A comparison of the noise and vibration performance of slab and ballasted track designs

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Abstract

In deciding between the use of ballasted track or slab track, an important issue is their noise and vibration performance, as slab track is usually considered to be noisier than ballasted track. The comparative performance of different track designs is assessed here in terms of both noise and vibration. The TWINS model is used to predict the rolling noise, including improved models for the influence of ballast absorption. The noise levels from two ballasted tracks and a typical slab track are compared for a common vehicle type, roughness level and train speed. A difference of around 4 dB in the track noise component is found between the two ballasted tracks with different pad stiffnesses. Consequently the total noise level for the case with slab track is around 3 dB higher than that for the ballasted track with stiff rail pads but is only 0-1 dB higher than the level for the one with soft pads. These results are sensitive to some extent to the assumptions made. A comparison is also made between the ground vibration performance of a ballasted track and a slab track using a semi-analytical model. For the same fastener stiffness it is found that there are only small differences, with the mass of the track slab leading to reductions of 1-2 dB at frequencies above 16 Hz. However, if softer rail fasteners are used in the slab track, as is usual, this leads to further reductions above 80 Hz. The critical velocity on soft soil is also considered; although there is little difference between the different tracks for a homogeneous ground, the critical velocity is increased by the slab bending stiffness for grounds with a soft surface layer. The maximum rail displacement is also smaller for a slab track.

Keywords: railway track, slab track, ballasted track, rolling noise, ground vibration, critical velocity.

1 Introduction

Traditionally, railway track is laid on sleepers in a layer of crushed stones known as ballast. However, concrete slab track has become popular for the construction of modern high-speed lines. In deciding between the use of ballasted or slab track, an important issue is their noise and vibration performance, as slab track is usually considered to be noisier than ballasted track. For example, Poisson et al. found differences of 3.5 dB(A) in the sound level, at 7.5 m from the track, between these two track types for TGV trains running at 225 km/h on a new high speed line in France [1]. According to the German calculation method Schall03, which is based on empirical data, the difference between ballasted track and slab track for an ICE 1 train is approximately 3 dB(A) at 200 km/h and 2 dB(A) at 260 km/h [2]. At speeds below approximately 300 km/h the dominant source of noise is rolling noise, produced by vibration of the wheels, rails and sleepers [3], whereas at higher speeds aerodynamic noise becomes dominant [4].

It is known that there are several reasons contributing to the differences between the noise of ballasted and slab track [1]. First, reflections from the concrete slab, in the absence of the ballast absorption, lead to an increase in the noise emitted to the wayside. Second, due to the lower track decay rates typically occurring on slab track, the rail vibration during the train pass-by is higher. It is important to note, however, that the noise from both types of track depends strongly on the rail pad stiffness [3], so it can be expected that the level difference will depend on the type of ballasted track used as the reference and on the type of slab track with which it is compared. Third, there may be differences in the rail roughness; Poisson et al. [1] found a small difference of less than 1 dB between the two track types in their study. However, it is not expected that there will be significant systematic differences.

As well as noise, the track design also affects the ground vibration due to trains [5,6]. There are few comparative studies of the performance of slab track and ballasted track for ground vibration, although some comparisons have been made of the effect of the track design on the critical velocity, i.e. the speed at which track displacements become large due to coincidence with the wave speed in the ground [7,8].

The purpose of this paper is to study the comparative performance of slab tracks and ballasted tracks for both noise and vibration. Section 2 presents a comparison the rolling noise performance of different track types and Section 3 gives corresponding results for ground vibration and critical velocity.

2 Rolling noise

2.1 Model

The TWINS model [9] is used here to predict the rolling noise. This model takes the combined surface roughness spectrum of the wheels and rails as the input and calculates the vibration of the wheels and track. It then uses engineering models of the sound radiation to calculate the sound power and the average sound pressure during the train pass-by. The model has been extensively validated through field tests [9,10,11]. In the present work the model has been updated to include results from Zhang et al. [12,13] who found that proximity to the ground and the absorptive nature of the ballast have an influence on the sound power radiated by the track. Taking these various effects into account gives a more reliable estimate of the difference between the noise from ballasted tracks and slab track.

2.2 Parameters

Three different tracks are considered. Two are ballasted tracks, one with a stiff rail pad and the other with a soft rail pad. The vertical pad stiffness of ballasted track 1 is 800 MN/m and that of track 2 is 120 MN/m. Both correspond to tracks in the UK for which field measurements have been made, although for the purpose of the present comparison the rail type and sleeper spacing applying to the slab track have been adopted. The third track is a Rheda slab track for which track decay rates are presented in [14]. This track has a two-layer fastener system with a stiff upper pad and a softer lower pad separated by an internal baseplate. The parameters used in the model for the three track types are listed in Table 1. For the slab track the 'sleeper' in the model represents the mass of the internal baseplate and the 'ballast' represents the lower pad.

The track decay rates obtained from the model are compared with measured data in Figures 1-3, which allows confirmation of the chosen track parameters. In the noise predictions these measured track decay rates are used, as they are expected to be more representative than the predicted ones. Nevertheless it is recognised that some measurement uncertainty is present which will affect the predicted results.

Table 1: Parameters used for the tracks for assessment of rolling noise, values given per rail

Parameters	Ballast track 1	Ballast track 2	Slab track
Rail cross section	60E1	60E1	60E1
Rail vertical bending stiffness	6.42 MN m^2	6.42 MN m^2	6.42 MN m^2
Rail lateral bending stiffness	1.07 MN m^2	1.07 MN m^2	1.07 MN m^2
Rail vertical loss factor	0.02	0.02	0.02
Rail lateral loss factor	0.025	0.02	0.02
Pad vertical stiffness	800 MN/m	120 MN/m	120 MN/m
Pad lateral stiffness	30 MN/m	15 MN/m	150 MN/m
Pad vertical loss factor	0.25	0.25	0.2
Pad lateral loss factor	0.25	0.25	0.2
Sleeper mass	140 kg	140 kg	6.0 kg
Sleeper spacing	0.65 m	0.65 m	0.65 m
Ballast vertical stiffness	100 MN/m *	60 MN/m *	32 MN/m
Ballast lateral stiffness	80 MN/m	60 MN/m	80 MN/m
Ballast vertical loss factor	0.5	0.5	0.2
Ballast lateral loss factor	2.0	2.0	0.2

*: frequency-dependent above 160 Hz

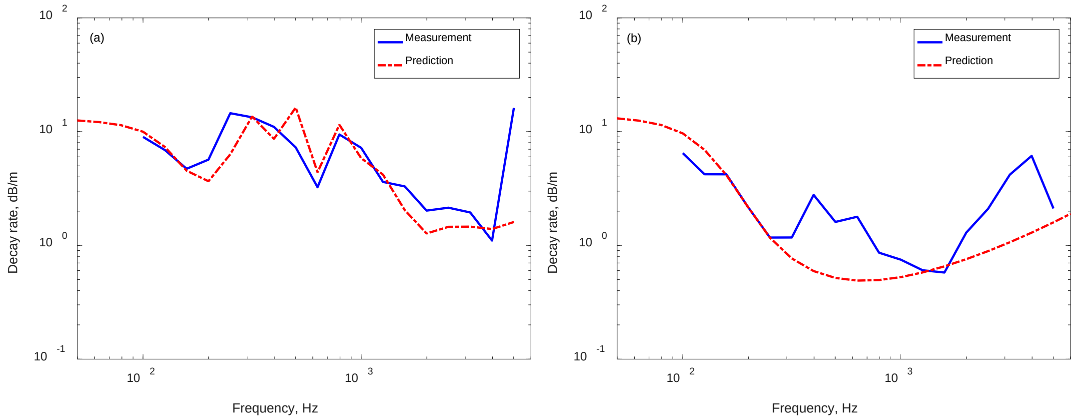

Figure 1: Decay rates of ballasted track 1. (a) Vertical motion, (b) lateral motion

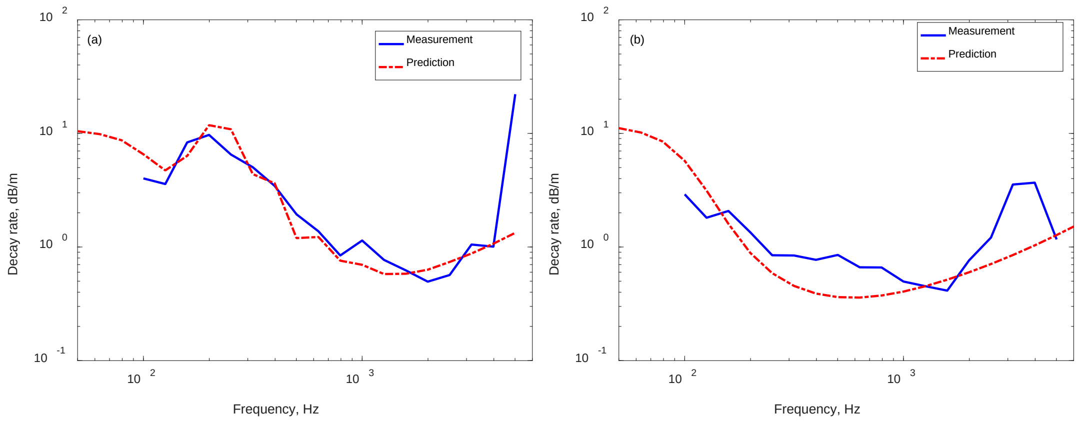

Figure 2: Decay rates of ballasted track 2. (a) Vertical motion, (b) lateral motion

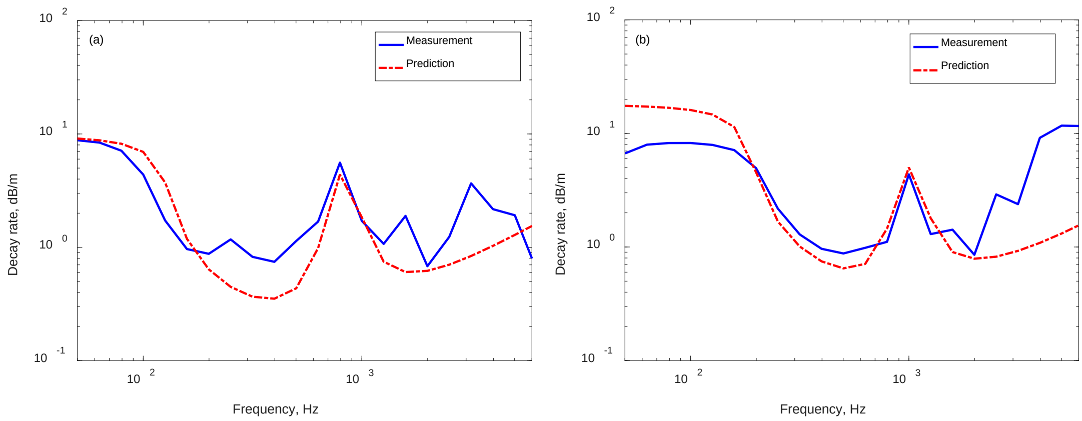

Figure 3: Decay rates of slab track. (a) Vertical motion, (b) lateral motion

The noise from each track is compared in the next section for a common vehicle type, roughness level and train speed. The combined roughness spectrum used in the predictions is shown in Figure 4; this is based on measurements at one of the test sites.

The wheel used in the calculations is a relatively quiet design with a straight web and a diameter of 840 mm. The receiver location is 7.5 m from the track centre and 1.2 m above the rail head. The ground is assumed to be 1.5 m below the rail head and is represented by the Delany & Bazley model [15] using a flow resistivity of 3×10^4 Pa.s.m^{-2}.

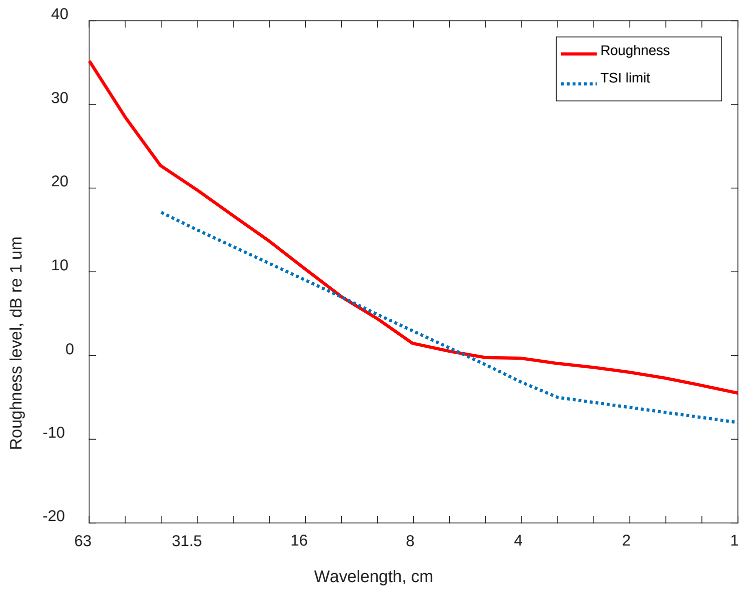

Figure 4: Total roughness spectrum used in the comparison

2.3 Results

The predicted wheel, rail and sleeper contributions to the radiated noise are shown in Figure 5 for each track type for a train speed of 120 km/h. In each case the wheel is the dominant source at 2 kHz and above, the rail is dominant in the mid-frequency region and the sleeper gives the highest levels at low frequency, apart from the slab track which has no sleeper contribution. It is assumed that the slab itself radiates negligible noise.

Comparing the two ballasted tracks, the rail noise is greater for track 2 with the soft rail pads, whereas the sleeper noise is greater for track 1 due to the strong coupling with the rail up to higher frequencies. The rail noise for the slab track is greater than that for ballasted track 2 between 250 and 800 Hz, but lower above 1 kHz. These differences can be attributed to the track decay rates (Figures 1-3), particularly those for the vertical direction. There are some differences in the wheel noise component at low frequencies but not in the high frequency region that is most important for the overall A-weighted noise level. Above 2.5 kHz the wheel noise component is around 1 dB higher for the slab track case due to the absence of absorption from the ballast.

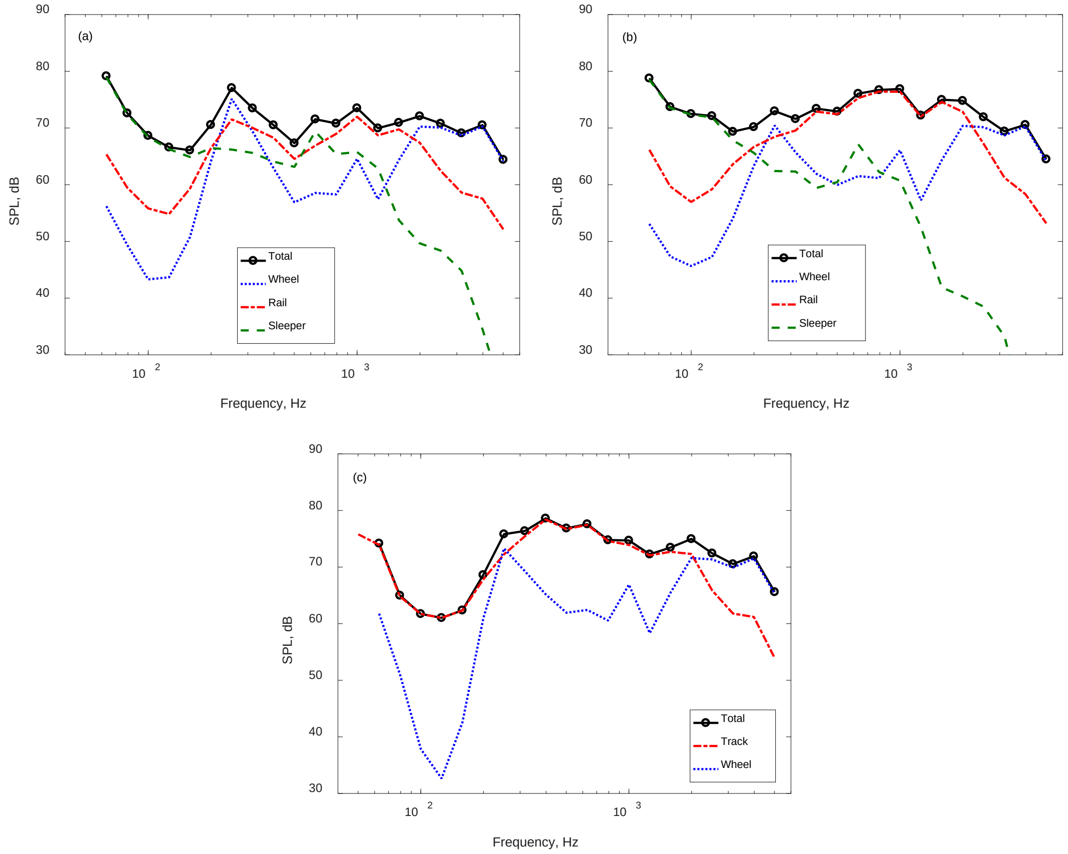

Figure 5: Components of sound pressure level spectrum for train speed 120 km/h. (a) Ballasted track 1, (b) ballasted track 2, (c) slab track

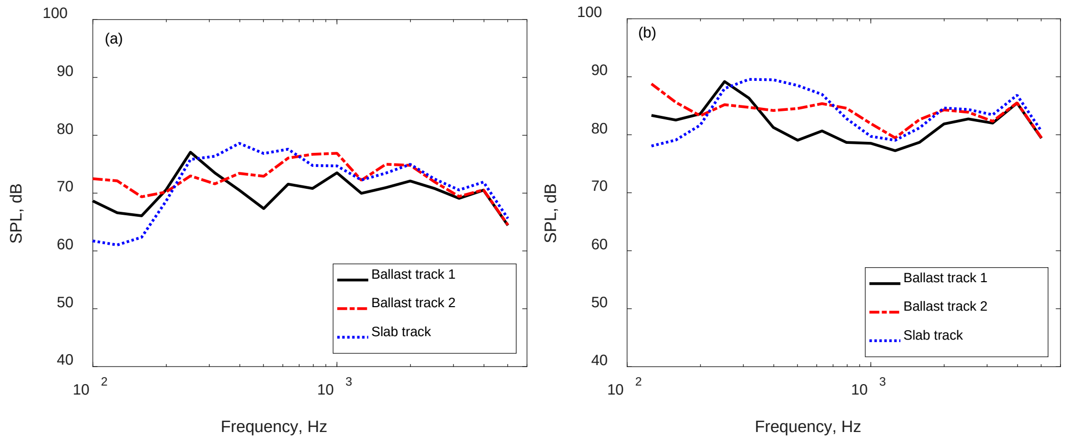

Figure 6: Comparison of the predicted total sound pressure level contribution due to rolling noise at 7.5 m for three different tracks. (a) 120 km/h; (b) 300 km/h

The overall rolling noise spectra predicted for the three tracks are compared in Figure 6 for two train speeds. In the frequency region from 315 to 800 Hz the slab track has the highest noise level due to its low decay rate. The noise level from the ballasted track with the softer pad is higher than that for the track with the stiff pad over most of the frequency range and is also higher than that for the slab track above 1 kHz.

The predicted overall A-weighted noise levels due to rolling noise are shown in Figure 7 for the same two speeds. The A-weighting is a standard frequency weighting intended to give improved correlation with human response to sound [16]. It gives most emphasis to frequencies between 1 and 5 kHz and attenuates the contribution of lower frequencies.

Due to the absorptive effect of the ballast, the wheel noise level is around 1 dB(A) lower for the ballasted tracks than for the slab track. Comparing the two ballasted tracks, the track noise level is around 4 dB(A) lower for the track with stiff pads than for the one with soft pads. Consequently the total noise level for the case with the slab track is about 3 dB(A) higher than that for ballasted track 1 but is only 0-1 dB(A) higher than the level for ballasted track 2.

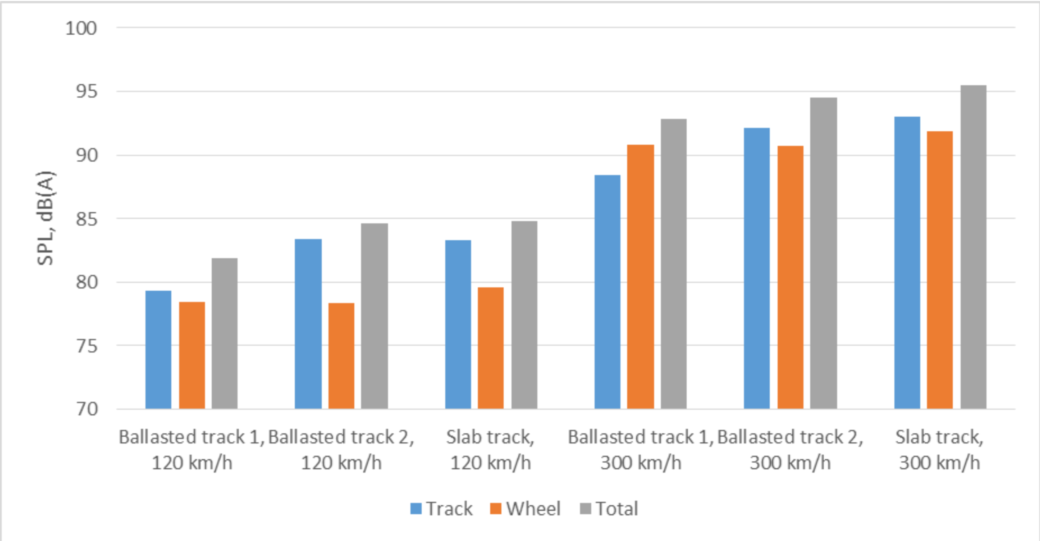

Figure 7: Total sound pressure levels due to rolling noise from different components for ballasted and slab track, in dB(A)

2.4 Discussion

The results presented here are for typical conditions; however, they are sensitive to a number of factors. It has been seen from Figure 6 that the slab track has higher noise levels than ballasted track 2 between 200 and 630 Hz and lower levels above 800 Hz. An increase in train speed leads to a greater emphasis of the higher frequency components which can change the balance of wheel and track components. Additionally, changes in the shape of the roughness spectrum can lead to a greater or lesser influence of these two frequency regions in the overall sound level.

The calculations have been based on a relatively quiet wheel design (0.84 m diameter, straight web). If a more conventional wheel design is used, with a larger diameter and a curved web, the wheel contribution will increase by up to roughly 5 dB, which will have the effect of masking the differences between the track types, especially at higher speed. It was seen in Figure 7 that the wheel component of noise is similar to the track component at 300 km/h; for a more conventional wheel, the wheel component will become greater than the track component by 4-7 dB and the total noise for the three tracks will be within 2 dB of each other.

The design of slab track will also affect the comparison. The design considered here has a fastening system with two layers of resilience and an intermediate baseplate. This has the effect of increasing the decay rate at higher frequencies and thus controlling the noise. A simpler fastening system with a single layer of resilient pads would have lower track decay rates, and hence higher noise levels, across most of the frequency spectrum.

The receiver location also affects the comparison to some extent by affecting the shape of the sound pressure spectrum and thereby the relative importance of the different components. In particular, a primary ground dip occurs at some frequency depending on the interference between direct and ground-reflected sound [16]. For the results shown here, for a standard receiver at 7.5 m from the track centreline and a ground height of 1.5 m below the rail head, the primary ground dip occurs at about 160 Hz which does not strongly affect the results. However, for a ground height of 1.0 m this would increase to around 300 Hz and for a height of only 0.5 m it would be close to 1 kHz. For a receiver location at 25 m from the track and 3.5 m above the rail, the ground dip frequency would increase further, for example to 500 Hz for a ground height of 1.0 m. Such changes will affect the relative importance of different frequency bands in the overall level.

3 Ground vibration

3.1 Model

To assess the differences in ground vibration, a semi-analytical model is used, that is based on one originally developed by Sheng et al. [5,17]. It has recently been extended in [18] to take into account the traction variation across the track-ground interface. The track is considered to be located at the surface of a layered elastic half-space and is modelled using multiple beams supported by vertical springs with consistent mass. The model is formulated in the wavenumber-frequency domain and uses transfer function matrices for the ground expressed in a moving frame of reference. Thus, it includes the effects of the moving loads and can also be used to assess the critical velocity. Results are presented for a number of sets of ground parameters.

3.2 Ground vibration results

For the assessment of ground vibration two tracks are compared, the parameters of which are listed in Table 2. The ballasted track has a rail pad stiffness of 120 MN/m, and is similar to ballasted track 2 used in the rolling noise study. However, the slab track is assigned a single layer of resilience which initially has the same stiffness as the ballasted track. The ballast stiffness in the vibration model is much higher than in the noise model as in the latter it includes the flexibility of the ground beneath the ballast.

The properties of the ground are given in Table 3. These are given in terms of the fundamental wave speeds of the material (compressional wave, or P-wave, c_P and shear wave, or S-wave, c_S) which are related to the Young's modulus E and Poisson's ratio ν by

$$c_p = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}\ ;\ c_s = \sqrt{\frac{E}{2\rho(1+\nu)}} \quad (1)$$

where ρ is the density of the material.

Three different grounds are considered: each has a 3 m deep layer of softer material overlying a stiffer half-space. Compared with the first ground type, type 2 has higher wave speeds in the upper layer whereas type 3 has lower wave speeds in the underlying half-space. A constant loss factor of 0.1 is assumed in each case, consistent with previous measurements [19].

Table 2: Parameters used for the tracks for ground vibration assessment

Parameters	Ballast track	Slab track
Rail cross section	60E1	60E1
Rail bending stiffness	6.42 MN m^2	6.42 MN m^2
Rail loss factor	0.02	0.02
Pad stiffness	120 MN/m	120 MN/m (50 MN/m)
Pad damping loss factor	0.25	0.2
Sleeper mass (whole sleeper)	300 kg	[-]
Sleeper spacing	0.65 m	0.65 m
Ballast stiffness (whole sleeper)	4640 MN/m^2	[-]
Ballast damping loss factor	0.1	[-]
Ballast mass per unit length	1740 kg/m	[-]
Slab mass (full track width)	[-]	3720 kg/m
Slab bending stiffness	[-]	232 MN m^2
Slab damping loss factor	[-]	0.015

Table 3. Parameters used for the different types of ground

Ground	Layer depth (m)	P-wave speed (m/s)	S-wave speed (m/s)	Density (kg/m^3)	Damping loss factor
Type 1	3.0	240	120	1800	0.1
	infinite	700	350	2000	0.1
Type 2	3.0	500	250	1800	0.1
	infinite	700	350	2000	0.1
Type 3	3.0	240	120	1800	0.1
	infinite	400	200	2000	0.1

Figure 8 shows the vibration at 8 m and 16 m from the track for the two track types on ground type 1. Results are shown for train speeds of 120 km/h and 300 km/h, as before. The vibration level rises to a broad peak between 16 and 63 Hz at 120 km/h and between 25 and 100 Hz at 300 km/h. This rise in level is associated with the cut-on of waves localised in the upper surface layer of the soil.

The level difference between the vibration for the ballasted track and the slab track, again both with a pad stiffness of 120 MN/m, is shown in Figure 9(a) for a speed of 300 km/h and distance of 16 m. Results are shown for the three different ground types listed in Table 3. In each case the differences in vibration level between the two tracks are quite small but in the frequency region above 16 Hz the slab track gives vibration levels that are consistently 1-2 dB lower. The differences are greatest for the softest soil, and these increase at frequencies above 100 Hz. Similar results are found for other speeds and distances (not shown here). By varying the properties of the track it has been established that the main reason for these differences is the mass of the track slab rather than its bending stiffness.

In practice, as seen in the previous section, a softer rail fastening is generally used on slab tracks than on ballasted tracks. Therefore Figure 9(b) shows the results for a slab track with a fastener stiffness of 50 MN/m, compared with the same ballasted track as before. A slight rise in vibration occurs around 40-50 Hz but at 80 Hz and above the vibration level is considerably reduced due to the soft fasteners.

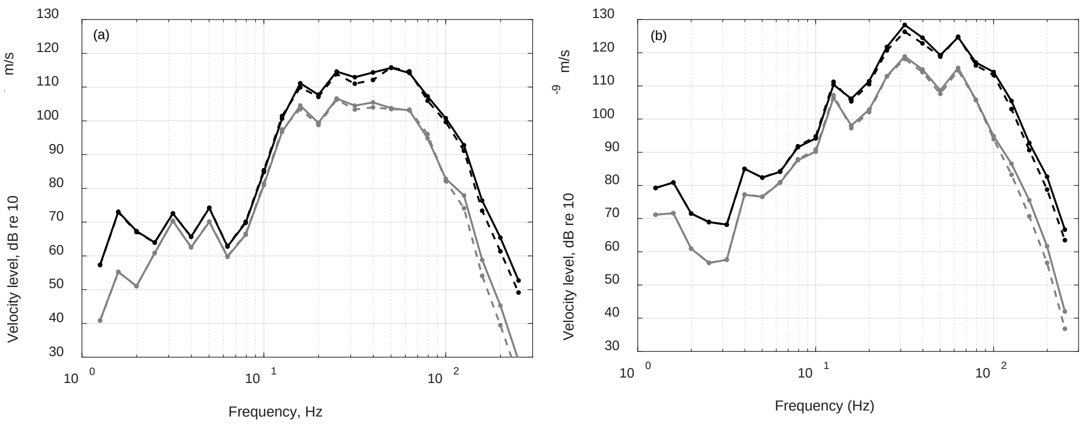

Figure 8: Total ground response level in one-third octave bands of (—) ballasted track A and (— — —) slab track with pad stiffness 120 MN/m, at 8 m (black lines) and 16 m (grey lines) from the track. (a) Train speed 120 km/h and (b) train speed 300 km/h

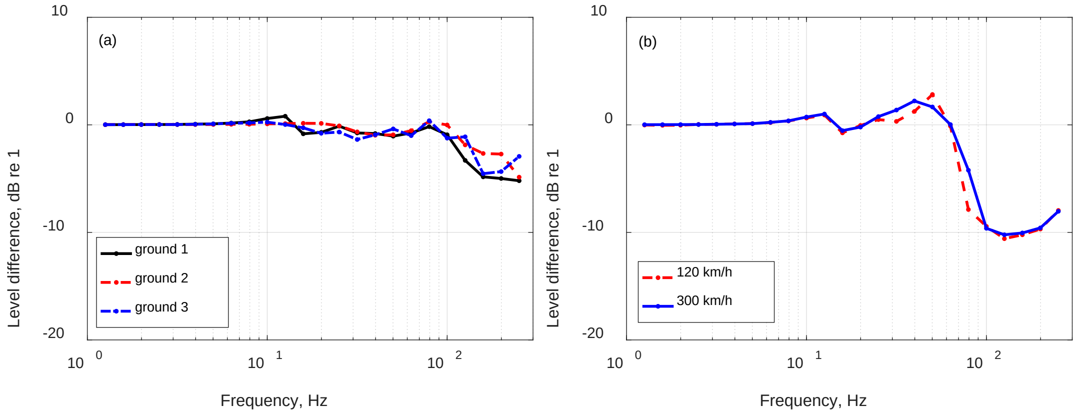

Figure 9: One-third octave band level difference between ballasted track and slab track ($L_{slab} - L_{ballast}$). (a) With pad stiffness 120 MN/m at 16 m from the track on different ground types for 300 km/h; (b) with pad stiffness 50 MN/m on ground type 1 at 16 m from the track

3.3 Critical velocity

When the train speed approaches the wave speeds in the ground, the deflections of the track under the moving loads can increase dramatically, leading to accelerated degradation of the track and substructure as well as leading to an increased risk of derailment. This is known as the critical velocity effect and can be studied using the same model as in the previous section.

To show the effect on the critical velocity, the model is run with the same track parameters as listed in Table 2, for a large range of speeds. However, for the ground properties the most important parameter is found to be the depth of the upper soil layer. Consequently, results are presented for the three ground types listed in Table 4; type A is the same as type 1 in the previous Section, whereas type B has a shallower surface layer and type C is a homogeneous half-space with the same properties as the upper layer in the other ground types.

Table 4. Parameters used for the ground for critical velocity study

Ground	Layer depth (m)	P-wave speed (m/s)	S-wave speed (m/s)	Density (kg/m^3)	Damping loss factor
Type A	3.0	240	120	1800	0.1
	infinite	700	350	2000	0.1
Type B	1.5	240	120	1800	0.1
	infinite	700	350	2000	0.1
Type C	infinite	240	120	1800	0.1

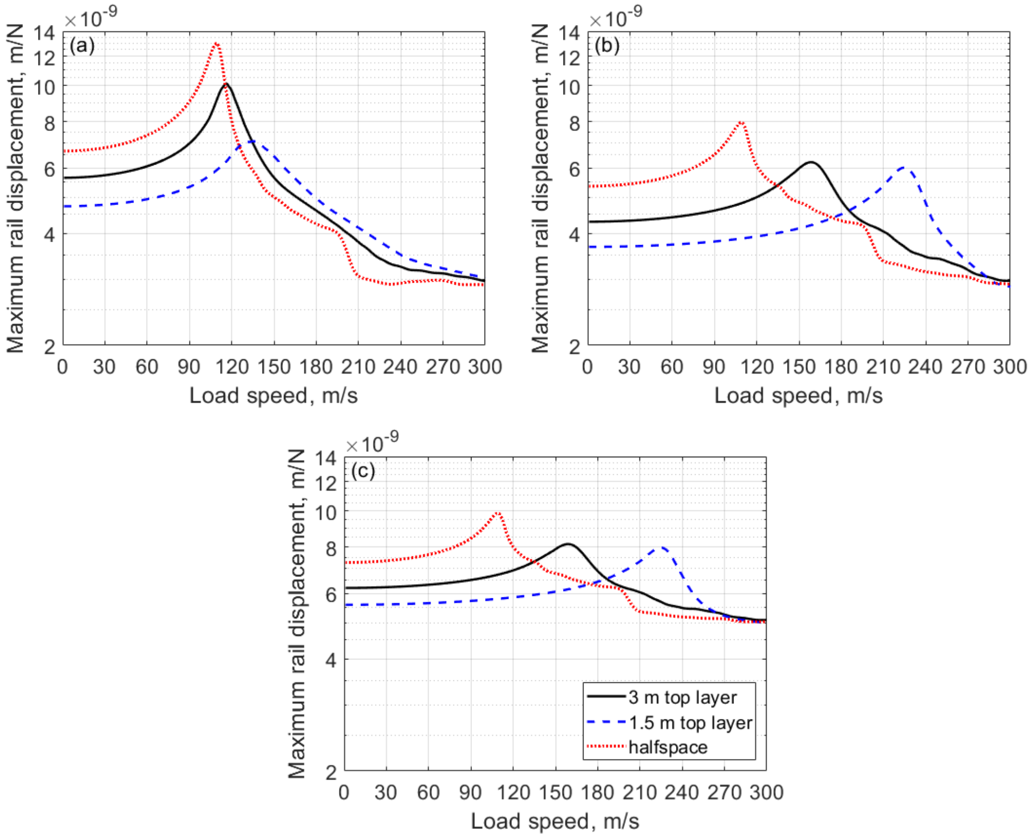

Figure 10: Maximum rail displacement for a unit load plotted against load speed for (a) ballasted track; (b) slab track, 120 MN/m; (c) slab track, 50 MN/m. (—) ground with 3 m surface layer; (– – –) ground with 1.5 m surface layer; (– · – ·) homogeneous ground.

The maximum rail displacement due to a unit moving load is shown in Figure 10 as a function of load speed. The results shown in Figure 10(a) are for the ballasted track, Figure 10(b) for the slab track with fastener stiffness 120 MN/m and Figure 10(c) for the slab track with fastener stiffness 50 MN/m. The maximum rail displacement rises from the static deflection value to a peak at a speed which can be identified as the critical velocity. For the ballasted track the maximum displacement occurs close to the Rayleigh wave speed of the upper layer (109 m/s) for each ground type, whereas for the slab track with both fastener stiffnesses the critical speed is much higher for the layered grounds. By varying the properties of the track it has been found that the main reason for these differences is the bending stiffness of the slab.

For the homogeneous ground, although the critical velocities are similar for the two tracks, the maximum deflection is smaller for the slab tracks: it is only around 3 dB greater than the static deflection (i.e. 40% higher) whereas for the ballasted track it shows an increase of 6 dB (i.e. 100%). The static deflections are slightly smaller for the slab track with stiffness 120 MN/m than for the ballasted track, whereas with the reduced fastener stiffness they are slightly larger than for the ballasted track.

5 Conclusions

The differences in noise and vibration performance of typical ballasted and slab tracks are assessed using established theoretical models. It is shown that there can be considerable differences between the noise produced by different ballasted tracks, depending on the rail pad stiffness. Consequently it is not straightforward to assign a noise level difference between ballasted track and slab track as the result depends strongly on the reference case considered. The overall noise level for a typical slab track is shown to be around 3 dB higher than that for a ballasted track with stiff rail pads, but only 0-1 dB higher than that for a track with soft rail pads. These results are sensitive to the assumptions. In particular, the roughness spectrum, train speed, wheel design and receiver location can all affect the balance of noise contributions to some extent. Moreover, a slab track with a simpler single-layer fastener system will have a higher noise level.

The vibration performance of ballasted track and of slab track have been shown to be very similar if an equivalent fastener stiffness is used. In the example considered, the slab track produces 1-2 dB lower vibration for frequencies above about 16 Hz. This can be attributed to the slab mass rather than its bending stiffness. However, slab tracks are usually fitted with softer rail fasteners which lead to further substantial reductions above 80 Hz.

Critical velocities on soft soils have also been evaluated. Here the bending stiffness of the slab offers some advantages; although there is little difference between the two track forms for a homogeneous soil, the slab track has higher critical velocities in the case of layered soil and generally has reduced maximum track deflections.

Acknowledgements

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