Life cycle analysis of railway noise and vibration mitigation methodologies with respect to curve squeal noises

Sadudee SETSOBHONKUL¹; Sakdirat KAEWUNRUEN¹,²

¹Birmingham Centre for Railway Research and Education, The University of Birmingham, Birmingham B15 2TT United Kingdom
²Department of Civil Engineering, School of Engineering, The University of Birmingham, Birmingham B15 2TT United Kingdom

ABSTRACT
Wheel/rail interface inevitably induces a travelling source of sound and vibration, which spread over a long distance of rail network and neighborhood corridor. The sound and vibration can be generated in various forms and spectra. The undesirable sound and vibration, is often called ‘noise’, includes rolling noise, impact noise, curve noise, mechanical noise, airborne noise, wheel/rail noise, structure- and ground-borne noises. The noise and vibration that is transferred back through the vehicle body mainly affects ride quality, customer experience, and structural integrity of the rolling stocks, whereas the vibration that is transmitted from the rails to the supporting structure of the track plays a main role in rapid track degradation and potentially affects the surrounding structures. This paper focuses on the effectiveness of noise mitigation measures on curved tracks located in urban environments. It highlights the practical methods for mitigating curve squeals and flanging noises, which are often observed along freight corridors and track infrastructures with nonlinear geometries. It is important to note that rail freight curve noises, especially for curve squeals, can be observed almost everywhere and every type of track structures. The most pressing noise appears at sharply curved tracks where excessive lateral wheel/rail dynamics resonate with falling friction states, generating a tonal noise problem, so-call ‘squeal’. Therefore, this paper is devoted to systems thinking approach and life cycle assessment in resolving railway curve noise problems. The life cycle of fifty years has been selected as it is coincide with the majority of common design life for railway tracks catering freights, heavy haul trains, mixed traffics and heavy suburban trains globally. Based on assumptions commonly derived in rail industry, the life cycle analyses under variant extreme weather conditions reveal that the jetting method (or on-board wheel-based friction modifier) seems to be the most efficient method for mitigating curve noises, whilst the noise barrier seems to be the worst counterpart in a long curve section but this case is untrue for a sharp short curved track.

Keywords: railway noises, systems thinking approach, life cycle analysis, railway noise monitoring and mitigation, curve squeal, flanging noise, top of rail friction modifier, jetting method, rail damper, noise barrier.

1. INTRODUCTION
Advances in research and development to mitigate railway noise and vibration have resulted in a wide variety of measures used in rail industry today. The progression of technology in noise and vibration mitigation and its improvement could be observed by many practical implementations. Although there have been a lot of efforts in such improvements by both industry and academia, the implementation of different methods portrays limitations due to the practical and physical constrains, tight budgets and timeframe, and the trade-off priority. In many cases, each implementation must strike the balance between the costs for maintenance and inspection activities and the need for environmental benefits, which sometimes creates a transient situational conflict. With respect to curve squeals, there are several methodologies that have been trialed and implemented in practice, including

¹ sadudee.max@hotmail.co.th
² s.kaewunruen@bham.ac.uk
rail damper, top of rail friction modifier, noise barrier and jetting method, which is an on-board wheel/rail friction control [1-4].

Globally, railway noises that community typically experiences are often derived from wheel/rail radiations such as rolling noise, impact noise, and curve noises (i.e. flanging and squeal). Recent investigations suggest that the wheel/rail mechanism is a complex source of wheel squeals and the mitigation methods could be much more effective by dealing with the tactical resolutions at the noise source, e.g. by applying friction modifications and rail lubrication strategy, or by controlling the angle of attack [5-6]. The community tolerance largely depends on the level and frequency spectra (or ‘tonal’ content) of the sound [5-6]. A higher level of noise can impair hearing damage, and a lower level one can disturb human wellbeing or activity. In addition, many other hidden and critical problems also exist such as rapid track degradation, ballast pulverisation, differential track settlement, audible sound within buildings adjacent to railway lines, depression at bridge ends, ballast dilation at turnouts and crossings, steel bridge noises, and so on [3-6]. These could later aggravate the level of railway noises over time.

Railway maintainers and operators have envisaged a large number of complaints due to excessive railway noise in many urban areas. As such, any noise mitigation strategy must conform to other systems parameters, requirements and constraints to avoid such penalties over asset life cycle. It is therefore important to promote a ‘systems thinking approach’ and cross-disciplinary collaborative effort in railway noise mitigation [2]. With special respect to curve squeal, research shows that at-source control of noises is relatively effective [2] compared to the methods that mitigate secondary noise radiation. Track-based solutions to curve squeal have been implemented in practice for over a decade [6]. Curve lubrication and lateral rail dampers are found to be an effective measure to combat curve squeal. In contrast, modification of trackform dynamic properties for curve squeal is not popular because differential material stiffness is highly likely to result in unplanned maintenance (through interfacial degradation of components), excessive carbon footprint and track instability over the infrastructure life cycle [7]. In Japan, a jetting device installed on a vehicle to apply friction modifier (FM) to wheel/rail interface has been developed and adopted in industry [8]. This device can optimally apply the FM at both low and high rails to combat curve squeals and can manage the wheel/rail interface effectively at any location. In many part of Europe, noise barrier has been built in curve section to suppress the noise radiation. Its effectiveness largely depends on the relative distance from the noise source and the capacity to encapsulate the sound pressure [9].

This paper highlights the practical implementations for mitigation of curve squeals during the operations of railways. Its emphases are placed on the methods employed in existing and aging railway infrastructures (so-called ‘brown field project’), including:

- Noise barrier
- Rail damper
- Track-based top of rail friction modifier, and
- On-board jetting method

Life cycle assessment has adopted industry assumptions from infrastructure managers and the discount rate of 6% has been used throughout the cash flows over 50 years. The influences of extreme weathers on those costing have been investigated. The insight will assist rail engineers and acoustic or environmental engineers work collaboratively to find a reasonable and viable solution with respect to curve squeal problems in railways.

2. CURVE SQUEAL AND ITS MITIGATION MEASURES

2.1 Mechanisms

Curve squeals are often referred to a (mono) single-tonal noise, generated by a train travelling on sharp curves (i.e. small radii). In contrast, flanging noise on curved track is multi-tonal noise that is generated by rubbing contact between wheel flange and rail in the absence of lubricant [10]. There were reasonable evidences suggesting that the root cause of curve squeal noise is due to a lateral stick-slip sliding of the wheel tread across the rail head. Observations around Europe, Australia and Japan show that all severe squeal noises (with high amplitude) are commonly generated from high wheel angle of attack [11]. Figure 1 shows the curve noises in comparison with rolling noise. The difference of noise characteristics can be observed, i.e. mono-tonal and multi-total around 1-6 kHz.

In Europe, majority of curve squeals occur from large magnitudes of wheel’s angle of attack, which is coincide with the concept of stick-slip over falling friction at inner wheel/rail contact (low rail).
Controversially, in Australia, it has been numerously observed in the fields that either inner or outer wheel can generate curve squeals. The outer wheel/rail interface is more likely to generate curve squeals, in comparison with those from inner wheel/rail interface. A study revealed that curve squealing can occur at any location and at any condition. Table 1 summarises the factors contributing towards curve squeal generation.

![Figure 1 – Rolling vs curve noises](after 10)

**Table 1 – Factors contributing towards curve squeal generation** [10]

<table>
<thead>
<tr>
<th>Factors</th>
<th>Likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>Train speed</td>
<td>It was observed that squeals could appear from walking pace right through to the maximum operational train speed.</td>
</tr>
<tr>
<td>Gradient</td>
<td>There was no significant difference of squeal generation on steep or gentle gradient, either accelerating or decelerating. Thus, traction and braking is not a governing factor.</td>
</tr>
<tr>
<td>Position in train</td>
<td>Squealing wagon can be varied throughout the train, such as immediately behind the locomotive, middle carriage, or even the last wagon.</td>
</tr>
<tr>
<td>Weather</td>
<td>There is no strong correlation between squeal noise generation and weather conditions such as humidity and precipitation. Even though it is noted that a train can generate high flanging noise right after the rain due to oxidation on rail surface.</td>
</tr>
<tr>
<td>Age of rail profile</td>
<td>Curve squeals were observed at different locations along the arc of the curve or transition. They were also noticed at different stages of rail life, new ground rail or even worn rails.</td>
</tr>
</tbody>
</table>

### 2.2 Mitigation methods

There are several methodologies that have been implemented for mitigating curve noises. However, there are very few methods that are successful in order to suppress curve squeals. In practice, the most common methodologies for curve noise mitigation (regardless of their effectiveness) are:
- Noise barrier
- Rail damper
- Track-based top of rail friction modifier, and
- On-board jetting method.
These methodologies have been implemented in many countries around the world as shown in Figure 2 [12]. However, their life cycle assessment has not been systemically carried out. It is essential to take into account systems thinking approach, which would look outside the lenses of just noise level suppression. Those advantages and disadvantages towards operation, construction, maintenance, inspection and resilience should have been considered for life cycle assessment. Most life cycle analyses in the past adopted some assumptions from environmental managers but have not extended to inspection practices and track renewals.

![Image of rail friction modifier](a) Top of rail friction modifier
![Image of rail damper](b) Rail damper
![Image of noise barrier](c) Noise barrier
![Image of jetting method](d) Jetting method

Figure 2 – Curve noise mitigation measures [12-14]

### 3. LIFE CYCLE ANALYSIS

#### 3.1 Assumptions

Assumptions from rail industry have been adopted in this study. Based on industry reports, Tables 2 and 3 show the benefit and cost assumptions related to the life cycle cost evaluation, respectively. The discount rate of 6% has been used throughout the cash flows over 50 years. This period has been considered appropriate for life cycle evaluation of railway lines because it is coincide with majority of rail tracks [8].

<table>
<thead>
<tr>
<th>Mitigation measures</th>
<th>Assumptions</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track-based friction modifier</td>
<td>£3,000 Benefit from reduced wheel/rail wear</td>
<td>[12]</td>
</tr>
<tr>
<td>On-board friction modifier (Jetting)</td>
<td>£3,000 Benefit from reduced wheel/rail wear</td>
<td>[12]</td>
</tr>
<tr>
<td>Rail damper (attached to rail web)</td>
<td>£0 (no financial benefit from track maintenance)</td>
<td>[12]</td>
</tr>
<tr>
<td>Noise barrier (outside transit space)</td>
<td>£0 (no financial benefit from track maintenance)</td>
<td>[12]</td>
</tr>
</tbody>
</table>
Table 3 – Cost assumptions for life cycle analysis of curve squeal mitigation measures

<table>
<thead>
<tr>
<th>Mitigation measures</th>
<th>Assumptions [12]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Track-based friction modifier</td>
<td></td>
</tr>
<tr>
<td>- Control case</td>
<td>Initial cost £20,000 per unit with 15 years life</td>
</tr>
<tr>
<td>- Extreme heat condition</td>
<td>Annual maintenance £16,000 per unit (3 times p.a.)</td>
</tr>
<tr>
<td>- Flood risk</td>
<td>Annual cost £32,000 per unit (6 times p.a.)</td>
</tr>
<tr>
<td></td>
<td>Replace every 5 year</td>
</tr>
<tr>
<td>On-board friction modifier (Jetting)</td>
<td></td>
</tr>
<tr>
<td>- Control case</td>
<td>Initial cost £15,000 per train with 15 years life</td>
</tr>
<tr>
<td>- Extreme heat condition</td>
<td>Annual maintenance £8,800 per unit (3 times p.a.)</td>
</tr>
<tr>
<td>- Flood risk</td>
<td>Annual cost £12,000 per unit (4 times p.a.)</td>
</tr>
<tr>
<td></td>
<td>No effect</td>
</tr>
<tr>
<td>Rail damper (attached to rail web)</td>
<td></td>
</tr>
<tr>
<td>- Control case</td>
<td>Initial cost £174,000 per km with 13 years life</td>
</tr>
<tr>
<td>- Extreme heat condition</td>
<td>Annual maintenance £38,000 per km (increased track inspection)</td>
</tr>
<tr>
<td>- Flood risk</td>
<td>Annual cost £51,000 per km (increased track inspection)</td>
</tr>
<tr>
<td></td>
<td>Replace every 5 year (increased track inspection)</td>
</tr>
<tr>
<td>Noise barrier (outside transit space)</td>
<td></td>
</tr>
<tr>
<td>- Control case</td>
<td>Initial cost £886,000 per km with 50 years life</td>
</tr>
<tr>
<td>- Extreme heat condition</td>
<td>Annual maintenance £500 per graffiti</td>
</tr>
<tr>
<td>- Flood risk</td>
<td>Replace every 25 year</td>
</tr>
</tbody>
</table>

3.2 Long curve section

Based on the assumptions, we can develop a discount cash flow of each mitigation measures as shown in Figure 3. The cash flow from each case has been evaluated based on the industry assumptions and the discount rate of 6%. Using a financial evaluation method, Net present value (NPV) can be obtained for benchmarking.

![Cost and benefit from track friction modifier method](image)

Figure 3 – Cost and benefit discounted cash flows (long section)
b) jetting method

c) rail damper

d) noise barrier

Figure 3 – Cost and benefit discounted cash flows (long section)
3.3 Short curve section

For sharp curved track with radii between 150m and 250m, the section of track and potential issue could be shorter than those with gentle curve radii. In urban environment, curved tracks that often cause squeal noises are about 200m to 250m long. Based on these actual track parameters, the cost assumption could be adjusted to reflect the track length. For the comparative purpose, 250m track length has been considered for life cycle analyses. Figure 4 displays the cash flows for short curved track section.

![Cost and benefit from track friction modifier method](image1)

a) top of rail friction modifier

![Cost and benefit from wheel friction modifier method](image2)

b) jetting method

![Cost and benefit from rail damper method](image3)

c) rail damper

Figure 4 – Cost and benefit discounted cash flows (short section)
4. NPV BENCHMARKING

Net present values (NPV) have been evaluated as shown in Figure 5 for long and short curved track sections, respectively. It can be observed that the top of rail friction modifier method tends to be sensitive to environmental challenges such as extreme heat and floods. Noise barrier is the mitigation measure that is least sensitive to extreme conditions. Based on these industry assumptions [8-14], it is found from the life cycle analyses that the jetting method seems to be the cost-effective solution for squeal noise mitigation, seconded by the noise barrier method.

Figure 4 – Cost and benefit discounted cash flows (short section)

Figure 5 – NPV

a) top of rail friction modifier (left for long curve; right for short curve)

b) jetting method (left for long curve; right for short curve)
This paper presents noise mitigation methods on curved track in urban areas by focusing on squeals and flanging noise, it is important to note that curve squeals generate high levels of noise that easily be observed all around the track. This paper focuses on four mitigation methods: noise barrier, rail damper, track-based top of rail friction modifier, and on-board jetting method. The track-based top of rail friction modifier and on-board jetting method have benefits from reducing wheel/rail wear whereas noise barrier and rail damper do not have this benefit. On the other hand, noise barrier and rail damper have longer life cycle and lower maintenance costs. This paper presents NPV analysis of cost and benefit of each method, separate in long curve section and short curve section, 50 years' life cycle is selected based on design life span of track. The analysis also includes the influence from extreme heat condition and flooding which reduce life cycle of the infrastructure and equipment. Based on assumptions commonly derived in rail industry, jetting method is the most effective method for both short curve and long curve and rail damper is the worst method for short curve whereas the noise barrier method is the worst method for long curve but effective as good as jetting method for the short curve. Future work will include the sensitivity analysis of assumptions and the potential of global warming on the life cycle assessments of railway noise and vibration mitigation methods.

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5. CONCLUSION

This paper presents noise mitigation methods on curved track in urban areas by focusing on squeals and flanging noise, it is important to note that curve squeals generate high levels of noise that easily be observed all around the track. This paper focuses on four mitigation methods: noise barrier, rail damper, track-based top of rail friction modifier, and on-board jetting method. The track-based top of rail friction modifier and on-board jetting method have benefits from reducing wheel/rail wear whereas noise barrier and rail damper do not have this benefit. On the other hand, noise barrier and rail damper have longer life cycle and lower maintenance costs. This paper presents NPV analysis of cost and benefit of each method, separate in long curve section and short curve section, 50 years’ life cycle is selected based on design life span of track. The analysis also includes the influence from extreme heat condition and flooding which reduce life cycle of the infrastructure and equipment. Based on assumptions commonly derived in rail industry, jetting method is the most effective method for both short curve and long curve and rail damper is the worst method for short curve whereas the noise barrier method is the worst method for long curve but effective as good as jetting method for the short curve. Future work will include the sensitivity analysis of assumptions and the potential of global warming on the life cycle assessments of railway noise and vibration mitigation methods.
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