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WHITE PAPER:

Good Practice for the Management of Wheel Squeal

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acoustic studio

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Executive Summary

Wheel squeal is a highly tonal, very loud, high-pitched noise emitted by rail vehicles negotiating tight radius curves. Wheel squeal presents a challenge to the sustainability of rail in built-up areas and is a leading cause of community complaint about rail. This White Paper describes how wheel squeal can be effectively managed on Australian rail networks.

Until recently, the causes and treatments of wheel squeal were not well understood. Considerable effort over the last decade, particularly in Australia, has identified the root causes of squeal and developed a suite of proven solutions to mitigate it.

Wheel squeal is generated by lateral slip of the wheel across the rail head. The probability of wheel squeal occurring increases as the wheelset angle-of-attack with respect to the rail increases, i.e. the more slip that is present the greater the chance that wheels will squeal.

This White Paper applies a hierarchy of control approach to mitigating wheel squeal:

- Elimination: highest priority is given to those measures that prevent lateral slip from occurring in the first place, such as improving bogie steering, controlling wheel and rail profiles, and removing tight radius curves.
- Substitution: consideration is given to reallocating rolling stock with a propensity to squeal to services either outside of built-up areas, or outside of night time services in these areas.
- Engineering controls: if lateral slip cannot be eliminated, then it can be prevented from causing the stick-slip excitation that leads to wheel squeal by managing the friction at the wheel/rail interface.
- Administrative controls: environmental regulation has a role to play in encouraging effective management of wheel squeal, and protecting the amenity of the community. Less attractive options such as curfews and access charges are frequently put forward by impacted communities. These would likely have a profound impact on the sustainability of rail, and therefore provide an incentive for the rail industry to proactively manage wheel squeal so that they never need to be implemented.
- Path and receiver treatments: if wheel squeal cannot be prevented, then its impacts can be managed through traditional noise mitigation measures, such as noise barriers and at-property treatments.

Addressing wheel squeal is in everyone's interests. It will reduce the impact on the community, bolster rail's social-licence-to-operate, and secure rail's future role in Australia's land transport market. For networks, eliminating squeal will reduce rail wear, defect generation and maintenance costs. It also reduces the capital cost of new infrastructure, and the associated ongoing maintenance costs by reducing the requirement for noise barriers. For operators, improving rolling stock steering will not only prevent wheel squeal, but will also reduce wheel wear, fuel and energy consumption, emissions, and both operating and maintenance costs.

Effective management of wheel squeal is now understood. The challenge for the rail industry lies with implementation.

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We'd like to acknowledge the contributions from across the industry in putting this White Paper together. This included reports, papers and the valuable time of key personnel for interviews and email correspondence. Contributors include Transport for NSW, Australian Rail Track Corporation, Sydney Trains, Yarra Trams, Queensland Rail, Pacific National, Public Transport Authority of Western Australia, SLR Consulting, Accon GmbH, Renzo Tonin & Associates, SMRT, Institute of Sound and Vibration Research, Southdowns Environmental Consultants, LB Foster, SNCF, Kiwi Rail, Rail Planning Services, Fremantle Ports, and George Stanley Consulting.

Table of Contents

Glossary & Abbreviations

Term	Definition
AoA	Angle of Attack is the angle between the plane of the wheel and the tangent to the curve. AoA is measured in milliradians (mrad).
CCSB	Constant Contact Side Bearers are load carrying elements that typically mount on the bogie bolster. CCSBs also provide damping of rotation between the wagon body and the bogie and thereby help to prevent hunting but can resist bogie rotation which affects steering.
dB	Decibel is a scale that is used for expressing sound pressure level (SPL) or power level (SWL).
dB(A)	Decibel expressed as an 'A – weighted' sound pressure level, based on the frequency response of the human ear and has been found to correlate well with human subjective reactions to various sounds, at relatively low sound levels. An increase or decrease of approximately 10 dB corresponds to a subjective doubling or halving of the loudness of a noise, and a change of 2 to 3 dB is subjectively barely perceptible.
GFL	Gauge face lubrication refers to the application of a material on the gauge corner / wheel throat to reduce the coefficient of friction to as low as possible, typically less than 0.25.
HIGH / LOW rail	The HIGH rail is the outer rail in a curve. The LOW rail is the inner rail in a curve.
Lozenging	Deformation of a bogie, usually under the loads applied during curving, whereby the side frames remain parallel but displace longitudinally relative to each other
mrad	AoA is typically measured in milli-radians, expressed as "mrad". One milli-radian is equivalent to approximately 0.06 degrees.
Rolling Stock	Any vehicle that operates on, or intends to operate on, or uses a railway track, including any loading on such a vehicle, but excluding a vehicle designed for both on- and off-track use when not operating on the track. Rolling stock is a collective term for a large range of rail vehicles of various types, including locomotives, freight wagons, passenger cars, track machines and road-rail vehicles.
Tangent Track	Straight track with no applied cant/superelevation.
Tight Radius Curve	A curve with a radius on which wheel squeal could occur. As a guide, a curve with a radius of less than around 150 times the maximum bogie wheelbase that operates on that track could be considered "tight radius". For example, curves of radius less than 400m may be considered "tight radius" on a track carrying passenger trains with a wheelbase of 2.5m.
TORFM	Top-of-rail-friction-modifier/modification refers to the application of a material on the rail head or wheel tread to control the coefficient of friction, typically to between 0.3 and 0.4.

1. Introduction

Community concerns about rail noise are increasing. This is driven by a number of factors, including a) increasing urban and regional housing development in proximity to railway corridors, b) more services operating through populated areas, particularly at night, and c) increasing awareness in the community about the health impacts of rail noise, and expectations around amenity.

One of the key noise complaints is the amount of wheel squeal caused by trains going around curves. This affects all rail modes – freight, passenger and light rail.

Until recently, wheel squeal has been an enigma. Its causes were not well understood, and efforts to mitigate wheel squeal were largely trial-and-error, with mixed and often conflicting results. This has changed over the last decade, with considerable research and collaboration between industry, government and academia – much of it in Australia. There is now a functional understanding of the causes of wheel squeal, and mitigation measures that have been proven in revenue service.

The purpose of this White Paper is to provide industry with an understanding of current national and international research and current practices employed by national and international railway systems in the management of wheel squeal. The White Paper is intended for practitioners in the rail industry, so a level of familiarity with common railway terminology is assumed. The White Paper focuses on practical information that users can apply to manage wheel squeal on their own networks, operations and regulations. Discussions on the theory of wheel squeal are limited to only those aspects that inform effective management.

1.1 Rail Noise Overview

There are many broad categories of noise associated with the operation of a railway. Some of these (by no means exhaustive) are summarised in Figure 1.

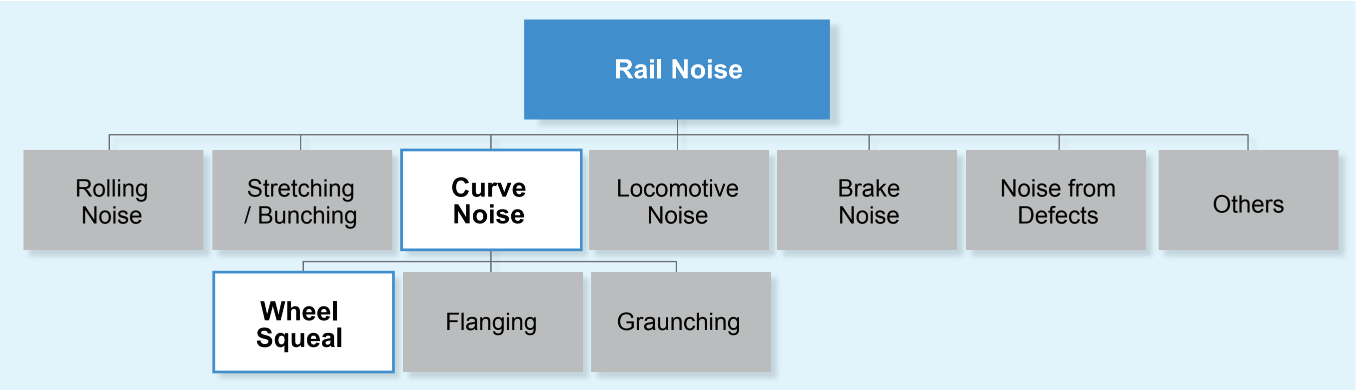

Figure 1 Categories of rail noise.

Rolling noise is the general noise emission generated from running a steel wheel on a steel rail. It is generated by microscopic scale unevenness, called "roughness", on the surfaces of the wheels and rails that, in turn cause the wheels and rails to vibrate and act like loudspeakers.

Stretching and bunching noise is usually associated with long freight trains but can occur to some extent on older passenger trains. It is caused by impacts that travel down the length of the train as slack in couplers and other components are suddenly taken up when the train changes speed.

On freight trains, it is sometimes described by the community as like explosions or booms.

Locomotive noise includes the noise emitted by the large diesel engines on the predominately diesel-electric locomotives used in Australia, and also noise emitted by other systems on the locomotives, such as fans associated with dynamic braking, radiators, and traction motor cooling systems.

Brake noise, as the name suggests, is noise emitted by the action of braking. It can manifest as a high-frequency noise like wheel squeal, or as a lower frequency rubbing noise, depending on the type of brake system.

Noise from defects includes impact noise from wheels hitting dipped welds, squats and other rail-head defects, low-frequency “howling” as trains traverse corrugated rails, and repetitive impacts from wheels with flat spots, among much else.

Other types of rail noise include (but are not limited to):

- Ground-borne noise, typically from underground railways and metros;
- Bridge noise, especially from steel bridges;
- Warning signals, such as at level crossings and from horns;
- Noise from track maintenance, including from track maintenance vehicles and general construction activities;
- Station noise, such as public address announcements and door-closing alarms;
- Aerodynamic noise, which is usually associated with high-speed rail and is not a common issue in Australia; and,
- In-car noise on passenger trains, particularly through tunnels.

1.2 Curve Noise

Wheel squeal is a type of curve noise. As the name suggests, curve noise describes distinct noise emissions associated with rail vehicles negotiating curves. Typically, this applies only to “tight” radius curves, where the wheel/rail interaction is distinctly different from tangent track.

There are three main categories of curve noise that commonly occur on Australian railways:

- Wheel squeal – a highly tonal and very loud noise, dominated by a single, typically high-pitched, frequency. Wheel squeal noise is associated with the resonant vibration of the very lightly damped modes of railway wheels. It is sometimes likened to the noise from running fingernails down a blackboard. Wheel squeal is usually (but not always) associated with wheel/rail contact on the top of the rail head.
- Flanging – a highly tonal and often loud noise, made up of a series of frequency components. Flanging noise is also high-pitched, and sometimes described as a “tching-tching” type of noise.

  As the name suggests, flanging noise arises from contact between the flange of the (usually outer) wheel and the gauge face/corner of the rail.
- Graunching – a generally lower frequency, rubbing/straining type of noise that is more broadband in nature and generally not as loud as either wheel squeal or flanging noise.

1.3 Characteristics of Wheel Squeal

Wheel squeal noise has several characteristics that make it particularly annoying to human ears:

- Pitch – wheel squeal occurs mainly in the frequency region between 1kHz and 5kHz. Human hearing is most sensitive in this frequency range.
- Tonality – wheel squeal is dominated by a single frequency tone. This type of noise is particularly annoying to human ears.
- Noise level – wheel squeal is often very loud. Wheel squeal can exceed 100dBA at the rail corridor boundary, a noise level akin to standing next to a motorcycle. This has a substantial impact in itself, but it also means that wheel squeal noise has a large emergence above the background noise level, particularly at night.
- Intermittency – typically, only a minority of wheels on a long freight train will emit wheel squeal. Similarly, only a minority of light rail or heavy rail passenger trains will emit wheel squeal noise on a particular curve on a particular day. This can have two impacts:
  - The fluctuation in noise levels, as the isolated squealing wheel approaches and then passes the receiver, is likely to cause more annoyance than a constant noise source. Human hearing is sensitive to intermittent changes in noise level.
  - If a community is already annoyed by rail noise, then the intermittency and unpredictability of wheel squeal can add to their frustration because it implies that it must be caused by an unnecessary defect, or by extension, that wheel squeal is a symptom of a lack of care or respect for the community on the part of the railway. To a resident, “a train is a train”, and there is no expectation that one wagon or train should be louder than any other. This impression may be reinforced by the observation that many wagons/trains are able to pass their home without

emitting wheel squeal. It can seem inexplicable therefore, that a minority can be allowed to cause such annoyance, i.e. “Most trains are fine, but every now and then one passes that is very loud. Why won’t they do something about that train?”. The perceived inability of the railway to deal with this issue over a number of years can seem like deliberate neglect.

These characteristics mean that wheel squeal can cause impacts both in terms of the noise level (refer to e.g. (1)) and subjective annoyance in the community. This can occur even in communities relatively desensitised to rail noise. An example of this is the recent track realignment on the Yarra Trams network on St Kilda Rd in Melbourne associated with the Melbourne Metro development (see e.g. (2)). This community has lived with train noise for decades, but the realignment introduced a curve to a previous straight section of track and the resulting wheel squeal noise has led to noise complaints.

1.4 Why is Wheel Squeal Important?

1.4.1 Wheel Squeal in Australia

Wheel squeal is a particular issue in Australia. While wheel squeal occurs on almost all networks across the world, the impacts from wheel squeal appear to be more significant in Australia than elsewhere. This could be due to a number of factors:

- Geography
  - Australia is one of the most urbanised nations (3) and some cities, such as Sydney and Adelaide, are located in basins surrounded by ridges. Rail lines must therefore climb over these ridges in order to access these cities, requiring tight radius curves to limit gradients.
- Network age
  - Much of the rail network in Australia was built in the steam era. The tracks tend to follow natural features in the landscape rather than favouring straight lines. As a result, there are many tight radius curves. For example, the Main North line between Strathfield in Sydney and Newcastle on Australia’s east coast has a “curve density” of over 20%. In other words, more than one-fifth of the line along one of the nation’s most heavily populated corridors has curve radii that can generate wheel squeal.
  - Residential development has extended along existing rail corridors (through both natural growth and transit-oriented-development). This has placed increasing numbers of people in close proximity to rail noise. The outdated argument that “the railway was there first” has gradually been retired, with an increasing awareness that railways must be “good neighbours”. For rail to be sustainable, it must support the amenity of growing populations.
- Rolling stock
  - Australian rolling stock is a blend of European, Asian (particularly Japanese and increasingly Chinese) and United States of America (USA) technologies. Freight rail in particular uses US rolling stock designs, including three-piece bogies. These generally have poorer steering performance than the more rigid European bogie designs, and hence are more likely to generate wheel squeal.
  - In Australia, freight rolling stock is maintained to standards set by each rolling-stock operator. In contrast, USA rolling stock is generally maintained to the common Association of American Railroads (AAR) standards (4). This arrangement means that maintenance regimes for Australian freight wagons can differ significantly, both between operators and from accepted international standards. For example, in the USA, centre plated are typically lubricated to ensure proper bogie rotation. In Australia, centre plates are often not lubricated, and the resulting steel-on-steel interface generates higher rotational resistance.
- Societal norms
  - Sensitivity to rail noise in Australia has lagged some European cities (see for example, initiatives such as the Environmental Noise Directive (5)), but is generally well in advance of many US cities. Many jurisdictions in the USA do not regulate rail noise, and rail noise emissions do not attract community complaint to the same extent as they do in Australia.
  - In terms of freight rail, technology from the USA which has a higher propensity to wheel squeal has been applied in Australia where the community is more sensitive to such noise.
- Network capacity constraints
  - Many of the heavy rail lines through populated areas in Australia are shared between passenger

and freight. Passenger rail is generally given priority access, which leads to more freight trains operating at night when communities are most sensitive to noise. As a result, the noise impacts from rail have increased over time, and will likely continue to increase in line with the nation's increasing freight task (see e.g. (6)).

- Cost of new rail development
  - Land in Australian cities is very expensive and a significant impost on the development of new rail lines. New infrastructure is therefore incentivised to minimise the amount of land it occupies, and hence to keep curve radii as small as possible. This sets up a conflict between the cost of developing new rail lines (tight curves preferred) and the generation of wheel squeal (large curves preferred).
- Concrete vs timber sleepers
  - Australia has been a leader in upgrading tracks from timber to concrete sleepers. Tracks with concrete sleepers generate substantially more wheel squeal than tracks with timber sleepers (7).

1.4.2 Sustainability of Rail

Wheel squeal impacts rail's social license to operate and threatens rail's sustainability and continued growth. Communities can point to government initiatives to manage noise from other transport modes and ask why these are not applied to rail. For example, several Australian airports are subject to curfews to limit their night-time noise emissions (8). The imposition of curfews on rail, particularly freight rail, would have a major impact on its sustainability. It is therefore imperative that wheel squeal noise is managed so that rail can continue to grow and serve Australia's society and economy.

The importance of managing wheel squeal has been recognised by the NSW Government. Managing wheel squeal is a key element of the Strategic Noise Action Plan (9) and specifically addressed in approval conditions for new infrastructure projects (see e.g. (10)).

1.4.3 Wheel Squeal as a Symptom

While the focus of this White Paper is on mitigating the impacts on the community from wheel squeal noise, another important perspective is through the lens of asset management. Wheel squeal provides an indication that some aspect of the wheel/rail interface is not optimal (11). This in turn can lead to excessive wear, increased maintenance requirements, and premature deterioration of assets such as wheels and rails.

To illustrate, consider the example of freight rail operations. It is well established that there is a dramatic difference in wheel defects between bogie designs that steer well (and don't emit wheel squeal) and those that steer poorly (and do emit wheel squeal) (12). Figure 2 shows that cross-braced bogies have significantly less wheel defects and wear than ride control bogies due to their design and steering quality.

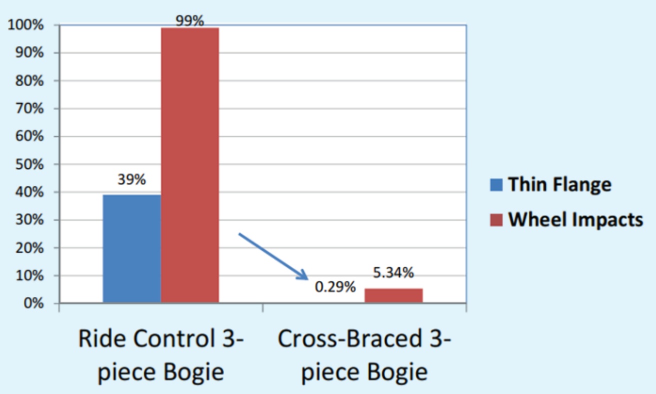

Figure 2 Comparison of wheel wear and defects in ride control and cross braced bogies (from (12))

Transport for NSW examined this issue more broadly (13; 14), and found that wheel wear, overall maintenance and operational costs (particularly fuel use) were substantially lower on the freight wagons with bogies that steer well. The payback period for upgrading the bogies that did not steer well was less than three years. The below-rail asset owner would also reap these benefits – high lateral creep is associated with excessive rail wear, deterioration of rail clips, and higher maintenance costs such as lubrication, rail grinding and rail replacement. Robertson's analysis (15) also supports this conclusion. When considering the cost-benefit proposition of the rolling stock operator alone, and ignoring the below rail benefits, purchasing wagons with higher warp stiffness, and hence good steering performance, delivers superior economic outcomes.

1.5 Summary

The temptation in trying to manage wheel squeal is to proceed directly to solutions. More effective management however, can be obtained by considering the broader railway system. The intention of this White Paper is to provide this whole-system perspective, as outlined in the sections below.

2. Investigating Wheel Squeal Noise

A typical rail noise investigation involves standing next to the track with a sound level meter and recording noise levels from passing trains. Measuring wheel squeal is a bit more involved however, and consideration of additional factors can add significant value and guide decisions around subsequent wheel squeal mitigation.

2.1 Separating Wheel Squeal from Other Noises

Wheel squeal noise can be distinguished from other rail (and ambient) noise sources by its frequency content, as shown in Figure 3.

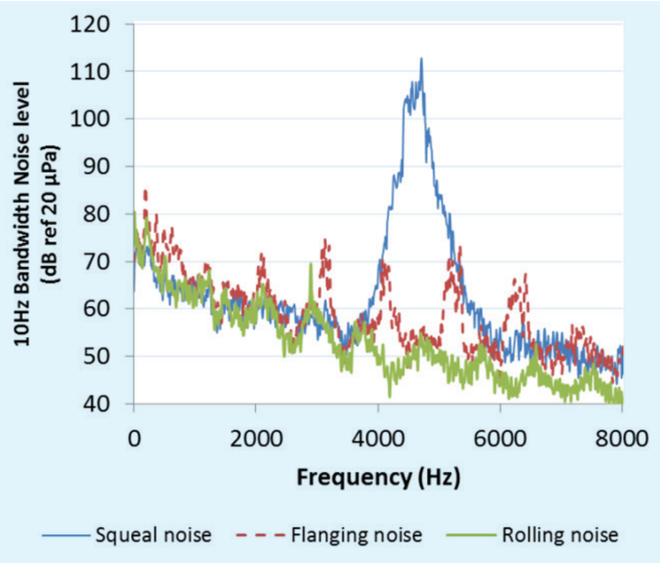

Figure 3 Wheel squeal noise is characterised by noise between 1kHz and 10kHz (from (16))

Bullen (17) outlines two approaches, the simplest of which was developed by Jiang and subsequently used widely by Transport for NSW. Jiang's approach is outlined below:

- A narrowband spectrum is calculated from the raw noise recording. In (17) this is described as a running 1/24-octave $L_{max,F}$ spectrum updated continuously through the passby. A running Fast Fourier Transform with sufficiently narrow frequency resolution to detect squeal (e.g. 10Hz as shown in Figure 3) would also suffice.
- Wheel squeal is detected when one band between 1 kHz and 10 kHz has the highest level of any band in the spectrum and has a level exceeding both the neighbouring bands by at least a threshold value (typically set at 10 dB).
- The wheel squeal noise level is simply the noise level in the selected band.

2.2 Quantifying Wheel Squeal Noise Levels

Wheel squeal can be more prominent at certain times of day and year, and it can occur more frequently with some types of rolling stock than with others. Therefore, the best way to quantify the incidence of wheel squeal at a particular location, is to measure for an extended period and to use a statistical approach.

It is generally not sufficient to quantify wheel squeal through attended noise monitoring. For many other types of rail noise, such as rolling noise and locomotive noise, it may be sufficient to record (say) twenty trains over the course of a few hours, to quantify the local noise environment. For wheel squeal however, it is generally necessary to record continuously for periods of a week or more, particularly if there is a substantial mix in the rolling stock fleet. Note that some references and guidelines (e.g. (18; 19)) do not emphasise this requirement for extended monitoring and hence noise measurements conducted in accordance with these references may not adequately describe the rail noise environment if curve noise is present.

In general, some of the principles outlined in AS2377 (20) can be applied for the measurement of wheel squeal noise. This includes the measurement equipment, the metrics to describe rail noise, definitions of rail passbys, and other general information. European standard ISO3095 (21) addresses wheel squeal noise measurement explicitly, albeit at a high level. This includes both on-board measurements to characterise wheel squeal noise across a network, and wayside measurements to focus on a particular location. Where wayside measurements must be conducted over an extended period for the results to be representative, on-board measurements would ideally also occur over many runs across the track sections of interest, and on several trains / classes of vehicle.

2.3 Additional Data

While noise measurements can help to assess the severity of wheel squeal at a particular site, capturing some additional data in parallel can assist in diagnosing the causes and determining mitigation. An example of additional data and the value it can provide is summarised in Figure 4 and described in more detail below.

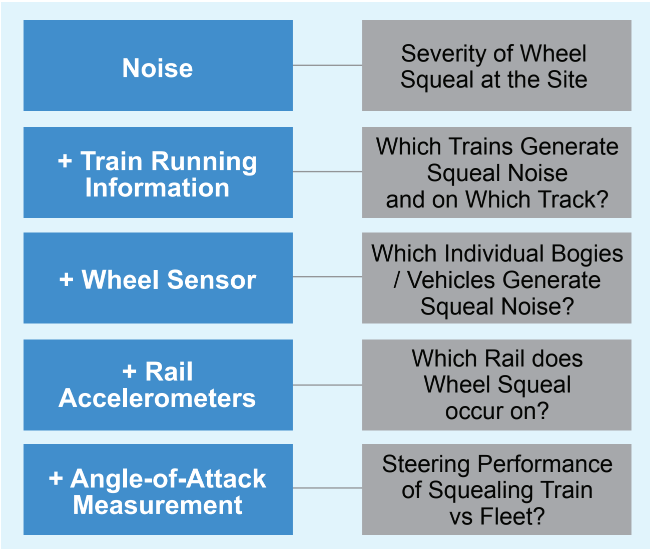

Figure 4 Additional data to accompany wheel squeal measurements.

- Train running information – this can be used to quantify how often particular trains and classes of rolling stock (for passenger and other consists of a single class) emit wheel squeal. Train running information can be obtained through installation of an AEI tag reader close to the noise measurement location, through live feeds published by some networks (e.g. (22)), through consultation with the operator, or even somewhat laboriously, through capturing images with a camera.
- Wheel sensor(s) – measuring the precise passby time of each wheel helps to assign wheel squeal to the individual bogie. This also helps to prevent misattributing squeal to neighbouring bogies, particularly at couplings where bogies on adjacent vehicles are closely spaced. This works best when the noise measurement location is sufficiently close to the track (e.g. 2m) so that the noise from each wheel can be distinguished. Wheel sensors can be rail specific (e.g. (23)) or generic (e.g. (11)).
- Rail accelerometers – As Jiang (24) explained, wheel squeal can be generated from either the LOW or HIGH rails, and the distribution can vary considerably between sites. Understanding this distribution can help to predict the likely effectiveness of some mitigation, such as lubrication. Rail accelerometers can be mounted to the underside of the rail, but caution should be exercised to ensure a) they are sufficiently electrically isolated from the track to avoid interfering with track circuits, and b) they have sufficient shock rating as squealing wheels can generate large amplitude, high-frequency vibrations (11).
- Angle-of-Attack measurement – this is described in more detail below. Angle-of-Attack (AoA) is not a straightforward quantity to measure, but there are commercially available systems for this purpose (25), and it can add considerable value in determining why particular wheels are generating squeal noise.

3. Necessary Conditions for Wheel Squeal

3.1 Wheelset Angle of Attack

Wheel squeal is generally associated with lateral creep/lateral sliding of the wheel across the rail head[1]. Under normal circumstances, when a bogie enters a curve, the trailing wheelset aligns with the rails and the leading wheelset adopts an AoA relative to the rail, as shown in Figure 5, causing the leading wheels to slip laterally across the rail head.

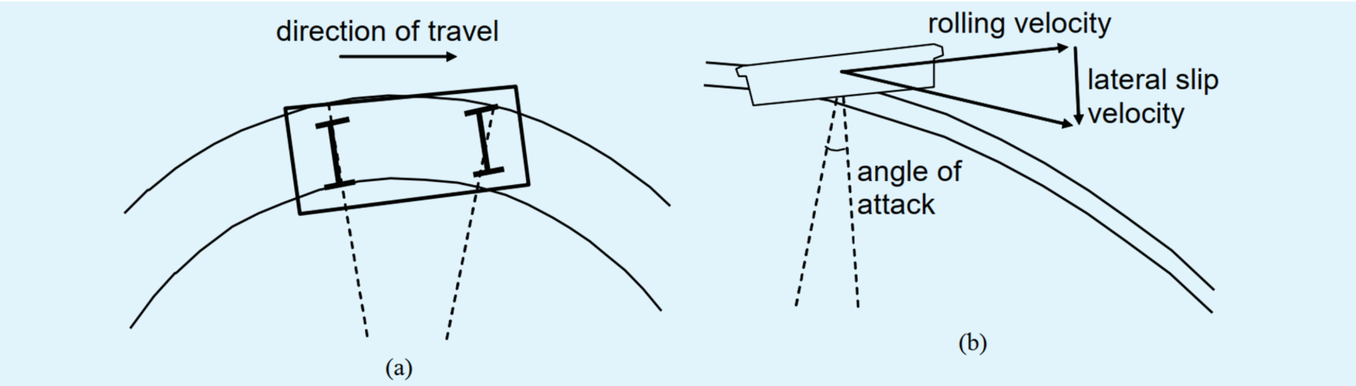

Figure 5 Wheelset alignment when negotiating a curve (from (26))

In some instances, the lateral movement along the rail head can excite vibration modes of the wheels, which effectively transforms the wheels (and in some cases the rails, see e.g. (27)) into highly efficient loudspeakers that broadcast wheel squeal noise[2].

Under normal conditions, the AoA of the leading wheelset angles slightly towards the HIGH rail of the curve to an extent that is directly related to the bogie wheelbase and the curve radius (28; 29; 30):

$$AoA = \frac{Wheelbase}{Curve\ Radius} \qquad \text{Equation 1}$$

, where both the wheelbase and curve radius are measured in metres.

The actual AoA of poorly steering vehicles (discussed in Section 3.1.2, below) may vary about this normally expected value due to differences in, for example, wheel and rail profiles on particular curves and vehicles and, differences in rail head friction between LOW and HIGH rails. This can explain why wheel squeal can differ profoundly across a network and between vehicles.

A general rule of thumb has been that wheel squeal is unlikely to occur if the AoA is less than 10mrad, i.e. if the curve radius is 100 times the wheelbase. Jiang (31) extended this understanding through a large-scale study at a curve in Sydney which involved noise, AoA and other measurements. An example of the results from this trial for a particular freight train is presented in Figure 6. The high-noise event shown in Figure 6 was a squealing wheel presenting a large AoA[3] and passing a microphone situated very close to the track.

1 A less common form of wheel squeal detailed in (37) is associated with longitudinal creep, but lateral creep is by far the most common cause of wheel squeal in Australia

2 The mechanisms of wheel squeal are examined in detail in (26; 31; 38; 97)

3 The sign convention for AoA is negative for wheelsets that attack the HIGH rail and positive for wheelsets that attack the LOW rail. Countering accepted wisdom, Jiang showed that wheelsets can attack the LOW rail of a curve. This occurred mainly on trailing bogies of poorly steering freight wagons and is discussed in (99).

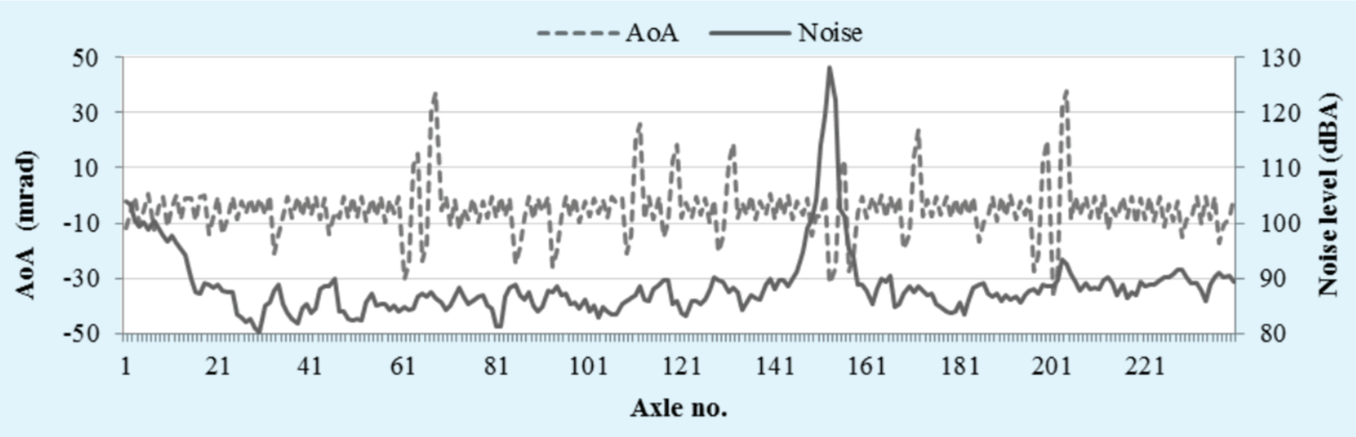

Figure 6 Example of a freight train passing the measurement location in (31).

Jiang showed that a large AoA is a necessary condition for wheel squeal to occur, but as Figure 6 shows, simply having a high AoA does not guarantee that a wheel will squeal. Jiang quantified the relationship between the probability of wheel squeal occurring and the wheelset AoA, as shown in Figure 7.

While the specifics of this relationship apply to the curve used for this study (i.e. the combination of rolling stock, track and wheel/rail interface conditions in place at that location), the general relationship is universal – the probability of wheel squeal increases as AoA increases.

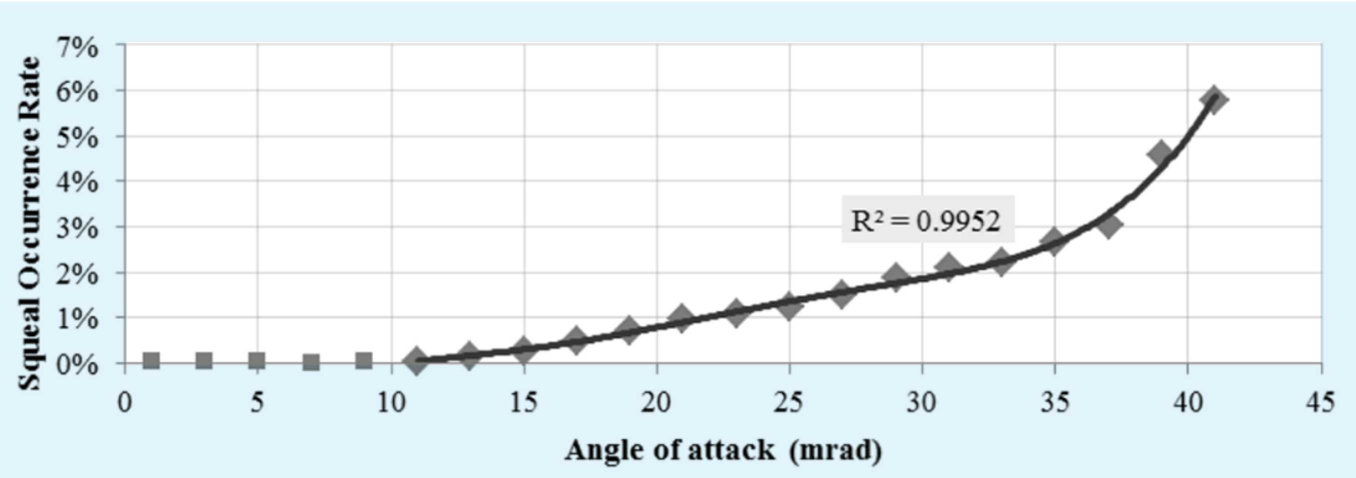

Figure 7 The likelihood of wheel squeal occurring increases with wheelset Angle-of-Attack (from (31))

Jiang's work also invites two further observations:

- Even with normally expected steering, the AoA can be large enough for wheel squeal to occur if the curve radius is sufficiently small relative to the wheelbase.
- It is possible for AoA to vastly exceed the theoretical/normally expected value, and this makes wheel squeal much more likely to occur.

These observations are discussed further below.

3.1.1 Bogies that Steer Well

From Equation 1, it is clear that the AoA can exceed 10mrad even when the bogie has near ideal steering performance. For example:

- On the North Shore Line in Sydney (32) there are curves of 200m radius. The passenger trains that operate on this line have wheelbases of around 2.4m. So, even with normally expected steering performance, the leading wheelsets on the bogies of these passenger cars would have an AoA of around 12mrad. In practice, AoA on these curves has been measured in the range 10-15mrad (33) – close to the expected normal value but still large enough to generate wheel squeal in some circumstances.
- On the extensive tram network in Melbourne, there are many curves with radius of around 25m. The D-Class tram has a wheelbase of 1.8m (34). As above, with normally expected steering performance, the AoA of leading wheelsets would be around 72mrad – easily large enough to generate wheel squeal under certain conditions.

In summary, on tight radius curves, it is possible for the AoA to be sufficiently large to generate wheel squeal, even when the rolling stock is steering correctly.

3.1.2 Bogies that Steer Poorly

3.1.2.1 Bogie Design

The range of AoA presented in Figure 7 greatly exceeds the normally expected steering performance predicted by Equation 1. Transport for NSW (Jiang et al) have done considerable work, in partnership with industry, to explain the relationship between steering performance and AoA.

Jiang showed that steering performance is directly linked to the design of the bogies. Figure 8 presents the AoA from more than one million freight wheel passes of an AoA detector at Beecroft in Sydney, broken down by bogie type.

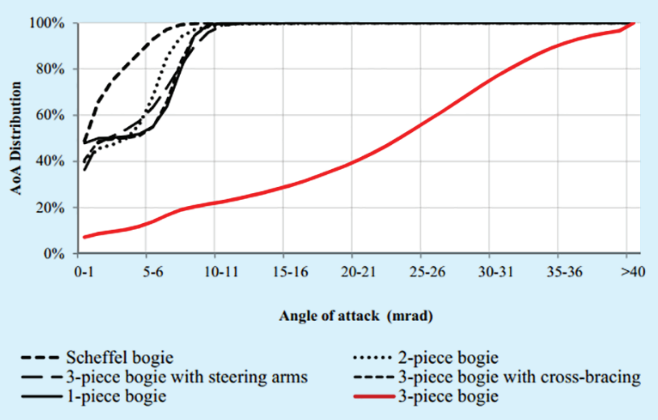

Figure 8 Distribution of AoA by bogie type, as measured at Beecroft in Sydney (from (35)).

Almost all bogie types shown in Figure 8 adhere to the normally expected steering performance, with trailing wheelsets aligning to the curve (zero AoA) and the leading wheelsets presenting an AoA predicted in Equation 1 (~8mrad in this case). As shown in Figure 7, these bogies generally do not emit wheel squeal.

The exception in Figure 8 is three-piece bogies, with a majority of such bogies returning AoAs far in excess of the value predicted in Equation 1. Unsurprisingly, it is also three-piece bogies that emit wheel squeal at this location. The crucial characteristic of three-piece bogies that make them susceptible to poor steering is low bogie warp stiffness.

A wagon in a curve is subject to steering forces, as shown in Figure 9 and described by:

Rotational Resistance = Steering Moment + Warp Moment

Equation 2

The steering moment acts to rotate the bogie underneath the vehicle to align with the curve. Elements such as centre plates, side bearers and/or yaw dampers resist this rotation[4]. Balancing these two opposing moments is the warp moment, resisted by the warp stiffness of the bogie. In short, if the warp stiffness is low, and the available warp moment and steering moment are less than the rotational resistance, the bogie will warp instead of rotating, and large AoA can result. Conversely, bogies with high warp stiffness can provide the necessary warp moment to overcome the rotation resistance with little lozenging. As a result, the bogie always rotates, AoA remains small, and wheel squeal generally does not occur.

[4] Rotational resistance helps to stop hunting at high speeds, and hence a minimum level of rotational resistance is required to ensure high-speed stability of the rail vehicle

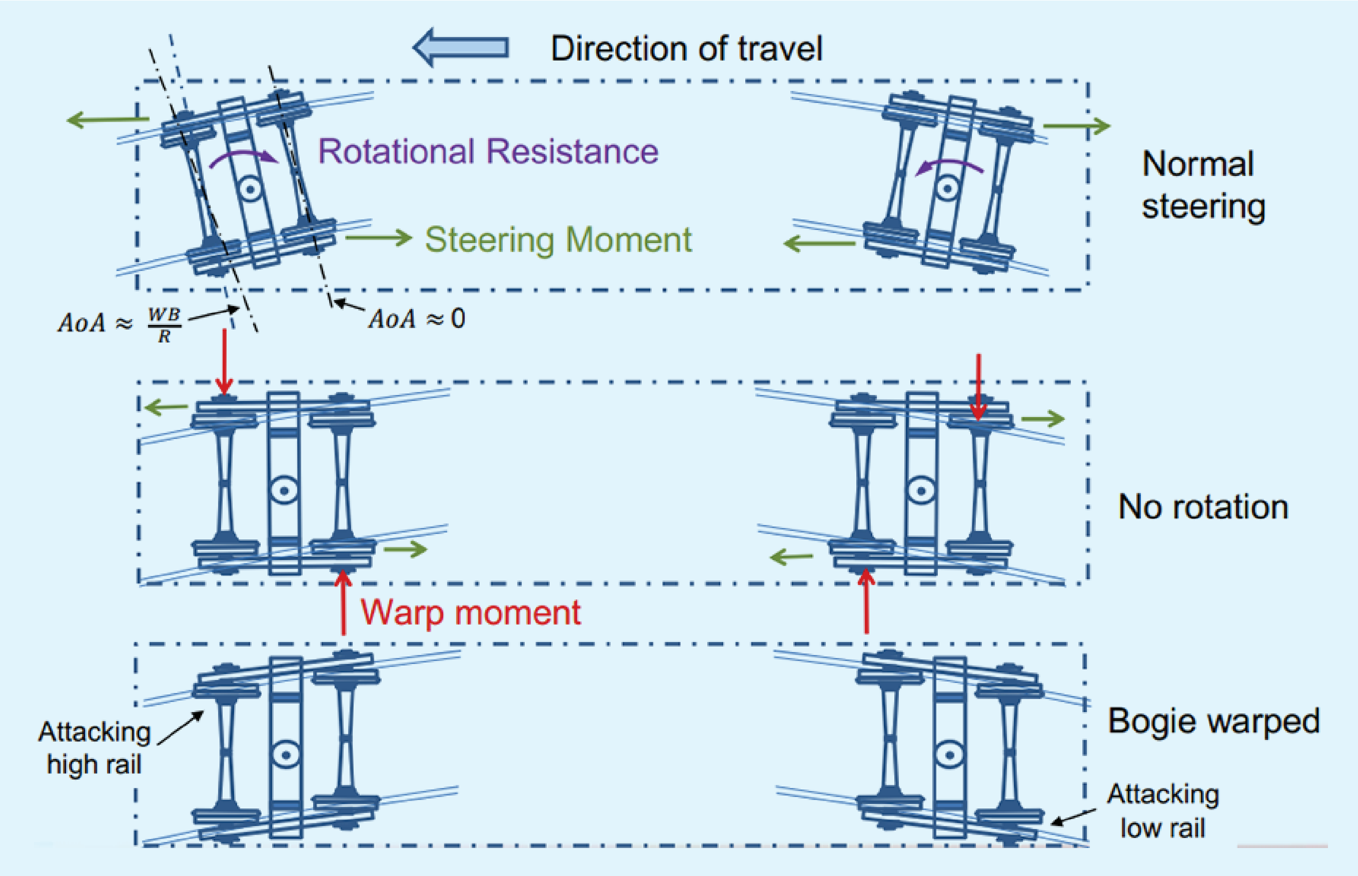

Figure 9 Bogie steering forces (from (35)).

In Figure 9, the bogies of a vehicle exhibiting 'normal steering' (top) align with the track, and wheelsets have relatively low AoA (zero AoA for trailing wheelsets and AoA as predicted by Equation 1 for leading wheelsets).

With no rotation (Figure 9, middle), the bogies are unable to rotate relative to the vehicle. Instead, the bogie is warped out of shape (Figure 9, bottom), also known as "lozenging". This can cause both the leading and trailing wheelsets to adopt extreme AoAs and generate wheel squeal.

Transport for NSW measured the warp stiffness and rotational resistance of various common freight bogie types using a bespoke test rig (Figure 10).

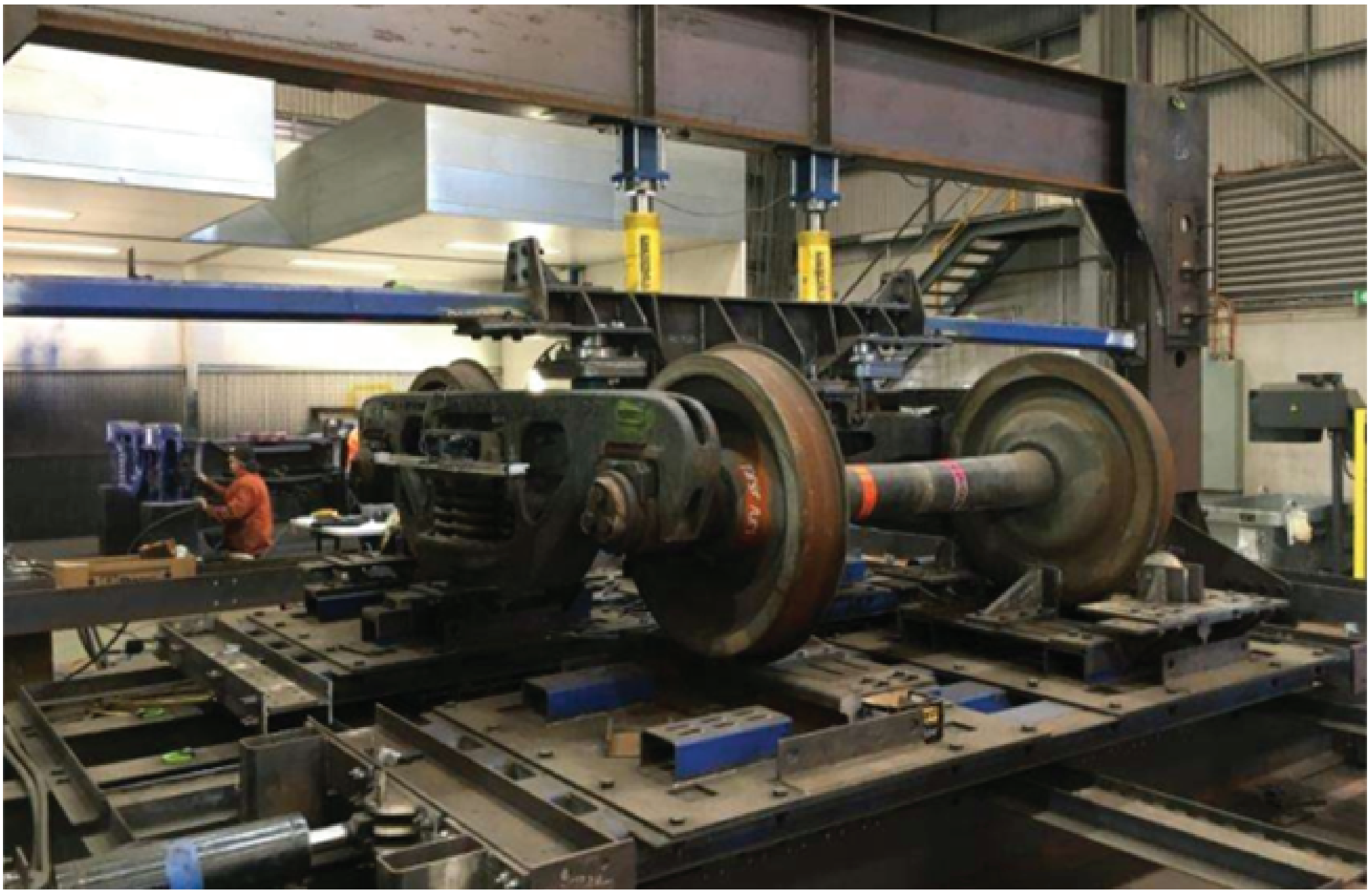

Figure 10 Transport for NSW bogie test rig (35)

The results are summarised in Figure 11 and Figure 12.

Note that bogies with rigid frames, such as one-piece and two-piece designs, were not tested as these have essentially infinite warp stiffness. Passenger vehicles generally have bogies with rigid frames.

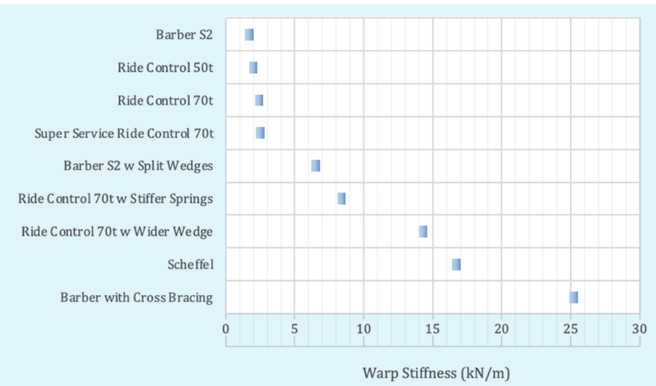

Figure 11 Warp stiffness (kN/m) of various freight bogie types as measured in the Transport for NSW test rig (adapted from (36)).

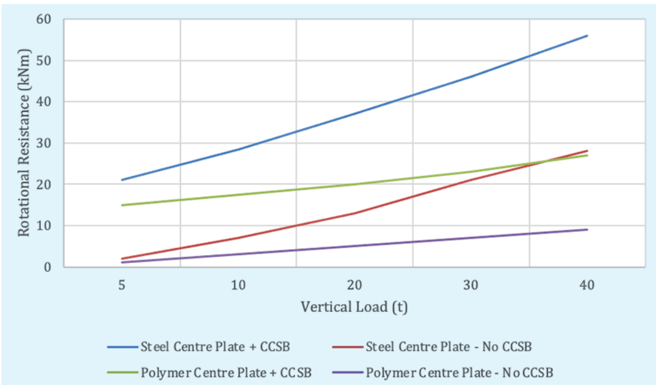

Figure 12 Rotational resistance of various bogie types measured in the Transport for NSW test rig (adapted from (36)).

Figure 12 shows that the minimum rotational resistance occurs at tare (this is important for preventing hunting) and is controlled by the side bearer settings. The rate of increase in rotational resistance with wagon load is controlled by the centre plate material, with steel centre plates offering the greatest rotational resistance and polymer centre plate liners offering lower rotational resistance.

The Transport for NSW results support the in-field AoA measurements – bogie designs with high warp stiffness steer well and do not generate high AoA. Further, reducing rotational resistance of the centre plate (e.g. with polymer centre plate liners) can reduce rotational resistance considerably. The rotational resistance is controlled appropriately at high wagon load, with only a minor impact on rotational resistance at tare and hence no compromise on high speed stability.

These results suggest wheel squeal can be largely eliminated if all bogies had a warp stiffness of 5-6kN/m or greater, combined with appropriate management of rotational resistance, which could be achieved by upgrading three-piece bogies with split wedges (for Barber bogies) or stiffer control springs (for ride control bogies), polymer centre plate liners and optimised side bearers.

3.1.2.2 Wheel and Rail Profile

Rolling stock steering is assisted by maximising the rolling radius difference between the inner and outer wheels. On a bogie with proper steering, the conical profile of the wheels will adjust so that the outer wheel contacts closer to the flange than the inner wheel and hence has a greater rolling radius. This can be aided by introducing asymmetrical rail profiles on curves such that the wheel contact position is not in the centre of the rail head, but rather displaced towards the gauge side on the HIGH rail and towards the field side on the LOW rail.

Asymmetrical rail profiles can increase the steering moment in Equation 2 and reduce the warp moment. This makes the bogie less likely to lozenge and reduces the probability of high AoA.

Equally, the conical wheel profile must be maintained to provide good steering performance. Worn and hollowed wheels will not steer as well as new wheels, and can even lead to wheel squeal being generated through a different mechanism (37).

3.2 Friction Conditions

For wheel squeal to occur, the friction conditions at the wheel/rail interface must be such that the unsteady stick/slip oscillations that cause the wheel to vibrate can occur. Friction at the wheel/rail interface is influenced by the rail and wheel metallurgy, environmental conditions such as temperature, precipitation and humidity, and third-bodies such as leaves, sap, and grease that can be introduced from the environment or as part of a friction management regime.

3.3 Wheel Dynamic Properties

Railway wheels have a high propensity to generate wheel squeal noise. They have a large surface area, and a series of very lightly damped resonances across the frequency region that is excited by stick-slip oscillations (38). This means that a relatively small amount of excitation can generate large vibrations across the surface of the wheel, which then acts like a loudspeaker to efficiently broadcast noise.

3.4 Track Dynamic Properties

The dynamic properties of the track also play a role. It is widely known that changing a track form from timber to concrete sleepers dramatically increases the likelihood of wheel squeal occurring (7). The reasons for this are not well understood, but clearly the dynamics of the track can influence the propensity of the wheel to emit squeal noise.

3.5 Factors with Minimal Influence

Some factors, as outlined below, have little support in the literature for contributing to wheel squeal generation. This is not to say they play no role, rather than their influence is minor compared to those factors described above.

3.5.1 Speed / Cant

As discussed above, a necessary condition for the generation of wheel squeal is a high AoA between the wheel and rail. As Jiang explained in (39), the speed of the train, and hence the cant excess or deficiency, has little effect on the steering performance and hence the AoA, as shown in Figure 13. By extension, speed has little impact on the generation of wheel squeal.

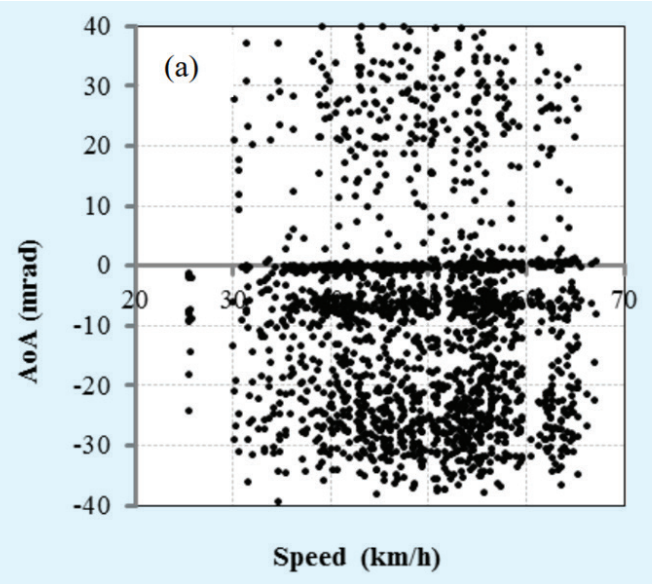

Figure 13 AoA is not correlated with train speed (from (39))

It has been observed that the noise level of wheel squeal can vary slightly with train speed (7). This effect, however, is relatively minor or even negative. A reduction of a few decibels does not substantially reduce the impacts of very high wheel squeal noise levels, but reducing speed has the perverse outcome of increasing the amount of time a squealing wheel takes to pass thereby increasing the duration of exposure.

Further, wheel squeal can still occur at very low speed. Wheel squeal is frequently observed in rail yards where rolling stock negotiate tight curves at walking speed.

3.5.2 Gradient and Ascending vs Descending Trains

The role of longitudinal train forces in the generation of wheel squeal was also examined by Jiang in (39) by comparing the AoA of ascending and descending trains. Jiang found that the bogie design is the predominant influence on the generation of high AoAs, and this result was obtained for both ascending (“stretched”) and descending (“bunched”) trains. Similarly, no effect due to train braking was detected in Jiang’s extensive study.

Squeal noise can occur due to longitudinal slip associated with traction and braking, but this is a distinct phenomena from wheel squeal in tight curves. Jiang’s study found no relationship between AoA and either traction or braking. In other words, neither traction nor braking had a substantial influence on wheel squeal in curves.

3.5.3 Rolling Stock Maintenance

A common complaint from impacted residences is that “the trains are not being properly maintained”. This perception can be reinforced by the observation that only some wagons / trains generate wheel squeal, implying that a lack of care or a drive to cut operating costs by reducing maintenance is to blame. Quite apart from the basic requirement to maintain rolling stock sufficiently for it to operate safely, additional maintenance has been found to have little or no impact on wheel squeal generation.

This concept of maintenance and inspection has formed the basis of wheel squeal management in South Australia. Freight rail operators are licenced by the South Australian Environment Protection Authority, and these licences include requirements to identify vehicles that frequently squeal, and remove these from service for inspection and maintenance (40). This approach has not been effective in managing wheel squeal noise. Inspections of these vehicles invariably find that all dimensions and tolerances are within specification and the vehicles are returned to service where they continue to generate wheel squeal.

One of Australia’s premier freight operators has taken this concept one step further. In a targeted study, they subjected wagons that were identified through this licencing process, to enhanced maintenance. This involved stripping down the bogies completely, and tightening tolerances across the bogies to well beyond the limits of specifications, including through laser alignment and careful configuration of side bearers and other components. This enhanced maintenance had no impact on the steering performance of these wagons and hence no reduction in wheel squeal.

These findings reinforce the conclusion of the extensive Transport for NSW studies (35; 31; 36), that it is the design / configuration of bogies, rather than their maintenance condition, that is the major determinant of steering performance and propensity to generate wheel squeal. Three-piece bogies have inherently low warp stiffness and are thus vulnerable to warping in curves. Even when maintained in accordance with appropriate standards, the warp stiffness is frequently insufficient to ensure proper steering behaviour. No amount of maintenance or inspection can make up for this fundamental deficiency.

3.6 Summary of Wheel Squeal Causes

Wheel squeal mechanisms are a complex field of research. It is still not possible to accurately predict which individual wheel on a train will squeal at a particular time and place. Most rail wheels, under certain conditions, can be made to squeal. Most curves can experience friction conditions under which wheel squeal can be generated.

Fortunately, it is not necessary to understand wheel squeal at this level of detail to effectively manage it. What is now well understood, and proven in practise, are the necessary conditions for wheel squeal to occur and how to control these conditions to effectively manage wheel squeal.

4. Wheel Squeal Management

4.1 Hierarchy of Control

The options for the management of wheel squeal can be considered through application of the "hierarchy of control" model, as outlined in Figure 14.

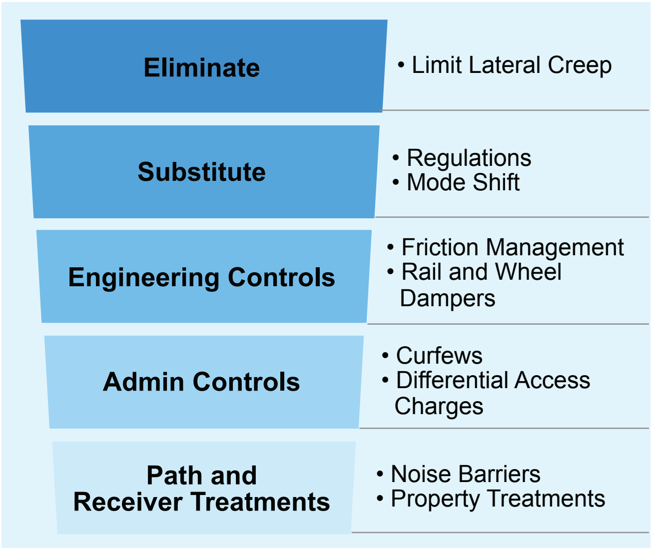

Figure 14 Hierarchy of control model for the management of wheel squeal

Each option in the hierarchy is discussed below.

4.2 Elimination - Limit Creep

The most effective means of managing wheel squeal noise is to prevent it from occurring in the first place. A high AoA is a necessary condition for wheel squeal to occur, therefore removing the conditions which lead to high AoA can eliminate wheel squeal. This is discussed below in regard to both new infrastructure/rolling stock, and existing infrastructure/rolling stock.

As discussed in Section 1.4.3, reducing large AoAs has flow on benefits in the form of:

» Reduced wear of both wheels and rails, including wear related defects;

» Reduced maintenance costs in terms of rail grinding and wheel turning, and hence less time for assets to be out of revenue service;

» Reduced energy/fuel consumption due to lower curve resistance, and hence lower emissions, particularly from diesel-electric locomotives; and,

» Lower capital costs for new infrastructure in terms of reduced requirement for noise abatement such as noise barriers and property treatments.

These are some of the reasons why addressing wheel-squeal at-source (by improving rolling stock steering performance) is economically beneficial for both above and below rail operators (13; 15).

4.2.1 Eliminate Tight Radius Curves

New infrastructure should be designed with curve radii that are as large as possible. With reference to Equation 1, the curve radius should be at least 100 times the largest rolling stock wheelbase in order to ensure AoA is less than 10mrad. Ideally, and to allow for natural variation in rolling stock performance, a more conservative factor of 200 times the wheelbase should be the target.

For example, for a passenger line that carries rolling stock with wheelbases up to 2.5m, a minimum curve radius of 500m would help ensure wheel squeal did not occur. Similarly, for a light rail network with wheelbases of up to 1.5m, a minimum curve radius of 300m would mitigate squeal.

The same principles apply to realignment of existing infrastructure. Wherever possible, curved tracks should be realigned with radii as large as possible. This includes the replacement of short curves with tangent or large radius track.

Even where large radius curves cannot be achieved, additional controls can be incorporated into the planning conditions for new infrastructure to manage wheel squeal in other ways. An example is the Moorebank Intermodal Terminal in Sydney. While this is an open access terminal, it has requirements under its Conditions of Approval to actively measure bogie steering performance and wheel squeal noise emissions, and to manage these emissions (10). This includes installing and maintaining an AoA measurement system and a noise monitoring system on the curves at the entrance to the terminal.

4.2.2 Procuring Rolling Stock

Procurement of new rolling stock should include requirements for steering performance to avoid wheel squeal generation on the tracks that the new vehicles will operate. This is not a new concept (41), but seems to have had limited adoption, with capital cost considerations outweighing life-cycle costs and noise emissions in procurement specifications.

New freight wagons should have bogies with high warp stiffness, such as one-piece, two-piece, steering (e.g. Scheffel, AR-1) or cross-braced bogies (42). Bogie rotational resistance should be properly managed through appropriate centre plate friction management, such as polymer centre plate liners or centre plate lubrication (35; 43). For lower speed operations where hunting is not a risk, side-bearers with roller elements can be used in place of friction elements (44), provided the bogie warp stiffness is sufficient, to help ensure proper bogie rotation.

New locomotives should have steering bogies (e.g. UGL's Flexicurve and EMD's self-steering radial bogies) for mainline applications in Australia. Curve radii on most main lines in built up areas is small enough that three-axle locomotive bogies will always generate an AoA of greater than 10mrad at the leading wheelset. Steering bogies will address this by ensuring wheelsets align with the curve.

New passenger trains and light rail vehicles should also consider steering bogies, especially for existing networks with tight radius curves such as Sydney, Brisbane, Adelaide and Melbourne. Steering bogies for passenger trains are used extensively in Europe, including for higher speed operations (see e.g. (45)).

In addition, procurement of new rolling stock for operation on tight radius curves should consider wheel dampers, as discussed in Section 4.4.4, below.

4.2.3 Wheel and Rail Profiles

Apart from major works to increase the radius of tight curves, eliminating creep on existing infrastructure is challenging. As discussed in Section 3.1.2.2, increasing the rolling radius difference between the inner and outer wheels can assist with steering. This can be achieved with asymmetrical rail profiles (41) and there is some suggestion that gauge widening can also be of benefit (46).

Wheel profiles can also be optimised to create the desired rolling radius difference. Compatibility with wheel profiles must be considered when designing rail profiles to promote good steering (and vice versa).

These strategies are likely to offer benefits mainly in circumstances where the rolling stock has normal steering performance. Where rolling stock steering performance is poor, the warp of the bogies and consequent AoA will likely over-ride the assistance to steering offered by increased rolling radius difference.

4.2.4 Upgrade Existing Rolling Stock

The biggest opportunities for reducing wheel squeal noise on existing rolling stock lie in upgrading basic three-piece freight bogies. In Australia, these bogies are generally of two main designs – ride control (with constant damping force) and Barber (with load dependent damping force). Warp stiffness of these three-piece bogies is achieved through friction wedges which act between the bogie bolster and the bogie side frames via control springs, as shown in Figure 15.

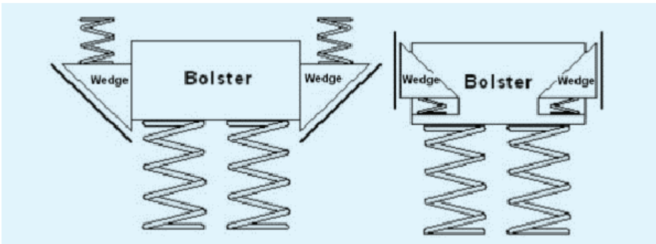

Figure 15 Common three-piece bogie types (47)

Barber bogies (Figure 15, left) use a longer control spring that is mounted in the secondary suspension spring nest, and hence it is compressed as the load on the bolster increases. The warp stiffness of Barber bogies therefore increases as wagon load (and hence compression of the spring nest) increases

In ride control bogies (Figure 15, right), the control springs are mounted in the bolster with the friction wedge, so that they impart a constant force onto the side frame irrespective of the position of the bolster.

Transport for NSW demonstrated the efficacy of inexpensive modifications for both Barber and ride control bogies, as shown in Figure 11.

For Barber bogies, this includes split wedges (48) in place of the older style friction wedges. For ride control bogies, this includes stiffer control springs. For both bogie types, additional improvements are achieved with polymer centre plate liners (49), resilient pedestal adaptors (50; 51), and optimised side bearer preloads. Note that manufacturers of three-piece bogies offer these upgrades as standard on new three-piece bogies (52; 53), and these upgrades are therefore akin to bringing older three-piece bogies up to the specification of modern three-piece bogies.

These components are generally interchangeable with the superseded components, as highlighted in Figure 16, so no modifications are required to the bogies. The upgrade can be achieved as part of a standard bogie overhaul. As with any modification, the safe operation of the wagon must be ensured. This typically involves testing the wagon in a worn condition at 110% of maximum design speed to ensure no hunting occurs.

It is also possible to retrofit some three-piece bogies, especially those of Barber design, with cross bracing arms. Retrofit kits are available, as shown in Figure 17, and Pacific National trialled these kits on wagons susceptible to wheel squeal. Jiang reported that the upgrade produced a step change in steering performance and eliminated wheel squeal, as shown in Figure 18. In some instances, the added mass of cross bracing arms may need to be considered in relation to the wagon payload.

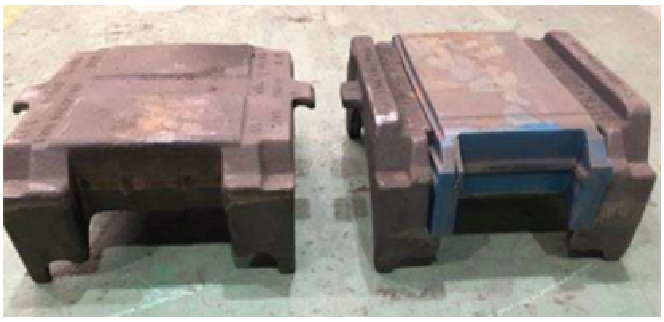

Figure 16 Traditional (left) and resilient (right) pedestal adapters in conjunction with other upgrades improve the steering performance of existing three-piece bogies

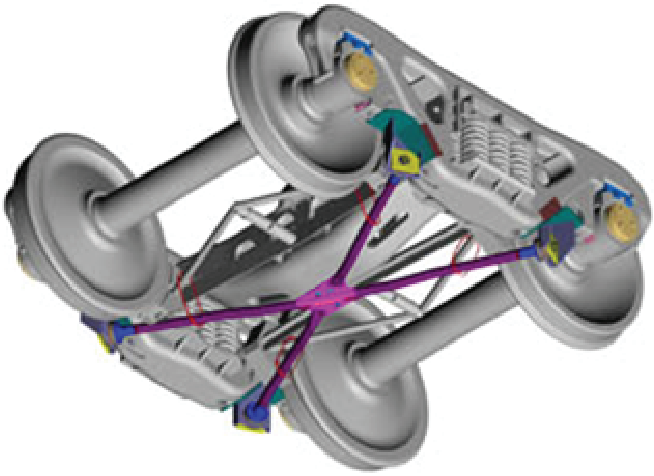

Figure 17 Cross bracing can be retrofitted to some three-piece bogies (image copyright Standard Car Truck Company)

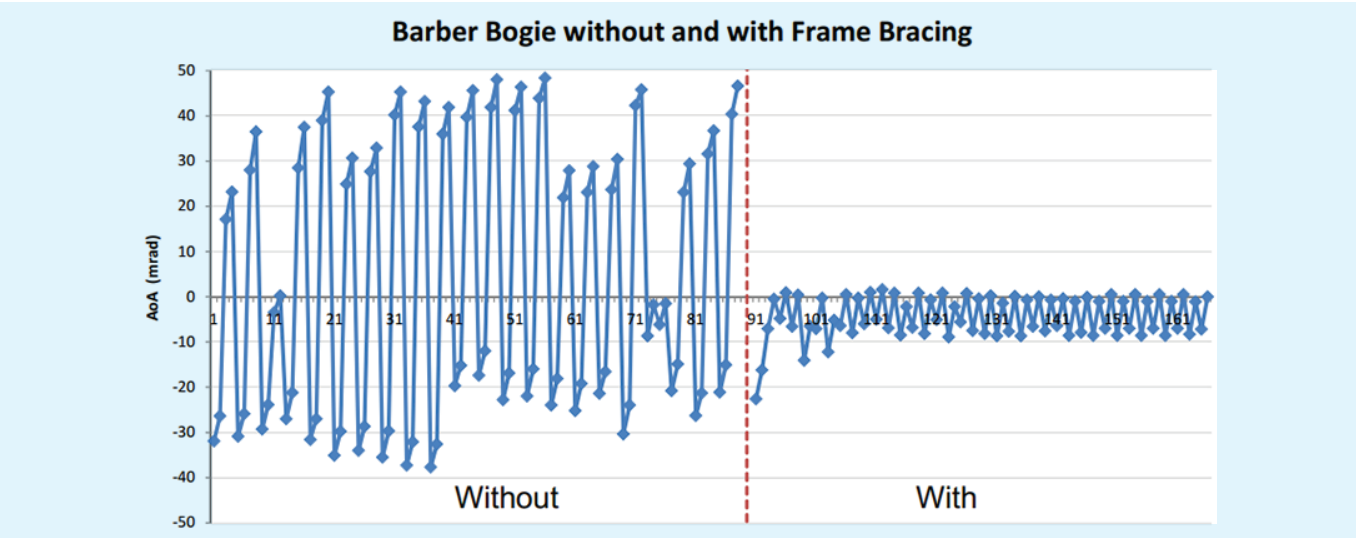

Figure 18 Impact of retrofitting cross bracing to three-piece Barber bogies (35)[5].

[5] A note about AoA plots. Each data-point represents a wheel pass from the wagon, i.e. four data-points each time the wagon passed the AoA detector. Prior to the upgrade, the wagon presented high AoAs, with both wheelsets on the leading bogie attacking the HIGH rail (negative AoA) and both wheelsets on the trailing bogie attacking the LOW rail (positive AoA) - a characteristic of poor bogie rotation and low warp stiffness. After cross bracing was installed, the bogie conformed to ideal steering behaviour as described in Section 3.1..

Some ride control design bogies can also be retrofitted with new bolsters that include a wider friction wedge. This substantially increases the warp stiffness of the bogie, as shown in Figure 11. While most of the existing bogie components can be retained in such an upgrade, it nonetheless represents a considerable expense with a so-called “hybrid” bolster costing around one-fifth of a new cross-braced bogie spider.

4.2.5 Manage Rail and Wheel Defects

It is a minimum requirement in managing wheel squeal, and safely operating the railway system more generally, that the railway assets, both below-rail and above-rail, are properly maintained. While maintenance is rarely in itself a solution to wheel squeal, extreme defects that can cause high AoA have the potential to cause wheel squeal.

There does not appear to be an established relationship between many common defects and the generation of wheel squeal. This includes defects such as out-of-round wheels, squats and studs, rolling contact fatigue, dips and large gaps at rail joints, although these defects lead directly to other types of rail noise. There is, however, a clear link between wheel squeal and poor management of wheel and rail profiles, which impede steering performance of some bogie types.

Some defects can have secondary effects, such as reducing the effectiveness of mitigation measures. One such example is discussed in Section 4.4.1.4, below. Other defects can occur under the same conditions that give rise to wheel squeal. An example is corrugation which, like wheel squeal, can occur under conditions of high lateral creep, i.e. tight radius curves.

4.3 Substitution – Replace Squealing Rolling Stock

Substitution, while effective, is not always possible in managing wheel squeal. The principle is to divert rolling stock that generates wheel squeal onto services that a) are not near residences, or b) operate only during the day when the impact of squeal noise is lower. Examples could include:

- Isolating freight wagons with poor steering onto regional shuttle services that don’t operate through built up areas, e.g. to access ports.
- Reserving classes of light rail vehicles that are associated with squeal noise for use in peak periods only, and using only other classes at night.

It is not always possible or practical to manage fleets to achieve this.

For completeness, it is necessary to mention substitution of modes for situations where squeal cannot be otherwise managed. This could take the form of buses replacing light rail services during the early hours of the morning, or replacing some late-night freight services with trucks. This approach is not consistent with broader transport strategies to shift more services onto rail however, and would have negative impacts in terms of congestion, emissions, and noise from road traffic (6).

4.4 Engineering Controls – Limit Stick-Slip Excitation

If elimination or substitution is not possible and large AoAs still arise, wheel squeal can be mitigated by preventing stick-slip excitation. This can be achieved by controlling the friction at the wheel/rail interface.

4.4.1 Gauge Face Lubrication

In general terms, the coefficient of friction on the gauge face and gauge corner of the rail (and hence on the contact interfaces – the flange and throat of the wheel) should be as low as possible. This helps limit wheel and rail wear, prevent wheel climb derailment, and is a key element of rail asset management. Control of friction at the gauge face and gauge corner is described in (54).

Maintaining low gauge face and gauge corner friction levels can also mitigate some types of wheel squeal. In (55) and (56), the results of a long-term trial of gauge face lubrication and top of rail friction modification at a curve in Sydney are reported. At this curve, 87% of wheel squeal events occurred with high rail gauge corner contact, whereas at other sites wheel squeal occurred predominately under the traditional top of low rail wheel contact conditions (24). Application of gauge face lubrication on both rails all but eliminated wheel squeal at the test site.

Gauge face lubrication (GFL) can be applied through wayside or on-train applicators.

4.4.1.1 Wayside Application

Wayside application of lubrication is the most common approach for main lines in Australia. This involves positioning of applicator units throughout the network at strategic locations to ensure friction is adequately managed. Wayside applicators generally consist of a reservoir and control box located in a safe place, and applicator bars that sit on the gauge side of the rail. The system delivers a controlled amount of grease through the applicator bars which is picked up by passing wheels and carried down the track. A process for designing a wayside lubrication system is described in (54).

Figure 19 Modern electronic wayside lubricators apply controlled amounts of lubricant to both rails in tangent track ahead of curves (image from (11))

Older style “grease pots” are gradually being replaced with modern electronic lubricators like that shown in Figure 19. Electronic lubricators have many advantages over the older units, including:

- Worker safety – the most common maintenance activity for lubricators is refilling the reservoir with grease. Electronic lubricators place the reservoir outside the danger zone, thereby eliminating the risk of being struck by trains. The reservoir can also be positioned further from the track, allowing maintenance vehicles to be positioned immediately adjacent. This avoids having to negotiate the ballast shoulder and reduces manual handling.
- Rail operations safety – electronic lubricators provide precise control of the amount and rate of grease application. This helps to avoid rail head contamination that can impact traction and braking. Such fine control is not possible with older mechanical lubricators.
- Reliability – electronic lubricators are entirely “non-contact”. Older grease pots rely on passing wheels depressing a plunger to pump grease to the applicator bars, and the wheel strike can often damage these plungers. Electronic lubricators, however, typically use inductive wheel sensors to detect the presence of trains, thereby eliminating the risk of wheel strike damage.

- Maintenance – electronic lubricators typically require very little maintenance. Once commissioned, they generally only require the reservoir be periodically refilled. These reservoirs are commonly ten to twenty times larger than those of grease pots, so maintenance visits can be far less frequent. In addition, the carry distance from modern electronic lubricators is far greater than older grease pots and can extend over many kilometres. This means that a network can be serviced by far fewer units - typically each electronic lubricator can replace three to four grease pots. In addition, the electronic control systems generally have remote, web-based access. This means that maintainers can monitor grease levels, application rates, etc. of each unit, and schedule maintenance only when required.
- Performance – largely through a combination of the reduced maintenance requirements, superior applicator technology and better reliability, electronic lubricators are more effective at managing gauge corner and gauge face friction levels. This provides better protection of the rail and wheel assets, and reduced emissions and fuel consumption through lower curve resistance.
- Cost – the much lower maintenance requirements, superior performance, and the reduction in the number of units, means that electronic lubrication systems have substantially lower life cycle costs than grease pots.

4.4.1.2 On-Train Application

Lubrication (and top-of-rail-friction-modifier (TORFM), discussed below) can also be applied through on-train (also referred to as "on-board") systems. There are two main types – those that apply liquid grease products and those that use solid grease products. The simplest and most common on-board applicators in Australia are those that use solid products (57; 58). In other jurisdictions, TORFM has been applied using dedicated vehicles that form part of freight trains consists (59; 60).

The principle of solid lubricant applicators should be familiar to anyone who had a "glue stick" in school. A "stick" of lubricant, or series of smaller interlocking blocks, is mounted in a tube that is supported on the bogie. A spring applies pressure to the stick(s) to ensure they remain in contact with the throat of the wheel. As the wheel rotates, the stick is slowly worn down as the lubricating product is dispensed onto the wheel throat.

One advantage of the solid lubricant applicators over the liquid applicators is that the product is less likely to migrate onto the wheel tread where it can interfere with traction and braking. Another is in the shear simplicity of the system. There are no pumps or other electronic components – just a tube, spring and stick of grease. Finally, the maintenance is simplified in that the rolling stock returns to a single base where lubricator sticks can be replaced. In contrast, wayside application systems require maintenance crews to traverse the network to service units and fill grease reservoirs.

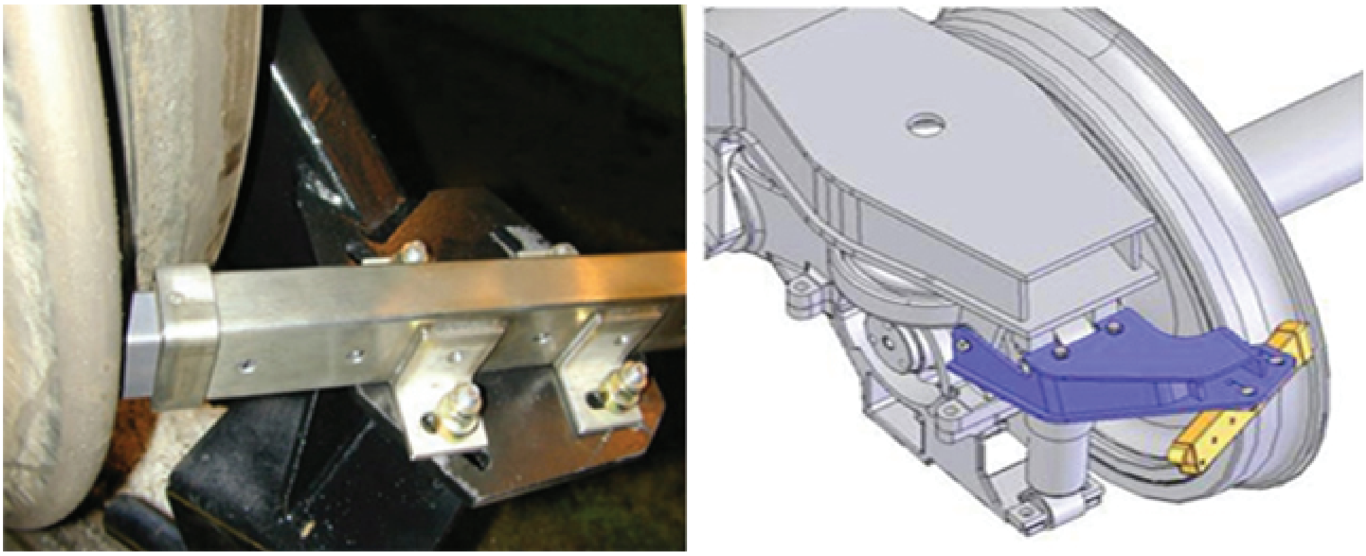

Figure 20 Solid stick on-board lubrication (and TORFM) systems are simple and easy to maintain (image from (61))

4.4.1.3 Shared Corridors

Implementing effective rail lubrication on light rail systems can be a challenge. On corridors that are shared with passenger, bicycle and road traffic, it can be hazardous for rails to have low-friction surfaces. Wayside application on shared corridors may therefore not be appropriate, and on-train systems, such as the solid block products, may be required.

Figure 21 Light rail systems often feature rails embedded in the road. Grease on these rails can be hazardous to pedestrians, cyclists and motorised road traffic.

4.4.1.4 Impact of Rail Grinding on Lubrication

The importance of rail (and wheel) profile management was outlined in Section 4.2.3. Proper management of rail profiles is also important for rail lubrication.

For lubrication to be effective, it must be present at the interface between the wheel and rail. Rail grinding can sometimes impede effective lubrication by leaving facets that a) prevent lubrication from migrating to the contact zones, and/or b) introducing two-point contact whereby the gauge corner is not in contact with the wheel throat impeding proper steering. This was examined in (16) where the incidence of wheel squeal more than doubled following poor rail grinding, as shown in Figure 22.

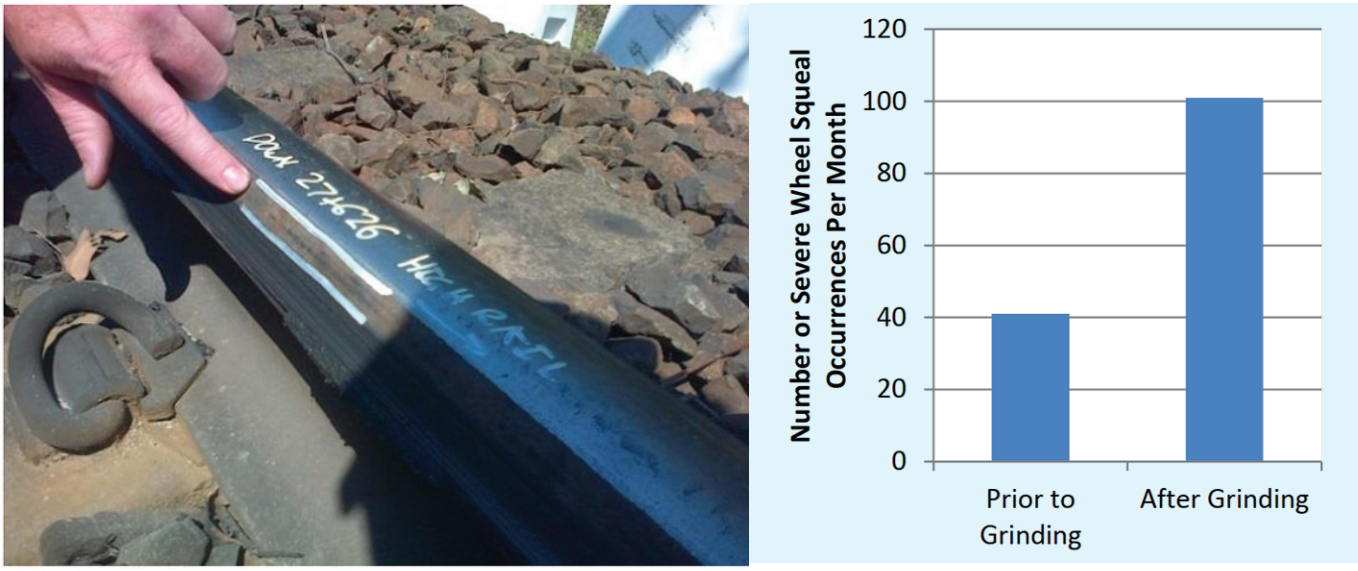

Figure 22 Poor rail grinding can leave large facets on the gauge corner which impede the performance of lubrication and increase the incidence of wheel squeal (16)

Poor rail profile management has implications beyond noise, including increased rates of wheel and rail wear, higher rail stresses and rates of defect generation, and greater risk of wheel-climb derailment. Most railways have standards that relate to rail grinding (62) which prohibit outcomes such as that shown in Figure 22. Careful oversight of grinding is required to ensure that standards are upheld, and outcomes are within specification. Otherwise, issues such as wheel squeal can result.

4.4.2 Top of Rail Friction Modification

Top of rail friction levels, by contrast, need to be maintained within certain limits. In order to preserve traction and braking performance, the coefficient of friction on the top of the rail needs to be above 0.3 (54). If the coefficient of friction gets too high however, then wear and rail defects can be promoted. It is generally sought therefore to maintain the top of rail friction coefficient between 0.3 and 0.4 (59). This can be achieved with top-of-rail-friction-modification (TORFM).

Unlike lubricants which seek to minimise the coefficient of friction, friction modifiers attempt to lock the coefficient of friction in a narrow band around 0.35. TORFM products are characterised by a “positive friction characteristic”. This means that the coefficient of friction increases with increasing creep. Controlling friction levels with TORFM therefore mitigates wheel squeal by preventing the falling friction conditions associated with high levels of lateral creep (63).

TORFM is widely used for the control of wheel squeal and appears to be effective. Even though the majority of wheel squeal was not generated by contact on the top of the rail, TORFM was still effective in mitigating wheel squeal during the Sydney trial (55). In (63; 64), TORFM is shown to mitigate wheel squeal noise on light rail, metro and heavy rail networks. TORFM has also been effective in mitigating other wear-related rail defects such as corrugation (65).

As with gauge face lubrication, TORFM can be applied through both wayside and on-board applicators. Indeed, much of the componentry of commercially available lubrication and TORFM systems is common. The obvious difference is the zone of application of the product – TORFM is applied on the top of the rail / wheel tread, whereas lubrication is applied to the gauge corner / wheel throat.

Wayside TORFM systems commonly use applicator bars that are mounted on the field side of the rail and dispense a "puddle" of product onto the rail head where it is picked up by passing wheels.

Solid stick TORFM applicators are similar to the solid stick lubrication applicators described in Section 4.4.1.2. Examples of both wayside and on-board TORFM systems are shown in Figure 23.

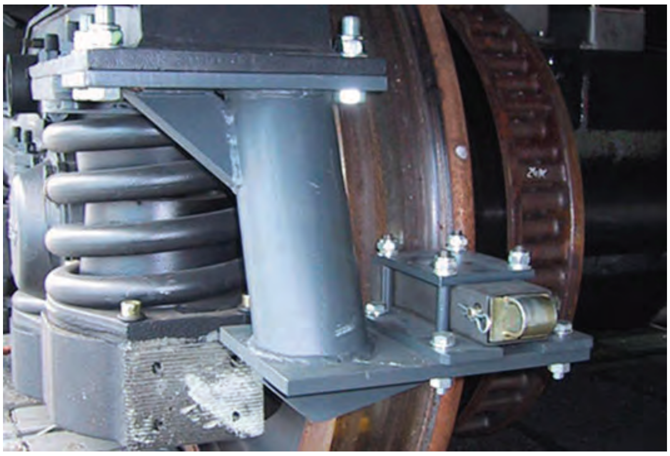

Figure 23 TORFM application systems – wayside (left) or on-board (right) (images from (57))

Unlike lubrication however, there is no equivalent of the "lubricator placement number" (54) for determining where wayside TORFM units should be located on a network. Rather, placement is generally guided by the actual prevalence of wheel squeal, which can be ascertained through noise measurements, community complaint data, front of train inspections, etc. This can guide decisions about which strategy to employ – wayside or on-board. If wheel squeal is occurring at only isolated locations then a targeted wayside strategy is likely to be most cost effective. If wheel squeal is widespread then an on-board strategy might be more efficient.

TORFM is generally best applied to both rails/wheels. This ensures the friction on both sides is equivalent. This is true even when wheel squeal is predominately occurring on only one rail. TORFM has been regularly observed to also mitigate flanging noise when applied in this manner (66).

Both TORFM and gauge face lubrication work by introducing a third-body layer between the steel wheels and rails. Liquid gauge face lubricants are often petroleum based whereas liquid TORFM products are preferably water based (67). The water quickly evaporates due to the heat generated at the wheel/rail interface, leaving the third-body material to gradually build up on the rail head. After an interruption to services, such as maintenance periods during the middle of the night or over weekend shutdowns, the third body layer can be diminished. Rain and early morning humidity can also introduce iron oxide layers on the rail head that impede TORFM performance. Following such events, it can take some time for this third-body layer to re-establish. During this time, wheel squeal can occur. This can create an impression in the community that the TORFM system is not working, but can be addressed with proactive communication to set reasonable expectations.

One drawback of TORFM products is their longevity – they are rapidly "burned up" at the wheel/rail interface. When applied at the wayside, effective wheel squeal mitigation can be limited to around 150-200m (66), sometimes requiring application at more than one location on a curve. The first wayside TORFM unit should be positioned at least 30m ahead of the curve transition to ensure the wheel/rail contact conditions support good pickup of the product from the applicator bars. On some long curves therefore, additional applicators may be required. The rail profile at the applicator location should be such that the contact band is wide enough to provide pickup over the whole wheel tread (66). TORFM and GFL units need to be spaced apart to limit cross-contamination between the two distinct products. Allowing 30-50m between GFL and TORFM units is a generally accepted approach.

In addition to mitigating wheel squeal, TORFM (and GFL) offers significant other advantages for the railway in terms of improved asset management and reduced operating and maintenance costs. Canadian Pacific has implemented a so-called "100% Effective Friction Management Strategy" (59; 60) which involves optimising GFL and TORFM through a combination of wayside and on-train applicators. The Strategy was not focused on noise mitigation, instead it delivered substantial savings in terms of reduced wheel and rail wear, locomotive fuel consumption, and defect generation.

4.4.3 Water Spray

It has often been observed that wheel squeal can be sensitive to humidity and precipitation. At some locations, wheel squeal is substantially reduced when it is raining, or during the early morning and evening when dew forms on the rail.

Some networks have trialled introducing water to the wheel/rail interface to replicate these observations. Yarra Trams wet the rails with a water cart ahead of trams (68), which eliminated squeal but for a very short duration. In Fremantle, wheel squeal on one tight curve has been effectively managed by water applied through an automated spray system that detects the presence of trains (69). In Queensland, water sprays have been used at Windsor and Mayne (43).

Water spray is generally not preferred for wheel squeal mitigation. Unlike TORFM, water can reduce friction at the wheel/rail interface to levels that can interfere with traction and braking. The examples cited above all involve very low-speed operations where this effect would be minor, but application in higher speed areas would require caution to ensure the safe operation of the railway is maintained. Water also increases the rate of corrosion of steel components like fasteners, clips and spikes. Perhaps counterintuitively, it can also be expensive to implement. Water must be applied throughout a curve, requiring piping and spraying infrastructure to be installed for potentially hundreds of metres.

4.4.4 Limit Wheel Response

As described in Section 1.2, wheel squeal is associated with unstable resonant vibration of wheel modes. These resonances are very lightly damped, so the addition of even a small amount of damping can not only reduce the resonant vibration, but can also prevent the instability from occurring in the first place and hence eliminate wheel squeal (38). For this reason, wheel dampers have been widely used, particularly (but not only) for passenger vehicles (43). There are several off-the-shelf solutions (70; 71; 72), which can be reused when wheelsets reach end of life, thereby offsetting the additional upfront costs. Some wheel manufacturers also offer damped wheels as part of their product range (73; 74).

There are several common wheel damper designs, as shown in Figure 24 and described below.

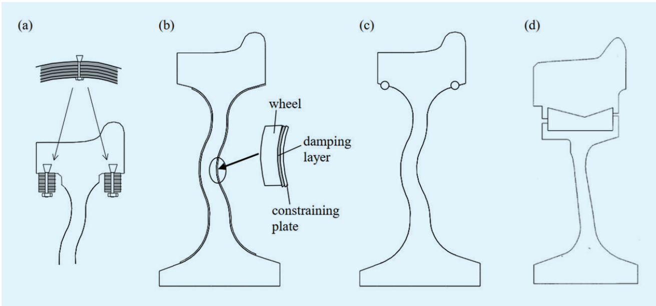

Figure 24 Examples of wheel damping treatments: (a) tuned mass absorbers; (b) constrained layer damping; (c) ring dampers; (d) resilient wheel (26)

- Tuned mass absorbers – these are spring-mass-damper systems that are attached to the wheel web. They are designed to vibrate in anti-phase to the wheel's resonant vibration modes and thereby reduce the vibration amplitude of the wheels (71).
- Constrained layer damping – this consists of a thin layer of damping material sandwiched between the wheel web and a stiff backing plate. The damping layer is deformed between the vibrating wheel web and the backing plate, thereby absorbing the vibration energy from the wheel (75).

- Ring dampers – these are steel rings inserted into a groove machined into the wheel. The rings are free to move within the groove, and the friction between the ring and the vibrating wheel absorbs vibration energy from the wheel (76; 77). Note that the performance of some ring dampers has been reported to deteriorate over time, as the groove becomes clogged with dirt and debris from service, which undermines the ability of the ring to absorb wheel vibrations (78).
- Resilient wheels – usually only found on light rail systems, resilient wheels include a resilient layer between the wheel tread and the wheel web. This layer provides a degree of vibration isolation between the wheel/rail interface where vibration is generated, and the noise radiating surfaces of the wheel web, thereby reducing noise emissions (79).

Figure 25 Wheels with dampers installed (70)

Wheel dampers can be an effective mitigation even for rolling stock with good steering, such as most passenger trains, light rail vehicles and locomotives, where tight radius curves still lead to high AoA.

4.4.5 Concrete vs Timber Sleepers

The incidence of wheel squeal across Australia significantly increased with the rollout of concrete sleepers (7). The advantages of concrete sleepers, including reduced maintenance and greater resistance to track buckling in high summer temperatures, mean that reverting back to timber sleepers on curves with wheel squeal is not a viable mitigation measure.

Jiang (80) identified two distinct differences in the dynamic properties of timber and concrete sleeper trackforms which could contribute to the different wheel squeal outcomes: the Track Decay Rate (TDR) in the wheel squeal frequency region, and the "dynamic gauge" under wheel pass. These are discussed below.

4.4.5.1 Rail Dampers

The impact of increasing the TDR of concrete sleeper tracks on wheel squeal outcomes was reported in (27). In short, the effect was modest. The TDR was increased using specially tuned rail dampers which targeted the high frequency region, rather than traditional rail dampers which focus on the lower frequencies associated with rolling noise.

Wheel squeal noise was reduced by around 3dB, which is not a noticeable reduction given wheel squeal noise is so loud.

The result was interesting for another reason, however, in that it highlighted the importance of eliminating (rather than simply reducing) wheel squeal noise. The reduction of 3dB implies that the rails were equally loud as the wheels at this site prior to introduction of the dampers. This is akin to having two equivalent noise sources, such as loudspeakers, and turning one of them off. In other areas of rail noise, this would represent a significant achievement. For example, in the Sydney Metro tunnels, mitigation such as rail dampers or acoustic tunnel linings that reduce in-car noise by 3dB is considered a worthwhile investment.

Wheel squeal however, is so loud that even reducing it by 3dB leaves a noise level that is still highly intrusive. That such a profound intervention can have so little effect on the subjective impact reinforces that effective management of wheel squeal can only really be achieved by preventing it from occurring in the first place.

Figure 26 In a NSW trial, rail dampers reduced wheel squeal noise by a modest amount (27)

4.4.5.2 Dynamic Gauge

Jiang (80) described the spreading of the rails under each wheel pass as "dynamic gauge". On timber sleeper trackforms, with far lower rates of wheel squeal, the dynamic gauge was 3-4 times greater than on concrete sleeper trackforms.

Dynamic gauge is distinct from "static" gauge. The "static" gauge of the track is the distance between the gauge faces measured at 16mm from the top of the rails (81). The "dynamic" gauge describes the amount of lateral motion, or spreading, that occurs under wheel-pass. Static gauge is nominally 1435mm for standard gauge track, but can increase by 20mm or more as the rails wear. This increase in static gauge does not appear to have any substantial impact on wheel squeal generation. In contrast, the dynamic gauge on timber sleeper trackforms measured by Jiang was of the order of 2-3mm, and it is postulated that this amount of spreading could contribute to the lower occurrence of squeal noise on timber sleeper tracks.

Implementing dynamic gauge on a concrete sleeper trackform remains a challenge. Resilient rail fasteners that allow lateral movement have been proposed, but not tested. Rail clips with zero toe loads have also been suggested but remain to be trialled.

Anecdotally, increasing dynamic gauge has been shown to eliminate wheel squeal. Wheel squeal on a curve in Australia carrying both freight and passenger traffic was observed to cease suddenly. On subsequent inspection, the clips on the HIGH rail right around the curve were found to have broken, i.e. the HIGH rail was unrestrained. The clips were subsequently repaired and the wheel squeal issue returned. In other words, accidentally reintroducing dynamic gauge eliminated wheel squeal at this location. Clearly, an unrestrained HIGH rail is not a feasible solution however, due to the increased risk of derailment. Further work is required to develop a viable approach for safely implementing dynamic gauge on concrete sleeper trackforms.

4.4.5.3 Composite Sleepers

While reverting from concrete to timber sleepers is unlikely to be viable, a compromise might be to use polymer composite sleepers on tight curves. It remains to be investigated however, as to whether composite sleepers enjoy the same low rates of wheel squeal generation as timber sleepers.

4.5 Administrative Controls

Administrative controls are not preferred solutions. They generally enforce a “lower limit” on performance rather than encouraging innovation and striving for best practice. Nevertheless, they have a role to play in ensuring fairness and driving action in parallel with other approaches.

4.5.1 Regulation

Where networks and operators have not addressed wheel squeal noise, regulators may take steps to enforce action. In NSW, the Environment Protection Authority (EPA) has introduced a new regime of rail regulation. Like their colleagues in South Australia, the NSW EPA now licences rail operators and networks separately (82). The rail operator licences include requirements to upgrade, by 2025, all vehicles that generate high AoAs and hence generate wheel squeal. The network licences include requirements that rail lubrication systems must be properly maintained. On the surface, this represents a positive outcome for the community in that wheel squeal will be largely addressed in NSW over the next five years if the new licences are successfully implemented.

The German Government has a noise-dependent route pricing system and associated Noise Protection Targets (83; 84). Since their inception, these schemes have funnelled more than one billion Euros into rolling stock upgrades, noise barrier construction, rail dampers and acoustic treatments for properties near rail lines. While these measures do not specifically target wheel squeal, this approach to funding could form a model for efforts in Australia to fast-track upgrades to rolling stock.

4.5.2 Curfews

Controls on network access are already in place on the Sydney Metropolitan network. Freight trains are held outside the Metropolitan area during the morning and afternoon passenger peak periods, to eliminate the risk of a freight train breakdown interrupting the busy commuter traffic. As discussed in Section 1.4.2, impacted communities can point to airport curfews (8) and wonder why network access controls are not also applied at night, at least for rolling stock that generates wheel squeal.

The implications of curfews for freight rail in particular would be devastating, and unviable. Freight operations in major cities are already constrained by expanding passenger timetables, forcing more services to run at night. Further curtailing network access would reduce the number of freight paths available and force freight onto road (where no curfew exists). It would also constrain access to ports with flow-on implications for shipping.

This emphasises the importance of the rail industry proactively managing wheel squeal (and other community impacts) so as to preserve its social licence to operate and ensure sustainability.

4.5.3 Differential Access Charges

One perspective on wheel squeal could be as a market failure. As discussed above, it is cheaper for all concerned – rolling stock operators, below rail asset owners, and the community - to run railways that don’t emit wheel squeal. What prevents this from occurring could be construed as inappropriate signals in the Australian land transport marketplace. A market-based corrective mechanism might therefore seem an appropriate response.

A market-based mechanism to drive change in rolling stock steering performance could be through charging reduced access fees for those vehicles that do not cause wheel squeal. Railways currently operate under several precedents for such a regime, although these target maintenance and other operating costs rather than noise impacts. In the European Union, differential access charges have been in place for some time (85), and a regime which offered lower access charges for rolling stock which caused less damage to the infrastructure was used in the UK (86). Even in Australia, different rolling stock types are charged different rates to access the network, and different charges for different parts of the network (87). It should be noted however, that pricing noise for rail in other jurisdictions has been accompanied by commensurate obligations and market interventions for road freight, as a whole transport/freight market, that are not present in the Australian freight and transport markets. Therefore any actions or recommendations to replicate this would need to apply to the whole transport /freight market and not only be targeted at rail freight. This approach in Australia has not been pursued due to the current regulatory regime that does not enable such interventions. Any consideration of moving to pricing noise for rail freight would also need to consider the existing government policy, legislation and freight costs, and consider the likelihood of triggering modal shift to road in the current freight market in Australia.

The regulatory environment would also need to ensure that all stakeholders continued to fulfill their requirements. A focus on rolling stock access charges could, without sufficient controls, allow RIMs and other stakeholders to relax their focus on the maintenance of the network.

If differential access charging was to be considered in the future, as part of a whole-market approach, then the German “noise-dependant route pricing” may offer a model for such a scheme, and the European Union’s broader, cross-state approach could provide some insights into how wheel squeal related pricing could be implemented across Australia’s federation of railways.

4.6 Path and Receiver Treatments

Traditional rail noise mitigation measures can also be effective against wheel squeal. The most common approaches, where mitigation is applied, are noise barriers and property treatments. Compared with solutions described in other sections above however, path and receiver treatments tend to be very expensive and deliver well defined but highly localised benefits.

4.6.1 Noise Barriers

Noise barriers are frequently constructed to mitigate rail noise. These are usually large structures that sit at the corridor boundary and require extensive foundations and land to accommodate them.

Noise barriers are expensive. In general terms, noise barriers cost around $1M per kilometre to construct, and $13-120k per year to maintain (including for graffiti removal) (88). The return on investment from noise barriers for wheel squeal mitigation is therefore orders of magnitude less than investing in at-source noise control to eliminate squeal.

Noise barriers typically provide 5-8dB of noise reduction depending on their height and the relative location of the track and surrounding residences. This is a substantial reduction, but given that wheel squeal noise is frequently more than 20dB louder than normal rail noise, it is a modest benefit compared with eliminating squeal.

Noise barriers mitigate wheel squeal by blocking the line-of-sight between the receiver and the wheels. Noise barriers are therefore less effective for receivers who are elevated. In multi-storey apartment blocks, barriers might only reduce noise levels for the ground (and possibly first) floor. Residents on higher levels may get no reduction in noise.

Figure 27 Noise barriers on the Epping to Thornleigh Third Track project to mitigate wheel squeal, locomotive and general rail noise (89)

Noise barriers specifically for wheel squeal mitigation can use light-weight construction (90). In addition, because the noise source (wheels) is quite low, the barrier height can be reduced if the barrier can be placed close to track (91).

4.6.2 Property Treatments

Wheel squeal noise can also be mitigated by applying acoustic treatments to individual properties. Typical acoustic treatments include replacing existing windows and doors on the facades facing the railway with acoustically rated equivalents, and providing fresh air ventilation or air conditioning so that windows and doors can be kept closed.

Transport for NSW offers at-property treatments under its Freight Noise Attenuation Program (92), and similar programs have been trialled by other networks (93; 94). As discussed above, the German program is quite extensive and includes property treatments, rolling stock upgrades, track based mitigation and noise barriers (95). In Australia, where noise barriers are generally not cost-effective, acoustic treatments to a typical home in a metropolitan setting cost around $30,000.

Acoustic property treatments can provide relief for residents inside their homes, but do not improve exterior amenity. This is another reason why at-source and planning controls offer greater benefit (9).

4.6.3 Noise Mitigation for New Projects

Regulations governing noise control on new infrastructure projects frequently require noise mitigation to be applied (19; 96). For projects with tight curves in proximity to residences, which is a common scenario in major cities, this can require millions of dollars to be spent mitigating wheel squeal noise.

Property treatments and noise barriers are the most common noise mitigation measures applied on new infrastructure projects in Australia. What if there was a way however, for this investment in noise mitigation to provide benefits not just for the residences near the new track, but across the whole network?

In most instances, each individual project is assessed separately, and is only responsible for noise mitigation within its geographical boundaries. As a result, decisions on noise mitigation are highly localised, and broader “best for network” and overall value-for-money perspectives are lost.

Other project specific incentives also inhibit broader solutions being applied. Delivery of mitigation is usually passed to the contractor engaged to construct the project. They are not equipped or empowered to consider solutions beyond the project boundaries. In addition, the project delivery team are often incentivised to prioritise delivery schedule and capital costs instead of whole-of-life costs.

The opportunity cost of this perspective is that projects are rarely a catalyst for network wide noise mitigation benefits. On one hand, the railway is being forced to spend money on noise mitigation due to regulations around new projects, but on the other hand, decisions on how that money is spent relate only the short section of track associated with the project.

Consider an individual project tasked with mitigating wheel squeal over several kilometres of track. For the project proponent, spending (say) ten million dollars on property treatments and noise barriers presents a low-risk means to meet their regulatory obligations. It is a small cost in relation to the overall project cost, and the construction of noise barriers and treatment of homes can be easily passed on to the delivery contractor. That same amount of money however, could potentially upgrade most of the rolling stock that generates the wheel squeal that the project is tasked with mitigating. Rather than benefiting only those residents next to the new track though, upgrading the rolling stock would benefit all residents near tight curves across the network.

It is difficult to conceive of how a civil works contractor could carry out upgrades to rolling stock that is owned and operated by private rolling stock companies. This is neither their area of expertise nor do they have any control over the rolling stock to be upgraded. It is therefore entirely understandable that the proponent will favour noise barriers and property treatments to meet their mitigation responsibilities. This approach will likely be adopted on each next project, such that over time, much more money will end up spent on barriers and property treatments than would be required to fix the issue of wheel squeal at-source.

How can this cycle be broken and the greater network-wide benefits be obtained?

Using projects as a catalyst for network wide wheel squeal outcomes is an administrative challenge, but one that is worthwhile tackling given it could deliver profound economic and community outcomes. One approach could be for the proponent to retain the responsibility for mitigation, rather than passing it on to their contractor. This would require support from regulators, such as Environment Protection Authorities and Departments of Planning, for an alternative approach to the traditional “barriers and property treatments” to help mitigate the project risk for the proponent. This support could recognise the potentially longer timeframes to deliver at-source noise control, and how the project’s initiatives can support the enforcement of existing controls, such as environment protection licences.

5. Summary: Effective Wheel Squeal Management

As with most rail noise, wheel squeal is a symptom of an inefficient railway. It indicates conditions (such as poor rolling stock steering, ineffective friction management, sub-optimal wheel and rail profiles) that are associated with increased wear of wheels and rails, increased fuel/energy consumption and hence emissions, and higher operating costs. It is therefore in everyone's interests to address these underlying causes and manage wheel squeal effectively.

Understanding of wheel squeal causes and mitigations has progressed substantially in the last decade. Strategies for effective management of wheel squeal, as outlined in this White Paper and summarised in Figure 28 and Figure 29, have now been proven in service.

The challenge remains however, with implementation. This requires both above- and below-rail managers doing their part and working together. The potential reward for such efforts is substantial – a more sustainable rail industry with lower operating and maintenances costs, and less community resistance to an expanding role for rail in our lives and economy.

Figure 28 Effective management of wheel squeal

Effective Management of Wheel Squeal

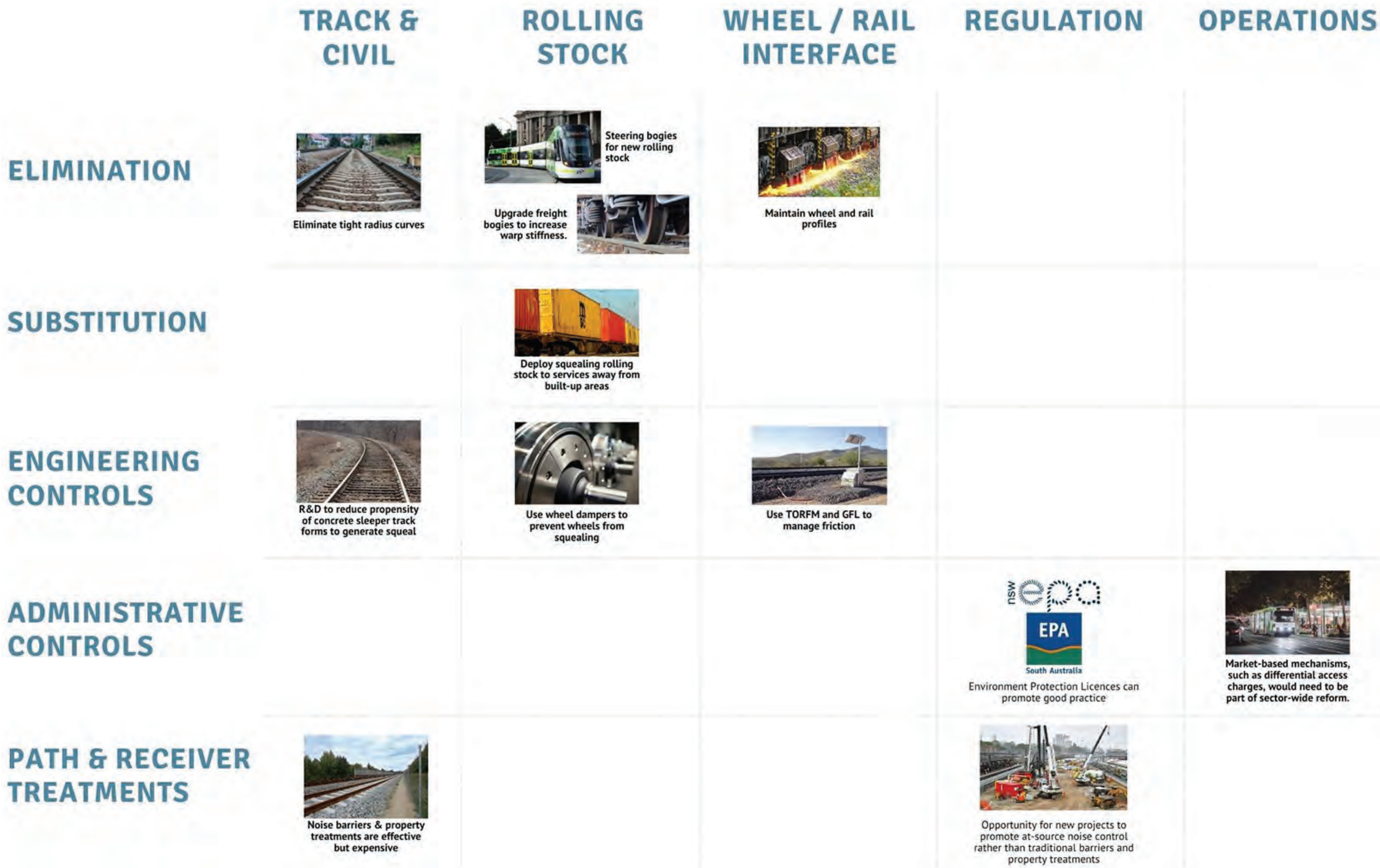

Figure 29 Hierarchy of control as applied to management of wheel squeal

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