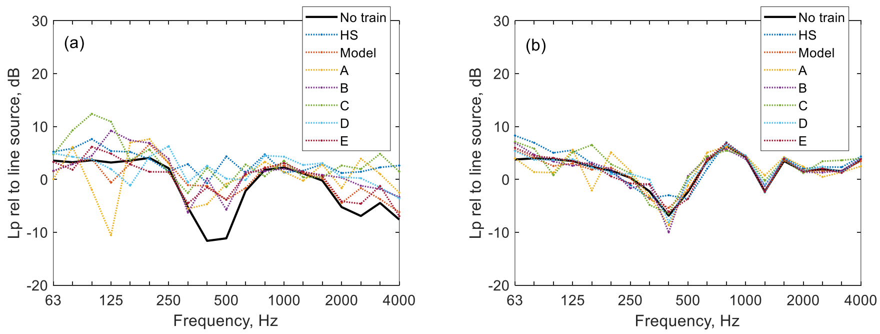


Fig. 11. Sound pressure from the rail, at 7.5 m from track centreline, normalised by sound calculated for line source – with rigid ground. (a) Vertical vibration; (b) lateral vibration.

4 Conclusion

The sound radiated by the rail towards the ground is found to be strongly attenuated by shielding due to the ballast shoulder. As a result, the ground reflection is considerably reduced compared with conventional estimates, especially for the vertical rail vibration.

The presence of the vehicle primarily affects the sound pressure from the vertical vibration of the rail whereas the effect is negligible for the lateral vibration. The vehicle body reflects the sound back towards the ballast. Absorption by the ballast then leads to a reduction in the radiated sound power but the sound pressure at the trackside is increased at most frequencies by 0-5 dB and in some frequency bands by up to 9 dB. To assess the effect of the vehicle in a particular situation, the 2D BE method can be used; alternatively, simple line source formulae give reasonably good results for the radiation including the vehicle.

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