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Developing Effective, Evidence Based Control Measures for Rolling Contact Fatigue

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1. Introduction

Rolling contact fatigue (RCF) presents a challenge to railway engineers due to the complexity of the interactions between wheel and rail which contribute to its formation, the risk to the safety and integrity of the infrastructure which the growth of RCF cracks presents, and the significant maintenance cost which are incurred in controlling it. This paper builds on the considerable body of research work undertaken in the UK over the last ten years to develop models to predict RCF initiation. The work has yielded an RCF crack initiation function based on the energy in the contact patch (Tγ) which has been shown to give good correlations with observed locations of RCF [1-4]. At low Tγ <15 J/m it is considered that insufficient energy is present to cause rolling contact damage whilst at Tγ >175 J/m, wear is the dominant mechanism. In between these values, crack initiation will occur with the RCF damage peaking at 65 J/m, as shown in Figure 1. Damage is only considered to occur if the rail is the driven surface i.e. the tangential forces are acting in the traction (rather than the braking) direction. The damage function is calibrated for 220 grade rail steel, that being the most commonly used currently on GB railways. Alternative rail steels may be considered by modifying the damage function to suit.

![Figure 1: RCF Crack Initiation Function](image)

For a chosen location, damage can be predicted using the Tγ output from vehicle dynamic simulations. The corresponding fatigue damage is obtained from the crack initiation function and the damage from each axle pass summed. When the fatigue damage reaches unity, crack initiation is predicted. Although the model only predicts initiation, empirical relationships have been established which have been found to give a useful indication of the development of RCF in terms of the observable surface crack length [1].

This paper describes the application of these RCF modelling techniques in evaluating the effectiveness of several proposed RCF remediation measures at a number of test sites. The objective was to develop straightforward guidance for track engineers allowing them to select the most appropriate RCF reduction measures without the need for detailed modelling and analysis.

2. Methodology

The methodology adopted is illustrated in Figure 2. To investigate the most appropriate RCF control measures eight GB mainline sites with RCF were selected [5]. These sites were selected from a 'long-list' which itself resulted from damage predictions based on simulations of the whole of the route concerned, together with site visits and examination of maintenance records.
Each site studied was typically 300m – 500m long. A detailed data collection exercise was undertaken at each site, the results of which were used as input to vehicle dynamics simulations which were in turn used with the RCF crack initiation model to provide RCF predictions for the sites. Modelling covered the majority of vehicle types running at each site, each of which was modelled with three different wheel profiles in order to represent the changing damage resulting from various wheel wear states. Simulations included realistic levels of traction and braking and speed profiles. Up to date track geometry was used and supplemented by historic geometry where conditions had changed significantly over time. RCF predictions were compared with site observations to give confidence in the validity of the modelling [6].

Several remediation scenarios were trialled in the simulation environment to determine which were most effective at reducing RCF at each of the eight sites. These included increasing cant deficiency, improving track lateral alignment and controlling rail profile shape by rail grinding and lubrication. Certain measures such as changing vehicle primary yaw stiffness and alternative wheel profiles were not considered as these are beyond the control of the track engineer. The benefits of using alternative grades of rail steel were also excluded as they were the subject of a separate research project.

Collaborating with the local track engineers at each site, the remediation measures predicted from the modelling to be the optimum for reducing RCF initiation were implemented on each site and their effectiveness monitored over a period of two years [7]. The RCF predictions for each site were re-run after each monitoring visit to understand any changes in the site conditions. The reduction in rolling contact fatigue resulting from the specified remediation was quantified for each site and cost modelling was undertaken to show the predicted savings at each site over a thirty year period. This could then be used to develop a business case for improving maintenance techniques. The results of the research have been distilled into straightforward guidance that can be applied by track engineers to improve the rail life at sites susceptible to RCF.
3. RCF Remediation Techniques

3.1 Increasing Cant Deficiency

When a bogie is curving at or near cant equilibrium, the leading wheelset is shifted laterally towards the high rail and can develop a significant angle-of-attack. The largest forces are therefore generated at the high (outer) rail leading wheel; this being the wheel that typically contributes the greatest RCF damage in all but the tightest curves. The trailing wheelset is shifted towards the low rail and the forces generated on the high rail from this wheelset are relatively small compared to the leading wheelset. If cant deficiency is increased by reducing installed track cant, the increased deficiency increases the net lateral force acting towards the outside of the curve. This ‘pulls’ the trailing wheelset off the low rail which in-turn reduces the angle-of-attack at the leading wheelset. The smaller angle-of-attack means the wheelset is nearer a radial position and the forces generated in the contact patch are consequently smaller. There is a corresponding increase in the forces at the trailing wheelset although this is not usually sufficient to increase rail damage. The overall effect is to distribute the steering forces more evenly between leading and trailing wheelsets which may reduce the propensity to generate RCF.

However, increasing cant deficiency will not necessarily lead to a worthwhile reduction in RCF. This will depend upon the absolute values of the forces in each contact patch which are in turn dependent on a number of factors including:

- The primary yaw stiffness (PYS) and bogie wheelbase of the vehicles concerned
- The suspension arrangement employed by the vehicle
- The shape of worn wheel-and rail profiles
- The lateral alignment and gauge variation of the track

If the wheel-rail contacts generate Ty greater than 65 J/m, then increasing cant deficiency (although reducing wheel/rail forces) may move the damaging contacts nearer to the peak of the damage function leading to an increase in RCF (Figure 1). Alternatively, if the wheel-rail contact forces are already low the change resulting from increasing cant deficiency may not have sufficient impact on the RCF damage to justify the cost.

![Figure 3: RCF Damage Reduction (+ve) for Increasing Cant Deficiency from Balance Speed to 150mm (Left) and 80mm to 150mm (Right) – Various Vehicles, New P8 and BS113a](image)

To understand the conditions under which changes to cant deficiency will have the biggest impact on reducing RCF a parameter study was carried out giving RCF predictions for a range of curve radii. Figure 3 shows an example of the results for a set of vehicles with various primary yaw stiffnesses. The results showed that between 1000m-1800m curve radius there is almost always a positive benefit from increasing cant deficiency although the magnitude of the benefit varies. At curve radii greater than 1800m, the parameter study shows that useful benefits may still be achieved under some circumstances. This is particularly true if either the traffic causing the RCF has a relatively high PYS, contact conditions result in moderate-high conicity and/or if a large increase in cant deficiency can be achievable. At curve radii less than 800m increasing cant deficiency often has the opposite effect and increases RCF damage. However, some benefit may be obtained in the 600m-800m radius range for vehicles with low PYS (<12MNm/rad) and/or if large increases in cant deficiency can be obtained.
Trial sites included ‘Site A’, a 1050m radius curve having a linespeed of 80mph and carrying approximately 13.5 million gross tonnes per annum (MGTPA). The site had a modest 54mm cant deficiency at linespeed. However, a significant proportion of the damaging contacts were due to freight vehicles whose maximum speed did not exceed 45mph and were therefore running at 74mm cant excess. The site exhibited continuous RCF throughout the body of the curve. Figure 4 shows the predicted annual RCF damage for the baseline conditions and for increasing the cant deficiency at linespeed to 110mm. This can be seen to give a significant reduction in the predicted damage. In this case, only half the desired lift was actually applied on site, giving approximately 80mm cant deficiency. Whilst still giving a useful benefit, this is clearly not as great as that which would have been achieved by the full lift.

Figure 4: Predicted Total RCF Damage for One Year’s Traffic – Site A, 54mm Cant Deficiency (Blue), 80mm Cant Deficiency (Red) and 110mm Cant Deficiency (Black)

The study indicated that increasing cant deficiency provides an effective mitigation for curves between 1000m and 1800m radius for conventional vehicles with typical PYS values. Outside this range of curve radii the reduction in RCF may be small and increasing cant deficiency is therefore unlikely to provide significant benefits.

For curves between 1000m and 1800m radius, the reduction in RCF will depend upon the increase in cant deficiency that can be achieved. It was found that in order to minimise RCF damage, the largest cant deficiency permissible within the infrastructure standards should be applied. It was also found that reasonably large lifts are required to obtain durable cant changes.

The research also highlighted the benefits that may be obtained by increasing cant deficiency in locations where the track is canted for linespeed but where a significant number of trains travel slower than this, increasing the propensity for RCF damage. These areas include:

- Major station throats
- In the vicinity of stations with a mix of through and stopping trains
- In the vicinity of busy junctions where trains may often be stopped at the controlling signals or approach under caution
- In the acceleration / braking zones associated with relatively large changes in linespeed where the curve is designed for the linespeed rather than the actual speed of passing trains
- Routes with significant freight traffic and where the linespeed is considerably higher than the maximum permitted speed of freight traffic (normally 60-75mph, although it may be as low as 45mph for certain freight vehicle types).
- On steep rising gradients where (particularly freight) traffic may not reach linespeed.

It was clearly shown from the site observations and modelling that increasing cant deficiency only provides an effective remediation measure when lateral alignment defects are also corrected. Poor lateral alignment and/or gauge variation is likely to reduce the beneficial effects of increasing deficiency.
3.2 Improving Track Alignment

Ideally, it would have been possible to develop relatively simple guidance for the track engineer that specified the reduction in track lateral alignment amplitude or change in wavelength required to eliminate RCF. However, both site and parameter study evidence showed that this is not possible. Many factors influence whether a particular alignment feature will generate RCF including:

- The steady state curving forces, which in turn are a function of curve radius, PYS and suspension design
- Cant deficiency
- Wheel and rail profiles
- The amplitude and/or wavelength of the alignment feature itself (though depending on the circumstances, RCF may be independent of one or both of these factors)

Depending on a combination of these factors, a given alignment feature may either increase or decrease RCF. These effects are easily predicted given sufficient knowledge of a site, the traffic mix and contact conditions as demonstrated by this study as well as much recent research [8,9]. However, considerable generalisation is required to allow them to be distilled into a simple set of rules.

![Figure 5: Predicted Total RCF Damage for One Year’s Traffic – Site B, Baseline Condition (Blue) and After Tamping / Lining (All Other Lines)](image)

![Figure 6: Predicted Total RCF Damage for One Year’s Traffic – Site B, Baseline Condition (Blue) and Improved Lateral Alignment with Cant Deficiency increased to 41mm (Red)](image)

A useful demonstration of the benefits of improving track lateral alignment was provided by ‘Site B’. This 1870m radius curve was installed with 49mm cant excess at linespeed. The site carried 14 MGTPA and exhibited extensive RCF clusters. Figure 5 shows the effect on the predicted annual RCF damage of improving the lateral alignment. Figure 6 shows the effect of combining improved
lateral alignment and increased cant deficiency. This highlights the need for underlying problems such as poor lateral alignment to be resolved in order to achieve the maximum benefits from other remediation works.

In order to study a wider range of conditions a parameter study was undertaken. This used a sinusoidal lateral track input of varying wavelength and amplitude. An example of the results of this study is shown in Figure 7.

Figure 7: Ty Generated at Various Wavelengths and Amplitude for Vehicles with 16MNm/rad and 32 MNm/rad PYS - 2000m Radius Curve, 80mm Cant Deficiency

The study showed that at shallower curve radii (>2000m), RCF damage is both wavelength and amplitude dependent. At wavelengths less than 20m, amplitudes of 3-6mm tend to move damage near to the peak of the damage function under the conditions simulated. At less than 2mm amplitude, damage remained substantially below the peak of the damage function under the majority of the conditions considered. There appeared to be a point, at approximately 20m wavelength, beyond which damage reduces noticeably and larger amplitudes can therefore be tolerated. It is suggested that for these longer wavelengths 4mm amplitude is tolerable. However as wavelength increases further above 35m amplitudes of 8-10mm are acceptable before peak damage levels are reached.

For curves between 1000m and 1800m radius it was shown (section 3.1) that cant deficiency is the primary remediation measure. However, the parameter study found that, for curves in this range, even small (1-2mm amplitude) lateral alignment irregularities could generate contact forces near the peak of the damage function. As such small amplitudes cannot be controlled by conventional track tamping, improved lateral alignment cannot be used as a primary RCF control in this range of radii. Nonetheless, the site investigations showed that improvements in lateral alignment are often necessary in order for the benefits of increasing cant deficiency to be realised.

For curves tighter than 800m radius, the parameter study showed that shorter wavelength lateral alignment irregularities (less than 20m) tended to reduce RCF damage and increase wear as they moved the resulting contact forces above the peak of the damage function and into the wear regime. Since grinding is used as the primary remediation measure in the tightest radii, this local increase in wear will cause the ground profile to wear out more quickly, negating the benefits of the shape of the ground rail. Poor lateral alignment also prevents even and continuous distribution of lubricator grease round the curve. Clear evidence of both these phenomena was found at several of the sites investigated.

3.3 Controlling Rail Shape
All eight sites studied were ground at some point during the period of the investigation providing a wealth of evidence regarding the effectiveness of the grinding. Repeated simulation runs allowed the evolution of the predicted damage to be followed over the course of one or more grinding cycles.
Figure 8 shows the change in damage over a grinding cycle at ‘Site C’, a 1250m / 1000m radius compound curve carrying approximately 15 MGTPA. Each plot represents the high rail of the curve, viewed from above with the gauge face at the top and traffic running from left to right. The colours represent the intensity of the damage predicted for the site.

These results show that grinding is initially effective in reducing damage in the vulnerable gauge shoulder area of the rail (10-25mm from the gauge corner). The ground profile in this case is designed to provide a small relief in this area of the rail, though it can be seen (top of Figure 8) that damaging contacts are not eliminated completely after grinding as worn wheels can still contact this part of the railhead. After 5-7.5 EMGT of traffic (4 months) significant levels of damage had returned, reaching the same magnitude as before grinding in many places. Wear rates in the RCF prone area of the railhead varied from 0.025 – 0.05mm per month. This suggested that the rail would return to its pre-ground shape in 2-6 months depending upon its position in the site. The grinding interval specified by the track maintenance standard in this case is 15 MGTPA, meaning that Site C would currently be ground every 12 months, which may not be sufficient for optimum control of RCF.

Similar results to those at Site C were found for all eight test sites. These may be summarised as follows:

- Both site observations and predictions showed that for most sites, damage returned to pre-grinding levels at relatively modest tonnages, considerably below the 15 EMGT grinding interval specified in the current track maintenance standard. Wear rates on the gauge shoulder (15-25mm from the gauge face) of the high rail were found to be 0.02 – 0.1 mm/EMGT.
- Wear rates varied considerably within this range throughout the sites. This in turn contributed significantly to reduced durability of the ground profile in certain areas of the sites.
- Wear rates were found to decrease by up to 50% on the gauge shoulder with effective lubrication and by considerably more than this on the gauge corner.
- Examination of worn wheel profiles from a variety of vehicle fleets showed that all worn profiles would contact on the gauge shoulder of the design case ground profile as well as the measured ground profiles from the sites investigated.

The body of evidence showed that whilst current grinding practice is effective at reducing damage, the durability of the ground profile was lower than expected and significant damage returns at much lower tonnages than the 15 EMGT grinding interval recommended in the current track maintenance standards. If the gap between the vulnerable gauge shoulder and the wheel can be increased, either by grinding a greater relief on the rail or by using an anti-RCF wheel profile such as the P12 profile which is now being used by some operators in the UK, the tonnage passed before grinding is required may be considerably increased. However, some caution is required as the inevitable trade-off is a further reduction in conicity and a consequent reduction in the ability of wheelsets to steer in curves. At the least, this highlights the need for effective lubrication to prevent excessive rail sidewear and wheel flange wear. Inevitably a balance is required that optimises the benefits to the system as a whole. Alternatively, the use of harder rail steels would be expected to have a significant benefit in preserving the ground profile.

Whilst the foregoing represents a key finding of this project, it should not be taken to mean that grinding, even to current practices, is not worthwhile. Grinding produces a number of benefits, some of which are not fully accounted for in the modelling. These include spreading the damage across a wider area of the railhead and reducing the depth of cracks (particularly newly initiated defects). Results for some sites also suggest that ground profiles reduce the sensitivity to lateral track irregularities.

4. Benefits and Business Case

Although the research did not seek to present a complete business case for adoption of the guidelines proposed, it sought to provide the building blocks from which such a business case could be generated. A key part of this was prediction of rail life and renewal requirements of the eight sites investigated. This allowed the cost of remediation works to be compared to the potential savings from increased rail life.

In order to calculate the volume of rail required at each site the following method was adopted:
- All calculations were carried out using a 30-year window.
- Each site was split into 18.2m rail lengths and the peak damage in each length was summed year-on-year for each length. If the peak damage exceeded 20 a rail replacement was triggered. This is essentially a short drop-in of rail to remove a cluster of RCF which would have reached the heavy/severe category.
- The amount of rail replaced was calculated as the length within the 18.2m section where the damage is greater than 80% of the peak damage. If the resulting length is less than 4.5m then 4.5m is replaced, this being the minimum allowed in the current Network Rail standards.
- The damage for the replaced rail is then re-set to the average for the length, and damage is then accumulated for subsequent years until further action is triggered.
- The mean damage is also summed year-on-year for a longer segment. This may be the entire length of the site, or where damage varies significantly due to transitions, the site may be split into several segments.
- A renewal of the entire segment is triggered when the accumulated mean damage reaches 10. Renewal in this case refers to replacement of the rail for the whole segment rather than ‘track renewal’ i.e. replacement of sleepers, ballast etc.
- Once a segment has been renewed, rail damage is re-set to zero.
Figure 9 provides an example of the predicted rail replacement and renewal requirements for the two cases shown in Figure 6 for Site B. It can be seen that the length of rail replacement ‘drop-ins’ vary as described above and that in the baseline condition the site requires a complete renewal of the rail for RCF after 19 years. With the recommended remediation measures rail replacement reduces considerably and no rail renewal is required within the 30 year window.

Once the RCF rail replacement and renewal requirements have been calculated, the associated costs can be determined. A 6.5% discount rate was applied to all costs to determine the net present value (NPV) of the work.

Analysis of all eight sites showed that, carrying out the recommended remediation at all of the sites, could reduce rail replacement / renewal by 2.9km over a thirty year period, resulting in a saving of 57% at current prices. Although this figure is in itself modest, it must be remembered that this relates to only eight short curves, a total of 3.75km of track.

5. Summary and Conclusions

The research has monitored the effectiveness of RCF remediation measures implemented on eight sites over a period of 24 months.

The monitoring and data collection activities were supported by detailed modelling to predict RCF crack initiation. Modelling results were shown to accurately re-produce the observed site behaviour over time. As individual test sites only provide results for a single (albeit detailed) set of conditions it was found necessary to supplement the site simulations with several parameter studies.

Three key RCF control measures were considered:
- Increasing cant deficiency
- Improving track alignment
- Controlling rail shape by grinding and lubrication.

Table 1 below summarises the conditions under which these measures were found to be most effective:
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<table>
<thead>
<tr>
<th>Curve Radius Range /m</th>
<th>&lt; 1000</th>
<th>1000 - 1800</th>
<th>&gt;1800</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Primary Control(s)</strong></td>
<td>Grinding (4 – 7 EMGT intervals) and/or Harder Rail Steels (Not Studied)</td>
<td>Increasing cant deficiency (Where possible)</td>
<td>Track Alignment Preferably: Amplitude &lt;2mm for λ&lt;20m Amplitude &lt;4mm for λ&gt;20m</td>
</tr>
<tr>
<td><strong>Secondary Control(s)</strong></td>
<td>Lubrication • To preserve ground profile • To prevent excessive sidewear</td>
<td>Track Alignment • To reduce differential wear of grinding • To ensure even distribution of lubricant • To prevent cyclic wear of rails</td>
<td>Grinding (15 EMGT intervals) • To reduce sensitivity to lateral alignment features</td>
</tr>
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</table>

Table 1: Summary of RCF Remediation Measures

The research led to a number of conclusions which have implications for rolling contact fatigue maintenance practices:

- Increasing cant deficiency is always effective for curves in the range 1000 – 1800m radius. However, the magnitude of the improvement is dependent on a number of factors including wheel-rail contact condition and vehicle primary yaw stiffness and suspension design.
- Increasing cant deficiency is most effective if relatively large increases can be obtained. In many curves increasing cant deficiency is most beneficial when combined with grinding and improving track alignment.
- Increasing cant deficiency for curves between 800-1000m radius and shallower than 1800m radius requires assessment on a case by case basis. In these cases it may not be possible to obtain useful benefits and in the tighter curves damage may be increased.
- Increasing cant deficiency for curves tighter than 800m radius is not normally effective and can lead to an increase in RCF.
- The durability of the ground profile used by GB railways was found to be lower than expected. It was found that significant damage returned within 4-7 EMGT of grinding. The durability of grinding could be increased by increasing the relief between the rail and worn wheels in the gauge shoulder area, by improving lubrication or by using harder rail steels (or a combination of all three). The trade off for increasing the relief would be lower conicity which implies increased wear and the need for consistent and reliable lubrication.
- Under current conditions the results suggest that tighter radius curves require grinding more frequently than every 15 EMGT. Evidence suggests that, ideally, grinding at 4-7 EMGT intervals would be required to control RCF in tighter curves.
- In curves shallower than 1800m radius, limiting the amplitude of track lateral alignment irregularities to <2mm for wavelengths <20m, and 4mm for wavelengths >20m was shown to provide an effective remediation for RCF.
- The dynamic response of vehicles induced by poor lateral alignment can conceal the gains offered by other forms of remediation. For this reason, improvement of lateral alignment should always form part of RCF remediation strategies.
These conclusions are broadly applicable to RCF under typical GB railway conditions. Inevitably they cannot account for the complexities of every site.

The work has highlighted the benefits of understanding the behaviour of RCF sites over time. Additionally linking remediation predictions to costs allows the overall business case for these works to be assessed.

6. Acknowledgement

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7. References