Some Pitfalls in Using AS2377:2002 for Passby Noise Measurement

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ABSTRACT

The measurement of passby noise for type testing of rail vehicles in Australia is governed by AS2377:2002 Measurement of Noise from Railbound Vehicles. This standard is referenced by many organisations including RailCorp, ARTC and Queensland Rail, and therefore type tests for rail vehicles on most Australian rail networks are conducted in accordance with its recommendations. AS2377:2002 lags behind the latest European standards such as ISO3095:2005 Measurement of Noise Emitted by Railbound Vehicles in two important areas however; it provides no guidance regarding either the acoustic scale roughness of the rails or the track decay rate of the test track section. This paper explores the implications of these issues, provides examples of the resulting changes in noise that can result, with consequences for compliance with RailCorp's EPA licence, and describes how these important track properties are handled in ISO3095:2005.

INTRODUCTION

Rail Vehicle Type Testing

RailCorp has a keen interest in reducing the environmental impacts of its operations, including the noise impacts. This is reflected in Environmental Protection Licence 12208 under which RailCorp operates, which includes noise targets for RailCorp operations, including locomotives. In addition, noise limits for both locomotives and electric multiple units are included in RailCorp Engineering Standard RSU150 (RailCorp 2011). The means by which these noise standards are enforced is type testing of new or modified rail vehicles, and these type tests are all required to be conducted in accordance with the provisions of AS2377:2002 (Standards Australia, 2002).

Other rail operators including ARTC (2010) and Queensland Rail (2007) also reference AS2377:2002 to describe the conditions under which type testing is to be conducted.

AS2377:2002

AS2377:2002 sets out methods for the measurement of noise from rail vehicles, both under stationary and dynamic conditions, and for the purposes of type, monitoring and immission tests. It details the noise metrics to be determined, the environmental conditions under which testing is considered valid, and requirements in terms of measurement equipment, measurement locations and test procedures. Importantly for this investigation, it also describes the track conditions required for dynamic type tests.

This paper discusses two aspects of the track conditions which are not adequately specified in AS2377:2002 but which have a profound impact on the outcomes of type tests. Specifically, these are the rail roughness and the track decay rate, and these are described in more detail in the following sections.

RAIL ROUGHNESS

Roughness and Rolling Noise Emissions

Wheel and rail roughness is a general term that refers to the longitudinal unevenness in the surface of the wheels and rails, as shown in Figure 1. This is distinct from concerns about the cross-sectional profile of either the wheel or rail, or defects such as flats, squats, burns or the severe corrugation associated with high axle loads. These are the focus of much attention from maintainers of rollingstock and infrastructure and are associated with localised impact, squeal and flanging noise.

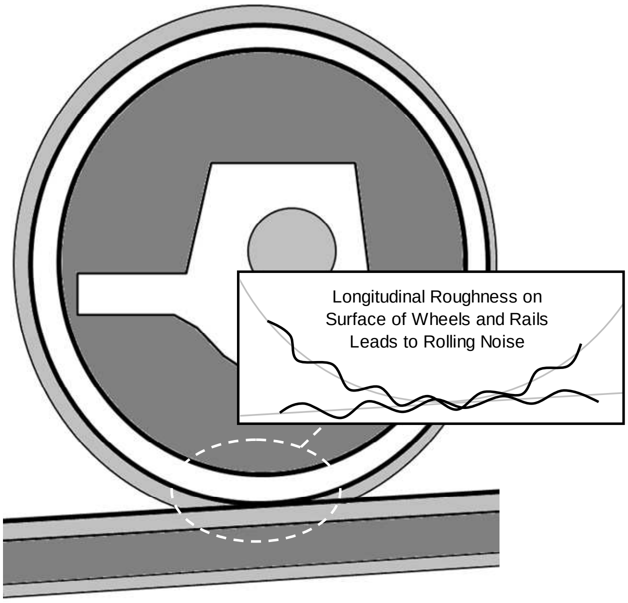

Figure 1 Roughness refers to the longitudinal profile along the wheel and rail running surface (inset)

In terms of noise generation, the wheel is excited equally by roughness on its own surface and roughness on the surface of the rail. Similarly, the rail is equally affected by roughness on the wheel as on its own surface. For noise considerations therefore, rather than considering the roughness of either the rail or wheel in isolation, it is necessary to consider the total combined roughness of both surfaces.

The relationship between roughness and airborne noise is represented schematically in Figure 2.

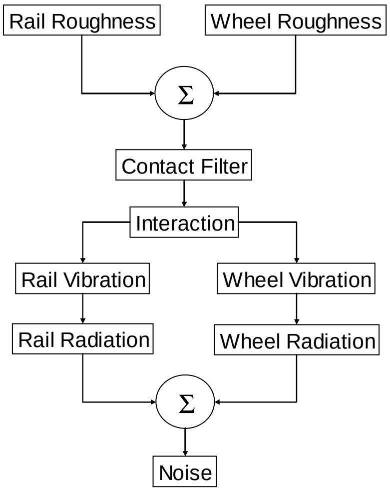

Figure 2 Schematic representation of the mechanisms of rolling noise production (Thompson 2009)

As this figure reveals, the wheel and rail roughness are the inputs to the noise generation process. In general terms for Australian conditions, the rolling noise spectrum will be dominated by the frequency region between 300 Hz and 2 kHz. In this region, the noise is predominately radiated from the wheels and rails. The rolling noise generated by the rail (L_p^R) and wheel (L_p^W) at a frequency ω and a distance R from the rail line is given by (Remington 1976):

$$L_p^R = 10\log_{10}\sigma_R + 10\log_{10}\left(\frac{W_H + W_F}{\pi R}\right) + 10\log_{10}\left|\frac{Z_W^*}{Z_W + Z_R}\right|^2 + 10\log_{10}\left[\left(\frac{\rho c\omega}{p_{ref}}\right)^2 \Phi_{mR}(k)\Delta k\left|H_{cp}(k)\right|^2\right] + 10\log_{10} G(\eta R, \eta L)$$

$$L_p^W = 10\log_{10}\sigma_W + 10\log_{10}\left(\frac{a^2}{2R^2}\right) + 10\log_{10}\left|\frac{Z_R}{Z_W + Z_R}\right|^2 + 10\log_{10}\left[\left(\frac{\rho c\omega}{p_{ref}}\right)^2 \Phi_{mR}(k)\Delta k\left|H_{cp}(k)\right|^2\right] \tag{1}$$

where, σ_R is the radiation efficiency, W_H and W_F are the widths of rail head and foot, Z_W and Z_R are the wheel and rail impedances, ρc is the characteristic impedance (415 Rayls), H_{cp} is the contact patch filter effect at wavenumber k, p_{ref} is 2e-5 Pa, and Φ_{mR} is the combined wheel and rail roughness at wavenumber k, and the wavenumber is related to the vehicle speed by $k=\omega/V$, a is the wheel radius, and $G(\eta R, \eta L)$ is a term which describes the decay rate of the rail.

In the above long and seemingly complex equations, at a given frequency and for a given vehicle speed and trackform, all of the terms are fixed except for the wheel / rail roughness Φ_{mR} which remains as a variable (i.e. to reflect variation from wheel to wheel, and as the rail roughness changes along the track). So in the above expression, for a given vehicle at a fixed speed and at a particular frequency, all the terms other than the wheel and rail roughness could be replaced by constants:

$$\begin{aligned} L_p^R &\approx C_R + 10\log_{10}[\Phi_{mR}], \\ L_p^W &\approx C_W + 10\log_{10}[\Phi_{mR}] \end{aligned} \tag{2}$$

In other words, a change in the wheel / rail roughness will manifest as an equivalent change in the noise emissions.

If the roughness on the rail is significantly greater than on the wheel, then the total roughness will be dominated by the rail roughness. The resulting rolling noise will likewise be dominated by the rail roughness (causing both the wheel and rail to vibrate). The literature suggests that the wheel roughness levels on disc-braked vehicles are generally low, with tread-braked vehicles with composite brake blocks, as are used in NSW, having wheel conditions which are nearly as good. Therefore it is likely that rolling noise emissions are governed by rail roughness for the majority of the RailCorp network.

Typical Variations in Rail Roughness

The level of roughness can change significantly along the track. An example is provided in Figure 3 which shows the variation in one-third octave roughness spectra for five adjoining and non-overlapping 20 m sections of track.

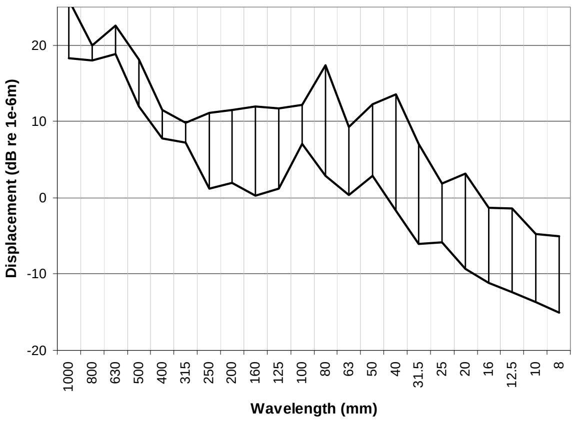

Figure 3 Maximum and minimum of one-third octave rail roughness spectra from five adjoining, non-overlapping 20 m sections of track

These results show differences of more than 10 dB in particular one-third octave bands of interest for rolling noise. At the posted traffic speed of 60 km/h, the 40 mm wavelength band would correspond to noise emissions in the vicinity of 400 Hz. The difference between the lowest and highest roughness in this wavelength band of 15 dB would therefore manifest as an equivalent 15 dB difference in the noise emissions at 400 Hz from these two track sections.

Another way to quantify this variation is presented in Figure 4 which shows the on-car noise levels, recorded in the vestibule of a passenger car, measured along a section of ostensibly homogeneous track which was recently ground.

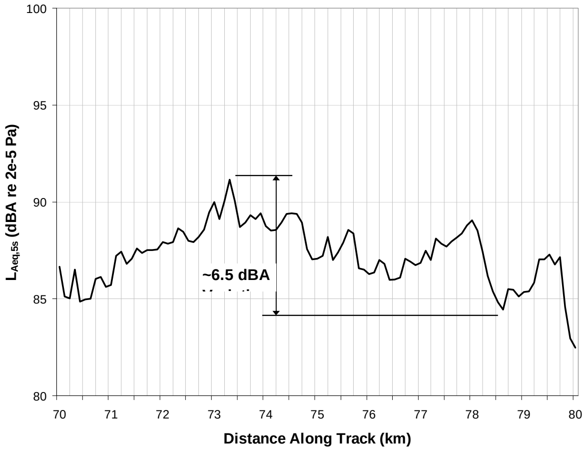

Figure 4 Variation in on-car noise levels along an ostensibly homogenous section of track (normalised for speed)

The noise level differs by more than 6 dBA when assessed on a 5 s L_{Aeq} basis. The difference in terms of $L_{Amax,F}$ would likely be even greater. In terms of type testing therefore, a scenario in which the noise emissions from the same train operating at the same speed etc. could differ by 10 dBA or more at two sections of the same track – even for tracks which are considered "well maintained".

AS2377:2002 requires that the track shall be "in good condition (both profile and surface)". Unfortunately, this requirement is both inadequate to capture the acoustic scale roughness and ambiguous in that no definition of "good condition" is provided. Indeed, the operators of the track from which the measurements in Figure 3 and Figure 4 were obtained may well argue that these tracks were in "good condition" given that they were relatively freshly ground.

A further complication arises with the small physical amplitude of acoustic scale roughness which would make it impossible to distinguish, with visual inspection, between two sections of track for which the noise outcomes are profoundly different. Inspection of Figure 3 reveals that the amplitude of the roughness in 10-100 mm, which has most impact on rolling noise emissions in this case, is of the order of -5 dB to 15 dB re 1 micron, i.e. between 0.3 – 30 microns RMS. It is unlikely that this amplitude of roughness, which is typically less than the width of a human hair, is visible to the naked eye.

A demonstration of this is provided in Figure 5 which considers the simulated roughness on two 1 m sections of track. The roughness on these two tracks is identical, with the exception that the one track (represented by the grey-dashed line) has had the tonal component removed.

The noise emissions from these two tracks would be expected to differ by at least 5 dBA with the corrugated rail also producing noise with an annoying tonal character. Yet, it is not possible to distinguish between the two based on a "visual inspection" as provided in the top plot, even on the exaggerated scale presented.

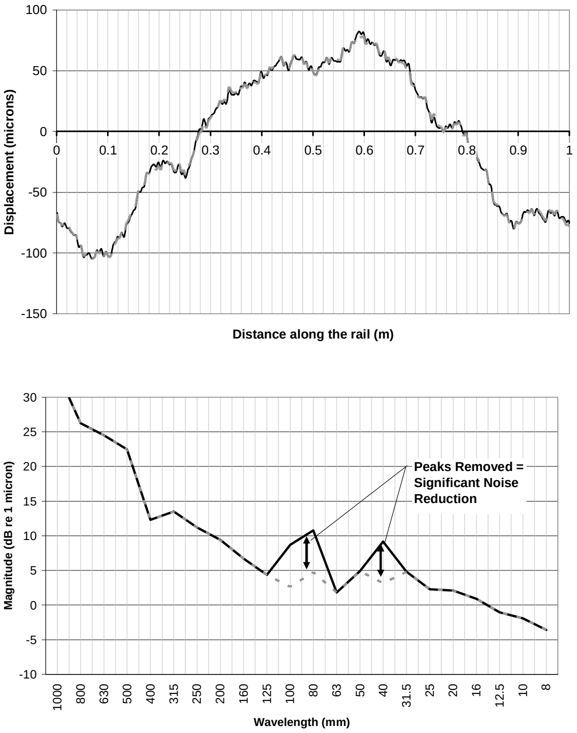

Figure 5 Simulated rail roughness for 1m of track (top) and the corresponding one-third octave roughness spectra (bottom) for a corrugated rail (black - solid) and a smooth rail (grey - dash)

Case Study 1 – Regular Rail Maintenance

The implications of rail roughness for type testing are clearly demonstrated by way of an example. Measurements were recently obtained of the passby noise from several trains in revenue service, and while this was not a type test scenario, the implications of roughness for the noise emissions would apply equally well to a type test.

The railhead near the test site is shown in Figure 6.

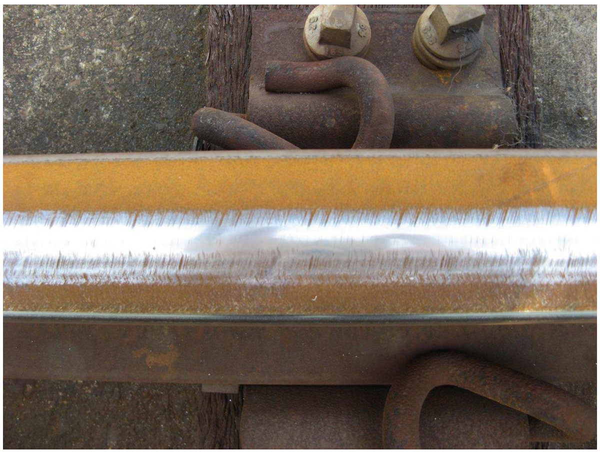

Figure 6 Photo of the rail head near the noise test site, showing the clear running band

The rail would appear to be in good condition, free of defects and joints, and there is clear evidence of the recent rail maintenance. There are no longitudinal roughness components visible in the running band.

The $L_{Aeq,passby}$ narrowband spectrum from one train is shown in Figure 7. Also shown is the narrowband rail roughness spectrum from the rail nearest the microphone, measured using a Corrugation Analysis Trolley (CAT) and scaled to frequency based on the measured train speed.

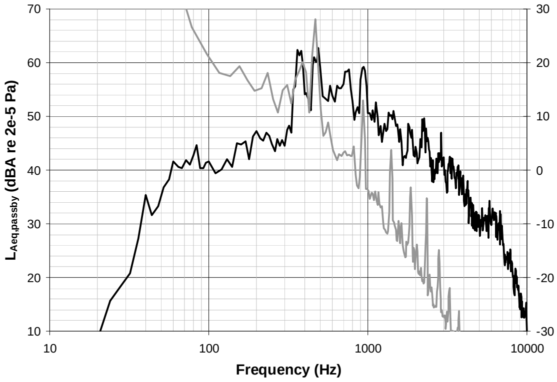

Figure 7 Wayside passby noise spectrum (black) and rail roughness spectrum (grey)

There are two tonal components in the noise, as well as their harmonics, clearly evident in the spectrum. These tonal components are greater than 10 dB above the adjacent frequency regions, and this particular train would fail the type testing requirements based on the tonality of the wayside noise spectrum (note that the spectrum shown was not recorded in accordance with the test requirements of AS2377:2002 in terms of both measurement location and vehicle speed, and hence the overall level is not indicative of a type test scenario).

The tonal components in the roughness spectrum align with those in the noise spectrum, indicating that the tonal noise is generated by the rail roughness components. As for the noise components, the tonal roughness rise 10 dB or more above the adjacent wavelength regions, yet there is not evidence of these high levels of corrugation in Figure 6.

The impacts of the roughness for the wayside noise emissions are profound, as shown in Figure 8. This presents two one-third octave noise spectra – the noise as-measured (in an $L_{Aeq,passby}$ sense) and the corresponding one-third octave spectrum with the tonal roughness components “mitigated”, i.e. artificially reduced in the narrowband spectrum then converted to a one-third octave spectrum.

The “mitigated” spectrum in this case was generated by artificially attenuating the tonal noise components associated with the tonal roughness by half their original amplitude, i.e. simulating the case where the roughness is not entirely removed but merely reduced. Even with this conservative approach to “mitigation”, i.e. assuming the tonal roughness will still be present but just not so significant, a profound difference on the wayside noise spectrum is evident. The overall level is reduced by 7 dBA and the tonal character of the noise is removed.

If it is assumed that these were type test results obtained from the same train but on two different but nearby sections of track, then these results would almost certainly represent a non-compliance with RailCorp EPL requirements in one case and a compliance in the other - for the identical train. In both tests, the track requirements in AS2377:2002 would seem to have been satisfied, i.e. both tests would conform to the standard and both would represent valid type tests.

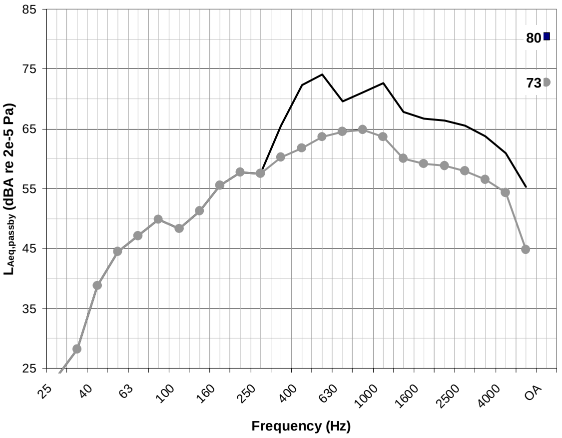

Figure 8 Wayside passby noise spectra – as measured (black - solid) and after “removal” of the tonal rail roughness components (grey - dot)

TRACK DECAY RATE

Track Decay Rate and Rolling Noise Emissions

Air-borne noise from the rails is generated by vibration waves which travel down the rail and decay with distance from the wheel/rail interface. In this way, the rail acts like a line noise source of finite length defined by the rate of decay of the travelling waves with distance, as shown in Figure 9.

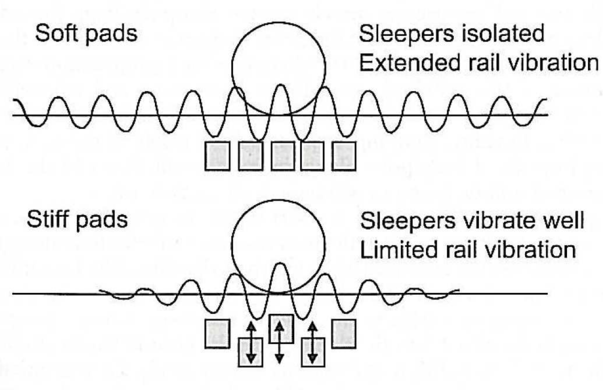

Figure 9 Rail vibration around the wheel/rail contact point for soft (top) and stiff (bottom) rail supports (from Thompson 2009)

As this figure demonstrates, on tracks with stiff rail fastenings, the rail interacts with the sleepers and ballast thereby transferring energy from the travelling waves in the rail to the ground. On resiliently mounted tracks however, the rail is relatively free to vibrate and the decay rate of the travelling waves is very low. In other words, on resiliently mounted tracks, the length of rail which is vibrating and generating noise is very long compared to tracks with stiff rail fastenings This is why rolling noise is often much greater on resiliently mounted tracks (note that resiliently mounted tracks are often employed in environments where the transmission of vibration is critical, such as tunnels, rather than airborne noise considerations). Put another way, the resiliently mounted track has a low Track Decay Rate (TDR) where as the TDR for the ballasted track with stiff pads is high.

Typical Variations in Track Decay Rate

The TDR describes the decay rate, in dB/m, of the vibration waves in the rail as a function of frequency. It is heavily influenced by the coupling with the underyling trackform, as described above, and the presence of additional damping elements such as rail dampers. The variation in TDR across four different trackforms on the RailCorp network is shown in Figure 10.

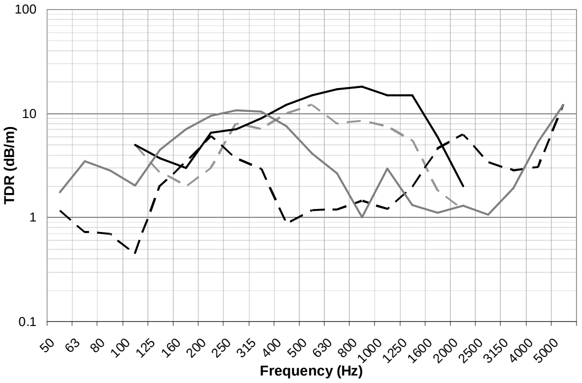

Figure 10 Measured track decay rates from across the RailCorp network, in order of increasing support stiffness: black-dash, grey-solid, grey-dash, black-solid.

These four decay rate spectra represent disparate trackforms from ballasted track with stiff pads through to resiliently supported rail on slab track. The difference in decay rates for similar trackforms is likely to be small, but seemingly similar trackforms may have quite different rail pad stiffnesses and hence different decay rates. This difference may be significant, for example, on tracks with concrete sleepers compared with wooden sleeper trackforms. Both tracks would be considered valid for vehicle type tests in accordance with AS2377:2002.

Case Study 2 – Variation in Decay Rates using Rail Dampers

The effect of changing the decay rate on noise emissions is demonstrated through an example as shown below. In this case, the decay rate at the test site was modified by adding dampers to the rails while all other factors, such as the rail roughness, remained the same. The track decay rates and the resulting in-car noise spectra (measured in the vestibule), are shown in Figure 11.

In this case, the in-car noise levels were reduced by nearly 5 dBA with the addition of rail dampers. While this is a relatively extreme example, as the track decay rate of the bare rail was unusually low in this case, these results do provide a demonstration of the potential changes in noise outcomes from modifying the track decay rate.

Significant changes in decay rate may also exist between two rails which were considered suitable for type testing in accordance with AS2377:2002, such as between track with wooden sleepers and track with concrete sleepers and stiff rail pads. In this case, the decay rate spectra may resemble that shown in Figure 12.

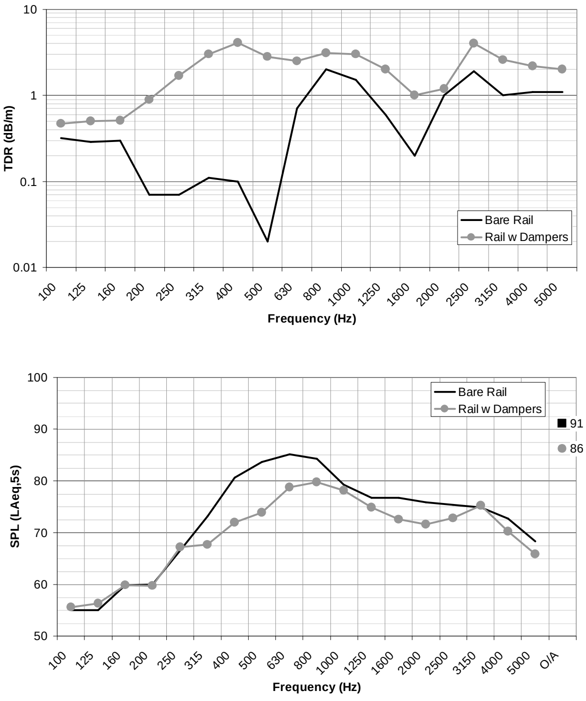

Figure 11 Track decay rates (top) and in-car noise measurements (bottom) on a test track with and without dampers

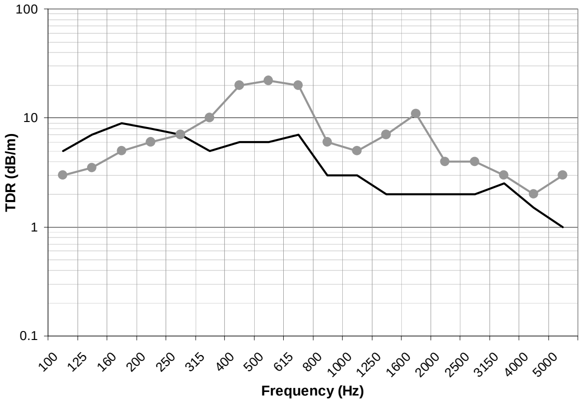

Figure 12 Track decay rates from ballasted track with stiff fastener on concrete sleepers (grey - dot) and with wooden sleepers (black - solid) (from Thompson 2009)

The track decay rate at between 400 Hz and 630 Hz is around three times higher for the track with concrete sleepers, and hence the track component of the rolling noise may be expected to be more than 4 dB lower over this region, if all other parameters were identical.

While it is likely that other trackform properties would also change with the change in trackform, these results serve as a guide to the overall impact of the increased decay rate on the concrete sleeper trackform. The difference in noise levels between the two trackforms in this example may mean the noise levels were compliant on the concrete sleeper track and non-compliant on the wooden sleeper track.

SPECIFICATION OF TYPE TEST CONDITIONS IN ISO3095:2005

The treatment of rail properties in the comparable ISO standard – ISO3095:2005 (ISO 2005) – is far more prescriptive than AS2377:2002. The ISO standard includes a rail roughness limit spectrum, shown in Figure 13.

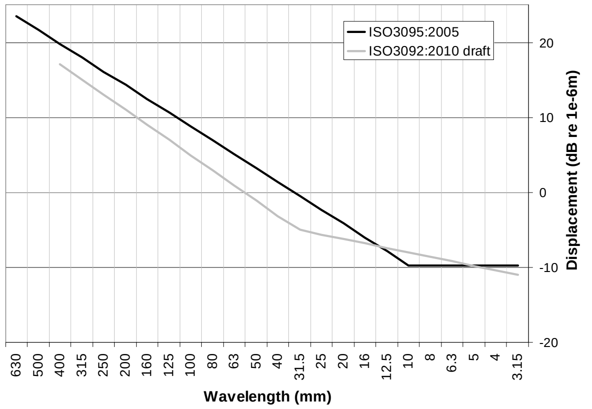

Figure 13 Rail roughness limit spectrum from ISO3095:2005 and the proposed limit spectrum from the draft 2010 revision

For type tests to be considered valid, the rail roughness at the test section should be less than the limit spectrum, although minor exceedances are permitted in the 10-80 mm wavelength region.

The new draft revision (2010) of this standard also includes similar limit spectra for both lateral and vertical track decay rates. In addition, it is noted in Annex D (Annex F of the 2010 draft revision) that the difference in noise levels between maximum and minimum pad stiffnesses (corresponding to maximum and minimum track decay rates) would be 5.9 dB and the difference between the smoothest and roughest rails would be 8.5 dB.

The advantage of this prescriptive approach is that type test results for different vehicles and different tracks can be reliably compared. One disadvantage is the requirement for additional instrumentation and processing to accompany a noise type test. Without quantifying the rail roughness and track decay rate however, as has been demonstrated in this paper, the following negative outcomes could occur:

- Possible non-compliance during type testing yielding contract changes and penalties
- Uncertainties on the results obtained during type testing
- The type test results cannot be reliably compared – either with other type test results or with applicable standards and noise targets.

DISCUSSION

While it has been demonstrated that AS2377:2002 does not sufficiently account for the impacts of rail roughness and track decay rate on the results of noise type tests, and that comparable European Standards adopt a more prescriptive approach to account for these parameters, it is not sufficient to simply conclude that RailCorp and other Australian operators should adopt the conditions in the European standard. A more fundamental question arises which defines the purpose of the type test.

Type testing is generally intended to quantify the vehicle specific components of the wayside noise, hence it may be appropriate to apply uniform “low noise” rail roughness and TDR requirements as outlined in ISO3095:2005. It would need to be understood however, that the resulting noise emissions were not representative of the train under normal operating conditions, and hence could not be used for comparisons with environmental licences and similar guidelines aimed at controlling noise pollution.

Tests which aimed to characterise the “standard” in-service noise emissions, i.e. in order to provide a direct link to the noise targets in the environmental interface standards and Environmental Protection Licence, may include “typical” or even “worst case” roughness and TDR conditions found on the network. In the case of “typical” roughness and decay rate therefore, the noise test would indicate whether the vehicle would comply with the noise targets under “average” conditions, whereas the “worst case” roughness and decay rate would ensure that the vehicle complied with the noise targets everywhere on the network. Clearly however, such a test would be distinct from the type test described above.

RECOMMENDATIONS

As a proposal for addressing the issues raised in this investgiation in the short term, RailCorp has proposed that measurements of the rail roughness accompany type test reports. This procedure was employed during the recent Waratah type testing where the rail roughness at the test site was measured using RailCorp’s CAT. In addition, measurement of the track decay rate would be beneficial, but it may be sufficient to quantify the decay rate for a similar trackform elsewhere on the network.

OTHER CONSIDERATIONS - PASSBY TIME AND MEASUREMENT LOCATION

AS2377:2002 specifies that microphones should be located at 15 m from the track centreline (with an optional additional measurement at 30 m). Unfortunately, this frequently places the microphone location outside the rail corridor and potentially in conflict with adjacent developments such as roads and ajoining properties. The measurement location specified in ISO3095:2005 is at 7.5 m from the track centreline, which in most cases will be within the rail corridor.

In addition, AS2377:2002 does not define the passby duration. While it may seem obvious, it nevertheless should not be left open to interpretation and RailCorp has observed different passby durations being employed in rollingstock type tests. The issue may be resolved by adopting the definition of passby duration in ISO3095:2005, i.e.

> the measurement starts when the A-weighted sound pressure level is 10 dB lower than found when the front of the train is opposite the microphone position….” and “is stopped when the A-weighted sound pressure level is 10 dB lower than found when the rear of the train is opposite the microphone position.”

FURTHER WORK

RailCorp is engaged with the RailCRC investigating techniques for quantifying rollingstock noise source contributions (e.g. from rail, wheel, engine exhaust), track decay rates, and wheel and rail roughness. This information could inform assessment of rollingstock noise emissions over and above the type test described in this paper. It may be possible to determine, based on knowledge of the range of roughness levels across the network and fleet, correction factors to apply to type test noise spectra which would indicate likely maximum noise emissions from a particular vehicle, and which could be used in assessments based on RailCorp Environmental Interface standards. This work is ongoing.

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