Investigation into the Root Causes of Rolling Contact Fatigue under Heavy Axle Loads

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ABSTRACT
The incidence of high impact wheels (HIW) is currently a primary cause for wheel removals in North America. Wheel replacement costs for North American railway systems are in excess of $800 million annually, with tread damage amounting to approximately two-thirds of this figure. HIW are attributed to two causes: (1) thermal mechanical shelling (TMS), which is a form of rolling contact fatigue (RCF), and (2) the traditionally known operational problem of unreleased handbrakes. TMS is about 50 percent of this figure and can thus be directly related to at least $270 million in maintenance costs.

Rail grinding continues to be a high cost component of track maintenance with costs in excess of $100 million per year. Grinding is used to restore rail profiles altered as a result of wear and material flow as well as to remove surface crack and spalls; all these defects are attributable to RCF.

Consequently, the Association of American Railroads, through their Strategic Research Program, has initiated a project to establish the root causes for RCF under heavy axle load (HAL) conditions.

Through this program, the root causes for TMS in wheels have been established, and the means to mitigate TMS are being developed (improved suspensions, brakes, wheels, and top-of-rail (TOR) friction control). These means require an accurate assessment of the resistance of wheel materials to RCF under vertical and lateral loads and temperatures in order to be successfully implemented. The applicability of shakedown and contact energy approach (T-gamma) under HAL is discussed and an alternative approach presented.

The common forms of rail wear, material deformation, and cracking/spalling are classified, and root causes are presented. Field observations of rails under HAL are correlated to load applications (wagon and locomotive passes), and models to predict degradation rates are presented.

Means to mitigate RCF are discussed, relating to wagon suspension design, wagon brake design, wheel and rail material properties, as well as TOR friction control and flange/gauge face lubrication. All these approaches are being used to reduce RCF and to develop the potential for increased axle loads. The means for implementation and management are practical in approach and will have a large impact on the railway business given the wheel and grinding costs quoted above and the benefits attributable to increased axle loads.

INTRODUCTION
Rolling contact fatigue (RCF) is traditionally thought of as resulting in surface cracking, spalling and shelling of both wheels and rails. The root cause for this degradation mode is also directly related to the mechanisms resulting in material flow (particularly in rails) and wheel and rail wear. All three of these degradation modes are used in the context of RCF in this paper.

A literature review\(^1\) suggests that there are two approaches to the prediction of RCF: the shakedown model of K.L. Johnson,\(^2\) and the surface energy (so-called T-gamma) approach,\(^3\) which was developed as part of the so-called "whole life rail model" developed by Network Rail. Both approaches are being used to predict RCF under heavy axle loads (HAL):

- Shakedown has proved useful in understanding the development of HIW.\(^4,5,6,7,8,9,10,11,12\) It can be used from first principles, but it lacks the influence of wear and does not predict cycles to failure, limiting its usefulness.
- The surface energy approach appears to be more useful for predicting rail RCF. It has been used successfully in the whole life rail model, it accommodates wear, and it can be "tuned" to accommodate the wide load and traction spectrum encountered by the rail.
High impact wheels (HIW) are a main cause for wheel removal in North America where the annual cost of wheel replacement is approximately $800 million. Figure 1 shows a typical HIW.

![Figure 1. Typical HIW](image)

Two-thirds of wheel replacements are for HIW, and it is thought that this may be divided equally between skidded wheels resulting from unreleased handbrakes and an RCF mode termed thermal mechanical shelling (TMS), which is considered to occur as a result of a wheel rolling under elevated temperatures and high contact stresses and surface tractions.

Rail RCF is managed by grinding and eventual rail replacement processes. The management process has been refined to optimize grinding cycles, and it may be asked why a further predictive process is required. The answer lies in the fact that rail grinding costs on HAL lie not only in crack removal, but in restoring the rail profile after heavy wear and material flow; an improved predictor of wear and flow would be useful. Another question is, how much damage is due to “average” contact conditions and how much can be attributed to the action of “outlier” vehicles (poorly curving vehicles making poor contact with the rail)? An answer to this question may be useful in focusing attention on addressing root causes for rail degradation.

**WHEEL RCF (HIW)**

Much work has been done to relate the incidence of HIW to TMS and shakedown. The mechanism for the development of HIW is thought to be understood.

- Surface tractions that develop, particularly on contact with the low rail in curving, result in contact stresses above the shakedown limit (Figure 2) and lead to the formation of surface cracks on the lead wheels of bogies, which are then subject to elevated temperatures. These cracks form in two bands on either side of the tape line on the tread.

![Figure 2. Surface Traction on the Wheel Tread in Relation to the Shakedown Limit](image)

- Subsequent rolling under lower tractions and where the Hertzian maximum shear stress lies beneath the surface of the wheel tread propagate these cracks into the wheel and under the tread at the tape line.
- Pieces of the tread of the wheel around the circumference of the wheel at the tape line breakout to form HIW.
Challenge C: Increasing freight capacity and services

Less understood mechanisms are normal and traction stress levels that give rise to fatigue, as well as the cycles to failure. In terms of design and operational parameters, the following questions need to be answered:

- How many cycles above shakedown result in crack formation?
- What is the influence of temperature on shakedown and the cycles to crack formation?
- What is the role of vehicle tracking inaccuracies in the formation of wheel RCF? RCF does not form on every wheel or any wheels in a predictable manner, although it does predominate on lead wheels of bogies. However, the number of high traction cycles a wheel is subjected to in curving in the North American environment is limited. Poorly tracking cars may experience many high tracking cycles, even on tangent track, and thus may contribute to wheel damage. Obviously, individual wheels can become overheated, which is a probable root cause.
- Brake block contact is being recognized as a significant contributor to wheel tread wear; consequently, the role of brake blocks needs to be quantified.

Quantification of the cycles to failure of the wheel is thus a critical element in determining the root causes for wheel RCF. The only suitable and controlled approach to this quantification appears to be the use of twin disk, rolling load experiments (Figure 3). This approach will be pursued in 2011, with particular attention to the role of lateral as well as longitudinal creepage in generating RCF, which may be different (in cycles to failure and material flow) to RCF developed under purely longitudinal creepage conditions. In addition to this experimental approach, observation and measurement of wheels on controlled fleets of wagons will be made to establish the role of suspension characteristics, suspension tolerances, and wheel profile condition on the development of wheel RCF.

![Figure 3 Twin Disk Process Showing Disk Alignment with an Angle of Attack to Generate Lateral Creepage](image)

**RAIL RCF**

In 2010, work focused on identifying rail degradation modes and degradation mechanisms, primarily on 440m radius and sharper curved track. However, it is recognized that much damage is occurring on HAL lines in curves as shallow as 3,500m radius, and this will be a focus in 2011.

**Low Rail**

Low rail degradation patterns in curves sharper than 440m radius is associated primarily with the lateral creepage developed as the lead wheel set of a three-piece truck curves under an angle of attack (Figure 4).
Typically, a primary crack band is generated along the center of the head of the rail. The cracks are principally longitudinal in nature, reflecting the dominance of the lateral creep force. In the instance of the rail depicted in Figure 4, the angle of alignment of the cracks of 70 degrees might reflect the dominance of braking on a steep (1:50, or 2 percent) grade track where wagon brakes are generally applied; tonnage is approximately equal in both directions at 44.6 million gross tonnes (MGTonne) per year with approximately annual grinding cycles. The crack band causes pieces in the center of the rail crown to break out; the cracks and material breakout inhibit ultrasonic test of the rail.

Associated with this cracking and the direction of the lateral creep force is the flattening of the rail crown and the flow of the head of the rail to the field side. Material flow degrades the steering of both the lead and trail wheels, and will, in turn, accelerate material flow and head wear, as well as increase the forces and wear on the high rail and the wheels of the wagon.

A secondary crack pattern forms on the gauge corner, likely a result of constrained curving and contact from the trailing wheel. The creepages are principally longitudinal as indicated by the principal direction of crack formation (Figure 4). The material flow to form a lip on the gauge corner will obviously encourage constrained curving as the gauge is reduced. The unanswered question is how the lip originated: by crushing of the rail crown or through gauge corner contact; this will be investigated further. Nevertheless, constrained curving degrades the steering of the bogie subject to low rail contact, further degrading both the low and high rail as discussed above.

Historic low rail profile and MGT figures were obtained for this rail, where the prevailing friction coefficient was approximately 0.6 and for a rail in similar curvature, where the top of the rail was subjected to top-of-rail (TOR) friction control and it is assumed that the friction was kept within a band of 0.3 to 0.4. Figure 5 shows the resulting head wear loss for each condition. Interestingly:

- The wear rate is relatively linear with MGT, which is later used to develop wear coefficients
- The rate of wear under TOR friction controlled conditions (μ = 0.3 - 0.4) is 60 percent of that under “dry” (μ > 0.6) conditions
- The effect of grinding on railhead loss is minimal
A similar analysis was made of the rate of flow and gauge corner and field side lip formation (Figure 6). Again:

- The lip growth rate is relatively linear with MGT, which suggests that a contact energy approach may be useful.
- The difference between the material flow rate under controlled friction conditions ($\mu = 0.3 - 0.4$) versus that under “dry” ($\mu > 0.6$) conditions is similar to that for wear.
- The effect of grinding on lip growth rate seems minimal, although it is significant on lip size, because the lip is removed with every grinding cycle.

An attempt was then made to calculate a wear coefficient for a number of sites in revenue service. It was considered a first step toward developing a surface energy model to predict crack formation. The wear model used TTCI’s accurate wear data, and thus an accurate evaluation of wear coefficients and the overall calculation process could be made.
The calculation process proceeded as follows:

- Five sites were chosen, having different curvatures (175m radius and 350m radius), different traffic patterns (four in revenue service and one at the Facility for Accelerated Service Testing (FAST), a test loop at TTCI), and different friction conditions.
- Wear rates were calculated as Figure 5 shows.
- The spectrum of axle loads across the site was determined (Figure 7).
- The resulting energy (T-gamma) dissipated on the low rail for the lead axle was calculated using a typical three-piece bogie modeled in NUCARS® for differing axle loads.
- A wear coefficient was developed according to the following equations:

\[
MGT = \sum_{i=1}^{n} Axle Load_i \times E_i \\
Wear_{mg} \left( \frac{\mu g}{m} \right) = k_R \sum_{i=1}^{n} T \lambda_i \times F_i
\]

\[k_R = k_1 k_2\]

\[k_1\] – wear rate coefficient
\[k_2\] – rail steel related coefficient

Figure 7. Typical Load Spectrum and Resulting Calculated Contact Energy (T-Gamma) on the Low Rail

Figure 8 shows the results of this exercise.

<table>
<thead>
<tr>
<th>Curvature (degree)</th>
<th>Tehachapi - TOR+GL</th>
<th>Tehachapi - GL</th>
<th>FAST _Dry</th>
<th>East Mega Site_TOR+GL</th>
<th>NS - GL</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGT</td>
<td>10</td>
<td>10</td>
<td>5</td>
<td>10.5</td>
<td>6</td>
</tr>
<tr>
<td>Wear (mm/MGT)</td>
<td>2.814</td>
<td>4.149</td>
<td>0.1479</td>
<td>0.5049</td>
<td>1.2456</td>
</tr>
<tr>
<td>Compared to Measured Wear Data</td>
<td>0.96</td>
<td>1.05</td>
<td>3.07</td>
<td>1.17</td>
<td>0.98</td>
</tr>
<tr>
<td>Rail Steel Ke-BHN</td>
<td>80ksi-400BHN</td>
<td>80ksi-400BHN</td>
<td>80ksi-400BHN</td>
<td>75.6ksi/80.8ksi/387-420BHN</td>
<td>69ksi/370BHN</td>
</tr>
</tbody>
</table>

Note: Curvatures — 10-degree = 175m radius; 5-degree = 350m radius
MGT — 50 MGT = 44.6 MGTonne

Figure 8. Calculation Results

* NUCARS® is a registered trademark of Transportation Technology Center, Inc., Pueblo, Colorado
Interestingly, the calculated wear constant $k_R$, for the sites in revenue service (compensating for friction, load, and curvature) was predicted within 6 percent. The calculated wear constant for the HAL test loop at TTCI, FAST, was a factor of 3, resulting in the prediction of wear rates 3 times less than in revenue service (notwithstanding the fact that FAST operates at 35-tonne axle load versus a maximum of 32.5-tonne axle load in revenue service). This is also seen in the actual wear rate/MGT shown in Figure 8.

A review of the calculation method and the test site and traffic conditions suggests that the calculation method did not accommodate the variability in vehicle condition. The calculation method assumed a single bogie/wagon type and condition (including wheel/rail contact). At FAST this assumption is approximately correct, because wagons, bogies, and wheel and rail profiles are monitored and kept reasonably consistent, but this is not true of revenue service, where observing and listening to passing vehicles suggest much variability. Consequently, in 2011, TTCI intends to place both vertical and lateral force measuring equipment at the monitoring sites or to access currently available lateral force measurements as a measure of vehicle variability. Subsequently, the abovementioned calculation exercise will be repeated.

**High Rail**

High rail degradation patterns (Figure 9) have not yet been fully analyzed. Gauge corner head checks are traditionally a critical component of high rail degradation. Initial observations suggest a critical sensitivity to contact stress/contact area. Tradition wisdom is that sharper gauge corners degrade faster. Since little can be done, or indeed is required to be done, to reduce the developed longitudinal creepages, attention is to develop conformal (line-on-line) contact between the gauge corner and flanging wheels.

Of particular interest will be to establish the root cause for the development of longitudinal crack patterns at the center of the crown of the rail with the resulting development of small spalls (Figure 9). The cracks and spalls again lead to loss of ultrasonic crack detection. Lead wheels should be making flange contact on the gauge corner of the high rail; trail wheels should contact the center of the rail crown with nominally zero angle of attack and consequently, little lateral creepage. It would seem as if outlier vehicle performance may be the cause for high rail degradation.
CONCLUSIONS
Initial surveys suggest that there is still much to be learned about the root causes for wheel and rail RCF. Observations of the high and low rails and calculations of low rail wear suggest that vehicle outlier performance may play a critical role in rail wear, material flow, and crack formation. Interestingly, a similar inference may be drawn from observations and calculations of wheel crack band formation.

TTCI will continue site and vehicle monitoring, monitoring vehicle vertical and lateral load conditions, and monitoring rail wear, crack formation and material flow, and wheel crack band formation. TTCI will also source means to induce RCF in the laboratory using twin disk rolling contact machines.

REFERENCES