Comparison of methods for estimating track decay rate

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Abstract. The track decay rate (TDR) is used to qualify the acoustic performance of a track for pass-by noise tests, in transposition from one site to another, and to update rolling noise models. Analysis is presented using a track vibration model to show the differences between the result of method defined in EN 15461 and the decay rate of individual waves. The TDR obtained from the EN method is consistently higher than the decay rate of the principal wave in the rail. A reduction of measurement effort is possible by reducing the measurement grid from the 29 points defined in EN 15461; even a set of 9 points leads to only small differences in the TDR obtained from the simulations. Using a sensor position above a sleeper instead of at mid-span leads to potentially large differences. Additionally, simulations to represent the pass-by method are shown for comparison. This method gives consistently higher TDR results than the EN method. The effect of reflections between wheels is shown to be significant for soft rail pads; the increase of pad and ballast stiffness under load has a significant effect.

Keywords: Rolling Noise, Track Decay Rate, EN 15461, Transposition, Measurement Methods.

1 Introduction

The QuieterRail project runs from 2024 to 2027 and aims to introduce a step change in the prediction and mapping of railway noise and vibration, in the acceptance testing of new rolling stock, and in the promotion of cost-effective noise mitigation. One area studied concerns the transposition of noise from one site to another, for which the respective track decay rates (TDRs) should be known. The TDR is an important quantity that helps to define the acoustical properties of a track [1]. Tracks with a low TDR radiate more noise than those with a high one. Track sections used for noise pass-by tests according to ISO 3095 should have a TDR that exceeds a defined limit spectrum [2]. Moreover, the TDR can be used as part of transposition of measurements from one site to another, and to update rolling noise models such as TWINS [3].

Early analysis of TDR was based on a regression method, similar to that used for determining reverberation time from the decay of sound energy. It was later replaced by a method based on the integration of squared vibration amplitude over distance [4]. This has been incorporated in EN 15461 [5] and should be seen as an ‘equivalent TDR’ [4] that is intended to reflect the influence on the average pass-by sound level ($L_{Aeq,Tp}$). In addition, pass-by methods have been developed that are used to estimate the TDR from operational rail vibration during a train pass-by [6].

Jones et al. [4] identified differences between the integration method and the decay rates of the principal wave. Li et al. [7] studied the pass-by method using simulations and measured data and showed differences with the direct (EN) method as well as sensitivity to parameters used in the method. A detailed analysis of the pass-by method is given in [8], based on an assumed exponential decay of vibration.

This paper aims to explore further the reasons for differences between TDR results obtained using these various methods. Predictions are presented using numerical track vibration models based on a Timoshenko beam on discrete supports. The models are used to simulate the various measurement methods. For conciseness, only results for the vertical TDR are presented, but similar conclusions can be expected for the lateral direction. Two rail pad stiffnesses are considered, 126 MN/m and 507 MN/m, with a loss factor of 0.2. The ballast stiffness is 100 MN/m with a loss factor of 1.0. The rail is UIC60, and the sleeper is represented by a mass of 150 kg (for a single rail).

2 Impact hammer methods for determining TDR

2.1 EN 15641 method

Using the response at different distances from the excitation, the TDR in each frequency band k can be determined according to the integration method from EN 15461 [5]:

$$\mathrm{TDR}_k = 4.343\left(\sum_{x=0}^{x_{\max}}\left|\frac{A_k(x_n)}{A_k(0)}\right|^2 \Delta x_n\right)^{-1} \quad (1)$$

where $A_k(x_n)$ is the transfer frequency response function (FRF) from $x = 0$ to $x = x_n$ and $A_k(0)$ is the point FRF at $x = 0$. The maximum distance considered $x_{\max}$ should be large enough such that the transfer FRF $A_k(x_{\max})$ is at least 10 dB lower than the point FRF $A_k(0)$ in all frequency bands [5]. In the results shown here, a threshold of −15 dB is used to exclude FRFs with small magnitude. A minimum decay rate that can be obtained for a given value of $x_{\max}$ is specified in the standard as $\mathrm{DR}_{\min} = 4.343/x_{\max}$ [5]. The distances Δx_n represent the length of track associated with each measurement point. For comparison, the decay rate of individual waves can be calculated directly using the track models.

2.2 Comparison of EN method with wave decay

It is useful to plot the magnitude of the transfer mobility against distance in each frequency band. Two examples are shown in Fig. 1. The response at a spacing of 0.15 m is plotted and the values at the grid points used in EN 15461 are marked. The threshold of −15 dB relative to the reference point is also shown. The decay is nonlinear but two straight lines are shown, which correspond to the decay rate of the principal wave and the result obtained from the EN method (Eq. (1)). As Eq. (1) includes the integral of the squared velocity, it gives a result that is most strongly influenced by points close to the reference point, whereas points further away follow a slope close to the wave decay.

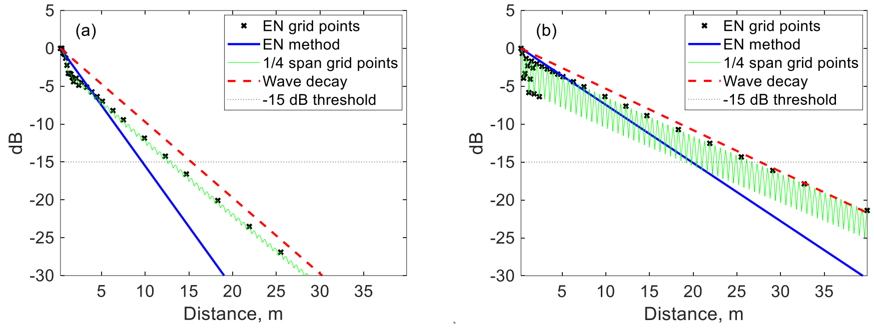

Fig. 1. Decay with distance for soft rail pad case at (a) 500 Hz and (b) 1000 Hz.

Curve fitting to the results (i.e. regression) can approximate the wave decay, provided that the near-field results are omitted and only results at mid-span positions are included. For the lateral vibration, not considered here, there are multiple propagating waves and regression would not be sufficient to determine wave decays.

The results from the EN method and the wave decay are compared in Fig. 2 for both soft and stiff rail pads; the EN method gives a consistently higher result than the wave decay due to the influence of the near-field vibration (see Fig. 1(a)).

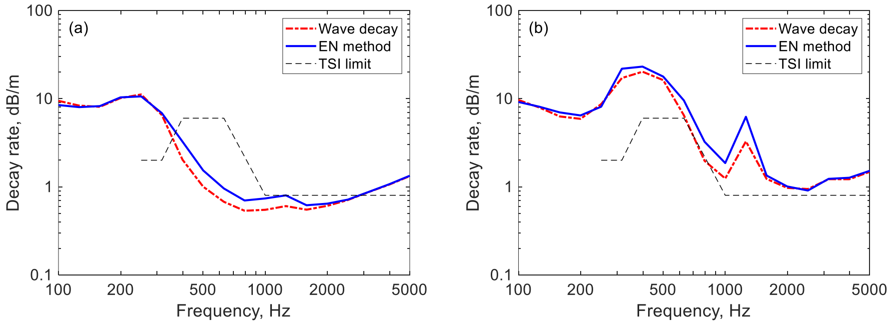

Fig. 2. Decay rate spectra obtained using EN method and decay rate of principal wave. (a) Soft pad, (b) stiff pad.

2.3 Measurement grids in the EN method

EN 15461 [5] defines a grid of 29 excitation points over a total distance of almost 40 m. Using simulations, various reductions to this grid have been considered. A grid consisting of 9 points, at 0, 0.5, 1, 2, 4, 8, 16, 36 and 66 spans from the reference point, gives results that are close to those from the full grid. This reduces the time needed to make measurements, which is often limited by track access. In Fig. 3, results from this reduced grid are compared with those from the full grid of 29 points, and an expanded grid with 265 points every quarter span, which gives a more exact evaluation of Eq. (1). The difference between 9 and 29 grid points is smaller than the difference to this 'exact' result. Nevertheless, some redundancy in the selected points would be beneficial in practice to allow for measurement error.

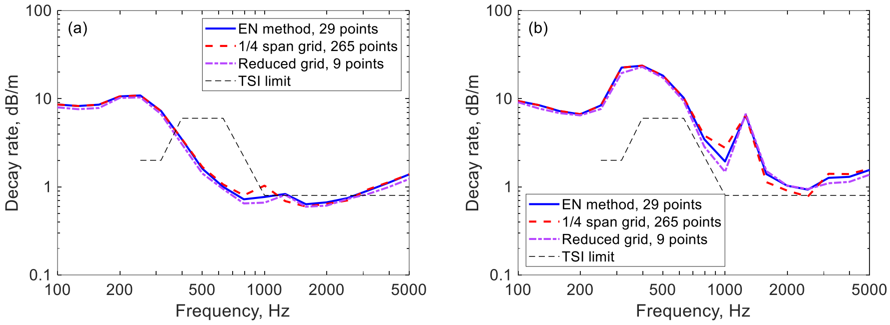

Fig. 3. TDR obtained with different measurement grids. (a) Soft pad, (b) stiff pad.

Results are shown in Fig. 4 for a track with very low TDR. To achieve this in the model, the rail pad loss factor of the soft pad has been reduced to 0.05 and the rail loss factor to 0.005. The smallest TDR found here for a measurement length of 40 m is 0.22 dB/m, which corresponds to twice the value of DR_{min} given in EN 15461. Increasing the measurement length to 80 m gives improved results, this length being sufficient to capture the decay. However, note there is a difference between the wave decay and the extended integration of up to a factor of 2 as a consequence of the near-field vibration.

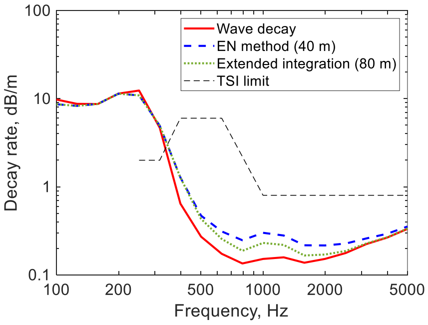

Fig. 4. TDR for track with very low damping, showing influence of measurement length.

2.4 Different sensor positions in the EN method

A comparison is made in Fig. 5 between the TDR measured with the sensor at the mid-span position (as per EN 15461 [5]) and the alternatives of using a sensor above a sleeper or at quarter span. For the soft pads, differences are limited mainly to the region of the pinned-pinned frequency (1000 Hz) and are more obvious in a narrowband presentation (not shown here). For the stiff pads, however, large differences are found. To capture the overall influence on track-radiated noise, consideration should be given to using sensors both at mid-span and above a sleeper.

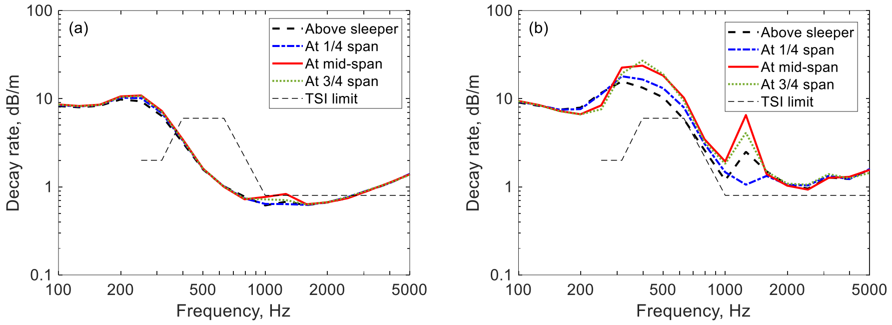

Fig. 5. TDR obtained using different sensor positions. (a) Soft pad, (b) stiff pad.

2.5 Wave reflections between wheels

Before studying the pass-by method, the effect of wave reflections in the rail is considered in the context of the EN method. Wheels are added to the rail, which are modelled (similar to [9]) as point masses of 600 kg connected to the rail through a contact stiffness of 1.2 GN/m, and a series spring of stiffness 4.8 GN/m with a loss factor of 0.1. The bogie wheelbase is 2.5 m, the bogie centre distance is 17 m, and the vehicle length is 24 m. The reference point is chosen at each of the wheel positions of a central bogie pair; in each case this is located at the mid-span position on the track. The results are shown in Fig. 6(a). For excitation at wheel 1, the vibration decay is ‘measured’ first in the region between the wheels, leading to an increase in the TDR. Conversely, for wheel 4 it is observed first in the region between these wheels and the next pair of bogies, in which case the TDR is similar to the result without wheels apart from some fluctuations. For the stiff rail pad, shown in Fig. 6(b), there is less influence of the wheels.

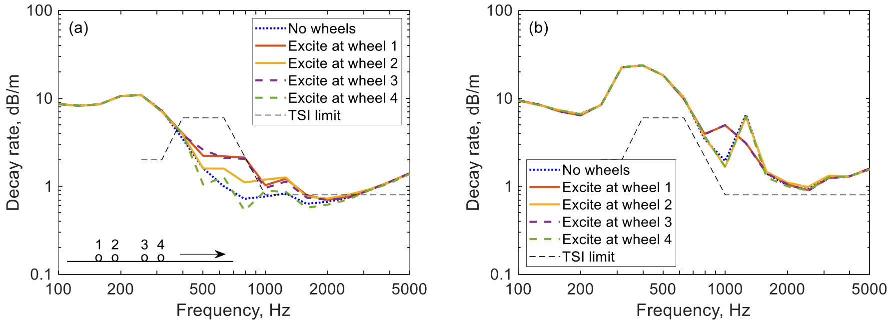

Fig. 6. TDR obtained using EN method with wheels located on the track. (a) Soft pad, (b) stiff pad. The stiffening of track components due to load effects is not considered.

2.6 Effect of track loading

Another difference between pass-by measurements and the EN method is the loading from the train. This has also been previously considered in [9]. In the current simulations, two rail pads have been used for which static load-deflection curves are available as well as dynamic stiffness measurements at different preloads. The load-deflection behaviour of the pads and the ballast (the latter derived from measurements in [10]) has been introduced in the form of a load-dependent secant stiffness into a nonlinear static track model. This model is then used to determine the rail deflection and thus the reaction force at each sleeper, see Fig. 7; wheel loads of 75 kN are used.

These reaction forces are then used to determine the dynamic stiffness of pad and ballast at each sleeper and these values are introduced in the model used to calculate the TDR (using the EN method). The result is shown in Fig. 8, for a reference point at the wheel 2 of the central pair of bogies. The wave reflection effect between the wheels is not considered in these results. The effect is larger for the soft pad, which has a greater load dependence, see Fig. 7(a). Compared with the results shown in Fig. 6, the effect of loading is greater than the effect of wave reflections in the rail.

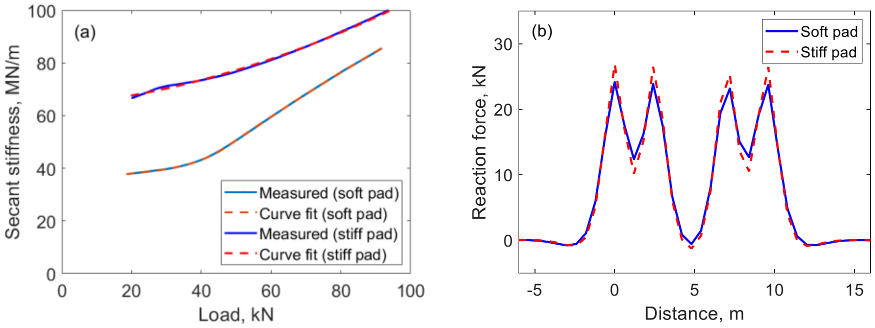

Fig. 7. (a) Secant stiffness of two rail pads relative to 20 kN; (b) reaction forces at sleepers for wheel loads of 75 kN.

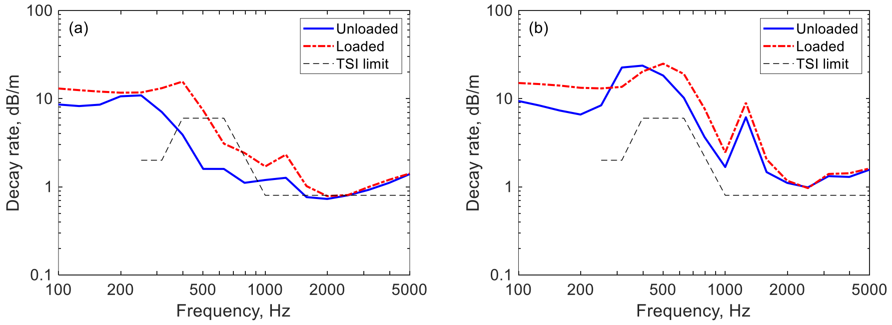

Fig. 8. TDR obtained using EN method with loaded track stiffnesses. (a) Soft pad, (b) stiff pad. The wave reflection effect between the wheels is not considered.

3 Pass-by method

The pass-by method is used to estimate the TDR from operational rail vibration during a train pass-by [6]. Here, the ‘energy iteration method’ will be used, which is based on an integration of the squared vibration, similar to Eq. (1). In this case, the integral over the whole train pass-by, length L_2, is compared with the integral over regions of length L_1 around each wheel instead of $A_k(0)$. An iteration procedure is applied to allow for the contribution of multiple wheels to the integral around a single wheel. In [6] it is recommended that L_1 should be chosen slightly smaller than the bogie wheelbase.

To simulate the pass-by method, the same track model has been used. Although this is a frequency-domain method, it has been used to determine the rail vibration for different train positions on the track, spaced at intervals of 0.1 m. The eight wheels of two vehicles are coupled to the rail through a wheel-rail interaction model and excited by a unit roughness at each frequency. The mean-square vibration from this model is integrated over L_1 and L_2, and used in the method of [6].

Results are shown in Fig. 9 for both loaded and unloaded track stiffnesses. The near-field integration length around each wheel L_1 is set to 2.2 m. These results are based on intervals centred on the actual wheel positions; if instead the peaks in the response are used, slight differences occur. The results are consistently higher than those from the EN method, partly due to the influence of the loading and the wave reflections between the wheels. However, the results at low and high frequencies are systematically higher.

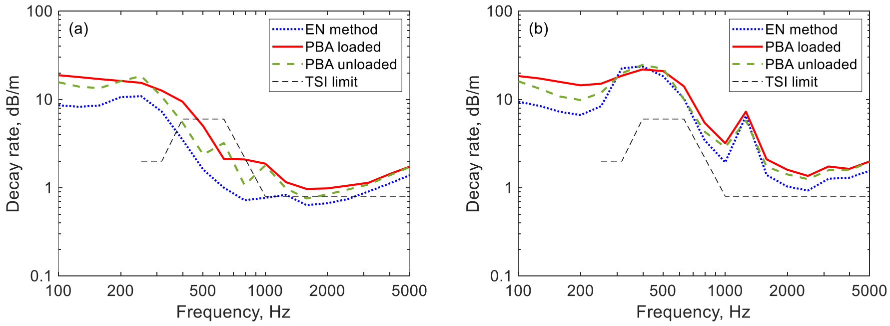

Fig. 9. TDR obtained using PBA method with loaded and unloaded track stiffnesses. (a) Soft pad, (b) stiff pad.

4 Conclusions

The method in EN 15461 gives an equivalent TDR, which is relevant for transposition. However, this result is consistently higher than the decay of the principal wave in the rail (due to the influence of the vibration near-field). Regression analysis can approximate the wave decay, which would be more useful for updating models such as TWINS.

A reduction of measurement effort is possible by reducing the measurement grid from the 29 points defined in EN 15461 to a set of 9 points; additional points could be added to provide some redundancy. Using a sensor above a sleeper instead of at mid-span leads to potentially large differences. A revised standard should consider including both points. The minimum measurable value DR_{min} should also be revised.

In the simulations, the pass-by method gives consistently higher TDR results than the EN method. The effect of reflections between wheels is significant for soft rail pads. The increase of pad and ballast stiffness under load has a greater effect and is larger for soft pads. These effects are specific to each type of rail pad. The pass-by method is also sensitive to the identification of wheel positions and the choice of integration length around the wheels. Further work will be carried out in QuieterRail, including validation of the use of the TDR in transposition methods.

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