The Impact of RCF and Wear on Service Failures and Broken Rail Derailments

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Abstract

A review of several recent significant broken rail derailments suggested that those incidents in which rolling contact fatigue (RCF) played a role also have in common multiple fractures of the rail which led to a significant loss of running surface. Rail breaks often occur in the vicinity of obstacles such as road crossings, turnouts and bridges. BNSF undertook a review of its own data to determine whether these observations applied to its railroad.

BNSF broken rail data shows that the frequency of breaks from detail fractures and transverse fissures, when adjusted for track miles and rail age, is roughly 4 times greater on high rails than tangent, while low rail breaks are about 80% that of tangent. The lower instance of low rail breaks is surprising given the relatively high stress environment compared with tangent running. After analysis this was explained as probably relating to the much lower frequency of turnouts in curved track. The service failure data shows a strong winter (November through February) peak that is consistent with the rest of the industry. Surprisingly, broken rail derailments show a sharp peak in October and November with the rest of the months showing a much lower rate. Analysis of temperature data has not yet provided an explanation. The October/November broken rail derailment peak remains unexplained.

The frequency of broken rails was found to be 5 times greater in the vicinity of turnouts and 1.5 times greater near road crossings when compared with open track. This is likely due to larger dynamic loading in the vicinity of those features, possibly combined with less frequent grinding. Both of these are the subject of ongoing study.

While some broken rail derailments occur on rail that is approaching its head wear limits, analysis of BNSF derailments fails to find any correlation between head wear and either service failures or broken rail derailments.

1. Introduction

Rolling contact fatigue (RCF) and wear are inevitable given the demanding conditions at the rail/wheel contact. The result is significant economic loss due to inspection, maintenance and rail replacement. Research continues into higher speed and hence more productive inspection technologies [1,2] and for improved maintenance approaches including rail grinding [3,4], friction management [5] and improved performance through better profiling [6] and improved metallurgies [7]. The impact of these improvements has been a steady increase in rail life over the last forty years, along with a steady decline in the number of broken rail derailments [8].

However, the economic and safety impacts remain significant. Considering economics first; on the BNSF railroad alone, rail grinding and defect repair costs total about $100M dollars annually. Annual rail replacement associated with wear and defects is another $200M. Considering next the safety impacts; a very small fraction of the broken rails experienced by the industry do lead to a derailment. The "clean" rail break is often not a problem, since in many cases the wheel can traverse the 4-6 inch gap [9] and on most tracks the signalling system quickly communicates that the broken rail has occurred. While some
derailments do occur on single breaks, BNSF experience is that the most serious derailments generally involve multiple fractures and the loss of at least a few feet of the running rail. It was also noted internally (and later validated through data) that a disproportionate number of service failures were occurring near crossings and turnouts. A hypothesis was formed that this was the combined result of:

- Condition of the rail head surface: since production grinders may pick up some or all grinding wheels to cross safely over obstructions, track lengths about 50 feet to either side of switches and road crossings may be less frequently ground and so may have greater severities of surface fatigue than open track.
- Dynamic forces: it is well understood (e.g. references 10 and 11) that the change in vertical stiffness at special trackwork gives rise to dynamic loads. Repeated stress at the same track location probably plays a role in the initiation and propagation of dangerous cracks.

For these reasons, service failures and derailments could be more frequent near these “non-grindable features”.

This hypothesis was explored through analysis of wear, rail condition, broken rail (i.e. service failure) and derailment data.

2. Analysis of derailment data

In the United States, derailments and their causes must be reported to the US-Federal Railroad Administration. A coding system has been derived, with track caused derailments associated with “rail, joint bar and anchoring” having cause codes ranging from T201 (Broken Rail - Bolt hole crack or break) to T223 (Rail Condition - Dry rail, freshly ground rail). With regards to this study there are two codes of interest:

<table>
<thead>
<tr>
<th>FRA code</th>
<th>Description</th>
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<tbody>
<tr>
<td>T207</td>
<td>Broken Rail - Detail fracture from shelling or head check</td>
</tr>
<tr>
<td>T220</td>
<td>Broken Rail - Transverse/compound fissure</td>
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</table>

From the US-FRA Track Inspector Rail Defect Reference Manual [12], we have the following descriptions:

- T207 - Detail Fracture: a progressive fracture originating at or near the surface of the rail head. These fractures should not be confused with transverse fissures, compound fissures, or other defects, which have internal origins. Detail fractures may originate from shelly spots, head checks, or flaking.

  A progressive fracture originating from shelling or head checking that turns downward to form a transverse separation. These fractures should not be confused with compound fissures, which have a horizontal component. This type of defect can only occur in the rail head.

- T220 - Transverse/Compound Fissure

  Transverse Fissure: a progressive crosswise fracture starting from a crystalline center or nucleus inside the head from which it spreads outward as a smooth, bright, or dark, round or oval surface substantially at a right angle to the length of the rail. The distinguishing features of a transverse

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1 While there is also a code T222 for “worn rail”, its application is inconsistent and subjective and the number of incidents attributed to that cause is very small. So it is not considered in this study.
fissure from other types of fractures or defects are the crystalline center or nucleus and the nearly smooth surface of the development that surrounds it.

Compound Fissure: a progressive fracture originating from a horizontal split head that turns up or down, or in both directions, in the head of the rail. Transverse development normally progresses substantially at a right angle to the length of the rail.

Although T220 is clearly intended to capture defects that originate within the rail head, it is possible that some portion has been miscategorised and could have instead initiated due to surface fatigue, since the resulting defect is similar in appearance. If a “true” type 207 is found after grinding when RCF may not be evident, it could easily be labeled a T220, so we have included T220 in this study.

<table>
<thead>
<tr>
<th>T207 - Detail fracture from shelling or head check</th>
<th>T220 - Transverse/compound fissure</th>
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**Figure 1: Examples of Transverse defects of Type 207 (left) and 220 (right)**

A review of the FRA data for mainline derailments over the last five available years is summarized in Table 2. During the period of Jan 2008 to November 2014, derailments identified as being due to surface fatigue (T207) amount to roughly 21 percent of all FRA reportable track caused derailments and 26% of the reportable damage costs.

**Table 1: Number of FRA reported derailments for various causes. Main line track only.**

<table>
<thead>
<tr>
<th></th>
<th>T207 Detail Fracture – shelling/head check</th>
<th>T220 Transverse / compound fissure</th>
<th>T203 + T204 Broken weld</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>26</td>
<td>28</td>
<td>1</td>
<td>55</td>
</tr>
<tr>
<td>2009</td>
<td>10</td>
<td>18</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>2010</td>
<td>14</td>
<td>21</td>
<td>5</td>
<td>40</td>
</tr>
<tr>
<td>2011</td>
<td>19</td>
<td>14</td>
<td>1</td>
<td>34</td>
</tr>
<tr>
<td>2012</td>
<td>17</td>
<td>14</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>2013</td>
<td>13</td>
<td>8</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>2014</td>
<td>19</td>
<td>5</td>
<td>5</td>
<td>29</td>
</tr>
</tbody>
</table>
Table 2: Summary for these three derailment causes, compared will all track caused derailments. Main line track only.

<table>
<thead>
<tr>
<th></th>
<th>T207</th>
<th>T220</th>
<th>T203+T204</th>
</tr>
</thead>
<tbody>
<tr>
<td>% of total (#)</td>
<td>21.1</td>
<td>19.3</td>
<td>4.1</td>
</tr>
<tr>
<td>% of total (damage costs)</td>
<td>26.1</td>
<td>14.2</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Derailments attributed to broken welds are much less frequent than those due to the detail fracture and transverse fissure, even though the number of service failures at welds tends to be larger (by about 30% in BNSF’s case). This is probably due to the clean break issue – welds do not cluster closely and lead to loss of a length of rail as clusters of transverse defects can. On the BNSF railroad, there was not a single reportable mainline derailment due to a broken rail at a weld for a period of nearly 8 years.

3. Analysis of railroad exceptions and service failures

3.1 Position in track

An analysis of 5 years of BNSF broken rail data is summarized in Table 3 below. Although defects are most common in tangent track, dividing by the number of miles of low, high and tangent rail finds that tangent rails are about 80% more prone to breaks than low rails while high rails are more than five times more likely to break. If one also accounts for the accumulated tonnage (assumed to be proportional to number of years in service) then the probability of failure for a given total amount of traffic is still 27% greater in tangent track than on low rails.

Table 3: Summary of broken rail data for 2010-2014 (inclusive) on BNSF

<table>
<thead>
<tr>
<th></th>
<th>Low</th>
<th>High</th>
<th>Tangent</th>
</tr>
</thead>
<tbody>
<tr>
<td>A) % of broken rails</td>
<td>5.1</td>
<td>26.8</td>
<td>68.1</td>
</tr>
<tr>
<td>B) % of BNSF mainline rail miles</td>
<td>10.5</td>
<td>10.5</td>
<td>79</td>
</tr>
<tr>
<td>C) Relative probability of broken rails (from A/B)</td>
<td>1</td>
<td>5.25</td>
<td>1.77</td>
</tr>
<tr>
<td>D) Average age of rail (years)</td>
<td>21.6</td>
<td>24.9</td>
<td>30.2</td>
</tr>
<tr>
<td>E) Scaled relative failure rates (from C/D)</td>
<td>1</td>
<td>4.56</td>
<td>1.27</td>
</tr>
</tbody>
</table>

While greater propensity for breaks on high rails is expected (due to higher gauge corner stresses and lateral forces), the higher failure rate on tangent rails than on low rails was not expected since the stress environment is much more demanding on low rails than tangent. One contributing factor might be that curves tend to have premium steels installed while tangents receive standard or intermediate hardness rails.

3.2 Seasonality

It has been reported elsewhere that broken rails are much more common in the colder winter months [e.g. 13]. BNSF data for broken rails from Compound Fissures, Transverse Fissures and Detail Fractures supports this generalization (see Figure 2). The winter peak is attributed to several factors, including greater tensile stresses in the rail, greater wheel impact forces due to greater rates of shelling and thermal damage in the winter, and a stiffer, less compliant track bed that amplifies wheel impacting force.

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2 January 2007 to November 2014
Figure 2: Service failures (i.e. broken rails) due to Compound Fissures, Transverse Fissures and Detail Fractures for all of BNSF 2010-2014 inclusive.

An analysis of the Type 207 detail fracture broken rail derailments on the BNSF shows that there is a strong peak in October and November (see Figure 3). These are not the coldest months of the year but are the time when the track structure may go from a “normal” to a frozen state. However, if that change of state were the key, then one might reasonably expect peaks to also occur in the spring as track thaws out. It has been suggested that derailments are most probable during times of greatest change in the system as opposed to extreme absolute values and that large temperature swings through a 24 hour period might be a strong contributing factor. Examination of freely available climate records fails to find support for that idea: the largest daily temperature difference for a given month generally did not show peaks in the October/November period (Figure 4).
The reason for the concentration of broken rail derailments in October and November remains unresolved.

3.3 Proximity to obstructions

To determine whether there are significant differences in the rates at which car detections or service failures are appearing near turnouts and road crossings, defect reports from 2010 to the end of 2015 were linear referenced onto BNSF’s GIS engineering track. A nearest neighbor algorithm was run against all detected defects and service failures to determine if there was a turnout or crossing within 150 feet. Any point that met this criterion was isolated for the analysis. The count of defects and service failures occurring within the zones were divided by the total track miles included in each of those categories leads to a conclusion that track within 150’ of crossings is 1.5 times more likely to develop a detected defect or service failure than in open track, while around turnouts the number is more than 5 times.

It is BNSF’s experience that the railhead surface condition at or in the immediate vicinity of road crossings and switches has the potential to be less optimal than the mainline track. There are at least two possible reasons for this:

1. Less frequent grinding: These non-grindable features cannot be treated with the normal 10” (250mm) diameter grinding stones of the high production mainline grinder, and so must be specially ground with a “switch and crossing” (S&C) grinder, which has 6” and 10” (150-250 mm) diameter stones. These S&C units are typically limited to 16 to 24 stones and, on average, will occupy a crossing for about 12 minutes for preventive work and 20 minutes for corrective. A turnout requiring corrective work would take approximately 40 minutes to complete due to
working both tracks. In that same 40 minutes, a production grinder could treat about 6 miles of mainline track. The lower efficiency of the S&C grinding process due to smaller machine size, slower grinding speeds, and relatively high deadheading losses (travel from location to location while not doing work) explain why switches and crossings are ground less frequently. Analysis of BNSF’s 2014 rail grinding records shows that on average, switches and crossings are ground roughly every 90 MGT, which is about 20% longer than the interval for tangent track, and double that for curves.

2. Track dynamics in the vicinity of these BSC’s: The nature of their construction usually results in switches and crossings having a greater vertical stiffness than the mainline track [14]. As a result the track has a tendency to deflect ahead of and after the feature, resulting in vertical dynamics. In turnouts, the transfer of contact from running rail to switch point, through the frog etc. gives rise to additional lateral and vertical forces as well as wheelset torsions that increase damaging slip at the wheel/rail contact.

Crossings and switches can be considered as “fixed structures” since their construction assures that they are rigid in the longitudinal directions. As rail responds to thermal stresses, or the action of braking and tractive forces, large longitudinal stresses can build up in the rail that will be superimposed on the vertical wheel loading. These additional stresses could contribute to additional rail breaks, especially in the winter.

3.4 Impact of rail wear on broken rails and derailments

The contribution of wear to broken rail derailments was examined in Reference [15]. Heavy wear (i.e. levels of wear approaching a railroad’s condemning limit) of the railhead was believed to increase risk because as wear increases, decreasing moment of inertia of the remaining rail section experiences higher internal stresses for the same vertical and longitudinal loads. This is especially so at the underside of the rail head, with values that are sensitive to off-centre loading [16].

Since the FRA does not capture rail wear data, the practical impact of rail wear on safety was examined using railroad data. An analysis of BNSF mainline service failures was performed that includes only broken rails from compound and transverse fissures and detail fractures. With the caveat that the wear data will not be perfectly accurate as it relies on extracting wear data based on approximated alignment of disparate data sources, the plot in Figure 5 shows that rail breaks related to RCF and wear can occur at all levels of head wear. Statistically, the effect of vertical and horizontal wear on the probability of a service failure is effectively random.
Figure 5: BNSF mainline service failures plotted against the level of gage-face and vertical wear at the time of incident. (Jan. 2015 to Apr. 2016 data)

The impact of wear on derailments was next considered. For the six years 2010-2015 inclusive, the vertical and gage face rail wear levels for main line, FRA reportable, broken rail derailments on the BNSF are shown in Figure 6. The data shows derailments can happen at any combination, high or low, of gage-face and vertical wear and that rail wear is not a direct factor in derailments.
4. Conclusions

FRA data shows that on mainline track, derailments from broken rails are a common cause of track caused derailments. While publically available data show that their incident rate has continued to decline annually, their impact remains significant enough that it is necessary to continue to understand and address the causes of failure.

Analysis of FRA data shows that derailments at broken welds are relatively few, even though they constitute roughly half of all broken rails. This is probably because broken welds most often result in a “clean break”, while broken rails at shelling and transverse defects are occasionally associated with clusters of defects and a short length of rail can be lost at failure.

BNSF broken rail data shows that the adjusted frequency of breaks from detail fractures and transverse fissures is roughly 4 times greater on high rails than tangent, while low rail breaks are about 80% that of tangent. Given the more severe loading conditions in curves the lower number of low rail breaks is unexpected (even considering that higher hardness steel is used in curves than tangent) and is probably related to the significantly lower frequency of turnouts in curves. The data also shows the expected seasonal variation, with the greatest number of service failures occurring in the November through February period. Surprisingly, broken rail derailments peak in October and November, with all other months suffering many fewer derailments. A suggestion that the day to night temperature difference is greatest during those two months was not supported by data and so the October/November broken rail derailment peak remains unexplained.

One clear finding was that broken rails occur much more frequently in the vicinity of turnouts and road crossings – roughly 5 and 1.5 times more frequently than on open track, respectively. This is likely due to larger dynamic loading and/or longer grinding intervals grinding at switches and crossings that may contribute to greater severities of surface fatigue through the turnout than along main track. Both of these
are being investigated – the first through analysis of VTI data and the second through detailed analysis of rail grinding records.

While rails with heavy wear might theoretically be more susceptible to breakage, analysis of a large set of railroad data fails to find a relationship between wear and broken rails.

Work is ongoing to understand and quantify the reasons for the strong clustering of service failures around switches and road crossings. That work may eventually lead to different approaches to rail grinding or prioritization of maintenance activities on the BNSF railroad.

5. References

8. E. Leishman et al, “Canadian Main Track Train Derailment Trends from 2001 to 2014”, Research Update from Canadian Rail Research Laboratory, Edmonton, Canada, December 2015
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FRA Reported Main Line Derailments

T207 – Detail Fracture from shelling or head check

T220 – Transverse/Compound Fissure

Summary of BNSF Broken Rail Data for 2010-2014 (Inclusive)

Table: Summary of V/TI Data for Three Subdivisions

Includes all VTI severity levels, urgent, near urgent and priority

Summary of all main line track caused derailments
**Proximity to Obstructions**

- Turnouts, crossings and bridges
- Dynamic forces
  - turnouts: discontinuous running band, load transfer
  - crossings & bridges: usually stiffer than open track
- Surface condition generally poorer
  - dynamic forces plus ground less frequently
    - 2014: 90 mgt grind interval vs 75 mgt for tangent
- Analysis: detected defects and service failures within 150' of bridges, crossings and turnouts
  - open track: 1.0
  - bridges: approximately 1.0
  - crossings: 1.5
  - turnouts: 5.0

**Causes?**

- Change from thawed to frozen?
- Largest day/night temperature difference?

**The largest difference in daily temperature for each month over five years for different cities on the BNSF system**

**BNSF Mainline Service Failures Plotted Against Gage-Face and Vertical Wear**

- Rail Section
  - 90
  - 115
  - 119
  - 129
  - 132
  - 136
  - 141

- Jan 2015 to Apr 2016
Conclusions

- Derailments from broken rails steadily declining
- Winter peak in service failures - same as rest of industry
- Derailments peak in October or November - no validated hypothesis yet
- Crossings are 50%, and turnouts 500% more likely to develop detected defects or service failures than in open track.

Next Steps

- Root cause for strong concentrations around turnouts
- VTI
- Profiles
- Grinding practices