Predicting and managing rolling noise emissions from trains on the Perth metro passenger rail network

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ABSTRACT

This paper presents an investigation of rolling noise emissions from trains operating on the Perth electrified passenger network, as an outcome of the Public Transport Authority's strategic initiatives in noise management. The study compared STARDAMP model results with field measurements for both ballasted and slab track, examining scenarios with and without rail dampers, and identified the contribution of track and rolling stock to overall rolling noise emissions. The work demonstrates that noise from the Perth metropolitan passenger train network can be effectively attenuated using rail dampers. A rolling noise reduction of up to 5 dB was predicted and measured for passenger trains on ballasted track. In a tunnel situation with Pandrol Vanguard slab track a reduction of up to 8 dB was achieved. The efficacy of rail dampers as a noise control measure in Perth is attributed to the Perth rolling stock wheel design and track support dynamic stiffness.

1 INTRODUCTION

Noise emissions from individual trains are generally not regulated in Western Australia, and there has not been a historical driver to reduce noise from the passenger network. The Public Transport Authority (PTA) are investigating options to better understand and manage noise in order to protect the amenity and wellbeing of communities living close to the railway. One option investigated was rail dampers. In Australia, previous physical trials testing rail damper effectiveness have tested Sydney suburban heavy rail on ballasted track (Parker and Weber, 2010), tunnel slab track (Weber et al, 2012) and above ground slab track (Weber and Sburlati, 2010). The original theoretical modelling, research and development of rail dampers was undertaken in the European context, also with an emphasis on intercity or suburban heavy rail systems operating on ballasted track.

Railway rolling noise is generated when the roughness of the surfaces in rolling contact excites vibration of the wheels, rails and track components, generating noise (Thompson, 2009). Rail dampers are a noise mitigation measure designed to reduce noise radiated from steel rails. Rail dampers take the form of tuned mass-spring-damper systems that can be attached to the rail in between the normal rail fasteners, e.g. Figure 1.

Figure 1 Installed rail damper, Perth Tunnel 6, 30 August 2016.

The concept of rail dampers was an outcome of the European Union funded Silent Track project between 1996 and 1999, as an at-source noise mitigation measure (Thompson, 2009). Rail dampers are a proven, commercially available product. However, they will not provide a benefit in all situations. The benefit achievable depends on the track design, the design of the wheel, and the dynamic interaction of the system as a whole. Rail dampers are much more effective on tracks with resilient rail supports than on track with stiff rail supports. For example, if a particular track design incorporates stiff rail supports, the track decay rate is inherently high, and the addition of rail dampers will have a negligible effect. This situation most commonly occurs with ballasted track and concrete sleepers. The rail pad stiffness used with ballasted track can vary considerably; but is often relatively stiff, which can limit the benefit of rail dampers.

2 METHODOLOGY

This study compares theoretical predictions of the benefits of rail dampers in Perth with the results of field trials on both ballasted and slab track. It identifies the relative contribution of track and rolling stock to the overall passenger rolling noise emissions on each track type. First, appropriate representative track sections for a field trial of rail dampers were identified. Relevant parameters to describe the track and rolling stock for modelling purposes were established, requiring measurements on track to quantify rail roughness and track decay rate. Then, the rail damper field trial involved noise measurements adjacent to a surface track section and in-car measurements for a tunnel track section. A theoretical model STARDAMP was used to predict the benefit of rail dampers for comparison with the field trial results. The model was then used to predict the benefit of rail dampers on other track types not included in the physical rail damper trials.

2.1 Perth rail track types and trial sites

The majority of the Perth network is ballasted surface track with concrete monobloc sleepers. There is some slab track in tunnels and dive structures. Highly resilient rail supports are typically used with slab track to control ground-borne noise and vibration, however these track types result in increased air-borne noise emissions from the rails relative to stiffer alternatives such as ballasted track. The increased noise can affect noise sensitive receivers adjacent to surface track or dive structures. In-car noise in tunnels is also increased by using resilient slab track forms, with potential to impact passenger comfort. Two locations were selected for the rail damper trials as outlined in the following table, one ballasted surface track section and one tunnel track section.

Table 1 Trial site details

Parameter	Trial Site 1: Joondalup line ('Butler')	Trial Site 2: Perth Tunnel 6 ('Perth T6')
Location	Between Clarkson and Butler stations, down main line chainage 39.900 to 40.000 km (100m trial section)	Fremantle up main line, Tunnel 6 chainage 2.500 to 2.600 km (100m trial section)
Photo		
Geometry	From straight to 805 m radius with 70 mm cant via 100.3 m long transition, 1067 mm gauge, AS 50 kg rail	Tangent Track, 1067 mm gauge, AS 60 kg rail
Design speed	100 – 55 km/h (slowing in direction of travel) 50 - 60 km/h in trial section	70-80 km/h
Track type	Ballasted with concrete Monobloc sleepers	Direct fix slab track
Rail support	Pandrol RP65221 static stiffness 65-70kN/mm, 8 mm thick natural rubber	Pandrol Vanguard, 5-5.6 kN/mm static stiffness
Rail damper	Schrey und Veit GmbH, model AMSA AS50 VS 11 kg installed mass per unit	Schrey und Veit GmbH, model AMSA AS60 VS 14.6 kg installed mass per unit

2.2 Perth rolling stock types

Two 'Series' of trains are in operation on the Perth 25 kV electrified network, an older 'A Series' and newer 'B Series'. The Series B train is typically used on the Joondalup and Rockingham (Mandurah) lines and is proposed for the future Forrestfield line; Series A trains are typically used on the 'Heritage' lines being the Fremantle, Midland and Armadale/Thornlie lines. Table 2 provides a comparison of the two train types.

Table 2 Perth EMU Characteristics

Parameter	'Series A'	'Series B'
Image		
Configuration and maximum design speed	2 car set, 90 km/h	3 car set, 140 km/h
TARE train weight	94,000 kg (2 car set)	120,865 kg (3 car set)
TARE / maximum static axle load	12,575 kg / 15,725 kg	10,281 kg / 13,431 kg
Unsprung axle mass (motor / non-motor)	2,160 kg / 1,400 kg	1,800 kg / 1,400 kg
Wheel diameter (new / worn)	840 mm / 760 mm	840 mm / 760 mm

2.3 Rail roughness measurements

Rail roughness is an important factor in rolling noise emissions, as it indicates the track condition at the time of the trial for input to the noise prediction model. A secondary objective of the rail roughness measurements was to facilitate future studies on changes in rail roughness in the rail damper trial sections, as some studies indicate potential for rail dampers to reduce rail corrugation growth rates (Croft et al, 2009; Liu et al, 2017).

Rail roughness measurements were undertaken at both test sites in accordance with European Standard EN 15610:2009. Results were compared with the rail roughness limit spectrum of International Standard ISO 3095:2013 which represents track in good condition, minimising the influence of track condition on rolling noise.

2.4 Track decay rate measurements

Track vibration decay rate testing was undertaken in accordance with EN 15461:2008+A1:2010 before and after rail damper installation to enable a direct comparison of the level of damping provided by the rail and track support structure. This is an important consideration in assessing the effectiveness of rail dampers since vibration decay rates are directly linked to the noise emission of each rail and its supporting elements. The results shown in Figure 2 for the Butler site (with ballasted track) show the improvements in TDR from around 300 and 500 Hz in the lateral and vertical directions respectively.

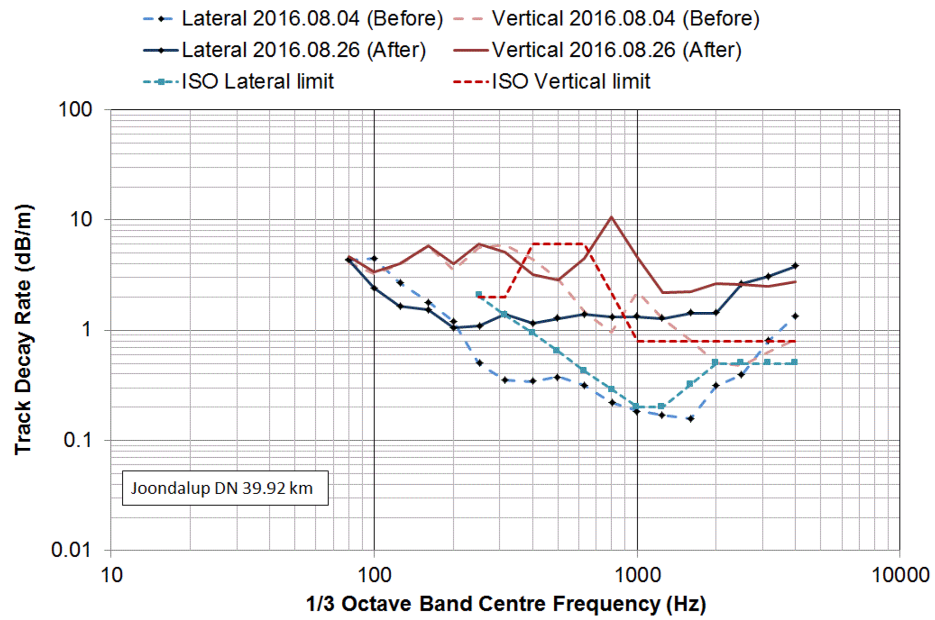

Figure 2 Track Decay Rate measurement results, Butler site, August 2016.

2.5 Sound pressure level passby measurements at Butler

A series of trackside noise measurements were undertaken before and after installation of the trial rail dampers. The measurements were designed to directly quantify overall passby noise emissions at the test site, before and after the trial damper installation. Three microphones were used to assess noise levels at 1.75 m, 3.75 m and 7.5 m from the track centreline. Passby sound pressure level data was collected for a total of 103 (before) and 105 (after) train passby events. Of these, 86 (before) and 83 (after) passby events were selected for analysis on the basis of their speed through the rail damper trial section. Noise data for trains travelling at typical speeds of 50 - 60 km/h through the trial section were analysed, with non-representative events at higher or lower speeds discarded.

2.6 In-car sound pressure level measurements in Perth T6 Tunnel

A rail tunnel is a reverberant noise environment. With a relatively short 100 m length of rail dampers to be installed for the trial, direct measurement of the noise benefit of the rail dampers was challenging due to the influence of noise from the train travelling on undamped adjacent sections of track. In-car noise measurements were undertaken before and after rail damper installation, within the same individual car travelling at a controlled speed of 72 km/h through the trial section.

Measurements were undertaken in accordance with ISO 3381:2005 *Railway Applications – Acoustics – Measurement of noise inside railbound vehicles,* with the exception that six noise loggers were located in the same specific fixed locations near known noise ingress points and passenger seating. The field notes, dash camera images, noise logger data and video records were reconciled to ensure that estimates of position and events were synchronised to obtain every second the average noise level ($L_{Aeq,1s}$) and speed for the entire test period. Approximately six return trips were completed before and after using the same method to improve repeatability.

2.7 STARDAMP modelling

Track Wheel Interaction Noise Software (TWINS) was developed in the 1990s and extensively validated by research institutes including the Institute of Sound and Vibration Research (ISVR) at the University of Southampton, in cooperation with various European railway and rolling stock companies. It is a recognised calculation model for assessing the effects of wheel and track design on railway rolling noise (Thompson and Jones 2000).

The rail damper concept was developed using the TWINS model, and tested in trials during various European Union research projects (Thompson et al. 2007). A benefit of up to 6 dB was achieved for a test train with low-noise wheels on ballasted track with relatively soft rail pads. From 2005-2009 the ISVR investigated the potential additional benefit of rail dampers in reducing roughness and corrugation growth (Croft et al. 2009).

Although TWINS was made commercially available, its cost meant that it was not widely adopted outside of the ISVR and the EU research project partners. To overcome this issue, in late 2010 a project “STARDAMP” was initiated to develop a standardised method to assess the noise benefit provided by rail and wheel damping treatments. As indicated in Figure 3, the STARDAMP tool implements licenced TWINS prediction methodologies to evaluate the effect of wheel and rail dampers on pass-by rolling noise on a straight track.

By using STARDAMP software, the benefits of rail dampers (or wheel dampers) for a particular location can be identified without the time and expense of a physical installation (Betgens 2013). Or, STARDAMP can be used to identify the potential benefits of rail dampers for projects that are in the planning stages.

STARDAMP incorporates a number of options to represent typical parameters that have not previously been tested in Perth conditions, and Table 3 outlines selections made. For example, the combined wheel and rail roughness spectra options incorporated in the software are representative of European systems. An objective of this study was to compare the STARDAMP predictions with actual data for the Perth network. With this trial validating the model for local conditions, STARDAMP can be used to predict the benefit of rail dampers for a wide range of scenarios, including for future track and rolling stock designs.

Also, the wheel design in Perth differs from the three “typical” wheel designs incorporated in STARDAMP (a European tread-braked freight wheel, a disc-braked intercity wheel and a high speed train wheel). A finite element model of the Perth wheel design was developed to determine the modal response of this specific wheel as an input to the STARDAMP software.

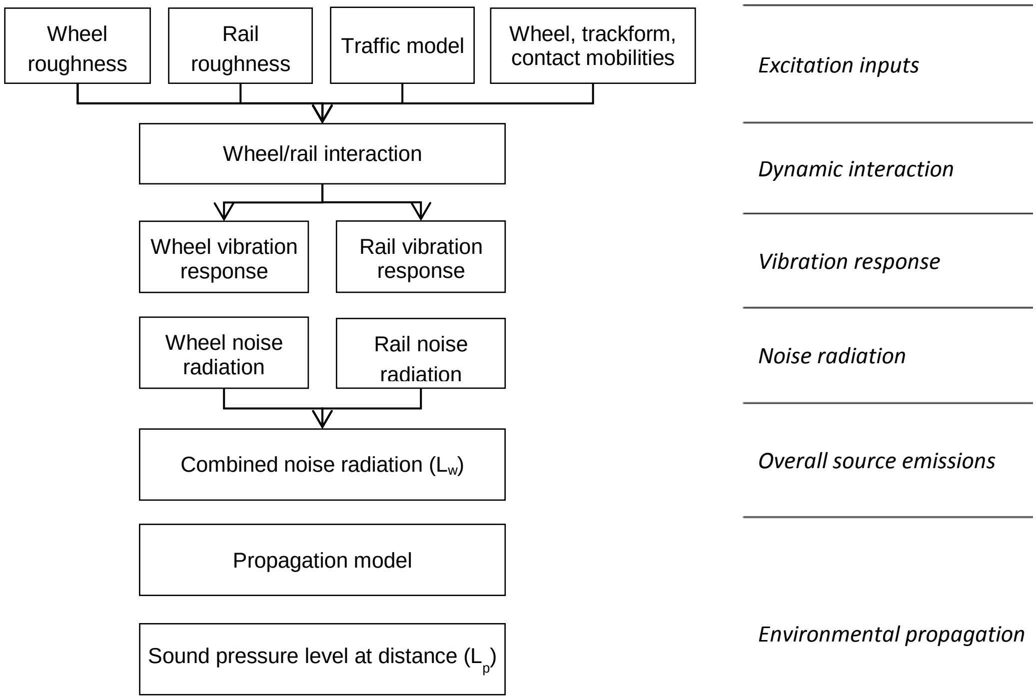

Figure 3 Basic overview of STARDAMP modelling process

Table 3 STARDAMP model parameters for each scenario

Parameter	**Butler**	**PerthT6**	**Source / Reference**
Speed, km/h	60	72	-
Wheel model	Perth wheel 840mm	Perth wheel 840mm	As supplied by PTA
Wheel Roughness	Disc	Disc	Default (in lieu of local data)
Rail roughness, Track decay rate	As measured	As measured	-
Track type	Ballasted	Slab track	Default
Sleeper type	Concrete monobloc	-	Default
Rail type	UIC54	UIC60	Default (in lieu of AS profiles)
Rail pad dynamic stiffness	120 MN/m vertical 41 MN/m lateral	7.4 MN/m vertical 11 MN/m lateral	Supplier data and published research (Gong 2013)
Rail pad damping loss factor	0.2 ('Normal')	0.2 ('Normal')	Default
Cross receptance factor	-12 dB	-12 dB	Default

3 RESULTS

3.1 Butler Ballasted Track Trial Results

Results are presented in Table 4 and Table 5 below for the measurements and modelled differences in noise level at the Butler site.

Table 4 Butler noise measurement results at 7.5 m distance, 1.2 m above top of rail

Parameter	Without Rail Dampers		With Rail Dampers		Difference	
	Median (L_{50})	Typ. Max. (L_5)	Median (L_{50})	Typ. Max. (L_5)	Median (L_{50})	Typ. Max. (L_5)
Speed (km/h)	52.9	56.7	54.3	59.5	+1.4	+2.8
Passby L_{AE} (dB)	85.7	88.9	82.0	83.8	-3.7	-5.1

Note Results include passbys recorded at 50-60 km/h speeds only, with the objective of minimising differences due to speed

Table 5 Butler L_{AE} prediction results at 7.5 m distance, 1.2 m above top of rail, 60 km/h

Parameter	Without Rail Dampers	With Rail Dampers	Modelled difference
Wheel contribution (dB)	79.3	79.3	-
Track contribution (dB)	88.0	82.0	-6.0
Total (dB)	88.6	83.9	-4.7

Note STARDAMP predictions indicates the sound pressure level during the train passby event, a correction based on passby duration has been applied to estimate L_{AE} values. 'Modelled difference' is unaffected.

The measurements indicated a 3.7 dB reduction in median passby noise level with the installation of the rail dampers. Typical maximum passby noise levels were reduced by 5.1 dB. In comparison, the STARDAMP v1.4 model predicts a 4.7 dB reduction in overall noise level. Overall, the agreement between the model prediction of the rail damper benefit and the measured results is very good.

Potential sources of differences between the field results and model include the contribution of traction system noise sources and auxiliaries at the relatively slow speeds measured, and the contribution of noise generated outside the relatively short rail damper trial section.

Figure 4 presents spectral results from the STARDAMP model showing the relative contributions from the wheel and track before and after the rail damper installation.

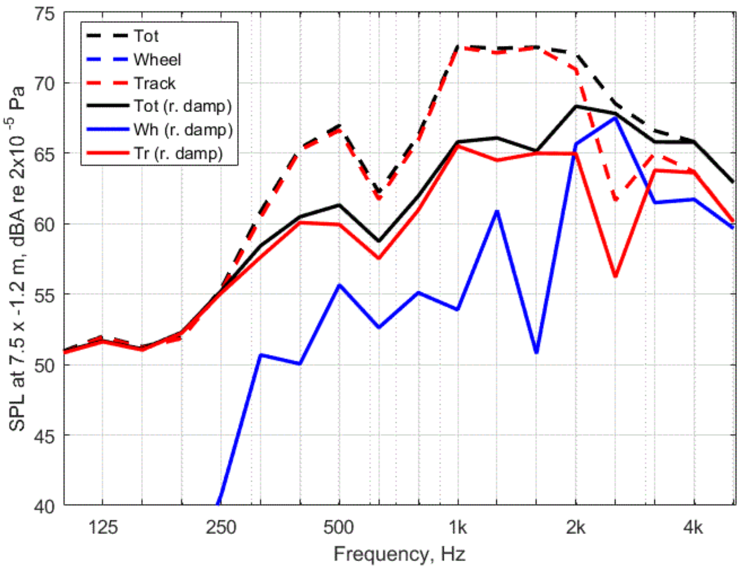

Figure 4 Modelled wheel and rail noise contributions with and without rail dampers, Butler, 60 km/h. There is no change in wheel noise; the rail damper reduces the overall total noise by reducing the track component.

For this ballasted track form, low frequencies are dominated by noise from the track including the rails and sleepers: the wheel dominates overall noise levels at higher frequencies. These results (and the overall contributions shown in Table 5) indicate that the track controls the overall noise emissions.

- In the untreated case, noise radiated from the wheel is relevant only in the third octaves with centre frequencies 2 kHz and above. The track contribution overall is 8.7 dB more than the wheel contribution, so the wheel does not contribute significantly to the overall passby noise level, which is the logarithmic sum of the wheel and track contribution.
- In the treated case, noise radiated from the wheel is still generally less (more than 4 dB below) than that from the track, except for the third octaves with centre frequencies 2 kHz to 3.15 kHz. The track contribution overall remains 2.6 dB above the wheel contribution, which is not altered by the addition of rail dampers. In this case, the wheel does begin to contribute to the overall passby noise level.

3.2 Perth T6 Tunnel Trial Results

Figure 6 shows an example of the measured in-car noise time history at one measurement position before and after the installation of the rail dampers. Note that the short trial section and reverberant nature of the tunnel environment means that the benefit of the rail dampers is not observed immediately as the front of the train enters the test section. The best indication of the rail damper benefit is the period just before the front of the train reaches the end of the trial section.

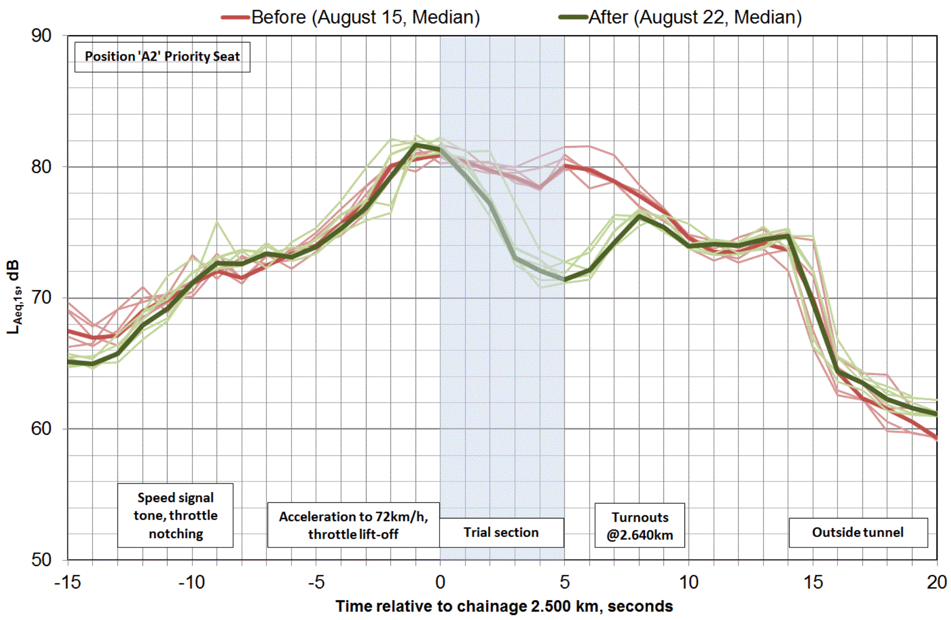

Figure 5 Example in car noise in T6 tunnel, one second L_{Aeq} versus time relative to trial section

Table 6 presents a summary of the measured difference in noise level at four positions within the vehicle, based on the 3 second time period before the front of the train leaves the trial section. Table 7 shows the corresponding model predictions for the rail damper benefit in the tunnel track trial section.

Table 6 Tunnel 6 measured in-car noise levels (median $L_{Aeq,3s}$) for various positions, dB

Position	Without dampers	With dampers	Difference	Comments
AD Driver	74.5	68.6	-5.9	Driver position affected by open door to cabin. Results have been corrected to remove the influence of ambient noise from auxiliary systems such as air-conditioning and traction system noise in the cabin. In all cases, the correction applied was less than 1.0 dB.
A1.5 Near Vent	82.3	75.4	-6.9	
A2 Priority seat	79.5	71.9	-7.6	
A3 Lobby	79.9	72.1	-7.8	
Passenger cabin average	79.7	72.0	-7.7	

Table 7 Tunnel 6 STARDAMP predictions for source sound power levels indicating in-car noise results

Parameter	Without rail dampers	With rail dampers	Difference
Wheel contribution (dB)	95.8	95.8	-
Track contribution (dB)	110.7	101.6	-9.1
Total (dB)	110.8	102.6	-8.2

The STARDAMP predictions for overall noise reduction (-8.2 dB) is in good agreement with the measured noise reduction in the passenger cabin (-7.7 dB). Figure 6 shows spectral results from STARDAMP indicating the relative contributions from the wheel and track before and after the rail damper installation in the T6 Tunnel. As for the Butler test site, the model indicates that the wheel contribution is dominant above 2 kHz, with the track dominating the overall level at lower frequencies. Figure 7 presents the modelled and measured reduction in noise emissions in each one-third octave frequency band. This figure indicates generally good agreement across the frequency range, despite the short test section. In practice, differences in emitted sound power at the wheel rail interface do not directly transfer to sound pressure levels at the interior position of evaluation due to various frequency dependent effects.

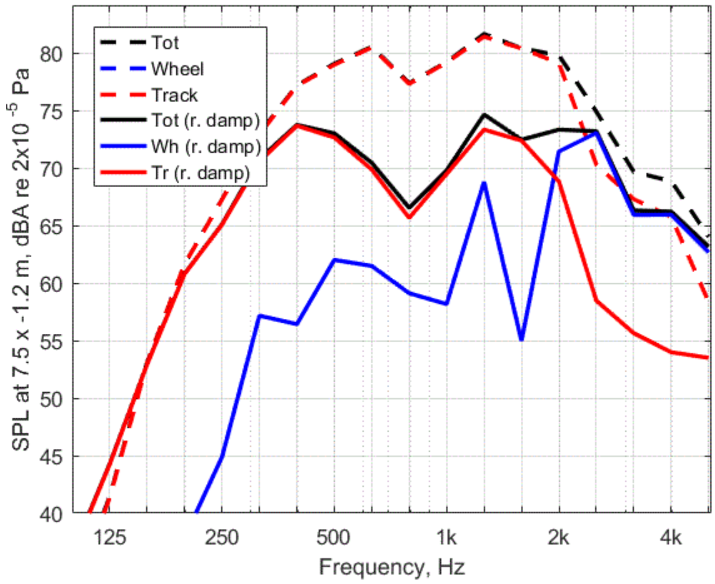

Figure 6 Modelled differences in wheel and rail noise contributions due to rail dampers, PerthT6, 72 km/h. There is no change in wheel noise; the rail damper reduces the total noise by reducing the track component.

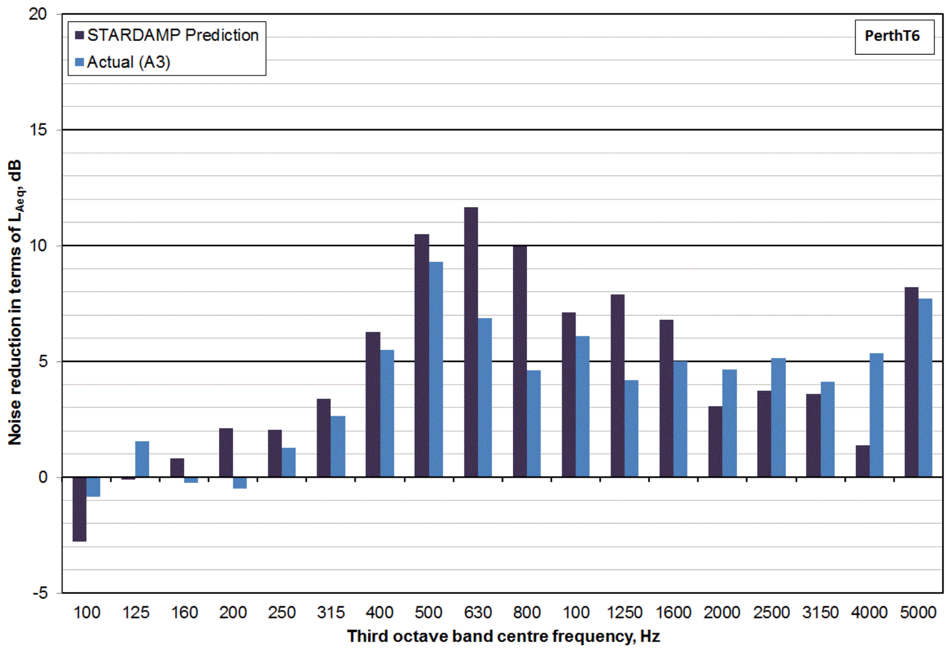

Figure 7 Difference in noise reduction at PerthT6 site, modelled versus actual measured

For this slab track form with very resilient rail fasteners, the low frequencies are again dominated by noise from the track, which includes the rails and the sleepers. The wheel becomes the dominant contributor to the overall noise levels at higher frequencies. These results (and the overall contributions shown in Table 7) indicate that the track controls the overall noise emissions. The track contribution is higher with this track form than is the case on ballasted track.

- In the untreated case, the track contribution overall is 14.9 dB more than the wheel contribution, so the wheel does not contribute significantly to the overall passby noise level, which is the logarithmic sum of the wheel and track contribution.
- In the treated case, the track contribution overall remains 5.8 dB above the wheel contribution, which is not altered by the addition of rail dampers. In this case, the wheel does begin to contribute to the overall noise level. This result suggests further treatments to the track (that do not reduce the wheel noise contribution) will have increasingly diminishing returns.

4 ADDITIONAL MODELLING SCENARIOS

4.1 Comparison of speeds

The STARDAMP model was used to forecast the differences in noise level and rail damper benefit for a range of different speeds at the Butler test track. The model results presented in Table 8 indicate that the rail dampers should be similarly effective at higher speeds.

Table 8 Variation in modelled passby sound pressure level at 7.5 m with speed over Butler section, dB

Speed	Baseline	With dampers	Modelled difference	Comment
60 km/h (**Table 3**)	78.7	74.0	-4.7	Similar reductions forecast at higher speeds
80 km/h	82.9	78.7	-4.1	
100 km/h	87.7	83.0	-4.7	
130 km/h	92.2	87.4	-4.8	

4.2 Comparison of other resilient track fasteners and rail conditions

The STARDAMP model was used to calculate the baseline track decay rates (TDRs) for other trackforms, and the 'treated' TDRs were estimated using the measured track decay rate spectrum for PerthT6 with the rail dampers, at the frequencies at which the dampers were shown to influence the result. The following table indicates the predicted relative benefit of rail dampers for a range of different trackforms, with the Perth B series rolling stock at 80 km/h.

Table 9 Variation in sound power (L_{wA}) with speed using alternative trackforms, dB (80 km/h)

Trackform	Dynamic stiffness, MN/m (Note [1])	Modelled		
		Without rail dampers	With rail dampers	Difference
Pandrol SFC / Fastclip	63 vertical, 30 lateral	109.2	103.8	-5.4
Pandrol VIPA	20 vertical, 10 lateral	110.4	104.1	-6.3
Pandrol VANGUARD	7.4 vertical, 11 lateral	112.6	104.1	-8.4

Note 1 Estimated from manufacturer data, with published sources including Bewes (2005) and Gong (2013)

5 DISCUSSION

The following presents a brief summary of results and contributing factors.

1. Rail dampers can effectively reduce rail noise emissions. The measured benefit in terms of noise emissions at both trial locations, without any significant compromise in other performance, are indicated to be:
   - around 4 to 5 dB on ballasted track; and
   - around 7 to 8 dB on Pandrol Vanguard slab track. Measurements were somewhat affected by the reverberant conditions in the tunnel and the short trial section.
2. The benefit in terms of noise reduction on ballasted track was higher than originally anticipated by the authors; this is largely attributed to the particular wheel design used on both Series A and B trains. Because the track contributes more to overall levels than would be the case with a noisier wheel, the effect of the rail dampers on overall levels is also greater.
3. Track decay rate measurements found substantial changes in track decay rate from the dampers, with the majority of benefit at frequencies above 400 Hz, corresponding to the dominant rolling noise frequencies. To be effective, a rail damper design must reduce the track decay rate at these dominant frequencies.
4. The overall measured benefit of the dampers matched reasonably well with model predictions, indicating the model's potential usefulness on predictions for other track types. The forecast benefit on other resilient track types varied from 5 to 8 dB depending on track support stiffness.
5. The Perth wheel design is well optimised for noise. At 840 mm in diameter it is relatively small, and it has a straight web which is beneficial for noise (Thompson, 2009). A quiet wheel design means that the rail contribution tends to dominate overall noise levels at key frequencies. In this situation, rail dampers are most effective while little or no benefit would be expected from wheel dampers.
6. In relation to environmental airborne noise control measures, the results suggest that rail dampers can be considered a reasonable and effective option. A 5 dB benefit is often used as a rule of thumb for assessing effectiveness of noise walls and other traditional controls. In comparison, rail dampers are likely to be a

cost-effective solution to mitigate noise from the Perth passenger train network, in situations where the track support components are relatively soft.

It is important to note that this does not mean that use of rail dampers on other passenger rail lines in Perth will automatically lead to a 6-8 dB noise reduction as measured in this study. The benefit would be expected to be less at locations with stiffer rail support systems. Other rail damper designs may give different results. The benefit would also be less noticeable at locations with rail discontinuities generating impact noise, and at locations with lower speeds where traction noise sources dominate the overall noise levels. Also, rail dampers may not provide as noticeable a benefit to control freight train noise. Freight trains have typically larger wheels which contribute more to the overall noise level. In addition, the contribution from non-rolling noise sources such as the engine and exhaust system may also affect the overall railway noise emission level.

6 CONCLUSIONS

The work demonstrates that noise from the Perth metropolitan passenger train network can be effectively attenuated using rail dampers. A rolling noise reduction of up to 5 dB was predicted and measured for passenger trains on ballasted track. In a tunnel situation with Pandrol Vanguard slab track a reduction of up to 8 dB was achieved. The efficacy of rail dampers as a noise control measure in Perth is attributed to the Perth rolling stock wheel design and track support dynamic stiffness. The STARDAMP model was found to give a reliable prediction of the noise damper benefit in both cases examined.

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