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The effect of Track Decay Rate on in-carriage noise for resilient track fixings

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ABSTRACT

The Track Decay Rate (TDR) of a railway track is a key factor influencing wayside and in-carriage railway noise, particularly in tunnel environments. Highly-resilient track fixing systems are commonly used in tunnels to mitigate groundborne noise and vibration (GBNV), but also result in low TDRs, and increased noise radiation from the rail component of the wheel-rail interface. Toward & Thompson (2012) indicate that the change in noise emission for different track fixing systems is proportional to the logarithm of the ratio of TDRs. This relationship suggests a large increase in noise emission for typical soft rail fixings, when compared to ballasted track. Measurements of TDR of tracks with a range of fixing systems (ballasted, slab-track with resilient fixings, and floating-slab-track) have been undertaken according to DIN EN15461:2008 as part of the in-carriage noise predictions for a new railway tunnel in Australia. The TDR corrections are validated against measurements of in-carriage noise undertaken on the same network and show that current assumptions are overly conservative. Reasons for these differences are discussed, and alternative methodologies are proposed to predict in-carriage noise for trains on resilient track fixings in tunnel environments.

1. INTRODUCTION

Railway operations generate vibration at the wheel-rail interface which can result in groundborne noise and vibration (GBNV) impacts at nearby sensitive receivers such as residential properties and very high-performance research facilities. Groundborne noise and vibration criteria are therefore usually incorporated into planning approval and project construction contracts for new projects to mitigate the impact of these railway projects on sensitive receivers.

Recent railway tunnel projects in Australia have therefore adopted highly-resilient track fixings and/or floating slab trackforms (FST) to mitigate GBNV emissions from the railway. However, because these soft track fixings also decouple the rails from the relatively massive and stiff track support structures, they increase the track mobility and reduce the damping of the rail. This results in an increase in the noise emission from the wheel-rail interface and increased in-tunnel and in-car noise levels.

The Melbourne Metro Rail Tunnel project includes a requirement to achieve an in-carriage noise level of 65dB$L_{Aeq,5sec}$ within the carriage and 67 dB$L_{Aeq,5sec}$ in the drivers compartment when the train is travelling in the tunnel, for 80% of the trip time.

Generally speaking, noise levels within the carriage are a combination of noise from several paths (see Figure 1). including:

- airborne noise from
  - vehicle systems, and
  - wheel-rail interface (red & green arrows),
- structureborne noise from vehicle systems (blue arrows)
- internal sources such as mechanical services and ventilation systems within the carriage (yellow arrows)

When a train enters a railway tunnel, there is usually an increase in in-carriage noise due to the addition of airborne reverberant noise around the carriage (orange arrows), called the ‘tunnel gain’.

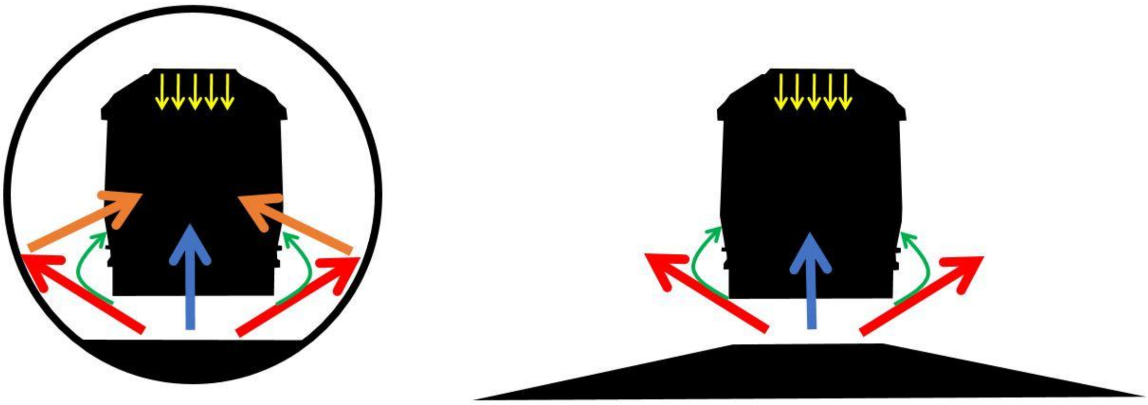


Figure 1 In-carriage noise imission paths, tunnelled railway, at-grade railway

Several early railway tunnels in Australia, the Melbourne Underground Rail Loop (MURL) and the Sydney Eastern Suburbs Line (ESL) incorporate in-tunnel sound-absorbing elements. These are usually affixed to the side walls of the rail tunnel to reduce the reverberant build-up of sound within the tunnel, but there is little acoustic design information publicly available for those systems. More recently, the Epping Chatswood Rail Link (ECRL) opened with relatively high in-carriage noise levels despite the inclusion of sound-absorbing panels in the tunnel. Additional sound-absorbing panels and rail dampers were required to reduce overall in-car noise levels to acceptable levels (Coker & Anderson, 2010) (Weber & Sburlati, 2010). It is noted that these types of treatments (especially track dampers) can introduce additional maintenance requirements in the tunnel environment. It is perhaps for this reason that tunnel sound-absorbing treatments and track dampers do not appear to be commonly used in underground metropolitan railway systems elsewhere in the world.

As noted above, the soft track fixings used to mitigate groundborne noise and vibration decouple the rails from the relatively massive and stiff track support structure, and result in increased rail mobility, decreased damping of the rail and therefore increased noise radiated from the rail, which increases in-tunnel (and in-carriage) noise levels. The damping of the rail can be characterised by the Track Decay Rate (TDR), a parameter expressed in units of dB per metre. Traditional fixing systems such as ballasted track have relatively high damping and therefore tend to radiate less noise. Very soft track fixings contribute to lower TDR, and result in more noise being generated by the rail (Betgen, 2013). The effect of various resilient track fixings on the TDR and the subsequent change in noise emission from the rail caused by various fixing types needs to be understood to make reliable predictions of in-carriage noise.

Theoretical tools such as STARdamp can be used to predict the performance of various damper systems (Betgen, 2013) on generic track types, however the TDR of systems with proprietary track fixings is not well documented. Major track component suppliers such as Pandrol, Delkor and Vossloh do not typically provide TDR data for their track fixing assemblies as part of their product information.

Toward and Thompson (2012) adopt the parameter Δ to account for the change in noise emissions between tracks with different TDR, shown in equation 1.

$$\Delta = 10\ log\left(\frac{TDR}{TDR_{ref}}\right) \qquad (1)$$

2. MELBOURNE METRO TUNNEL IN-CARRIAGE NOISE DESIGN PROCESS

As part of the design process for the new Melbourne Metro Tunnel (MMT) project, the acoustic engineering team (Arup, WSP) has developed a model to predict in-car noise levels. The model allows types of treatment to be evaluated (particularly rail dampers) and the required extents of tunnel absorption to be designed.

The model adopts two prediction paths shown in Figure 2 below, based on reference in-carriage noise level measurements either:

- within an (existing) X'Trapolis vehicle running within the MURL (Path A), or
- within a (future) HCMT train travelling on at-grade ballasted track (Path B)

In each case, corrections for the trackform noise emission, tunnel gain and vehicle sound insulation are considered.

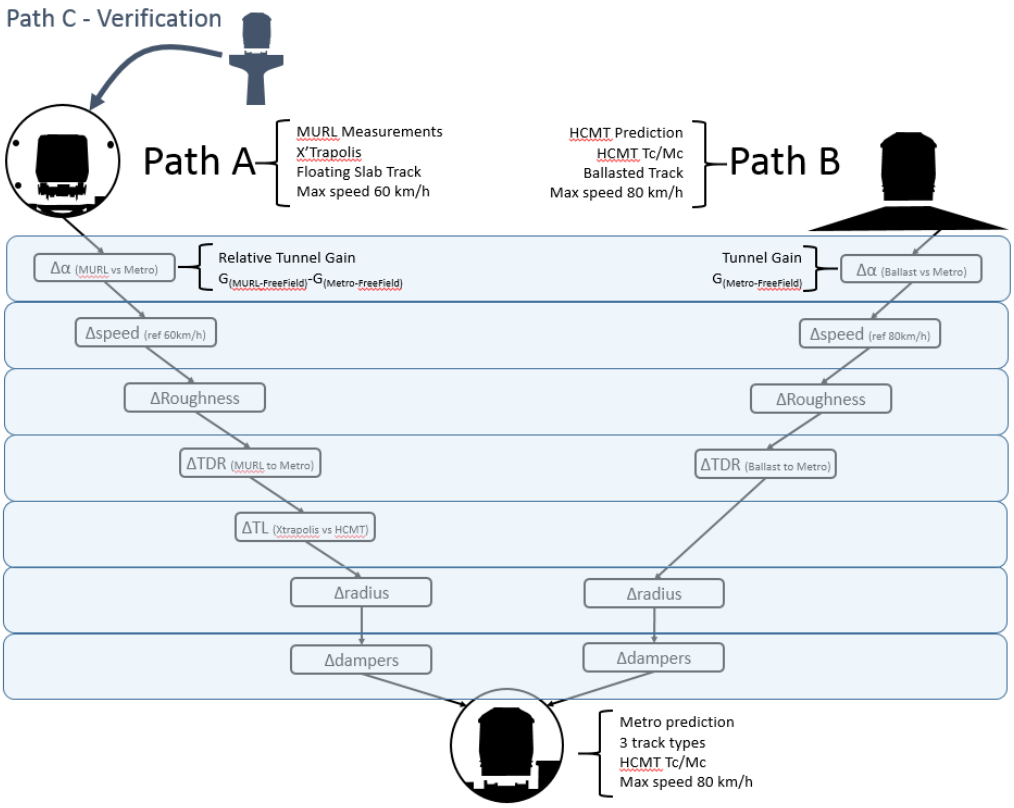


Figure 2 Model Flowchart

Tunnel-gain and the effect of in-tunnel absorption has been determined by creating a detailed Odeon room-acoustic model of both the MURL and MMT spaces with a train in it. The Odeon model (without train) was validated based on in-tunnel reverberation time measurements undertaken within the MURL. This is a reasonably well-established process, and is not examined in further detail here. The model also accounts for roughness correction (not found to be a dominant correction in this case) and speed correction shown in equation 2. These are also not further examined in this paper. Note that the speed relationship was based on in-carriage noise level measurements undertaken in a test train in the MURL and was found to be lower (20log) than the usual 30log speed corrections adopted for noise emissions from at-grade train passbys (Thompson, 2009).

$$Speed\ Correction = 20\ log\left(\frac{v}{vref}\right) \tag{2}$$

Individual proprietary track fixing systems had not been selected during the design of in-tunnel absorption treatments. Representative track fixing systems were selected for Standard, High and Very High Track types, indicating levels of trackform insertion gain performance (Burgemeister & Greer 2004), as described in the planning stages for the MMT, these are shown in Table 1.

Table 1 Rail track fixing system properties

Track type	Fixing System	Track Fixing Dynamic Stiffness
Standard	Vossloh 300/Pandrol VIPA/Delkor Alt-1	20 kN/mm
High	Vossloh 336/Delkor Egg	8.5 kN/mm
Very High	FST (as installed in MURL)	N/A
Ballast	Wooden Sleepers on Ballast	N/A

3. TDR MEASUREMENTS

In order to characterise the TDR of the trackforms (MURL, At-grade ballasted, and Vossloh System 300) TDR measurements were undertaken on in-service railway tracks in accordance with DIN EN 15461:2011-01, at the following locations:

- on the FST system within the MURL
- at several at-grade ballasted tracks across the Melbourne Metropolitan railway network, and
- on the newly installed viaduct slab track system on the Pakenham/Cranbourne Line

The TDR measurements on the Pakenham/Cranbourne line, near Clayton Station, were undertaken during a 3-day shutdown of the system in April 2019. Some photos of the measurements are shown in Figure 4.

TDR measurement involves accelerometers mounted on the rail to measure the response in the vertical and lateral directions to an instrumented 'force hammer' exciting the rail. According to DIN EN 15461:2011-01, 28 impact locations over an approximately 50 m section of the track are required to establish the TDR. Impact locations are shown indicatively in Figure 3.

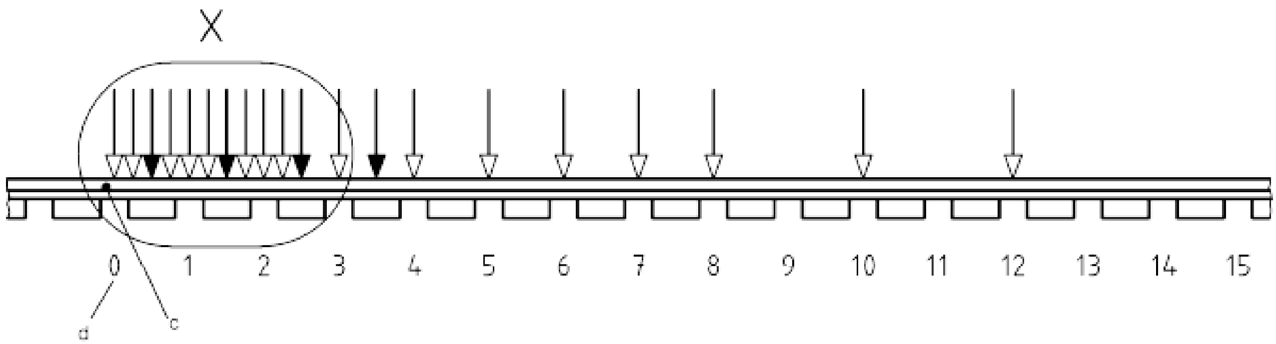


Figure 3 Diagram of impact locations for TDR measurements [from DIN EN 15461:2011-01]

Figure 4 Track Decay Rate Measurements: On site personnel (left); accelerometers and instrumented hammer (centre); vertical and transverse accelerometers (right)

The location of rail-mounted accelerometers was selected to be the median point between two sleepers, with no rail defects (i.e. the absence of: missing fastening clips, rail expansion joints, pumping sleepers etc.) along the remaining distance of track up to the final impact location. Typically a rail weld was present at some distance along the measurement path; in accordance with DIN EN 15461:2011-01 the accelerometers were located more than 5 m from any weld.

Measurements were taken with a Brüel & Kjær Lan-XI 4-channel data acquisition system, transverse and vertical magnet mounted PCB 352C33 accelerometers, and a small mallet instrumented with a Brüel & Kjær Type 8339 accelerometer. It is noteworthy that the measurements of TDR were undertaken with no load on the rails.

Fast-fourier transform (FFT) measurement processing parameters were modified to window the vibration data to reduce the effects of noise on the measurements.

At least four impacts, for both the transverse and vertical directions, were measured at each impact location, and the quality of each frequency response function (FRF) was checked using its coherence function. Measurements were recorded in frequency bands from at least 100-5,000 Hz.

In accordance with the standard, the measured data was post-processed to obtain a one-third octave band FRF. As per Annex A of the standard, the decay rate is calculated using Equation 3.

$$Decay\ Rate\ \approx \frac{4.343}{\sum_{n=0}^{n_{max}} \frac{|A(x_n)|^2}{|A(X_0)|^2} \Delta x_n} \quad (3)$$

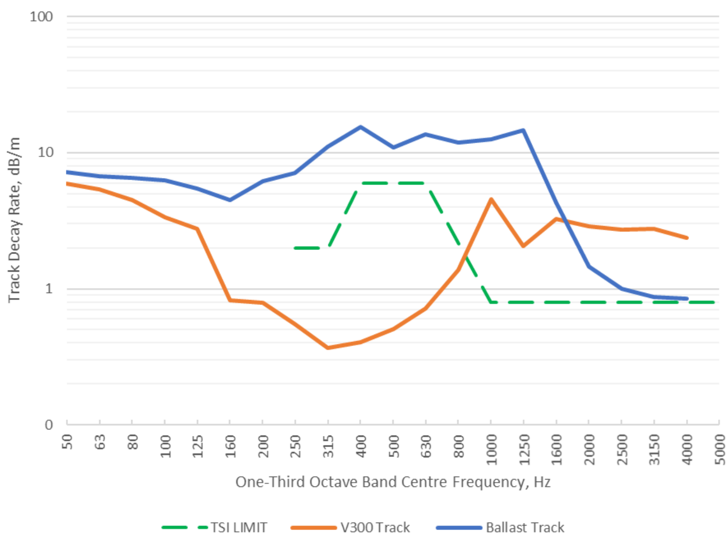


Figure 5 Track Decay Rate for V300 (on plinth) and Ballast (concrete sleeper) Trackforms

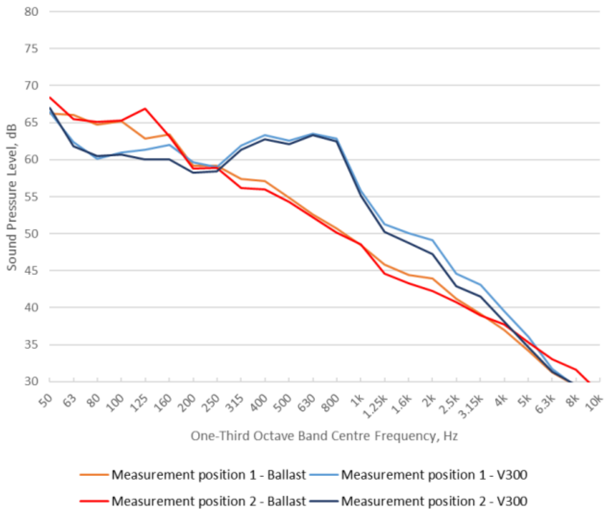
Due to the presence of the $A(x_0)$ term as a constant in equation 3, the calculated TDR is sensitive to the variance in the measured direct FRF. As such, multiple measurements of the direct FRF were recorded on site.

Rail roughness measurements were also undertaken at each TDR measurement site using a corrugation analysis trolley (CAT), in general accordance with BS EN 15610:2009. The results showed that the roughness profile was typical to that of other locations in the Melbourne Rail Network.

4. IN CARRIAGE MEASUREMENTS

In order to validate the relationship between the change in TDR and track noise emission shown in equation 1, measurements of in-carriage noise levels were undertaken on the Pakenham/Cranbourne line, on sections of ballasted and Vossloh 300 track types. This section of track was selected for measurements as the installed track fixing system was considered representative of the fixing systems considered for MMT. Measurements were undertaken on 14 June 2019 at two positions inside a single carriage, each near the doors. Measurements were undertaken on Seimens and Comeng Trains. One-second L_{eq} spectra were measured in two positions per train, with a total of three trips.

Vehicle speed was logged using a GPS tracking application on a smartphone, with the measurements between the two SLMs and GPS time synchronised. Continuous five-second blocks were selected for analysis, from periods when the train was travelling at speeds close to 80km/h, with speed correction (as per equation 2) applied to each one-second spectrum; then results are averaged for each measurement location. Noise from on-board PA announcements, structure-borne noise, and other extraneous noise was noted in the measurement logs and excluded from the analysis. The effect of sound reflections off buildings and changes in rail roughness were both considered to be negligible.



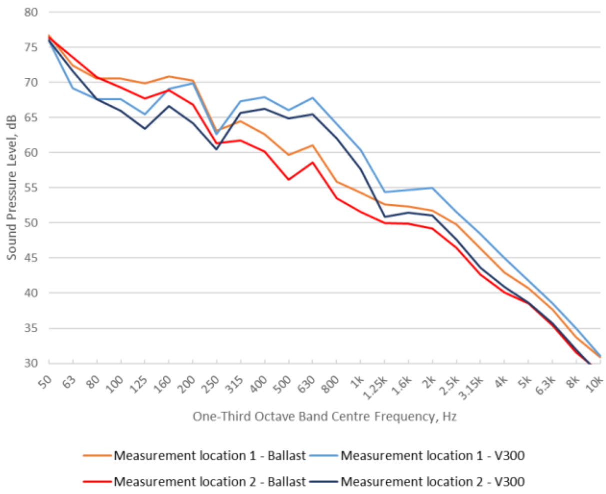


Figure 6 Ballast vs V300 spectra – Trip 1 (Seimens) & Figure 7 Ballast vs V300 spectra – Trip 2 (Comeng train)

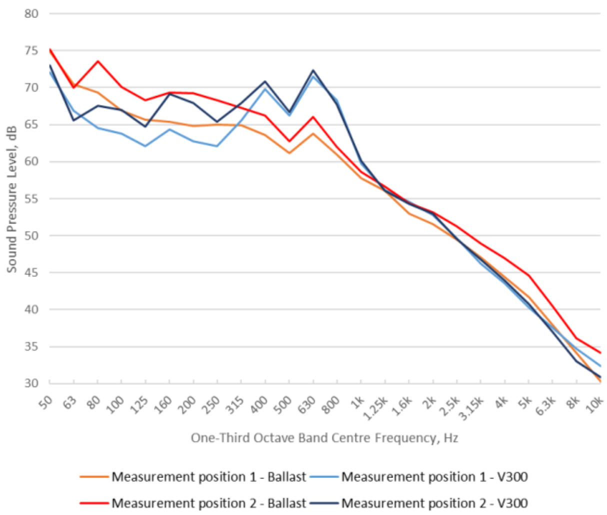


Figure 8 Ballast vs V300 spectra – Trip 3 (Comeng train)

Figure 9 shows the average of all one-second, speed-corrected SPL spectra for both measurement positions. Note the increased noise levels between 250-1,000 Hz for the V300 spectra. There was an audible change in the character of noise within the carriage. There were no audibles tones or impulsiveness to the character of noise. The overall A-weighted SPL increase due to the track fixing was between 4–7 dBA.

Figure 9 Ballast(left) vs V300(right) SPL spectra

As other variables were reasonably controlled, the dominant effect is presumed to be that of the track fixing. The average difference in the measured spectra (V300 minus Ballast) is shown in Figure 10 together with the predicted difference from the literature (equation 1).

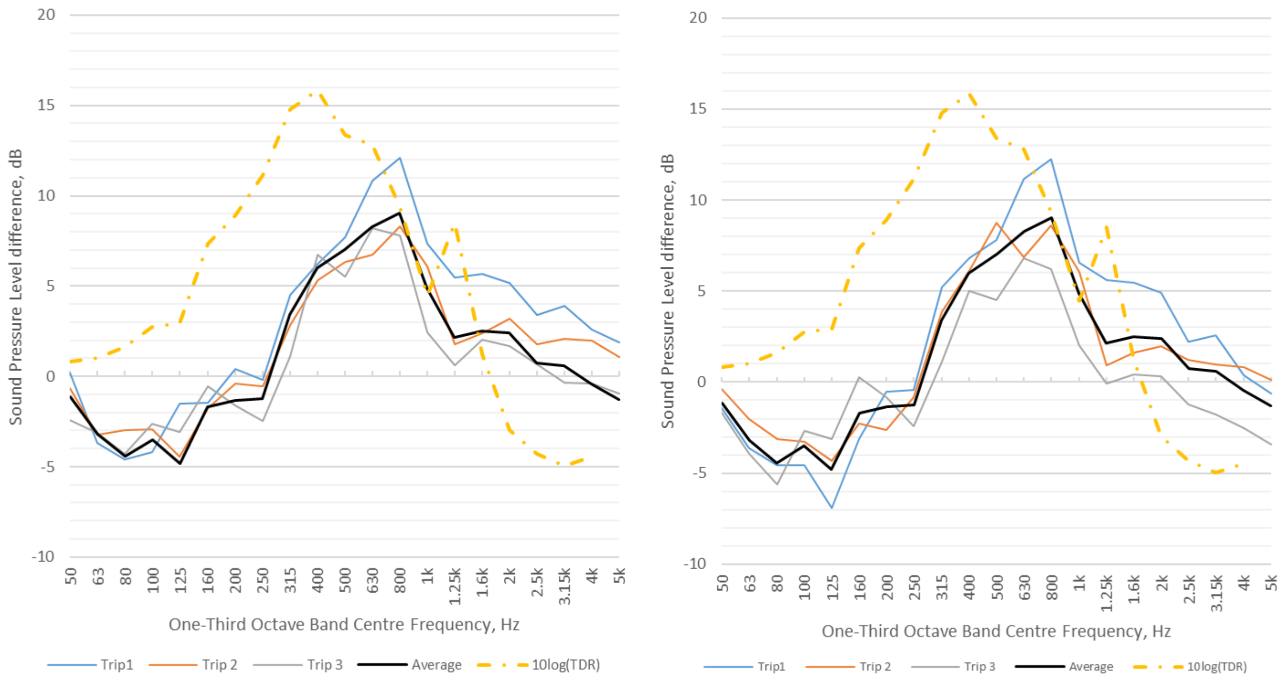


Figure 10 SPL differences – Ballast minus V300, position 1 (left) and position 2 (right)

The results show notable differences in the measured effect of TDR on in-carriage noise, compared to the expected values. The magnitude of the difference is approximately 7dB lower than predicted from the change in TDR and the peak frequency occurs an octave higher than predicted.

5. ALTERNATIVE TRACK DECAY RATE RELATIONSHIP

From the measured in-carriage noise levels, the change in sound power produced by different track fixings appears to be less than that predicted using the 10log relationship given in equation 1. While reasonable care has been taken in the measurement and analysis of the results, there is insufficient data to confirm exactly why this is the case. That said, when considering the effect of TDR on in-carriage noise levels, it is clear that using this relationship can lead to an overprediction of track noise emission, and therefore of in-car noise levels for the in-tunnel scenario, which could lead to a risk of overdesign of tunnel noise mitigation. It has been shown that the effects of train loading can increase the effective decay rate (Jones, et al., 2006).

When proposing a new relationship between in-carriage noise and TDR, it was clear that a simple magnitude change only would not match the results and that a shift in frequency would also be required. The proposed relationship developed for the project was:

$$\Delta = 5\log\left(\frac{TDR_{i+3}}{TDR_{i+3,ref}}\right) \quad (4)$$

$where\ i\ is\ the\ one - third\ octave\ band\ number$

While it is not feasible to fully investigate the underlying mechanism between TDR and airborne noise for this paper, a number of mechanisms have been considered as possible reasons for differences observed. Firstly, as noted earlier, measurements of TDR were conducted on an unloaded track. The loading of the pads by the train changes the stiffness of the fixings and subsequently the decay of energy along the rail (Thompson, et al. 1999) (Kalivoda 2005). While pads may be considered to behave like springs, their deflection vs load relationship is not linear, see Figure 8. The mass of the train may result in the load on the pad occurring in a different region of the curve and therefore the energy decay along the rail differing from the unloaded TDR results.

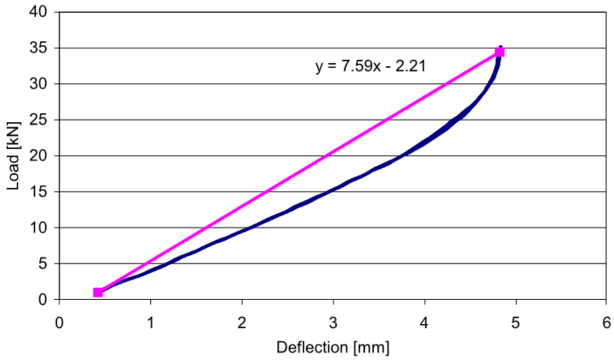


Figure 11 Dynamic load testing of rail pad system

Secondly, it is also important to consider the differences between static and dynamic stiffness. Even if a static load were imparted to the rail for testing, the pads may not respond as they would under a condition where their load is carried along the passby event, with the passage of each wheel (Wu & Thompson 2000).

If should also be noted that the ballast may provide some absorption, compared to the smooth concrete surfaces underneath the V300 track. This effect could not be accounted for in the analysis, although absorption of ballast is not known to have such a dominant peak in the frequency range where the increase in SPL was observed, see Figure 12.

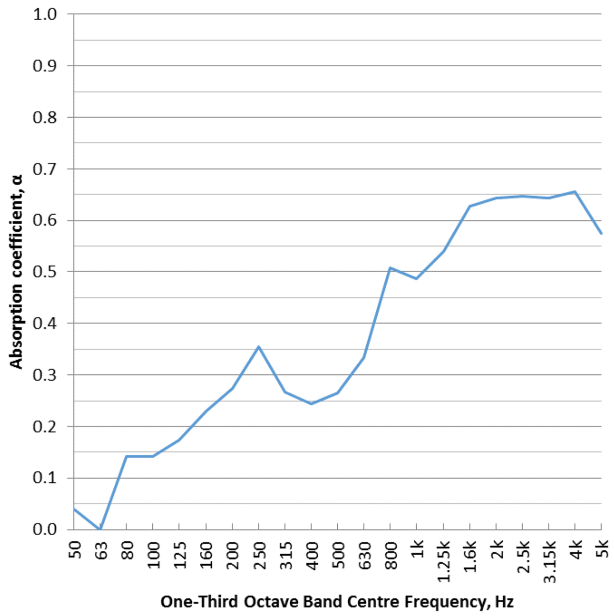


Figure 12 Absorption coefficient of 300mm thick ballast (Broadbent, 2009)

The frequency shift of the proposed relationship also suggests that the train-rail-pad-plinth itself may have a 'natural frequency'. If we consider this system as a mass-spring-mass system then the doubling of natural frequency would imply a quadrupling of the pad stiffness.

It is also worth noting that the predicted SPL difference from TDR may result in a design recommendation for the inclusion track dampers. This design decision reduces risk to the project however as a consequence, finding rail systems with suitably soft track fixings but without dampers to study may be difficult. As soft fixings become more used in rail projects, it is of benefit to understand the noise levels emitted from rails on soft fixings without the effect of dampers.

6. CONCLUSIONS

Track Decay Rate is an important factor for predicting in-carriage noise levels. Soft rail fixings are increasingly being used on rail projects due to ground-borne noise and vibration requirements. The 10log relationship has been shown not to apply for between ballasted track and V300 track. A 5log relationship with a shift of one octave higher has been found to correlate better with the measured levels.

A better understanding of the mechanisms by which TDR influences air-borne noise emitted by the rail for these systems may have the benefit of reduced extents of in-tunnel absorptive treatment and rail dampers, which could reduce project costs while still achieving in-carriage noise design targets.

ACKNOWLEDGEMENTS

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