Failure Analysis of Railway Switches and Crossings for the purpose of Preventive Maintenance

Master Degree Project

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Abstract: In the Swedish railway network there are about 12000 units of track switches and crossings, which at 13000 Km, make up about 5.5 percent of the total track length. However, the maintenance cost for S&C is more than 13 percent of the total maintenance cost which is high in comparison with their proportion. The aim of the project is to conduct research into classification of the different modes of failure in S&C components and to perform a statistical analysis to converge the data in order to determine the most important failures that occur in turnouts.

KEY WORDS: Turnout; Rail; Sleeper; Ballast; Sub grade; Failure Mode and Effect Analysis (FMEA); Rectification; Risk Priority Number (RPN);
Acknowledgement

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Stockholm, November 2011
Seyedahmad Jalili Hassankiadeh
### List of Abbreviations

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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>FMEA</td>
<td>Failure Modes and Effects Analysis</td>
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<tr>
<td>BR</td>
<td>British Railway</td>
</tr>
<tr>
<td>S &amp; C</td>
<td>Switch and Crossing</td>
</tr>
<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>FFD</td>
<td>Failures Frequency Distribution</td>
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<tr>
<td>OCCUR</td>
<td>Occurrence Number</td>
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<tr>
<td>SEV</td>
<td>Severity Number</td>
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<td>DETEC</td>
<td>Detection Number</td>
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<tr>
<td>RPN</td>
<td>Risk Priority Number</td>
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<tr>
<td>RCF</td>
<td>Rolling Contact Fatigue</td>
</tr>
<tr>
<td>NDT</td>
<td>Nondestructive testing</td>
</tr>
<tr>
<td>GPR</td>
<td>Ground Penetration Radar</td>
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<td>P-Way</td>
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1. Introduction

Provision of a reliable infrastructure plays a very important role in achieving a reliable system. Railway Turnout consists of Switches and Crossings with specific complexity which is exposed to several defects. A high percentage of Railways infrastructure component failures occur in turnouts. In order to understand the importance of Turnouts, one needs only to be reminded of 10 May 2002 in the UK. Seven people lost their lives and a further 76 were injured. Within an hour, the poor condition of the turnouts would be identified as the cause. Their safe and reliable operation must be assured by high levels of routine maintenance. Identification of possible failure modes, determination of corresponding rectifications and an analysis of their associations help us to identify the most critical components and the likely failure mechanism. This finally leads to a better approach to preventive maintenance of Turnouts.

1.1. Objectives

The main objective of this study is to develop a better categorization of different modes of failure in Turnouts. This will enable us to understand which components are most likely to fail, and which type of failure is more likely to occur in each component. The objective of the present work is to carry out a Statistical Analysis of a set of data collected. Data from 2458 failed S&C components were used to determine the failure distribution. All data corresponded to occurrences in the year 2009 in the UK.

Turnout definition represents function of turnout and its failure classification. Section 3 discusses the literature review of Failure mechanisms in Rail. The failure mechanism in Sleeper is described in Section 4. The failure mechanisms in Ballast and in the subgrade are explained in Section 5 and Section 6, respectively. Following the description of the different failure mechanisms, failure analysis is discussed for a set of data used in analysis. Methodology section, presents the methodology used to study the information. The analysis of results, conclusions and recommendations will be discussed in Result section. Appendix A and B present a complete data analysis and corresponding graphs.
2. Turnout Definition

2.1. Turnout Function

Turnouts are the devices which use to divide one track into two or three tracks. They allow tracks to intersect at the same level. Also, they provide movement in a straight or divergent direction [1].

2.2. Turnout Components

Turnouts consist of the following major parts:

1. Rail
   - Set of switches
     • Two switch blades
     • Two stock rails
   - Closure rail
   - Common crossing
     • Through rail
     • Check rail
     • Wing rail
     • Nose

2. Sleepers (bearers)

3. Ballast

4. Substructure (subgrade)

The exact position of turnout components can be seen in Figure 1.
2.3. Classification of turnout failures

2.3.1. Failure Classification Based on Components’ Failure

- Rail Failure
- Sleeper Failure
- Ballast Failure
- Subgrade Failure
2.3.2. Failure Classification based on Nature of Failure

- Fatigue cracks failure
- Rolling contact fatigue cracks
- Wear failure
- Material deformation failure
- Shear failure
3. Failure Mechanism in Rail

3.1. Fatigue Cracks Failure in Rail

- Rail head cracks with internal origin (Subsurface origin)

3.1.1. Kidney-Shaped Cracks

This type crack usually initiates from manufacturing defects which show up when the rail starts to age. Accumulative tonnage borne or progressive cracking of the rail head leads to kidney-shape flaw. [2]

![Figure 3. Illustration ‘Kidney-shaped’ crack in rail head [2]](image)
• Rail Foot Cracks

3.1.2. Transverse Rail Foot Cracks

This is described as a progressive fracture in the base of the rail which develops substantially on a transverse plane. Transverse cracks are usually initiated from the outer edge of the foot (Galling) due to wear and/or corrosion at the rail support. As a result of relatively high bending, torsional and residual stresses, very small underside foot cracks can lead to complete rail fracture. [2]

![Image of rail foot crack](image)

**Figure 4. Rail foot crack starting from a corrosion pit at a foot underside [2]**

3.1.3. Longitudinal Rail Foot Cracks

This defect is thought to be caused by improper seating of the rail or poor manufacturing. The defect usually starts as a vertical longitudinal split which can be seen away from the center line of the foot that probably causes a piece of the foot to break away, and more severe damages happen near the center line of the foot by causing a complete fracture of the rail.[2]
Figure 5. Fracture due to a longitudinal crack. Left: Side view, Right: foot underside [2]

- Rail Web Cracks

3.1.4. Longitudinal Vertical and Horizontal Cracks

Cracks in the web usually originate from poor manufacturing. These can be in a vertical (piping) or horizontal direction leading to rail fractures. They are initiated at shrinkage cracks at the outer edge of the weld collar. Typically, impact loading is a contributing factor. [22]

Figure 6. Left: vertical web crack, Right: Horizontal web crack [2]
3.1.5. Broken Stretcher Bar

The sharp bend in a stretcher bar is a weakness that can result in many failures of spring steel stretcher bars. Similarly, the twist in the stretcher bar brackets has proven to be a stress raiser. Stress concentration in this area leads to many failures. Asymmetric force as a result of switch movement or fatigue force due to loading and unloading are known as the main causes of failure. A replacement stretcher bar or bracket of the correct type should be fitted as soon as possible. This may require the line to be blocked. [18]

Figure 7. Broken stretcher bar [18]

3.1.6. Broken or Cracked Fishplate

The cause of the majority of cracked fishplates lies in inadequate support to the sleepers. Cracks may originate at either the upper or lower edge of the fishplate. Transverse crack emanates from behind the fishplate and extends to a position. [18]

3.1.7. Switch Anchor Loosing

Because of loose switch anchors, heel blocks, loose fastenings at the switch heel or loose fishplate joints at the switch heel, an interference between the first slide baseplate bolt and the switch rail extension
bracket occurs. This prevents the switch rail from closing against the stock rail. [18]

3.1.8. Point and Splice Rails Separating

Due to failure to check fastenings and crossing bolts, or to control the rail creep in abutting track and the effects of traction force, separation of the point and splice rails of a fabricated common crossing is likely to occur. Prior to installation of the new crossing, it will be necessary to find and correct the underlying cause of the separation of the point and splice rails. [18]

Figure 8. Point and Splice Rails Separating [18]

3.1.9. Broken Bolts

Bolts may become broken as a result of excessive longitudinal forces acting on the crossing. For this same reason, the crossing itself may be pulled longitudinally. Often times, if the track is jointed, regulating expansion gaps, fitting rail anchors, and repairing track fastenings will be required. [18]
3.1.10. Broken baseplate

When a baseplate is seated incorrectly on the timber, a breakage in the baseplate is likely to occur. Not only will castings be unable to perform their design function when this happens, but they may also cause damage to supporting timber. For this reason, it should be replaced when found. [18]

Figure 9. Broken baseplate [18]
3.2. Rolling Contact Fatigue in Rail

3.2.1. Head Checks

Surface fatigue originates from the stress-exhausted surface layer of the material. As wear rates on the rails are low, the metal remains in place longer and finally reaches the fatigue limit which lead to head check cracks. Head checks are groups of fine surface cracks at the running (gauge) corner of the rail with a typical interspacing of 0.5–10 mm. They run initially into the interior of the rail at an angle of 15-30° against traffic direction. Head check cracks normally shallow and removed quite easily by rail grinding. [2]

![Head Checks](image)

Figure 10. Head Checks [19]

3.2.2. Squats

This type of failure is characterized by the appearance of micro cracks below the surface of the tracks. Squat cracks occur due to high dynamic load
of track leading to rolling contact fatigue. At first, these cracks look like a small dark dot. They then become enlarged from the bottom of the dot and grow at a shallow angle in the longitudinal direction. Sometimes the growth of cracks under the surface is in direction to the gauge corner that is common in moving cross frogs. Cracks finally turn down vertically and can eventually result in a rail breakage. The significant characteristic of squats usually appears on the running surface and less commonly from the gauge corner. Welding is known as common treatment of squats defect. [2]

![Figure 1. Squat Defects [19]](image)

3.3. Wear or Material Removal Failure in rail

3.3.1. Rail Corrugation

Rail corrugation is a frequently occurring rail wear pattern which appears as an irregularity developing on the running surface of rail. The term corrugation is considered with wavelengths of less than about 1 m. For the purpose of maintenance, it can be convenient to categorize the corrugation according to wavelength: short wave in the range of 0-100 mm, medium wave in the range of 100-300 mm, and long wave in the range of 300-1000 mm. Joints and weld are known to be a common source of excitation, especially if there is acceleration or braking force in this area. Corrugation often propagates from such irregularities. Plastic flow on mixed traffic railways which is due to excessive wheel/rail contact stresses is one of the most common causes of corrugation on heavy haul railways. Disturbed (white) ballast due to the vibration of short wave corrugation and rough riding are known as the
consequences. A useful rectification would be to grind the existing corrugated rail over a length of a few hundred meters. [19]

![Figure 12. Rail Head Corrugation](image1.png)

**Figure 12. Rail Head Corrugation [19]**

### 3.3.2. Switch Rail Shelling

Fine fatigue-induced cracks at the gauge corner of the rail, form a network on the surface of the rail. These Specific cracks under the gauge corner lead to a breaking out of material (gauge corner shelling). Remedial grinding is known as a rectification. [18]

![Figure 13. Transverse crack propagation starting from gauge corner shelling](image2.png)

**Figure 13. Transverse crack propagation starting from gauge corner shelling [2]**
3.3.3. Stock Rail Head Wear

Severe headwear, leading to lipping of the stock rail, could cause the switch rail to stand proud of the stock rail, leading to a switch splitting type of derailment, or at least failure of the switch and stock rail to provide correct locking an detection to the signaling system. A remedial grinding is suggested in primary stage and in sever headwear replacement could be as a rectification. [18]

![Image of Stock Rail Headwear](image.png)

**Figure 14.** Stock Rail Headwear Associated with a Used Switch Rail [18]

3.3.4. Damaged Crossing Nose

Due to inherent defects in the casting or as a result of strikes because of inadequate guidance from the check rails, some damages appear in crossing nose. Depending upon the resulting shape of the crossing nose it might remove excess lipping by means of an angle grinder and weld repair or replacement of the crossing. [18]
3.3.5. Dry Slide Chair or Baseplate

When not properly lubricated, slide chairs can become desiccated, and patches of rust may begin to appear on the slide table. Once this problem is discovered, new lubricant should be applied to the slide chairs immediately. Redistribution of existing lubricant taken from other parts of the slide chair can also be an option in resolving the problem before leading a switch blocked. [18]
3.4. Material Deformation in Rail

3.4.1. Plastic Flow

Plastic flow refers to plastic deformation of the stock rail (near switch rail) due to cyclic loads and high rail stresses called lipping. Plastic flow of rail material appears often on the low rail in sharp curves. This could result in a reduction of gauge width. Overall, Plastic flow and development of lip usually occur in different components of turnout. In such a situation a remedial grinding is suggested as a rectification. [19][21]

![Figure 17. Lipping [21]](image)

3.4.2. Sharp Gauge Corner

The sharp corner which has formed on the switch rail occurs most commonly. It causes the wheel to subsequently derail. In addition, as a result of a wheel strike, a deformed nose might form, which leads to a change in check rail gauge dimension, especially when there is a loose bolt. Sharp corners should be removed by grinding. [18]
3.5. Shear Failure in Rail

3.5.1. Failed Stud

Prior to fitting a stud, the stock rail has to be seated properly on the slide baseplate. If this has not been done correctly, the stud becomes increasingly unstable after being repeatedly subjected to both shear and tensile force, and the end result will be a failed stud. Replacement of Failed Stud should be undertaken after discovering.[18]
4. Failure Mechanism in Sleeper

Sleepers or ties receive the load from the rail and distribute it over the supporting ballast. They also hold the fastening system to maintain the proper track gauge and restrain the rail movement. Failure mechanism in sleeper has been followed in this section.

4.1. Bending Cracks

Bending cracks are often detected at the bottom of mid span of the sleepers by allowing a sleeper to settle on the ballast packed under the center of the sleeper. It also sometimes comes from the soffit underneath rail seat of the sleepers. It eventually decreases flexural stiffness of the sleeper. Likewise flexural failure appears as top surface cracks located near the rail seat. [7][19]

![Center Bending Cracks](image)

**Figure 20. Center Bending Cracks [19]**

4.2. Concrete Spalling

Concrete Spalling occurs on the top fiber of the rail seat; also rail irregularity in the joint area which sometimes reaches 15 mm in length causes a large wheel impact load of about four to six times of the serviceability conditions. This magnitude of impact load damages sleepers by appearing as cracks under the joints of the rail. [6]
4.3. Fracture Cracks

Due to infrequent but high magnitude impact force fracture cracks can be detected under the rail seat on the surface of the sleepers. In addition, tensile fractures appear in the upper central segment of the sleepers which run vertically down and spread throughout the central segment. [7] [8]

4.4. Split Concrete Sleeper

Longitudinal splits in concrete sleepers often arise as a result of being struck by tamping machine tines. They may also be caused by torsional loading on sleeper owing to non-uniform support over the whole of the width of the rail seat. It finally decreases flexural stiffness of the concrete sleeper. Failed sleeper should be replaced before imposing bad effect on other components. [19]
4.5. Damaged Concrete Bearers

A number of concrete bearers damage during the fitting of the chair screws, either as a result of using chair screws of the wrong diameter, or because they are over tightened. [18]
4.6. Shear Cracks (Diagonal Cracks)

After a slightly bending crack stopped, sleepers have sudden brittle failure due to shear diagonal crush at top fibre. This causes a severe damage like spalling without any deflection warning. [8] [14]

4.7. Abrasion

Once it exceeds a depth of about 2 mm, Sleeper in the rail seat will not provide a reasonably smooth surface to accept the rail pad without undue distortion. Abrasion of the soffit of the sleeper leads to a reduction in cover of the prestressing wires and tendons or strands. [19]

4.8. Wet Spot (Slurry Spot)

Voids under the concrete sleepers, denoted by lighter colored and less angular ballast on the upper surface, encourage ballast attrition. When mixed with material abraded from the concrete sleepers, weak-mix concrete results, thereby failing to keep the sleepers well packed. [19]

Figure 24. Wet Spot (Slurry Spot) [19]
5. Failure Mechanism in Ballast

The ballast is the select crushed granular material placed as the top layer of the substructure in which the sleepers are embedded. The most important functions of the ballast are to retain track position, reduce the sleeper bearing pressure for the underlying material, store fouling materials, and provide drainage for water falling onto the track. [17]

In the past, most attention has been given to the track superstructure consisting of the rails, the fasteners and the sleepers, and less attention has been given to the substructure consisting of the ballast, the subballast and the subgrade. Even though the substructure components have a major influence on the cost of track maintenance, less attention has been given to the substructure because the properties of the substructure are more variable and difficult to define than those of the superstructure (Selig & Waters, 1994).

Figure 25 shows a typical profile of the relative contributions of the substructure components on track settlement, assuming a good subgrade soil foundation (Selig & Waters, 1994). This figure shows that ballast contributes the most to track settlement, compared to subballast and subgrade.

![Figure 25. Substructure contributions to settlement (Selig & Waters, 1994).](image-url)
5.1. Crack Failure in Ballast

5.1.1. Micro-Cracks and Particle Breakage

Short wave corrugation on the rail can cause a vibration on the sleeper, and this can disturb the support under the sleeper. This vibration causes particle contact force and the ballast stones may lose their sharp ages. Breakage also occurs from cycles of freezing and thawing and from chemical breakdown due to environmental factors. White powder builds up and contaminates the ballast, as shown in the figure below. [21]

![Disturb (white) Ballast due to short wave corrugation](image.jpg)

**Figure 26.** Disturb (white) Ballast due to short wave corrugation [21]

5.2. Plastic Deformation in Ballast

5.2.1. Ballast Pockets

Ballast pockets are load-induced depressions in the subgrade surface directly under the tie. They also can result from a process of ballast accumulation in the subgrade soil that forms during maintenance and repairs. The water falling on the track flows down and gets trapped in the depressed zone. It leads to a weakness in this area and eventually a track settlement. A common remedy to minimize ballast pocket development is draining the ballast pocket with a cross-drain excavated perpendicular to the track at the
lowest point of the ballast pocket. Figure 27 shows a typical track cross-section with deforming subgrade. [12]

Figure 27. Ballast Pocket [22]

5.2.2. Erosion Pumping

Where the ballast runs on a clay subgrade condition, under dynamic loading, water in the subgrade can turn this soil into slurry, which is pumped upward through the ballast by expansion of the voids. This contamination of the track ballast (fouling of the ballast) may cause localized undrained track ballast and reduce its load support properties. It also causes a loss of lateral track restrain or track alignment and eventually leading to unacceptable movements of the rails. Placing a layer of blanket material could be a relevant preventive maintenance. Once the failure occurred replacement the ballast should be undertaken.[15]
Figure 28. Wet-Bed Due to Pumping Near Fishplate Joint [21]

5.2.3. Ballast Settlement

Due to sleeper-ballast interaction, the ballast gradually becomes contaminated by fines which impair drainage and cause the ballast to perform less effectively. We have seen that a free ballast movement and also low bearing capacity of the sub-grade can cause:

- Complete shifting of the switch to the sides of original position
- Unevenness on one side due to subsiding which cause an unwanted superelevation

Hence this ballast loosening due to tamping declines its ability to hold the track geometry and eventually leads to a high settlement in the track. [16]

5.2.4. Ballast Fouling

Over time, the ballast is progressively contaminated by fine-grained aggregate and metal dust that fills the void space between ballast stones. This contamination is called fouling. The effect of ballast fouling is that it prevents the ballast from fulfilling its function, especially when the fouling materials contain silt and clay sized particles. In most cases to identify ballast fouling special instruments like Ground Penetration Radar (GPR) involves scanning the track is needed. Once it discovered replacement the ballast is known as a treatment before imposing a bad effect in other components. [20]
Figure 29. Ballast Cross Section [20]

5.3. Shear Failure

5.3.1. Breakage of the Sharp Edge

Micro-cracks can develop when the ballast rock is stressed and can make pores in rocks. Numerous micro-cracks can increase a zone of weakness. This causes breakage of the sharp edge ballast particles during shear deformation. [9]
6. Failure Mechanism in Subgrade

The subgrade is the platform upon which the track structure is constructed. Its main function is to provide a stable foundation for the ballast layer. Subgrade is a source of rail differential settlement which is considered as follows:

6.1. Plastic Deformation in Subgrade

6.1.1. Accumulative Plastic Deformation

Progressive soil compaction in soft soils leads to excessive plastic deformation. In addition, in a saturated silt and fine sand condition, repeated loading can cause a large displacement called liquefaction. This finally leads to track settlement. Removal and replacement the subgrade could be as a rectification. [11]

![Figure 30. Accumulative plastic deformation](image)

6.1.2. Consolidation Settlement

Embankment weight in saturated fine-grained soils causes an increased static soil stress and settlement. Also, changing moisture content in highly plastic soil by moisture loss (shrinkage) or moisture increase (swelling) causes subgrade settlement. Excessive subgrade settlement can lead to unacceptable track geometry changes. [11]
6.1.3. Frost Action

The bearing capacity of the frozen soil decreases when its temperature increases. Periodic freezing in frost-susceptible soils causes heave and softening, which occurs usually in the winter/spring period. Freezing temperature in the soil, source of water, and a frost-susceptible soil are the main factors contributing to this problem. During the period of thaw softening, severe plastic deformation can result in rapid loss of track geometry and accelerated damage to track components. [11]

6.1.4. Attrition with Mud Pumping

In a situation of high water content in the subgrade surface, liquefied soil and water rise to the surface due to high ballast-subgrade contact stress. Such failure is normally associated with hard, fine-grained materials such as clay and soft rock. Pumping can lead to a loss of lateral track restraint or track alignment. Pumping failure can be prevented by placing a layer of blanketing material between the ballast and the subgrade. [11]

6.2. Shear Failure in Subgrade

6.2.1. Progressive Shear Failure

In fine-grained subgrade soils or soils with high water content associated with repeated over-stressing of the subgrade. Progressive shear failure can manifest as squeezing near the subgrade surface, heaves in the shoulder, or depression under the ties. This process is known in the United Kingdom as ‘Cess Heave.’ This happens because the vertical stress in the layers in the loaded state is greater than the horizontal stress. Before removing the subgrade material, using injection system like cement grouting is known as a treatment. Applying stone column in both sides of the railway is suggested in high embankment subgrade with more than Five meters thick soft soil. [12]
6.2.2. Massive Shear Failure

Because of inadequate soil strength due to the weight of trains, track, and the subgrade, we can see slope instability in high embankments, especially with increased water content. This may occur for example at times of heavy rainfall and flooding, even without train loading being present. Hence, the subgrade strength properties are a major factor in terms of safety with regard to massive shear failure. Replacement the material from the toe of the slip should be undertaken.[12]
7. Failure Analysis

A set of data have been conducted to investigate the Turnout failures. The actual P-Way failure modes data which were recorded in the UK in 2009 is our input parameters for analysis. Permanent Way failures are attributed to the rails, sleepers, ballast and subgrade. To analyze the data correctly, we needed to split the data into different categorization base on components and modes of failure. The total number of failure modes was 2458.

7.1. Failed Components Data

To analyze the data recorded, we performed a failure classification based on components. Table 1 shows a breakdown of all failed components.

<table>
<thead>
<tr>
<th>Failed Components</th>
<th>Total Number</th>
<th>Frequency distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch rail</td>
<td>1113</td>
<td>45.3</td>
</tr>
<tr>
<td>Slide chair</td>
<td>747</td>
<td>30.4</td>
</tr>
<tr>
<td>Ballast</td>
<td>194</td>
<td>7.9</td>
</tr>
<tr>
<td>Schiwag Roller</td>
<td>138</td>
<td>5.6</td>
</tr>
<tr>
<td>Stretcher bar</td>
<td>111</td>
<td>4.5</td>
</tr>
<tr>
<td>Stock rail</td>
<td>71</td>
<td>2.9</td>
</tr>
<tr>
<td>Crossing</td>
<td>33</td>
<td>1.3</td>
</tr>
<tr>
<td>Fishplate</td>
<td>24</td>
<td>1.0</td>
</tr>
<tr>
<td>Back Drive</td>
<td>18</td>
<td>0.7</td>
</tr>
<tr>
<td>Sleeper</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>Spacer Block</td>
<td>4</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td><strong>2458</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

*Table 1. Total Number of Failed Components in 2009*
Figure 33 shows a bar chart of failed Turnout components in the UK in 2009.

The Chart shows that Switch rail and Slide chair were the most common failed components which made up more than 75% of failed components in the UK in 2009. In contrast, Ballast, Schiag Roller, Stretcher bar, Stock rail made up about 20.9% of failed components. Finally, some components like Crossing, Fishplate, Back drive, Sleeper and Spacer Block comprised less than 4% of failed components.

**Figure 33. Total Number of Failed Components in 2009**
7.2. Number of Potential Failure Modes

Another condition was considered while analyzing the failure variety in components. Data demonstrated that Turnout failures can occur in various modes. An important outcome of assessment of different defects was a categorization of possible failure modes in turnouts. A classification of different types of failure modes in Turnouts is shown in Table 2.

<table>
<thead>
<tr>
<th>Failure Modes</th>
<th>Total Number</th>
<th>Frequency Distribution %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obstructed ( Iced,..)</td>
<td>986</td>
<td>40,1</td>
</tr>
<tr>
<td>Dry Chairs</td>
<td>441</td>
<td>17,9</td>
</tr>
<tr>
<td>Cracked/Broken</td>
<td>233</td>
<td>9,5</td>
</tr>
<tr>
<td>Voiding (Ballast)</td>
<td>190</td>
<td>7,7</td>
</tr>
<tr>
<td>Out of adjustment</td>
<td>137</td>
<td>5,6</td>
</tr>
<tr>
<td>Contaminated (Leaves,..)</td>
<td>136</td>
<td>5,5</td>
</tr>
<tr>
<td>Plastic deformation/Lipping</td>
<td>127</td>
<td>5,2</td>
</tr>
<tr>
<td>Wear</td>
<td>93</td>
<td>3,8</td>
</tr>
<tr>
<td>Loosed/missing(Nuts)</td>
<td>89</td>
<td>3,6</td>
</tr>
<tr>
<td>Squat, RCF</td>
<td>8</td>
<td>0,3</td>
</tr>
<tr>
<td>Creep (Switch,..)</td>
<td>8</td>
<td>0,3</td>
</tr>
<tr>
<td>Track gauge variation</td>
<td>7</td>
<td>0,3</td>
</tr>
<tr>
<td>Wet bed</td>
<td>3</td>
<td>0,1</td>
</tr>
<tr>
<td>Sum</td>
<td>2458</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2. Total Number of Failure modes in 2009

The complete series of graphs from the data sets about the failure modes are presented in Appendix A.
The circumstance of failure modes distribution represents in Figure 34.

The chart shows the importance of Obstructed and Dry chairs failures with 58% of occurrence. In contrast, Cracking or Breaking, Ballast Voiding, getting Out of Adjustment, contaminated and Plastic Deformation made up 40.9% of failures whereas Squat, RCF, Creep, Widening Track and Wet Bet failures had the lowest portion of occurrence with only 1%.
7.3. Relationship between Weather and Failure Modes

Many factors contribute to the Turnouts failure. Since all information included the time of year when the failures occurred, in order to find out how failure frequency varies with climate, an additional attention has been given to determination of climate effects on failure occurring. The seasonal failures frequency is shown in Table 3.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Number of Failure Modes</th>
<th>Frequency Distribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>421</td>
<td>17.1</td>
</tr>
<tr>
<td>Summer</td>
<td>427</td>
<td>17.4</td>
</tr>
<tr>
<td>Autumn</td>
<td>830</td>
<td>33.8</td>
</tr>
<tr>
<td>Winter</td>
<td>780</td>
<td>31.7</td>
</tr>
<tr>
<td>Sum</td>
<td>2458</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 3. Association between Seasons and Number of Failure Modes in Turnouts in 2009

Probability of Turnouts failure occurrence in different seasons in the UK in 2009 has been shown in Figure 35.
Figure 35. Probability of Turnout Failures by Season in 2009

Analysis has revealed a relationship between Seasons and failed components. It is clear that the weather plays a very significant role in the probability of failure. In Table 2 Seasonal failures represent a better view of climate effects on failure, where a large number of failures occurred in the period of autumn and winter. It means cold weather is a problem of great significance to the railway system. Indeed, much attention should be given to the inspection during the cold weather. The small difference between autumn and winter failures frequency might be as a result of leaves falling in autumn that train drivers are warn about it in this season. Additional information about the determination of weather effects on failures frequency is available in Appendix B.
7.4. Rectification of Failed Components

After identification of Turnout failure modes, determination of possible rectification gains a great importance. Actions that are available or can be taken by an operator to negate or mitigate the effect of a failure on a system are called Rectification. Rectification concerning turnout failures has been investigated through the recent data. It has been recognized that the frequency of some rectification actions allocated to the Turnout is variable for different components. Table 4 represents different types of Turnout rectification.

<table>
<thead>
<tr>
<th>Rectification</th>
<th>Total Number</th>
<th>Failed Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>De-Iced</td>
<td>559</td>
<td>Switch rail, slide chairs, Schiwalg Roller, Back drive, Stretcher bar</td>
</tr>
<tr>
<td>Lubricated</td>
<td>445</td>
<td>Slide chairs, Schiwalg Roller</td>
</tr>
<tr>
<td>Remove Obstacle</td>
<td>427</td>
<td>Switch rail, slide chairs, Stretcher bar, Back drive</td>
</tr>
<tr>
<td>Renewed</td>
<td>243</td>
<td>Stretcher bar, Slide chair, Crossing (nose crack), Fishplate, Switch rail, Stock rail, Sleeper, Space block, Ballast</td>
</tr>
<tr>
<td>Lift &amp;Pack</td>
<td>190</td>
<td>Ballast</td>
</tr>
<tr>
<td>Grind</td>
<td>167</td>
<td>Switch rail, Stock rail, Fish plate</td>
</tr>
<tr>
<td>Adjusted</td>
<td>143</td>
<td>Schiwalg Roller, Switch rail, Stretcher bar, Back drive, Slide chairs, Ballast</td>
</tr>
<tr>
<td>Cleaned</td>
<td>136</td>
<td>Slide chairs, Switch rail, Schiwalg Roller</td>
</tr>
<tr>
<td>Weld repair</td>
<td>71</td>
<td>Switch rail, Crossing, Fishplate</td>
</tr>
<tr>
<td>Tightened</td>
<td>70</td>
<td>Slide chairs, Stretcher bar(nuts), Back drive, Fish plate</td>
</tr>
<tr>
<td>Gauged</td>
<td>7</td>
<td>Switch rail, Stock rail</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2458</strong></td>
<td>-</td>
</tr>
</tbody>
</table>

Table 4. Different Rectification Actions Allocated to Failed components
Failed components in the Table 4 has sorted based on the number of rectification frequency acted on them. It is considerable that the number of some specific rectifications is noticeable in some components. This information provides us a better prediction about dominant rectification mechanism in each component.

Figure 36 shows the rectification Frequency Distribution in Turnouts.

![Frequency Distribution of Different Rectification Modes in Turnouts in 2009](image-url)

**Figure 36.** Frequency Distribution of Different Rectification Modes in Turnouts in 2009
8. Methodology

In order to analyze the potential failure modes within a system for classification by the severity and probability of the failures we used a Failure Modes and Effects Analysis (FMEA) procedure. FMEA consists of breaking a system down into specific data. A successful FMEA process helps an investigator to identify potential failure modes based on past experience. The analysis begins with identification of the possible failure modes associated with a certain item which results an end effect. Along with the end effect, the analyst may also determine the probability of occurrence of that effect, the severity of that effect and how the effect could be detected. Once the detection of failure modes is complete, some type of ranking criteria is employed. The ranking is then used to determine how critical failures can be eliminated or the risks mitigated. After determination of different ranking we can approach to a Risk Priority Number (RPN) which reveals the overall risk of a particular failure mode occurring in our system. FMEA cycle is shown in Figure 37.

![Risk Priority Number (RPN) = OCCUR*SEV*DET]

Figure 37. Failure Modes and Effects Analysis Cycle (FMEA)
8.1. FMEA Procedure

Step 1. Occurrence

In the first step we defined a mode failure rate as an occurrence number.

Occurrence is an assigned value that designates how frequently that particular failure mode occurs over a time period. Table 5 shows a Failure occurrence ranking.

<table>
<thead>
<tr>
<th>Rating</th>
<th>Meaning</th>
<th>Range ( % )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No Effect</td>
<td>FFD = 0</td>
</tr>
<tr>
<td>2</td>
<td>Low ( Few Failure)</td>
<td>0 &lt; FFD &lt; 5</td>
</tr>
<tr>
<td>3</td>
<td>Moderate ( occasional Failure)</td>
<td>5 &lt; FFD &lt; 10</td>
</tr>
<tr>
<td>4</td>
<td>High ( Repeated Failure)</td>
<td>10 &lt; FFD &lt; 20</td>
</tr>
<tr>
<td>5</td>
<td>Very High</td>
<td>FFD &gt; 20</td>
</tr>
</tbody>
</table>

Table 5. Failures Occurrence Ranking

In this way a failure mode is given an occurrence ranking (O). Also Failures Frequency Distribution (FFD) is categorized in different range.

Step 2. Sensitivity

Sensitivity is an assigned value that indicates the severity of the effect of a particular failure mode. A failure mode in one component can lead to a failure mode in another component; therefore each failure mode should be listed in technical terms and for function. Hence, the ultimate effect of each failure mode needs to be considered. Table 6 shows the Failure Sensitivity Ranking.
Table 6. Failures Sensitivity Ranking

In this step a failure effect is defined as the result of a failure mode on the function of the system. Each effect is given a sensitivity number (S) from 1 (no danger) to 6 (critical) to prioritize the failure modes and their effects.

Step 3. Detection

Detection is an assigned value that indicates how often that particular failure mode can be detected. In this step each failure receives a detection number (D). The assigned detection number measures the risk that the failure will escape detection. Table 7 represents a Failure Detection Ranking.

Table 6. Failures Detection Ranking

According to Detection Ranking, a high detection number indicates that the chances are high that the failure will escape detection or the chances of detection are low.
Risk Priority Number (RPN)

The RPN reveals the overall risk of a particular failure mode occurring in our system. Actually, RPN is a threshold value in the evaluation of failure. After ranking the occurrence, severity and detectability the RPN is calculated as \( \text{RPN} = S \times O \times D \). The result is a categorized breakdown of failure modes based on risk. Once this is done it is easy to determine the areas of greatest concern. The failure modes that have the highest RPN should be given the highest priority for preventive maintenance. This means it is not always the failure modes with the highest severity numbers that should be treated first. There could be less severe failures, but which occur more often and are less detectable.
9. Results

The main objective of this study is to get a better categorization of the most critical failure modes in Turnout in UK railway. This may lead us to know that which components have higher potential to get failed. According to the failure classification in chapter 7, turnout failures have been divided into 13 major parts. Studying the turnout failures behavior and following the FMEA procedure led to the final results in Table 7.

<table>
<thead>
<tr>
<th>Failure Modes</th>
<th>Occurrence Rate</th>
<th>Sensitivity Rate</th>
<th>Detection Rate</th>
<th>RPN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obstructed (Iced,..)</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>75</td>
</tr>
<tr>
<td>Dry Chairs</td>
<td>4</td>
<td>5</td>
<td>3</td>
<td>60</td>
</tr>
<tr>
<td>Crack/Broken</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>Voiding (Ballast)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>Out of adjustment</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Contaminated (Leaves,..)</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>27</td>
</tr>
<tr>
<td>Plastic deformation/Lipping</td>
<td>3</td>
<td>4</td>
<td>2</td>
<td>24</td>
</tr>
<tr>
<td>Wear</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Loose/missing(Nuts)</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>12</td>
</tr>
<tr>
<td>Squat, RCF</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>Creep (Switch)</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Track Gauge variation</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Wet bed</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 7. Final FMEA Results
9.1. Discussion

All assigned values in Occurrence Rate are based on Failure Frequency Distribution (FFD) ranges defined according to Table 5.

Sensitivity Rate indicates the severity of the effect of failure modes according to Table 6.

Due to obstructed failure, the Switch Rail loses its primary function to move, hence the five values assigned to Sensitivity Rate.

Dry Chairs failure usually occurs in the slide chair. The switch rail rests on the slide chair, so when a slide chair doesn’t work properly it causes the switch rail to lose its primary function. This means slide chair needs immediate lubrication. Five values have been assigned under Dry Chair.

About 70% of cracked or broken failures occur in slide chairs and stretcher bars. These failures cause a loss of primary function. In most cases these components must be replaced immediately after failure. Five values have been assigned to Cracked and Broken Failures.

Ballast voiding is the degradation of the ballast because of no tamping in the turnout area. In most cases it negatively affects other components. In some conditions the switch blade has become bowed causing tight back drive. Broken chairs or loose bolts are other consequences. Lifting and packing the ballast is considered a good rectification in voiding failure. Three values have been assigned to Ballast Voiding.

When a Schiwag Roller gets out of adjustment, it affects the slide chair’s ability to perform, and needs to be adjusted at immediately. Four values have been assigned to Out of Adjustment Failure.

Leaves, dust and dirt often contaminate components. For example, leaves can cause problems in the braking system. However, the big concern is in the slide chair where contamination over time leads to serious problems such as dry chair. Three values were allocated to Contaminated Failure.

Plastic deformation and wear, particularly in the switch and stock rail, lead to a failure to provide correct locking or a loss of primary function. Four values were assigned to them.

Loose or missing nuts, most commonly found in the slide chair and less often in the stretcher bar, cause a delay for tightening or in some cases
renewing. Usually this doesn’t stop a component's function and is less dangerous. Two values were assigned to this issue.

Squat and Rolling Contact Fatigue (RCF) rectify with weld repair or grinding. They are generally not dangerous, but if left for a long time with no repair, rail breakage may occur. They were evaluated with two ratings.

The long term effect of trains moving along a section of track can cause longitudinal movements of rail, or "creep". An environmental factor like temperature is known as a motivator item. This occurred in the UK due to warm weather which led to an out of adjustment switch. Creep may cause a hazardous situation because it adversely affects welding due to rail movement. Three values have been assigned to it.

In a wide track, gauge variation usually exceeds standard. It sometimes leads to track vibration or even wear on the track. It must be adjusted before negatively affecting other components. Three values have been assigned to this issue.

Wet bed or erosion pumping in the ballast may reduce its load support properties. It might affect other components over a long period of time. Two values were assigned to this.

Assigned values in Detection Rate allocated according to Table 6.

Obstructed Turnout occurs when a switch ices or ballast particles are thrown out due to high speed train movement. This was assigned three values, because it is easy to see ballast obstacles in switches or observe an iced switch.

As with obstructed turnout, dry chair is easily observable by sight. Therefore the Detection Number has three values assigned to it.

Since some cracks are difficult to see, especially when they have an internal origin, two values were allocated to it in Detection Rate.

Ballast voiding in most cases is easy to see when viewing from beside the ballast section. Three values in Detection Rate were assigned to it.

Out of adjustment failure usually shows itself through the slide chair function, so it is not detectable directly. Accordingly, two values have been assigned to it.
Contamination is observable easily on the track. Contamination by leaves can be seen by the train driver and they usually report it to monitoring center. Thus, three values in Detection Rate were attributed to it.

Lipping and wear, Squat, or RCF identification depends on their regression. In a critical condition these are easy to spot. However, in other cases, Nondestructive testing (NDT) methods like Ultrasonic or Eddie Currents are needed for visual condition monitoring. Two values assigned to these.

Loose or missing nuts are easy to see. Therefore, three values of detection number are attributed to them.

Since Creep misalignment is less evident during a walking inspection. It must be identified by NDT. Thus, only one value was assigned to it.

Track gauge variation is not easy to see. It usually gets measured by a track geometry recorder trolley. Therefore, only one value was attributed to it.

Wet bed is easy to see in critical conditions when slurry pumps upward through the ballast. But in most cases, to identify wet bed, special instruments like Ground Penetration Radar (GPR) are needed to scan the track. For wet bed, only one value was assigned.

After ranking the Occurrence (O), Severity (S) and Detect ability (D) the RPN is calculated as $\text{RPN} = O \times S \times D$. To identify the areas with greatest concern we categorized the failures based on their RPN in three different categories.

Group 1. High Risk Priority Number

Group 2. Moderate Risk Priority Number

Group 3. Low Risk Priority Number

Failures with a RPN probability of more than 10 percent belong to Group 1. Failures with a RPN probability between 5 and 10 percent belong to Group 2. Failures with a RPN probability of less than 5 percent belong to Group 3.

According to the top categorization all failure modes attributed to three groups.
Group 1. Obstructed, Dry Chair

Group 2. Voiding, Contaminated, Out of Adjustment, Plastic Deformation/Lipping, Wear

Group 3. Loose/ Missing(NUTS), Squat, RCF, Creep, Track Gauge Variation, Wet bed.

Figure 38 shows failure zones of different Groups.
Studying the Turnout failure behavior led to the following results. The failure modes in Group 1 with highest RPN should be given the highest priority for preventive maintenance. Group 2 is in the second priority for preventive maintenance. Group 3 needs to get rectified before imposing a serious effect on the system in long term.

Figure 38. Failure Zones
9.2. Conclusion

Turnouts are probably the most important infrastructure elements of the railway system. They are subjected to high risk owing to many potential failure modes. The assessment of failure risk in turnouts in order to ensure high availability and safe operation can be based on historical data and occurrence of failures. This analysis was conducted by investigation of different defects appearing in turnouts, which allowed identification of the most critical failures. FMEA procedure has been introduced to approach the classification of critical failures in turnouts. Consequently, failure risk evaluation based on a wider range of data may support a maintenance development by providing precise criteria for deciding how often routine tasks should be carried out. This policy might include improved service levels of inspection and repairment.
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Appendix A

The data in this appendix were collected from UK railway in 2009. The data set consists of 2458 measurements collected over a year period.

A pie chart in Figure A1 represents the distribution of failure modes in Turnouts components. Figures A.2, 3, 4, 5, 6, 7, 8,9,10, 11, 12, 13 show the distribution of failure modes in Turnout’s components.

![Pie chart showing failure mode distribution]

Figure A1. Distribution of Failure Modes in Turnout’s Components
Figure A2. Distribution of Obstructed Failure in Turnout’s Components

Figure A3. Distribution of Dry Failure in Turnout’s Components
Figure A4. Distribution of Out of Adjustment Failure in Turnout’s Components

Figure A5. Distribution of Plastic Deformation/Wear Failure in Turnout’s Components
Figure A6. Distribution of Contaminated Failure in Turnout’s Components

Figure A7. Distribution of Track Gauge Variation Failure in Turnout’s Components
Figure A8. Distribution of Cracked/Broken Failure in Turnout’s Components

Figure A9. Distribution of Loose (Nuts) Failure in Turnout’s Components
Figure A10. Distribution of Voiding Failure in Turnout’s Components

Figure A11. Distribution of Wet Bed Failure in Turnout’s Components
**Figure A12.** Distribution of Creep Failure in Turnout’s Components

**Figure A13.** Distribution of Squat/RCF Failures in Turnout’s Components
Appendix B

The data in this appendix were collected from UK railway in 2009. The data set consists of 2458 measurements collected over a year period.

Figure B.1 shows Number of Failure Modes in different months.

Figure A13. Relationship Between Number of Failure Modes and Months.