Mitigation of Curve Squeal Noise in Queensland, New South Wales and South Australia

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SUMMARY

Operational noise is an increasingly important issue for the rail industry. One source of operational noise is curve squeal, a high pitched screech noise that can occur when trains traverse curves in the track. Curve squeal is one of the Australian rail industry’s top noise mitigation priorities, on account of the acute levels of noise it generates, together with the large number of populated locations near curves.

This paper provides an overview of many of the curve squeal investigations and trials that have been carried out in Australia, and summarises the lessons learnt and the patterns observed. Observations suggest that the majority of curve squeal effects can be categorised into one of three types. Importantly, the techniques for investigation and effective treatment can differ significantly between the types.

The first type, referred to in this paper as “friction controlled”, is normally relatively moderate curve squeal associated with a small proportion of the passing rolling stock (typically less than 10% of axles). Noise can be very substantially reduced (or even eliminated) by changes in top of rail friction characteristics, either due to the deliberate introduction of a friction modifier, or due to changes in tribology that can be brought about by environmental conditions (fluctuations in meteorological conditions or the presence of foreign material, such as brake dust or pollen). It is the latter effect that causes one of the defining features of this category of curve squeal, namely that it exhibits what appears, on first inspection, to be random variation. For example, the same train may pass the same curve several times during a day with substantially different curve squeal outcomes.

The second type, referred to in this paper as “steering controlled”, is often relatively severe curve squeal associated with a very small (but more repeatable) proportion of the passing rolling stock (typically less than 2% of axles). Changes in top of rail friction characteristics provide little or no improvement, but studies have demonstrated a high correlation with poor steering. Wayside detection systems can be used effectively to identify the responsible wagons so that corrective maintenance can be carried out.

Finally, a third type is referred to in this paper as “systemic” as it involves curve squeal effects caused by a relatively high proportion of axles. In some cases, improvements can be obtained with relatively minor adjustments, such as lubrication practices. However, in other cases, noise reductions may only be possible with significant changes to the track and/or rolling stock configuration.

1 INTRODUCTION

Noise generated by the operation of passenger and freight trains is an increasingly important environmental and community issue for the rail industry, both in Australia and internationally. Sources of noise include normal wheel on rail “rolling noise”, traction equipment (motors, locomotives) and safety warning systems such as horns.

Trains traversing tight curves can give rise to high intensity and high pitched screech noise, referred to in this paper as “curve squeal”. Curve squeal levels may be substantially (30dB or more) higher than normal rolling noise. Although the effect is limited to locations near curved track, curve squeal is one of the Australian rail industry’s top noise mitigation priorities, on account of the acute levels of noise it generates, together with the large number of populated locations near curves.

The significance of curve squeal as a community issue has also increased over the last 20 years. This is partly due to heightened community awareness and expectation, coupled with recent growth in rail transport and expansion of residential populations near rail operations. However, changes in the design, maintenance and operation of rolling stock and track are also likely to be a contributing factor.

Noise barriers are often considered as a way of mitigating operational rail noise but experience shows that they provide poor cost-benefit performance (typical costs being in the region of $1m per kilometre of barrier) and that they often give rise to a range of other impacts (such as visual intrusion and graffiti problems).
Noise barriers are particularly ill-suited to the treatment of curve squeal because:

- A barrier may provide around 10dB of noise reduction to affected properties, whereas the curve squeal level may be 30dB or more above general train noise. In other words, a barrier would alleviate, but not eliminate, the problem.
- In any case curves are generally found in hilly terrain, where noise barriers would fail to block the line of sight to many surrounding properties, and thereby provide little or no noise reduction.
- Similarly, the visual intrusion of a noise barrier may be incompatible with the expansive views and/or natural beauty associated with this type of terrain.

In common with rail networks overseas [1], substantial effort has been expended in Australia to attempt to understand and tackle curve squeal at source (rather than the use of noise barriers). There is also growing recognition that curve squeal may be an indicator of undesirable wheel and rail contact conditions which lead to high wear rates and reduced fuel efficiency.

In contrast to some overseas research [2], the Australian focus has been on monitoring the effects and evaluating treatment options in the field, rather than on laboratory analysis or theoretical modelling.

Some aspects of the Australian work in this area are groundbreaking, including:

- The extensive use of wayside angle-of-attack (AoA) detection systems for the specific purpose of studying curve squeal [3, 4]
- The development of trackside applicators for top-of-rail friction modification [5, 6]
- The trial of a wide range of mitigation techniques on the Brisbane rail network in Queensland [6]
- The development of a sophisticated wayside noise detection device to accurately identify axles that generate curve squeal in South Australia [7]
- The development of techniques to allow unattended monitoring of noise from a very large number of trains, over extensive periods (usually several weeks), and
- Work on detection of, and differentiation between, squeal and flanging noise characteristics.
- Another important feature of recent work on this issue is the extent of collaboration, both between states and rail networks, and between industry and the academic sector under the Rail Cooperative Research Centre.

2 NOTATION
Hz cycles per second, Hertz
kHz thousands of cycles per second
dB sound pressure level relative to 20 micro Pascals
dBA A-weighted sound level
AoA Angle of Attack of a wheel traversing a track. On a curve, positive AoA indicates the wheel is “attacking” the high rail.
mRad AoA in milli Radians
BPR Band Power Ratio, the ratio of acoustic energy between two frequency bands

3 DIFFERENTIATION BETWEEN SQUEAL AND FLANGING NOISE
For some years, Australian practice has been to differentiate between tonal “wheel squeal” and the more broad-band metal-on-metal rubbing noise termed “flanging”. It is not clear how widespread this practice is internationally, but it is notable that some researchers use the term “squeal” interchangeably between the two effects.

Although sharing some features, there are often differences in community response as well as differences in the underlying causes and treatments. Affected members of the community usually express more concern about tonal squeal noise than flanging noise [8, 9], probably due to the “piercing” tonal nature of squeal and the perception that it may be caused by some kind of fault with the rail system.

Rail engineers generally consider “flanging noise” to arise due to high lateral forces and the resulting wheel flange contact and/or creep at the gauge face/gauge corner of the rail [10]. It is clear that it is gaining recognition as a possible separate effect from squeal [2, 10, 11, 12]. It is also interesting to note that several researchers have found that flange contact actually eliminates squeal [13] (but not, obviously, flanging noise).

Researchers have discussed the frequency characteristics of the two effects [7, 12, 14], although not all agree on the frequency ranges. Jiang and Dwight [14, 15] suggest the two effects can be differentiated by tonality and report flanging noise as covering the frequency range 1 to 10kHz. Eadie et al [12] suggest that the two effects cover different frequency ranges (<5kHz for squeal, >5kHz for flanging).

More work is required to clarify the extent to which the treatment of the two effects may differ. It has long been considered that flanging noise can be controlled by the application of lubricant to the wheel flange / rail gauge interface [16, 17], but recent work has indicated that this is not always
the case [18]. However, what is clear is that squeal noise is not directly influenced by gauge face lubrication. (An indirect effect of gauge face lubrication can be degraded wheel-set steering resulting from grease contamination on the top of the rail, which can create the conditions for squeal).

Table 1 summarises the differences between flanging and wheel squeal and their likely causes. In the remainder of this paper, the terms “wheel squeal” and “flanging” are used to differentiate between the effects, while “curve squeal” is used to describe the combination.

4 SUMMARY OF CURRENT KNOWLEDGE

4.1 Theory

Established theory indicates that the prerequisites for wheel squeal are:

- Lateral creep (or sliding) between the wheel tread and the top of the rail,
- A friction characteristic that promotes (or allows) stick-slip motion of the lateral sliding, and
- A wheel disc with sufficiently low damping to allow build-up of a large forced response at one or more modes.

For flanging noise, it is generally accepted that the prerequisites are:

- Wheel contact in the gauge face or gauge corner region of the rail, resulting in high slip (or creep) rates,
- Sufficient friction for this sliding to generate noise.

4.2 Observed effects

For some years, anecdotal evidence has suggested that track with concrete sleepers has a higher likelihood of generating wheel squeal than track with timber sleepers. Field trials have now confirmed this (see section 5), but theoretical models are not yet able to explain this effect, nor to offer guidance on what changes would be required to track with concrete sleepers to avoid it.

One of the most notable features of the majority of curve squeal effects is the inconsistency in squeal noise between events that are, on the face of it, identical. Recent improvements in noise monitoring techniques (explained in section 8) have enabled much more data to be obtained over longer time periods. This, together with some specific detailed studies, has provided the basis for putting some order to the often chaotic data. In particular, this has led to the observation that the majority of curve squeal effects can be categorised into one of three types. Importantly, the techniques for investigation and effective treatment differ significantly between the types.

4.3 Types of Curve squeal

Three types of curve squeal effect are described in this section, and referred to throughout the case studies presented in this paper. Where typical noise levels are discussed, it should be noted that normal rolling noise (that is, in the absence of curve noise) is typically 80 to 85 dBA at 15 m from the track.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Wheel squeal</th>
<th>Curve squeal effect</th>
<th>Flanging</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>Usually sustained</td>
<td>Usually intermittent</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td>Highly tonal</td>
<td>Usually broad band, high frequency</td>
<td></td>
</tr>
<tr>
<td>Description</td>
<td>High pitched scream</td>
<td>Hiss, “tisk-tisk”, “ching-ching”, metal on metal sliding / screeching, grating noise</td>
<td></td>
</tr>
<tr>
<td>Normally arising from</td>
<td>Low rail</td>
<td>High rail</td>
<td></td>
</tr>
<tr>
<td>Suspected cause</td>
<td>Lateral creep combined with stick-slip motion (which efficiently excites wheel bending vibration modes)</td>
<td>Longitudinal / vertical sliding at wheel flange / gauge face (or gauge corner) contact</td>
<td></td>
</tr>
<tr>
<td>Dependent on speed or tractive effort?</td>
<td>Generally not</td>
<td>Yes [19]</td>
<td></td>
</tr>
<tr>
<td>Dependent on curving performance?</td>
<td>Yes, particularly Angle of Attack</td>
<td>Yes, particularly lateral position and wheel / rail interaction characteristics</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Curve squeal characteristics
The first type, referred to in this paper as "friction controlled", is relatively moderate curve squeal (typically 80 to 100dBA at 15m) associated with a small proportion of the passing rolling stock (typically less than 10% of axles). Noise can be very substantially reduced (or even eliminated) by changes in top of rail friction characteristics, either due to the deliberate introduction of a friction modifier, or due to changes in tribology that can be brought about by environmental conditions (fluctuations in meteorological conditions or the presence of foreign material, such as brake dust or pollen). It is the latter effect that causes one of the defining features of this type of curve squeal, namely that it exhibits what appears, on first inspection, to be random variation. For example, the same train may pass the same curve several times during a day with substantially different curve squeal outcomes.

An apparent contradiction with friction controlled sites is that, on the one hand, squeal noise tends to increase with increasing humidity whereas, on the other hand, squeal decreases when the rail is wet. The former is explained by the changes in the friction characteristic of the "third body layer" (the layer of material between the wheel and rail at the contact zone) brought about by changes in temperature and humidity; the latter is explained by the fact that water itself has a friction characteristic that suppresses squeal. Clearly these apparently contradictory effects can hinder attempts to understand the problem.

The second type, referred to in this paper as "steering controlled", is relatively severe curve squeal (typically 100 to 120dBA at 15m) associated with a very small (but more repeatable) proportion of the passing rolling stock (typically less than 2% of axles). Changes in top of rail friction characteristics provide little or no improvement, but studies have demonstrated a high correlation with poor steering (section 6). Wayside detection systems can be used effectively to identify the responsible wagons so that corrective maintenance can be carried out (described in section 8).

Finally, the third type is referred to in this paper as "systemic", and involves curve squeal effects caused by a relatively high proportion of axles. In some cases, improvements can be obtained with relatively minor adjustments, such as lubrication practices. However, in other cases, noise reductions may only be possible with significant changes to the track and/or rolling stock configuration. The defining feature of systemic curve squeal is the proportion of wagons and axles that generate the noise. However, evidence suggests that the underlying effects actually involve one or both of the friction controlled and steering controlled types. The apparent systemic nature of the problem merely indicates that the controlling factors are prevalent, rather than being isolated to a small proportion of rolling stock or friction conditions.

Figure 1 below summarises these types of curve squeal according to the typical proportion of axles generating noise and the noise levels themselves.

4.4 Unknowns

There are, of course, limitations in current knowledge. The most notable are:

- That theoretical models can not adequately explain the effects,
- Whether rolling stock maintenance, prompted by detection at wayside systems, will prove practical and effective in mitigating steering controlled curve squeal,
- That the optimum procedure for the application of top-of-rail friction modifier has not yet been studied in detail (in terms of how much and how frequently the product should be applied, for example).

5  FRICITION CONTROLLED EXAMPLES

Wheel squeal problems in NSW were first studied in detail at Wollstonecraft (Sydney) in the early 1990's [20]. Squeal noise levels up to 100 dBA were measured at 15 m from the track. Initial efforts failed to establish the cause of the problem or identify an effective solution. With hindsight, this was an early indication of friction controlled curve squeal effects.

An in-depth study was carried out in 1996 [3], including measuring angle-of-attack (AoA) in tandem with noise monitoring. The curve is approximately 200m in radius and carries passenger rail traffic. The study found that approximately 5% of axles caused squeal (translating to over 30% of trains) while 0.5% of axles generated flanging noise (which was not considered further).

Average AoA was 11mrad for leading axles and 0.6mrad for trailing axles, but there was no
correlation between squeal and irregular AoA or lateral position. The contact band on the high rail was located near the centre of the rail, rather than being approximately 20mm to the gauge side to promote rolling radius differential, but grinding an asymmetrical rail profile (to promote improved steering) did not reduce noise. Both of these observations show that the effects at this site are not steering controlled.

Squeal effects varied significantly during the study, particularly with changes in humidity and, at one point, as a result of organic matter being deposited on the rail during nearby grass cutting. Application of a friction modifier to the top of the low rail eliminated the squeal, confirming that top of rail friction conditions control squeal noise at this site.

Contrary to the supplier’s previous experience, the effectiveness of the high positive friction product disappeared after a few passing axles or trains. An automatic trackside applicator was therefore developed to deliver friction modifier to the running surface of the rail prior to each train [5]. This is explained further in Section 5.

Powell [6] and Nelson [8] describe the extensive investigations, trials and treatments carried out to combat wheel squeal on the Queensland Rail network in Brisbane between 1997 and 2000. Squeal noise levels of over 110 dBA had been measured at some of the affected residential locations.

At sites such as Keperra in Brisbane, moderate squeal noise became more prevalent with increasing humidity. Application of friction modifier to the top of the rail was generally successful, indicating that these curve squeal effects are also “friction controlled”.

However, at some locations, squeal was also noted from certain freight wagons and traced to poor steering due to ineffective centre-bowl lubrication, suggesting that some effects were “steering controlled”.

In NSW, a 320 m radius curve was upgraded from 53 kg/m rail on timber sleepers to 60 kg/m head hardened rail on concrete sleepers. Freight trains were found to have generated wheel squeal on timber sleepers, but at relatively low noise levels, whereas wheel squeal increased substantially following the track upgrade, with approximately 40% of freight trains generating severe levels. This confirms the previously anecdotal evidence suggesting curve squeal effects are worse following installation of concrete sleepers.

6 APPLYING FRICTION MODIFIER

6.1 Flutek applicator, NSW

In NSW, Fuchs TramSilence friction modifier is used successfully at a number of curves to control wheel squeal. Standard practice is to install trackside applicators in the transition to curves (rather than on tangent track prior to curves). Following a number of reliability problems with an early design of applicator, RailCorp recently developed a new applicator design (Figure 2) in conjunction with a private company (Flutek).

![Figure 2: New applicator system](image)

The system consists of the following components:

- A pump and 25kg reservoir adapted (with minor modification) from the standard gauge face lubricator used by RailCorp, (right hand side, Figure 2). The pump plunger is fixed to the gauge face of the high rail and, when activated by passing traffic, increases pressure in the line.

- A battery powered control unit designed and supplied by Flutek (front left, Figure 2). The unit remains dormant, with product recirculated to the reservoir, until pressure in the line reaches a threshold (the default setting being 35psi, or approximately 24kPa). When the threshold is reached, the unit activates a valve to divert product to the applicator for a set period. The unit then recirculates product for a pre-set delay (normally around 10 to 15 seconds, adjusted to exceed the typical passage time of a passenger train) before activating the valve again if line pressure remains above the threshold.

- A product delivery unit comprising a modified distribution frame together with a specially designed rubber pad (as seen in Figure 2, attached to the rail to the left of the pump). The pad is designed to flow the friction modifier on to the field side of the head of the rail. Passing wheels then collect and distribute the product along the track.

Following initial trials, a number of refinements have been made to the applicator to extend the maintenance cycle. These include:

- Three power source options (solar, battery and mains) to improve flexibility of installation (Figure 3).
- Wiring improvements to reduce the power consumption.
- Implementation of a time delay to turn the unit off (instead of a pressure reduction threshold), further reducing the power consumption of the unit.
- Inclusion of an in-line valve to regulate the proportion of product supplied to each rail and to stop back-flow from high rail to low rail due to superelevation (Figure 4).

A data logger is now under development to provide a record of the unit performance and allow remote status monitoring, if required. Each time the unit turns on and off, the data logging system will record:
- Date and time
- Ambient temperature
- Battery voltage
- Amount of product delivered

The data will then be suitable for export to an excel spreadsheet which will allow a check on the number of trains detected by the unit at the site. It is intended that uploading of data from the unit by phone will allow access to any of the monitored parameters and also facilitate notification of maintenance staff in the event of:
- Low battery
- Low product

### Keltrack and water application, Qld

During investigations in 1997 trials of the Kelsan Keltrack products included application in liquid form by hand and both solid and liquid form by hi-rail vehicle. Ongoing application involved the development of purpose-designed trackside applicators and, more recently, the installation of Portec applicators as shown in Figures 5 and 6.

Issues noted during the trials included rain washing friction modifier from the rail and wind blowing the dried product during hot dry weather. As is the case in NSW, friction modifier is generally applied to both rails (all three rails in the case of dual gauge track). Although wheel squeal can be controlled by applying the product to the low rail only, application to both rails promotes consistent friction between rails and thereby improves wheel-set steering and lateral force.

Water spray, activated by each approaching train, is also successfully used in a yard location although it causes some issues with weed growth, corrosion and ballast degradation.
7 STEERING CONTROLLED EXAMPLES

Curve squeal complaints have continued to increase at many parts of the rail network, even though friction modifier applicators have subsequently been installed at many of these locations. Further investigations [21] indicate that freight trains are the main squeal noise source at these sites and that friction modifier is, at best, only partially effective at mitigation. This is indicative of “steering controlled” curve squeal described in section 4.3, and is illustrated by the following examples.

In NSW, noise monitoring was carried out over a 4-month period near a 315 m radius curve (with 60 kg/m head hardened rail on concrete sleepers), spanning the installation, upgrade and duplication of a track-side applicator for top of rail friction modifier. 47% of freight trains generated “moderate” or “severe” squeal with no friction modifier, reducing to 35% with friction modifier, 29% with an improved applicator design, and 24% following the installation of an additional applicator at the mid-point of the curve.

Also in NSW, an extensive monitoring program over nearly six months in 2006 involved five simultaneous recording locations spanning four reverse curves (300 to 560 m radius). Two track-side applicators for top of rail friction modifier had been installed at this location in 2001 and the tests were carried out during the installation of two additional units, intended to improve the coverage of product over the 2 km section. Results showed negligible difference in wheel squeal following the installation of additional applicators and gave a very mixed picture when analysed in terms of particular types of freight train. Some categories showed no change, others showed improvement, while others performed worse. Monitoring at a complaint location 33 m from the 300 m radius curve showed that around 20% of freight trains continue to generate noise levels exceeding 105 dBA (equivalent to approximately 110 dBA at 15 m).

As mentioned in Section 4, at some locations in Queensland squeal was also noted from certain freight wagons and traced to poor steering due to ineffective centre-bowl lubrication, suggesting that these effects were “steering controlled”. Improved centre-bowl lubrication eradicated squeal from these wagons.

In South Australia, the interstate freight network traverses the Adelaide Hills via numerous 200 m radius curves on relatively steep grades. It is also an expanding residential area. The Australian Rail Track Corporation (ARTC) is manager of this network and has been addressing wheel squeal and flanging noise since 2000 [4, 7]. Trials with a top of rail friction modifier were not successful, providing an early indication that curve squeal effects here are not predominantly friction controlled.

Detailed studies in 2000 and 2003 were carried out using AoA detection in tandem with an acoustic detection system (using a microphone array with horizontal resolution to pin point each noisy wheel). These studies identified that less than 4% of the passing axles accounted for the majority of the noise issues and that, of these axles, nearly 90% were also displaying irregular AoA or inter-axle misalignment. This shows that the effects are actually steering controlled, and led to the installation of a permanent acoustic detection system (termed “RailSqad” [4]) in October 2005. This is discussed in more detail in Section 9.1.

8 NOISE INVESTIGATION TECHNIQUES

Rail noise is normally readily assessed and quantified during attended site visits. In contrast, experience shows that brief monitoring at curve noise sites can provide misleading data and that longer term surveys are necessary. This generally necessitates the use of unattended equipment, typically for 1 to 2 weeks, and subsequent analysis.

A Cooperative Research Centre project [14] has developed algorithms for detecting various types of wheel/rail noise, including wheel squeal and flanging. It was originally developed for on-train monitoring to identify track without effective lubrication, but the same algorithms are now providing rapid processing of wayside noise recordings obtained from simple, low cost, portable battery-powered monitoring systems.

This has allowed monitoring for extended periods for minimal cost, which is of particular benefit to studying curve squeal because events can vary randomly between trains, times of day, and meteorological conditions. Numerous studies have now exploited this approach [21], allowing the analysis of thousands of trains at curve sites and reducing many hundreds of hours of audio data into a simple table of noise events by date, time, noise level and whether squeal or flanging occurred.

The benefit of the approach over conventional wayside noise monitoring is the ability to verify the output data against operational data and to identify the likely mechanism causing the noise. Often peak noise intensity data from wayside monitoring can only confirm the complainant’s concerns and further investigation is necessary to identify the source of the noise and develop solutions. Often a desktop analysis of the algorithm outputs can confirm that the problem is global and local treatments are not the appropriate solution.

The system works by distinguishing squeal or flanging noise from normal rolling noise. The identification of squeal noise is based on its tonality characteristics. The narrow band squeal noise level is much higher than the background rolling noise level. Squeal noise identification is
achieved by finding a peak frequency band which exceeds its neighbouring frequency bands by a specified threshold in the high frequency range (normally 1 kHz to 10 kHz).

The squeal noise identification algorithm consists of three steps:

1. Find the maximum noise level and its corresponding frequency;
2. Filter out the squeal noise band, and those of its neighbouring frequency bands, with band-pass filters;
3. Compare the narrow-band squeal noise level with its neighbouring band's levels. If the difference exceeds the specified threshold, squeal noise is confirmed.

In contrast to squeal, the notable feature of wheel flanging noise is the high noise level across the full frequency range. Therefore it is straightforward to use a single threshold to detect the occurrence of flanging noise: if the noise level of all the high frequency bands, for example from 1 kHz to 10 kHz, exceeds a specified threshold, flanging noise is confirmed.

However, in some extreme cases, such as impact noise from severe wheel defects, the high frequency noise level may exceed the specified threshold and is falsely identified as flanging noise. False identification of flanging noise can be avoided because an impact normally excites all frequency components (both low and high frequency), causing a general increase in noise across a broad frequency range similar to rolling noise (although of a very short time duration) [22]. This is illustrated in Figure 7.

\[
BPR = \frac{\text{Band Power of High Frequency Range}}{\text{Total band power}} \times 100\%
\]

Normal rolling noise decreases in level with increasing frequency. In contrast, flanging noise levels remain high at high frequencies. It is expected that the BPR of rolling noise is significantly less than the BPR of flanging noise.

9 PERMANENT WAYSIDE MONITORING

9.1 Noise Detector, Adelaide Hills

A permanent ‘RailSquad’ noise detector [7] has been operating at Heathfield in the Adelaide Hills for over 2½ years. The system involves a horizontal array of microphones 6m from the low rail to provide accurate horizontal location of the source of curve squeal noise, together with a vehicle identification tag reader to confirm the identity of the wagon and axle in question.

The majority of squeal and flanging noise events are in the region of 95 to 100 dBA at 6 m (corresponding to approximately 90 to 95 dBA at 15 m). However, some events have exceeded 115 dBA (about 110 dBA at 15 m). The system allows detailed analysis of a very large data-set and trends established to date include:

- A very weak correlation between speed and squeal or flanging noise level.
- A strong correlation with travel direction, with more squeal and flanging noise occurring in the uphill direction (1:45 grade, bi-directional track).
- Leading axles of leading bogies consistently have a higher tendency to generate squeal or flanging noise.
- Certain types of wagon have a higher tendency to generate squeal or flanging noise.
- Consistent with experience at Wollstonecraft in NSW and Keperra in Brisbane, moderate squeal noise becomes more prevalent with increasing humidity, whereas temperature and humidity have almost no influence on the occurrence of the noisiest events [4]. This suggests that the noisiest events are steering controlled, while the more moderate events are friction controlled.
- There has been a general reduction in repeat squealers.

Figure 8 shows results for “WhlSql1” (squeal events that exceed 105 dB at 6m) and “WhlSql2” (events between 90dB and 105dB at 6m) since November 2005. The general trend is a decline in the proportion of axles recorded with curve squeal.

To date some wagons identified as “repeat offenders” have been inspected at the workshop.
and often found with defects that may explain poor curving performance. Most commonly, repairs and adjustments have been made to constant-contact side-bearers, brake rigging, mismatched side frames, worn wedge blocks and broken bogie springs. The process of corrective maintenance of “repeat offenders” is in its infancy but some classes of rolling stock have started to show improved noise performance at the monitoring site.

Figure 8: Proportion of axles at Heathfield by squeal category

Ongoing analysis will involve investigating correlations between wheal squeal and vehicle class type, bogie type, side bearer set-up and maintenance activities on both rolling stock and track.

9.2 Angle of Attack Detector, Sydney

RailCorp installed a permanent wayside Angle of Attack (AoA) detection system [23] on the main north rail line in Sydney in June 2007. The line carries a substantial proportion of the freight traffic traversing RailCorp’s network.

Most, if not all, previous AoA detector installations have been on tangent track for the purpose of rolling stock condition monitoring. (In addition, if 3 units are spaced along the track, the system performs as a hunting detector.) On tangent track, the expected value of AoA is near zero for all axles and there is limited dependence on pass-by speed. This leads to consistent and repeatable AoA data and a high degree of confidence that readings above a certain threshold correspond to defective rolling stock.

In contrast, it was decided to install this system on a curve (284 m radius). It was noted that this would reduce the repeatability of the data and make it difficult to set thresholds above which AoA readings could be confidently defined as “defective”. However, the advantage of detecting actual curving performance (rather than just the curving anomalies that manifest on tangent track) was considered to outweigh this.

RailCorp has carried out noise monitoring adjacent to the detector for much of the time since the device was installed. The detector and noise monitor are shown in Figure 9.

Analysis of the data is being progressed via a Rail Cooperative Research Centre project, led by the University of Wollongong. The AoA results to date indicate that:

- The vast majority (95%) of rolling stock passing the site shows very consistent AoA close to the expected range for the curve (+/-10mRad).
- A very small proportion (around 2%) of the axles show rather high AoA (greater than +/-30mRad).
- Of the axles detected with irregular AoA, many show repeatable performance. For example, over a 6 month period, less than 10 individual wagons (out of a total of over 33000 recorded wagon pass-bys) accounted for more than 10% of the irregular AoA events.

The noise data is summarised in Figure 10 (below) and shows that:

- The noisiest wheel squeal events (exceeding 110 dB at 2m, or approximately 100 dB at 15 m) occur when axles pass with irregular AoA (exceeding 30mRad).
- Generally the higher the squeal noise level, the higher the AoA of the corresponding axle. Events exceeding 120 dB at 2m (equivalent to 110 dB at 15 m) only occur when axles pass with AoA exceeding 30mRad.
- Not all axles with irregular AoA generate squeal noise.
- Squeal noise can occur with either positive or negative AoA (positive being when the wheel “attacks” the high rail).
Figure 10: Summary of squeal events by AoA and noise level band

In summary, the curve squeal effects at this location are predominantly steering controlled and the data from the AoA detector shows good consistency and repeatability.

10 SYSTEMIC SQUEAL EXAMPLES

The Cairns Kuranda Tourist railway operates in northern Queensland through a series of tight radius curves. Curve squeal problems began after the wheels on the heritage rolling stock were changed from spoked wheels to mono-block wheels. While no studies were done to quantify the level or frequency content of noise, the fact that all vehicles were subject to squeal suggests that the effects were systemic. The steps taken to resolve the problem were:

- Firstly, a period of intensive bogie maintenance to improve steering.
- Secondly, the installation of water drippers in the lead vehicles.

It can be seen that this systemic issue involved both steering controlled and friction controlled curve squeal effects.

11 CONCLUSIONS

The many case studies and investigations presented in this paper illustrate the importance of the curve squeal issue and the effort being taken by the Australian rail industry to tackle it.

It is clear that the issue is complex and that the controlling factors can vary significantly between sites, despite the audible character of the noise being essentially the same. The most important lessons learnt are:

- That short-term monitoring techniques used for normal rail noise investigations are generally unsuitable for curve noise.
- That curve squeal effects fall broadly into three types, or patterns.

Table 2 (overleaf) summarises the curve squeal types discussed in this paper together with lessons learnt about the monitoring and mitigation techniques that are likely to be required in each case.
Table 2: Summary of curve squeal characteristics, monitoring techniques and mitigation options.

<table>
<thead>
<tr>
<th></th>
<th>Normal rolling noise</th>
<th>Curve squeal effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Friction controlled</td>
</tr>
<tr>
<td>Typical noise levels at 15 m</td>
<td>80 to 85 (at 80km/h)</td>
<td>80 to 100</td>
</tr>
<tr>
<td>Typical proportion of axles</td>
<td>100</td>
<td>&lt;10</td>
</tr>
<tr>
<td>generating noise, %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Noise monitoring requirements:

- in terms of number of nominally identical train events to obtain reliable pattern: 5 to 20 >100 >100 (possibly with wayside detection) 5 to 20
- in terms of typical duration of monitoring program: A few hours Several days Several weeks A few hours

Treatment options likely to be effective:

<table>
<thead>
<tr>
<th></th>
<th>Top of rail friction modifier</th>
<th>Maintenance or modification to rolling stock to improve steering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Variable</td>
<td>Variable</td>
</tr>
</tbody>
</table>

REFERENCES