Investigate the track gauge widening on the Iron-ore line and suggest maintenance limits

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Abstract

Iron ore export remains a major player in the Swedish economy to date, with 90% of all iron ore produced in Europe stemming from the relatively small northern country. A large amount of this ore is transported from the mines to harbours for world-wide freight on railways. On such railway is the Swedish Iron-ore Line running from Kiruna to Riksgränsen, connecting to the Norwegian Ofoten line which continues to Narvik. The line has the highest permissible axle-load in Europe at 30 tonnes, which poses challenges in its own. Historically, damage on the high rail of curves have been problematic, but remedies introduced in the form of wear adapted rail profiles has brought light to a new issue.

Low rail spalling damage, caused by rolling contact fatigue (RCF) has been problematic on the line, as it reduces the life of the rails and increases maintenance costs. It is believed that a major factor to this damage is the track gauge width. The current limit values for maintenance of the track gauge is set at 1450mm, a figure derived from empirical studies. It is therefore the wish of the infrastructure manager Trafikverket to investigate the effect the gauge width has on this RCF induced damage, in order to review current maintenance practices. By applying current state of the art in rail vehicle dynamics simulations and contact mechanics, the current maintenance limit has been investigated.

The outcome of said investigation has yielded a foundation of support for the current maintenance limit, as it closely aligns with where damage is calculated to form at a significantly higher rate than at lower gauges.
Sammanfattning

Malmexport utgör idag en av de största pelarna av Sveriges ekonomi och står ensamt för produktionen av 90% av all järnmalm som produceras i Europa. En stor del av denna malm transporteras från gruvorna till hamnar för vidare frakt på fartyg med hjälp utav järnvägar. En sådan järnväg är den Svenska Malmbanan som går mellan Kiruna och Riksgrensen, med direkt anslutning till norska Ofotenbanan som fortsätter till Narvik. Banan är den tyngsta i sitt slag i Europa med en största tillåten axellast på 30 ton, vilket innebär egna utmaningar. Rälskador på ytterrälen i kurvor har tidigare varit problematiska, men tidiga åtgärder i form av slitageanpassade rälprofiler har motverkat dessa, och istället skänkt uppmärksamhet åt ett annat problem.


Den nämnda utredning har resulterat i en grund som stöttar den nuvarande underhållsgränsen, då den nära överfinnsstämmen med den plats där skadorna ökar mycket kraftigt i förhållande till smalare spårvidder.
Acknowledgement

I would like to start of with thanking my supervisors Saeed Hossein Nia of KTH and Matthias Asplund of Trafikverket, as well as my examiner Carlos Casanueva Perez, for their support and assistance throughout my thesis. I would like to direct very special thank you to Saeed, who has taken an active interest in my work, and made great efforts to aid me when necessary, despite the special conditions that has been prevalent throughout the spring.

Further, I would like to thank Ingemar Persson of DeSolver AB, for his assistance with the GENYS program, who have greatly contributed to the process of getting both the program and model working. Finally I’d like to thank the following people for their assistance with the project:

- Visakh V Krishna, Doctoral student, KTH
- Lars Sundholm, Railway Engineer, Trafikverket

Finally, I would like to dedicate the work in this thesis to my late grandfather Tommy Flodin, who has been a great influence for me wanting to become an engineer.
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Chapter 1

Introduction

1.1 Looking north

Running from the mines in the Swedish Lappland to the ports of Narvik and Luleå, the Swedish iron ore line is a major player in the Swedish economy, as the country is supplying 90% of all iron ore produced in Europe [1]. There line is split in two main sections, the northern loop (Kiruna to Riksgränsen) and the southern loop (Gällivare to Luleå). The line has continually been upgraded throughout the years as necessary, with the latest major rework being done in 2004, when the entire line was upgraded to allow for a maximum permissible axle load of 30 tonnes, an increase of 20% compared to the previous 25 tonnes (typical maximum permissible axle load). A large part of the line runs through the Swedish mountains in Lappland and the line has a relatively high amount of curves (ca. 48%), especially with a small radii (See figure 1.1).

Figure 1.1: Distribution of curves per radius on the northern loop of the line.
The line’s main purpose is to link the iron ore mine in Kiruna to the harbour in Narvik, where it is loaded onto ships for export. Naturally, this brings with it that the main traffic on the line is gonna be in the form of iron ore trains. Said trains are operated by the mining company LKAB, who are currently operating 10 trains daily per direction, running loaded to Narvik with an axle load of 30 tonnes. Two of these however loaded at 32.5 tonnes axle load as part of a study to investigate the feasibility of a permissible axle load increase from 30 to 32.5 tonnes for all trains. These extreme running conditions have lead to a number of different problems being discovered, both on rail and vehicles.

1.2 Rail damage, experience and action

As the infrastructure manager of the Swedish rail network, Trafikverket is responsible for the upkeep and safe operation of the iron ore line. As part of their responsibility, they regularly carry out inspections of the rail, both using visual inspections as well as different measurement tools. Soon after the track upgrade in 2004 an increase in rolling contact fatigue (RCF) related damage was found on the track. It mainly showed itself in the form of head checking on the high rail in curves. Nowadays, the head checking damage is under control thanks to the introduction of wear adapted rail profile, specially designed for the conditions on the iron ore line. By relieving the gauge corner of the nominal UIC60E1 rail profile, the damage situation was improved [2] (gauge corner = corner on the inside of the rail). This new profile was given the name MB1 (MB = Malmbanan, Swedish for: Iron ore line), and later an optimized wear adapted profile with the name MB4 was introduced (See figure 1.2). Although mainly used on the high rail where damage problems was identified, test was carried out with the rails on tangent track as well as on the low rail. The rail used prior to these adjustments were made used the UIC60E1 rail profile. These wear adopted rail profiles mainly differ from the UIC60E1 profile in the gauge corner, where the MB4 is 0.5mm lower at -20° and the MB1 1.6mm lower at the same angle. The rail profile on the low rail is still the UIC60E1 profile.
The effects of the new wear adapted rail profiles proved efficient as the wear on the rail has been reduced and thus the overall maintenance necessary. Besides the development of the MB1 and MB4 profiles, the grinding schedule for the track has been overhauled. In 2014 and additional yearly grinding campaign was added in order to prevent development of surface initiated fatigue. This was done in parallel with an increase in the traffic intensity, that raised the yearly Mega Gross Tonnes (MGT) from 27 to 34 MGT. In addition to this, another wear adapted rail profile with the objective of solving the low rail RCF called MB5 has been created. This profile is 0.4mm higher in the field side than the UIC60E1, which provokes a wider contact band, somewhat relieving the aforementioned RCF problems (field side = outside of the rail). It was found though that this profile, although beneficial to the low rail, actually aided the forming of RCF damage on the high rail [2]. This profile is as of now not in operation, but rather only part of the investigative efforts to control the degradation rate of the rails on the iron ore line.

Whilst the head checking issues could be resolved using a wear adapted rail profile, the low rail damage remains a problem. As Asplund et al. [2] notes there was still a problem with RCF damage in the form of material loss from the rail surface, or spalling, as it is more commonly called within the field, on the low rail of curves with a radius below 650m (See figure 1.3). A study of the track parameters was carried out, as the characteristics were quite different in the problem sections. This pointed to one common factor, a wide gauge. Wherever the damage was seen, the track gauge was wider than
1450mm. As can be seen in figure 1.3, the track gauge widening forces a very narrow contact band, pushed toward the field side, at times as small as 15mm wide, something that was not observed in areas with a narrower track gauge. This has had the unwanted consequence of low rail surface cracks developing. The concentrated loads have allowed the cracks to grow deep enough so that they may no longer be removed during the grinding campaigns. This allows the crack to propagate which results in the spalling damage visible below.

![Image of rail with cracks and spalling]

Figure 1.3: Left: Concentrated contact on low rail with wide gauge, Right: Spalling along center-line of low rail [2].

1.3 Thesis scope

With the above mentioned methods, Trafikverket has attempted to control the damage on the line, but wish to gain a better understanding of when and where the damage occurs. The current maintenance limit of 1450mm is line wide and only based on experience.

With this context, the aim of this master’s thesis will be to develop a method based on current state of the art in vehicle dynamics and contact mechanics to predict damage and better understand how the gauge width affects the risk of surface initiated rolling contact fatigue on the low rail of small radii curves.
Chapter 2
State of the Art

2.1 Rolling contact fatigue

While this thesis will be a simulation based approach to rolling contact fatigue initiated damage prediction it is still crucial to understand how it is formed, what it looks like, and what can be done to prevent it in real-world applications. This section will go over the basics of rolling contact fatigue, how it can be prevented, and finishes with a section on damage prediction.

2.1.1 An introduction to RCF

Rolling contact fatigue (RCF) is a type of fatigue damage that can occur in the sliding/rolling contact interface between two bodies. A rail vehicle driving along a track naturally involves the wheels rolling along the rail. The nature of the steel wheel on steel rail contact is such that it generates very high loads on very small contact areas, usually not larger than a coin [3]. Under the conditions present on the iron ore line, with extreme axle loads on what in essence is standard issue rails, the contact pressures can reach the magnitude of 1500 MPa.

Cracks can form either as surface or sub-surface cracks. According to Ekberg and Kabo [4], surface cracks initially grow at a shallow angle into the material. The cracks grows comparatively longer to what is experienced in railway wheels before deviating either towards the head surface of the rail, or down towards the web. A growth toward the surface will lead to a complete crack between two surface points, which then lets loose a piece of material, leaving a small pit on the surface. This process is more commonly referred to as spalling. While a growth to the surface is the most common, growth toward
the web is not uncommon, and will lead to rail breaking (See figure 2.1). Subsurface cracks are generally most commonly found on heavy-haulage lines. Initiation is most common between 3-15mm below the surface and often in the gauge corner of the high rail.

Although the iron ore line within all regards qualify as a heavy haulage line at its 30 tonnes of permissible axle load, squatting and other subsurface fatigue damage is not something that has compromised the integrity of the operations. As was touched upon earlier, head checking (small transverse cracks on the rail-head on the wheel-rail contact) has previously been a great cause of problems on the line, with extensive damage on high rails of curves with small radii. The spalling problems experienced, which also form the basis for this work, is a surface initiated damage type. It is also worth mentioning that it has previously been established that cracking of rails is especially apparent during traction application, which naturally only applies to the locomotives as the wagons are not powered [5]. Considering that 80% of the line lies in some sort of gradient, this means that a large portion of the line will experience increased traction loads due to positive gradients.

### 2.1.2 RCF detection and prevention

Methods that predict RCF damage can help infrastructure managers to optimize their maintenance programs, but the track must still regularly be controlled for defects as anomalies can appear without prior prediction. There are a number of measurement methods available, the ones employed by Trafikverket being ultra-sonic and eddy-current measurement, as well as visual inspections.

Ultra-sonic measurement as the name suggest uses ultra-sonic waves in order to determine the integrity of the rail. A set of probes transmit the waves into the rail, with a set of transducers detecting the reflection. The amplitude
of the reflected original signal, as well as the time it is returned reveals information about the state of the rail. Commonly multiple probes are used, set at different angles in order to increase the probability of detection [6]. Measurements can be carried out both manually, using a walking device, as well as with measurement trains, equipped with an array of probes and transducers, able to measure at higher speeds. Although noted by Roberts [6], ultra-sonic measurement with vehicles has shown a 90-95% success rate in detecting faults, experience from Trafikverket tells that ultra-sonic measurements have difficulties in detecting cracks smaller than around 3mm deep. This is supported by what Papaelias et al. [7] stated, although with the limit value being somewhat larger at 5mm crack depth. This is problematic as the damage at this stage is too extensive to be corrected with grinding measures.

The second measurement method used by Trafikverket is eddy-current inspection. Eddy-current inspection was for some time limited in its application, but has become more common due to its ability to detect surface cracks initiated by rolling contact fatigue [6]. The device measures the electromagnetic interaction between the sensor and the rail material, detecting damage as a change of impedance when moved over a damage area of the rail. A great complement to the shortcomings of ultra-sound, eddy-current measurements are able to detect cracks as small as 0.2mm deep [8]. In this state, grinding intervention is able to fully remove the cracks, yielding a crack free rail head once again. According to Rajamäki et al. [8], the two main shortcomings of eddy-current inspection is for one the fact that it is not able to penetrate the entire rail as the currents diminish with the depth from the surface. Secondly, as the measurement uses value comparison (real v. nominal rail impedance) it is critical to have established an accurate baseline, as it has a significant impact on the measurement accuracy.

Finding signs of defects although is only the start, if possible, a corrective measure may be necessary. To this end, there are two main methods employed, grinding and milling. Rail milling is a relatively new method of rail maintenance, and can efficiently remove large amounts of material. Its use in industry is as of 2019 limited, and it is not a method used on the iron ore line, for which reason it will not be further discussed [9].

Grinding on the other hand is a slower process, which can not remove as much material per pass as milling. Conventional grinding methods use vehicles equipped with a number of grinding stones which rotate and lie in contact with the rail. In difference of milling, which cuts the material much
like the manufacturing method with the same name, grinding removes material through the sliding between the grinding wheel and the rail [9]. A schematic of the basic grinding process, with two wheels in different orientations can be seen in figure 2.2.

In order to achieve higher material removal, multiple passes of the same section has to be made. One advantage compared to milling is the fact that it removes less material per pass, allowing for more corrections before a rail replacement is be necessary. Although it is still limited in the amount that is possible to remove. According to the current operational guidelines on the iron ore line, grinding is done between $+5^\circ$ and $-70^\circ$, and at least 0.2mm has to be removed when grinding the rails between $+5^\circ$ and $-50^\circ$ (see figure 2.3).

Figure 2.2: Railway grinding [9].

Figure 2.3: Cross-section reference for grinding operations per Trafikverket. $[+] =$ field side, $[-] =$ gauge side.
2.1.3 RCF Prediction models

One of the biggest difficulties as an infrastructure manager is to balance the amount of corrective work undertaken, compared to the cost of replacing the rails. To carry it out at too high a frequency will lead to increased costs at diminishing returns, reducing profitability of the line and overall viability of rail-transport as an option. In contrast, not doing enough poses a serious risk to operational safety, as damage can grow unobserved, in the worst case causing catastrophic accidents. Therefore, prediction tools are a necessary part of the maintenance program, as it reduces the amount of unnecessary maintenance undertaken, thus reducing the overall cost. The subject of RCF prediction was touched on in chapter 1.1, and accurate prediction of damage is critical to ensure safe operation, as well as not to over-estimate damage and replacing or grinding rail before it is necessary.

Whilst sub-surface cracks can occur, they are rare. In addition to this, the problems experienced on the iron ore line is in its very essence surface initiated through the spalling process as explained above. For this reason, most literature focus on prediction models of this type of surface initiated damage. It is also worth noting that sub-surface damage is not possible to treat with the grinding methods employed at the iron ore line and therefore require a rail replacement to be fixed.

According to Ekberg et al. [5], the propagation of initiated surface cracks is not only dependent on the repeated loading from the loaded wheels passing over, but the effect of hydro-pressurisation must also be considered. This is caused by fluids being trapped in the crack and under a compressive load creating load which works to open the crack. This is further supported by the findings of Boyacioglu et al. [10] in their case study on the Jubilee and Bakerloo lines of the London underground. Another interesting concept related to the removal of cracks, brought up by Ekberg et al. is the so called "magic wear rate", which is refers to a certain rate of natural wear in the rail contact that ensures the wearing away of initiated surface cracks before they can grow to more severe damage, in a process similar to grinding maintenance. Although his studies only looked at the phenomena w.r.t. rail wheels, Boyacioglu et al. [10] has found the similar results for rails.

The Whole life rail model

Previously, different damage prediction models have been developed. The two most popular approaches is the Whole life Rail model (WLRM), with
an energy dissipation based approach to damage prediction, and the shake-
down map, where the shear stress in the contact patch is looked at. Beginning
with the WLRM, it is based on the energy in the contact patch, which can be
described by equation 2.1 [11].

\[ T_\gamma = F_x \gamma_x + F_y \gamma_y + M_z \omega_z, \]  (2.1)

where \( \gamma_x, \gamma_y \) \& \( \phi_z \) are the longitudinal, lateral and spin creepages respec-
tively, and \( F_x, F_y \) \& \( M_z \) the corresponding creep forces and moment. This
value is compared with a damage function as seen in figure 2.4.

\[ E_i = \frac{\nu_i A}{2\sqrt{3}} (\sigma_y + \sigma_U) \]  for \( i = 1, 2, 3, \) (2.2)

Figure 2.4: \( T_\gamma \) damage function for RCF prediction [12].

The turning points marked by dotted lines in figure 2.4 are in turn depen-
dent on the contact conditions. Both through the creepage, contact area, as
well as yield and ultimate strength of the rail. The points \( E_i \) is calculated as

where the three cases in turn correspond to different levels of creepage,
with the suggested values being \( \nu_1 = 0.1\%, \nu_2 = 0.3\%, \) and \( \nu_3 = 1\% \). The
WLRM model although simple in its application, is not suitable for the prob-
lem at hand due to the very high traction forces. The model is also limited in
the way it predicts RCF. Looking only to the \( T_\gamma \) value, very different contact
conditions can predict the same value.
Shakedown theory for prediction of Rolling Contact Fatigue

The other model popularized by literature is the Shakedown map. This prediction model rather than looking at energy dissipation, looks to the shear stress in the wheel-rail contact. The underlying mechanism believed to cause surface initiated RCF is ratchetting. It is a stress state where a material experience a repeated load above its yield limit, and deforms little by little each load cycle. The shakedown name comes from the behaviour experienced before entering the ratchetting state. Generally speaking, ratchetting is not the first damage state a material enters, but it rather progresses from its basic elastic response, through a number of damage states. The three states preceding ratchetting are as described by Fouvry et al. [13]:

- Elastic
- Elastic Shakedown
- Plastic Shakedown
- Ratchetting

The same states as described above can be seen in the stress-strain diagrams of figure 2.5. The first, purely elastic state experiences no plastic deformation, and any stress induced strain will return to its initial state. If the material reaches a point where it exceeds its own yield limit, it will start to get residual strain after loading, which, due to material hardening among other things may reach a stable elastic response once again. This is what is meant by the term shakedown, that the material has fallen to a new state of deformation. Further exceeding the stress limit for the elastic shakedown region, the elastic shakedown limit, will force a transition to the plastic shakedown region. Initially, plastic deformation occurs every cycle, but stabilizes at a certain level, creating a closed loop. The final stage when the plastic shakedown limit is exceeded is called ratchetting, where the material continuously deforms in every load cycle [13].
In literature, the elastic and plastic shakedown limits are defined as functions of the contact pressure according to the hertz theory and the friction coefficient, $\mu$ [13]. In rail vehicle applications though, we rather use the utilized traction, as this represents the amount of available adhesion "working" at the contact interface.

To create the shakedown map (See figure 2.6), which in turn is used to determine the risk of RCF requires a few variables to be calculated. As explained by Hossein Nia et al. [14] the two axes are defined by the traction coefficient, $\mu$,

$$\mu = \frac{\sqrt{F_x^2 + F_y^2}}{F_z}$$  \hspace{1cm} (2.3)

where $F_z$ is the normal contact force and $F_x$ & $F_y$ longitudinal and lateral creep forces, and the normalized vertical load $\nu$,

$$\nu = \frac{P_0}{k}$$  \hspace{1cm} (2.4)

where $P_0$ is the maximum normal contact pressure and $k$ is the material yield shear stress. The Thick line across the map is the so called shakedown limit (SL, noted as BC in figure 2.6), and is roughly defined by the relationship

$$SL = \frac{1}{\mu}.$$  \hspace{1cm} (2.5)

The shape and $y$-intersection of this line depends on which failure criteria is used, with the two most popular methods being the Tresca and Von Mises methods. Selection generally depends on convention, as the methods

Figure 2.5: The four material response states as presented in [13].
are viewed indifferent with regard to the validity of the result. Previously at KTH, and in other RCF related work carried out with regard to the iron ore line the Tresca condition has been used.

In order to evaluate the simulation results with respect to the shakedown map, Ekberg et al. [15] developed the $FI_{surf}$ (Surface fatigue index) method, which determines the presence of ratchetting, and therefor RCF facilitating conditions. In summary, the index is the calculated as the distance between the SL and the working point (WP) of the current case. As the authors note, this distance will in most cases, except for very large values of $\mu$ and very small values of $\nu$, lie within a few percent of the horizontal projection of said distance (See $FI_{surf}$ and BC-WP in figure 2.6). With this, a simplified equation to calculate the $FI_{surf}$ as

$$FI_{surf} = \mu - \frac{2\pi abk}{3F_z}, \quad (2.6)$$

where $a$ and $b$ are the semi axes as per the Hertzian contact theory, and $k$ is the yield limit of the work hardened rail material.

The model predicts surface fatigue for running cases that yield a $FI_{surf}$ values larger than 0. The working point and a visual representation of both $FI_{surf}$ and the true distance between the SL and the WP can be seen in figure 2.6. The working point is simply a point representing the normalized vertical load and the traction coefficient in the current case. A limitation with the
shakedown map though, is that it and the $F_{I_{surf}}$ is only valid for full slip condition [16]. With more advanced algorithms, such as FASTSIM and FaS-trip, which considers the partial-slip condition a more accurate solution can be found.
Chapter 3

Methods

3.1 Track and vehicle models

As with any simulation, an accurate representation of the real-world conditions are both in most cases the most challenging and critical part to get right. While this can be difficult to achieve, knowing the nominal performance and specification of the input variables is somewhat easier. As such, this first section will discuss the vehicle and track models that have been used, and some of their general characteristics.

3.1.1 Vehicle models

As has been previously mentioned, the iron ore line sees a mix of traffic on it, with the bulk being ore trains from the mines in Kiruna. Focusing on these, this section aims to explain the vehicles in more technical detail, how they will be used, and what variables in their specifications that will be considered.

IORE locomotive

Tasked with hauling the up to 8000 tonnes of iron ore, the aptly named IORE (read Iron ore) locomotives developed and manufactured by then AdTranz (currently Bombardier transportation) for the mining company LKAB specifically. The locomotives are always operated as a pair, with a total weight of 360 tonnes over 12 axles. The each locomotive run on a pair of Bombardier Flexx Power 120H bogies, in a Co’Co’ configuration, meaning that they are three axle bogies, where each axle is independently driven. A short summary of some important vehicle parameters can be found in table 3.1:
Table 3.1: Per unit vehicle parameters for the IORE locomotive [16].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>22.9 [m]</td>
</tr>
<tr>
<td>Bogie pivot center distance</td>
<td>12.89 [m]</td>
</tr>
<tr>
<td>Bogie wheelbase</td>
<td>1.92 [m]</td>
</tr>
<tr>
<td>Width</td>
<td>2.95 [m]</td>
</tr>
<tr>
<td>Height (Lowered Pantograph)</td>
<td>4.465 [m]</td>
</tr>
<tr>
<td>Weight</td>
<td>180 [t]</td>
</tr>
<tr>
<td>Max. speed</td>
<td>80 [km/h]</td>
</tr>
<tr>
<td>Wheel diameter (New/Final re-profiling)</td>
<td>1250 / 1179 [mm]</td>
</tr>
</tbody>
</table>

The vehicle model for the simulation application GENSYS has been developed by Hossein Nia [16] in connection to his PhD-thesis.

As has been previously mentioned, a number of the departures are running at an increased axle load. In these cases, the locomotive’s axle load remain the same. Additionally, the effect of the different wheel diameters after each re-profiling is necessary to consider. These diameters are provided by measurements done in the workshop at LKAB and can be found in Table 3.2. Due to the limited running distance of the locomotive wheels before re-profiling (<50000 km, [16]) only the nominal wheel profile will be used.

Table 3.2: The diameter of the locomotive wheel after each re-profiling [17].

<table>
<thead>
<tr>
<th>Reprofiling no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [mm]</td>
<td>1250</td>
<td>1222</td>
<td>1200</td>
<td>1176</td>
</tr>
</tbody>
</table>

**Kiruna Wagon Bottom dumper**

For transportation of their iron ore, LKAB uses Fammoor050 wagons made by Kiruna Wagon. These are bottom-dumper designs, which allows for quick unloading at the harbour of Narvik, minimizing the downtime of the trains. Like the locomotives, the wagons operate in pairs of two, with one master unit equipped with braking system controller and one passive slave unit. They are running on two three-piece frictional damping bogies with two axles each, and have a maximum payload capacity of 100t, or a maximum axle load of 30t. One train may consist of as many as 68 of these units (34 master+slave pairs) in addition to the two locomotives. A summary of the important parameters belonging to the wagons can be found in table 3.3. Just as the I-ORE loco-
motive, the vehicle models have previously been developed by Hossein Nia [16].

Table 3.3: Per unit vehicle parameters for the Kiruna Wagon wagons.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>10.29 [m]</td>
</tr>
<tr>
<td>Centre plate distance</td>
<td>6.77 [m]</td>
</tr>
<tr>
<td>Bogie wheelbase</td>
<td>1.778 [m]</td>
</tr>
<tr>
<td>Height</td>
<td>3.64 [m]</td>
</tr>
<tr>
<td>Width</td>
<td>3.49 [m]</td>
</tr>
<tr>
<td>Tare weight</td>
<td>20 [t]</td>
</tr>
<tr>
<td>Max. payload</td>
<td>100 [t]</td>
</tr>
<tr>
<td>Wheel diameter (New/Final re-profiling)</td>
<td>915 / 857 [mm]</td>
</tr>
</tbody>
</table>

As with the locomotive there are a number of parameters above that change in operation. One, naturally is the load, which is varied between the three states unloaded (5t per axle), normal load (30t per axle) and super loaded (32.5t per axle). The wagon wheels run much longer than the locomotive before being re-profiled, which is why it was decided to use two wheel profiles, which allows for consideration of wheel wear. The worn profile was measured in 2019 on a wheel that had run 168,000 km, which is roughly two thirds of the nominal running distance before re-profiling, 250,000km. The target diameter of the wagon wheels after re-profiling have also been provided by LKAB and are listed in Table 3.4, variations to these numbers are dependent on any apparent damage on the wheels.

Table 3.4: The diameter of the wagon wheels after each re-profiling.

<table>
<thead>
<tr>
<th>Reprofiling no.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [mm]</td>
<td>915</td>
<td>898</td>
<td>882</td>
<td>864</td>
</tr>
</tbody>
</table>

### 3.1.2 Track data

Trafikverket has an extensive database of track design data, as well as line measurements and maintenance logs, yielding excellent reference data for the track which can be used for simulation purposes. With the aim of investigating the effect of the track gauge on the creation of RCF initiated rail damage, this is the only parameter which will not be taken from measurement data, but will rather be a controlled variable with the purpose of seeing the effect it has on the contact conditions between wheel and rail. One important input to consider...
is the track irregularity. From the measurements, line and longitudinal level irregularities (see figure 3.1) are used in the simulations. It can be mentioned that also cant irregularity and gauge irregularity are also measured, but the former has no effect on the classification which will be used and the latter is not used as track gauge is a controlled variable.

Beside track irregularities, the rail itself also experiences changes over time. Friction is also a factor that needs to be considered, and in this regard, the conditions on the Iron ore line are vary a lot depending on environmental and operational conditions. Values used will lie in the range from 0.2 to 0.6, with 0.1 increments yielding five values in total. Something that simplifies the simulations is that all curves on the northern loop of the line are using the UIC60E1 profile on the low rail of curves, and the MB1 profile on the high rail, both inclined at 1:30. Because of this, two different rail profiles are used, one new and one worn, for each rail. They will always be used in combination as both naturally would be ground together following a regular maintenance schedule, meaning that any divergence from this state would be through unexpected damage. Comparisons of the nominal and worn rail profiles can be seen in figure 3.2a & 3.2b. It is clearly visible that there is a considerable amount of gauge corner wear on the high rail (Fig. 3.2b), coinciding with early observations made as was stated in Chapter 1.

![Figure 3.1: The four measured forms of irregularities [16].](image)
Figure 3.2: Comparison of the new and worn rail profiles used for simulations, (a) = UIC60 (low rail), (b) = MB1 (high rail).

Finally, it is worthwhile mentioning an artefact of the simulations that comes as a result of the the initiation step of the simulation. During the first few seconds of the simulation, the vehicle acts in a disturbed manner, as it is simply dropped on the track with curve and cant, unsettling it, which may give unrealistic effects on the results. To mitigate this, a zero-irregularity tangent track section is created before the curve, on which the vehicle can stabilize, before entering the transition curve leading to the curve itself. In figure 3.3, a plot over the curvature can be seen with comments on where curve, transition, and tangent track are.

Figure 3.3: Figure explaining how the curve is inputted in GENSYS, 1 = Tangent track, 2 = Transition curve, 3 = Curve at radius.
The track measurements are a combination of irregularity measurements from 2014, along with an updated curvature measurement which was done in April of 2019.

### 3.2 Simulation and post-processing

With the vehicles and the track defined, one may proceed to the simulation stage. Which software is used, and what methods you apply to solve problems within the simulation, such as the contact-stress solution, will have an impact on the results. In this section, the simulation software and post-processing solutions will be discussed.

#### 3.2.1 GENSYS

In order to carry out the investigation the track gauge has on RCF initiated rail damage, simulations will be the main tool at hand. For this purpose, many different vehicle dynamics and multi-body simulation software can be used. Modelling of railway vehicles in Sweden started in the 1970s at the then named ASEA AB (Today ABB), with simple linear programs in the frequency domain, and although useful, the engineers had bigger plans. Already in the 1960s plans for the X2 tilting train were laid out, and these linear programs would not be enough. Development of a non-linear time-domain program started in 1973 and was first presented in Graz in 1977. Called SIMFO, it was used in developing the X2 train and was what later led into the development of the 3D multi body dynamic program that is GENSYS in 1992. The latest version of the program available when the project was started, GENSYS-1908 build, will be used for the simulations.

#### 3.2.2 RCF calculation

Naturally, to study the presence of RCF an evaluation model will be needed in order to decide on the prevalence of it. Some of the basic prediction models that exist were described in chapter 2, under the title RCF Prediction, while this section will discuss the actual algorithms used to solve the tangential stress problem using the output data from the GENSYS simulations. These algorithms are necessary in order to solve the stresses in the contact patch, which in turn are used to predict RCF.
**FASTSIM-algorithm**

A recognizable name within the field of contact mechanics and rolling contact is Joost J. Kalker. Not only did Kalker define his own theory on contact mechanics, but also produced solutions for the contact problems themselves. CONTACT is a solution to the complete Kalker theory, but is rarely used in vehicle dynamics simulations. It is a very rigorous solution, and thus demanding to calculate, which makes it time consuming. To get around this, Kalker introduced the significantly faster FASTSIM algorithm [18]. It is based on the simplified theory of rolling contact, which in short assumes that the surface displacement at a point depends only of the surface traction in that same point, rather than as the theory of elasticity states that there is a dependency between the displacement of a point on the surface with the surface traction of all other points on it.

**Strip theory**

Strip theory is a contact mechanics approach to solve the surface shear stresses in rolling contact. In 1926, the first 2 dimensional theory was presented by Carter [19]. By approximating the contact area between a cylinder (wheel) rolling on a plane (rail), the surface shear stresses could be calculated, albeit under the assumption of no spin. The theory has been expanded, in 1958 and 1964 by Johnson [20] and Vermeulen and Johnson [21] to be extended into a three dimensional case with two spheres rolling, that could include both lateral and longitudinal creep. Haines and Ollerston [22] and Halling [23] extended Carter’s theory in 1964 where the elliptical contact patch described by Johnson and Vermeulen is divided into a number of strips in the rolling direction. This way, Carter’s solution is applicable to all strips individually assuming there is no interaction between them. This is what is called strip theory, and is only valid for pure longitudinal creepage, and shows agreement with experiments. A limitation of this theory has always been its inability to accurately estimate the shear stress in the contact surface with spin. Only in Kalker’s model from 1967 [24], spin up to a limited level ($\text{abs}(\phi) < 1$) can be handled, and its accuracy is also reduced with a larger ratio between the semi-axis of the contact patch ($\frac{a_0}{b_0}$).
FaStrip-algorithm

In 2016 a new, novel method for solving the contact problem was presented by Sh. Sichani et al. [25] at KTH. By combining FASTSIM and strip theory, the new method named fast-strip, or FaStrip is able to be as fast as the FASTSIM method, while achieving a significantly higher accuracy. For example, it was found that using the shear stress from the strip theory gave a more accurate estimation of the growth of the forces in the stick zone from the leading edge. The main improvements include the ability to be able to handle a larger amount of lateral creepage and spin, with a lower error in force estimation, as well as a better estimation of slip velocity distribution which in turn improves wear analysis according to the Archard method. For prediction of RCF damage, the shakedown method from chapter 2.1.3 is used, which applies the stresses calculated within the FaStrip-algorithm. This method has previously been used for similar projects at KTH ([26] & [16]) and is the method that will be used for this project as well.

The Polach modification

One of the shortcomings of the FASTSIM-algorithm is that it yield the maximum adhesion value at lower creepages than in measurements. Something that becomes a problem for locomotives where the creep values are usually large, and the agreement between simulation and measurement deteriorates.

By replacing the earlier constant Kalker reduction factor used in the FASTSIM code [27], with a variable one (a variable reduction factor is already included in the FaStrip code, but is modified in the Polach addition), along with an empirical creepage-dependent friction coefficient, agreement between simulation results and measurements showed a notable improvement at large creepages, without any modification of the modelling methodology used at low creepages. This theory was first developed by Polach [28], and has been implemented on the FaStrip algorithm by Hossein Nia, S. of the Railway Group at KTH.
3.3 Simulation strategy

With models and methods defined, this section will discuss the simulation strategy at large, and how problems such as time constraints have been approached, and influenced said strategy.

3.3.1 System integration

In order to be able to handle the large amount of data that will have to be processed, a form of automation in the software is necessary for the work to even be feasible to complete within the given time frame. Although GENSYS has tools to do this, it is far more convenient to use a separate software, in this case MATLAB. Using MATLAB to create the running cases allows for automatic calculation of all running cases for a given track section (read curve). This not only simplifies this stage of the simulations, but also allows for easier file management in the post processing stage, when the RCF is calculated.

3.3.2 Model validation

In order to validate the results outputted from the GENYS model, a more detailed analysis of a certain section of the line will be performed, where the location and magnitude of the risk of RCF on the rail surface will be more closely looked at. Trafikverket has specified the last section of the line from Vassijaure to Riksgränsen as the one to use for this purpose.

The curve in question is a left-hand curve with radius of 508m. The thresholds calculated for this curve will be used for all simulation cases, regardless of radius. Only the real track gauge, irregularities, and rail profiles will be used in these simulations, all vehicle parameters will remain as stated in the respective sections above. The rail profile and track gauge measurements were done in May of 2019, with only a few weeks between them. At this time, the track gauge was 1477mm. The traffic scaling will be done with the same variables as the rest of the simulations.

As the real gauge and rail profiles are used, a limit value in terms of Shear stress and gross ton passing with RCF can be decided. The final ingredient in order to calculate this limit is the expected time it takes for rolling contact fatigue to appear on the rail in its current state. Discussions with maintenance engineers are used as a reference when it comes to deciding the threshold as
when RCF appears. This has resulted in a period of 3.5 months, or 105 days, before damage appears at the current state of the track.

### 3.3.3 Full scale investigation

The northern loop of the iron-ore line has a total of 113 curves with a radius below 750m, which from the get go presents a difficulty. The capacity to carry out simulations on this scale does unfortunately not exist, without access to super-computing resources, which means a selection has to be made. Considering the vehicle parameters, five curves, one in each 50m interval from 500-750 meters will be selected and will represent a larger sample. Differences in track alignment, specifically the cant excess/deficiency is no considered here and is discussed in more detail in further down. The curves selected for simulation, and their radius can be seen in Table 3.5.

Table 3.5: The five curves selected for evaluation with their respective curve radii, location on the line and cant deficiency (negative value indicates cant excess).

<table>
<thead>
<tr>
<th>Curve no.</th>
<th>Radius [m]</th>
<th>Start km</th>
<th>End km</th>
<th>Cant deficiency [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>112</td>
<td>508</td>
<td>122.216</td>
<td>122.689</td>
<td>-11.2</td>
</tr>
<tr>
<td>58</td>
<td>594</td>
<td>78.086</td>
<td>78.446</td>
<td>-1.3</td>
</tr>
<tr>
<td>45</td>
<td>621</td>
<td>61.930</td>
<td>62.105</td>
<td>-21.3</td>
</tr>
<tr>
<td>12</td>
<td>683</td>
<td>13.735</td>
<td>14.155</td>
<td>1.3</td>
</tr>
<tr>
<td>35</td>
<td>724</td>
<td>47.153</td>
<td>47.313</td>
<td>7.4</td>
</tr>
</tbody>
</table>

Some of the limitations above mentioned has been taken both with regard to real life conditions, but also with workload in mind. With the current set up, the simulations amount to a total of 15,400 different running cases, which means that an iterative approach will not be possible. What this entails in practice, is that the results will be scaled up in accordance with how probable they are to appear. For example, the traffic in terms of axle loads is available from time tables, while other distributions, such as wheel diameter and wheel rail friction has to be assumed. Figure 3.4 contains a summary of all the individual parameters used in the simulations.
Assumptions in traffic scaling

In order to create the strategy as above, a number of assumptions are necessary. There are of course more than what is stated here, as many of the models and methods used are simplifications of reality. One part of this is the effect of cant deficiency/excess, and how this influences the risk of RCF initiated damage. Secondly, in order to be able to compare the time it takes for RCF to appear, with the real world observations, assumptions about the traffic has to be made.

Rather than looking at each curve individually, the strategy is to select one curve in each 50m radii segment as described above, and to use this as a representation of a larger set. By comparing two curves with significantly different cant excess/deficiency, the magnitude of the influence from this factor can be better understood. For this comparison, two curves with a radius of 604 and 609 meters in radius respectively, which will henceforth be referred to as C1 and C2 are selected. These have the largest amount of cant deficiency and cant excess respectively, at 28mm and 42mm. This test is also limited as it only considers normal friction conditions ($\mu = 0.4$) and the nominal rail profile, and a rougher track gauge step of 10 mm, rather than the 2mm used in the full scale investigation. The summary of those simulation results can be found in Table 3.6 with comments below. Three values have been used to compare the different cases. For one, the difference in surface fatigue index ($F_{I_{surf}}$) which is the main predictor of the shakedown model used. In addition, the maximum difference in longitudinal and lateral shear stress (which are both...
used to calculate the $F_{I_{surf}}$) are shown, in order to highlight the difference in magnitude between the two curves.

In the case of the wagon’s two loaded cases, there is a difference in shear stress, but more importantly, the $F_{I_{surf}}$ is indifferent, suggesting that the same deformation type in both cases (elastic v. plastic). For the locomotive, there is a difference, it should be noted though, and suggest this might influence the results.

Table 3.6: Comparison between the two aforementioned curves C1 and C2 with radius 604m and 609m respectively.

<table>
<thead>
<tr>
<th>Vehicle (Absolute differences)</th>
<th>$\Delta_{\text{max}} F_{I_{surf}}$</th>
<th>$\Delta_{\text{max}} \text{ long. shear stress [MPa]}$</th>
<th>$\Delta_{\text{max}} \text{ lat. shear stress [MPa]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loco (C2 to C1)</td>
<td>1</td>
<td>54</td>
<td>560</td>
</tr>
<tr>
<td>Wagon nominal wheel (C2 to C1)</td>
<td>0</td>
<td>81</td>
<td>194</td>
</tr>
<tr>
<td>Wagon worn wheel (C2 to C1)</td>
<td>0</td>
<td>221</td>
<td>53</td>
</tr>
</tbody>
</table>

The other issue, regarding the traffic, concerns mainly friction, wheel/rail characteristics, and load. These are three parameters that all affect creation of RCF initiated damage, and have to be considered. Since the model is not using wear updating, the friction, wheel/rail characteristics, and load will have to be scaled with the expected traffic for one wear period, in this case three months (105 days). Some things, such as the distribution of loads on the vehicles is known from the traffic schedule, but other parameters like the friction will include estimations of the distribution of values. The equally distributed parameters in the model are wheel and rail diameters/profiles. These are assumed to be equally likely to appear in traffic, yielding a scaling factor $p_d = 0.25$ for each wheel diameter and $p_r = 0.5$ for each rail profile. For the wagon one additional parameter is considered, namely the wheel profile, as both a new and a worn one is used, yielding $p_s = 0.5$, with both alternatives equally probable. Traffic scheduling tells how large portion of the traffic is at which axle load. With 10 departing trains per day from Kiruna, and 2 at 32.5 tonnes axle load per day, the weights for the locomotive and wagon as per Table 3.7. Note that the weight of the locomotive is unchanged regardless of the weight of the wagons.

Table 3.7: Distribution of axle loads for the traffic on the Iron ore line

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>32.5t</th>
<th>30t</th>
<th>5t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Locomotive</td>
<td>N/A</td>
<td>100%</td>
<td>N/A</td>
</tr>
<tr>
<td>Wagon</td>
<td>10%</td>
<td>40%</td>
<td>50%</td>
</tr>
</tbody>
</table>
The final parameter to be mentioned here is the friction. Conditions on the Iron ore line create a very varying friction condition between wheel and rail. Where melting snow may have a lubricating effect and reduce it, a very dry winter with extremely low humidity may increase it. In discussion with the supervisor and experience from Trafikverket, the friction can reasonably be assumed to vary between 0.2 and 0.6 on the tread. This distribution although is not as simple as the aforementioned ones, as it is not necessarily equally distributed. Instead, 1000 numbers on the interval 0.2 to 0.6 with 0.1 increments are randomly generated from a normal distribution with \( \mu = 0.4 \) and \( \sigma = 0.1581 \), after which the probability of the appearance of each friction number is calculated. This yielded probabilities as per Table 3.8.

Table 3.8: Distribution of wheel-rail friction values for the simulations

<table>
<thead>
<tr>
<th>Friction, ( \mu )</th>
<th>0.2</th>
<th>0.3</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability [%]</td>
<td>8.2%</td>
<td>25.4%</td>
<td>32.8%</td>
<td>25.4%</td>
<td>8.2%</td>
</tr>
</tbody>
</table>
Chapter 4

Results

In this section, the results from the simulations will be presented in sections regarding each of the curves. Each section will be accompanied with comments on the results which form the basis for chapter 5. Before the full set results are presented, some comments on the results from the validation curve will be presented, along with the found limit values which are used in the former mentioned parts. As this thesis has not been focused on the high rail, those results have been moved to Appendix A.1, the plots and the way they are to be read remain the same as in this chapter though.

The three sections will cover the complete results for each curving case, both damage calculations and damage locations. Beyond this, three sections focusing on the curve comparison, cant deficiency and damage location will be presented.

4.1 Validation case

The validation case provides a reference value which for the other simulations will be a do not exceed value related to the RCF creation on the rail. It also provides and opportunity to study how well the predicted damage contact band aligns with visual inspections. The limit values for each of the two rails using both the mega gross tonnes of axle passes and accumulated shear stress above the shear strength of the rail can be seen in table 4.1. These are the values that will be referenced in the subsequent result plots for the full scale investigation.
Table 4.1: Limit values calculated for the high and low rail used to evaluate the results.

<table>
<thead>
<tr>
<th>Rail</th>
<th>Limit in MGT with RCF</th>
<th>Limit in accumulated shear stress [MPA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low rail</td>
<td>0.357</td>
<td>7,430,000</td>
</tr>
<tr>
<td>High rail</td>
<td>0.095</td>
<td>1,460,000</td>
</tr>
</tbody>
</table>

By plotting the location of the contact points with RCF, one is able to identify where on the rail approximately the contact band lies. Comparing this plot with a photograph, taken of the rail in this corner in May of 2020 (See. figure 4.1) it is possible to see that there is a good agreement both in width of the damage contact band, as well as location. It is important to note that the plot only includes points with RCF, and does not include all points with contact, which explains the width difference. The top of rail on the in the plot is slightly skewed toward the gauge side, meaning that rather than lying on the zero point, it lies closer to $-5$ on y-axis in figure 4.1a. The region indicated in the aforementioned figure then lies slightly skewed to the field side on the top of rail band, which agrees well with the location of the spalling damage found on rails in visual inspections (See figure 1.3).

![Contact points with RCF, Low Rail](image1)

![Field side, 30mm contact band, Gauge side](image2)

(a) (b)

Figure 4.1: Picture comparing the calculated RCF contact band (a) with the real life contact band (b). A brighter colour indicates more contact cases with RCF.
4.2 Full scale investigation

As a comment to the reader, the diagrams used in this section will be thoroughly explained in 4.2.1 for future reference in the following sub-chapters, where references to the figures will be lighter, and not describe the data plotted in the same detail. As was touched on before, the results presented here are only for the low rail.

4.2.1 Curve 1, Radius 508m, Cant deficiency -11.2mm

The first results are from the curve with a radius of 508m. Adjusting the result after traffic and track conditions per above, the first results show the accumulated mega gross tonnage (MGT) that has passed with a contact patch condition that facilitates RCF over the determined 105 day period on the low rail of the curve (See figure 4.2). The figure is split in two parts, the left bar chart showing the passed MGT with RCF per train specification. Each bar stack represents one 105 day period at the specified gauge. The thin black horizontal line represents the limit value as calculated per Table 4.1, a stack higher than this line indicates that RCF is predicted to appear faster than what is currently observed in the field. The line chart to the right indicates how many percent of the load cases with the specified vehicle combinations induces RCF at each track gauge.

The results show a stable behaviour up to 1447mm, with a slight increase at 1443mm in gauge width. From 1447 up to 1451mm, a new plateau is reached, where damage is at a stable level. Beyond 1451mm, the values increase dramatically, indicating a significant shift in the contact behaviour. By comparing the bar chart with the line plot showing the relative amount of MGT with RCF, it is possible to attribute the increase to the overall vehicle behaviour, and not any specific load case. It is also noteworthy that the wagons running empty have a larger magnitude of load cases with RCF at any given track gauge.
Figure 4.2: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the low rail at R508m, L = locomotive, W = wagon.

Figure 4.3 shows the simulation regards but expressed in terms of accumulated shear stress above the yield limit in 105 days. The bar chart on the left is identical to what was presented in figure 4.2 in all but the Y-axis, where accumulated shear stress in 105 days of running is indicated. The right plot in turn shows the value of each of the bars at each gauge, easier relating them to one another.

It is possible to see a clear trend that the loaded and unloaded trains at each gauge is very close together (only considering the loaded trains at 30t axle load), this suggests that the additional MGT passages with unloaded wagons is not of a very large magnitude, compared to the locomotive. There is a large difference between the trains running at 30t and 32.5t axle load, which boils down to the different amount of vehicles running, something which gives a lower overall damage accumulated. Also here, the maintenance limit of 1450mm lies close to the fall of point where the amount of shear stress accumulated greatly increases, and subsequently the amount of RCF damage.
4.2.2 Curve 2, Radius 594m, Cant deficiency -1.3mm

Looking at the results of the second curve, the behaviour is quite different to those of curve 1. Firstly, the magnitude of the amount of MGT is lower, this is not unexpected as overall lateral forces tend to decrease with an increase curve radius, as well as the steering requirement on the bogies, which in turn yields a nicer contact condition. Here though, the amount of MGT with RCF passing is steadily increasing from 1443mm, up to 1453mm, where it jumps dramatically, as in curve 1. The large fall-off at 1455mm is mainly attributed to the loaded trains. This can be observed by looking to the relative amount of MGT with RCF, which shows a kick at 1455mm for the red and blue lines, corresponding to the loaded trains at both axle loads. Again, the unloaded trains show the highest relative amount of RCF, but their relatively low tonnage tones down its influence on the accumulated values in the bar chart.
Looking at the accumulated shear stress above the yield limit (See figure 4.5), the same pattern as for the development in figure 4.4 is visible, gradually increasing from 1443mm, before a similar dramatic fall off point at 1455mm is reached. This is also visible in the line plot, showing a clear increase for the loaded trains at 1455mm. The same pattern as could be witnessed for for the first curve, with the accumulated shear stress of loaded and unloaded vehicles being even is also visible here, indicating that the higher appearance of conditions which induce RCF for the wagons is offset by the higher shear stress values with the loaded trains. Only at 1455mm a large difference between the two is visible.
Figure 4.5: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the low rail at R594m, L = locomotive, W = wagon.

4.2.3 Curve 3, Radius 621m, Cant deficiency -21.3mm

The third curve is of course yet larger in radius, but also has the largest cant excess of the simulated cases. Here, there is a significant first rise in the amount of MGT passing with RCF first at 1441mm gauge, before rising steadily from 1449mm to the final gauge width 1455mm (See figure 4.6). Also visible is that the fall-off point behaviour visible in figures 4.2 & 4.4 at the higher gauge widths. As before, there is a difference between loaded and unloaded vehicles in terms of how many of the running cases yield RCF, with a change at the lower gauges, where there is no distinguishable difference up to 1439mm in track gauge.
Figure 4.6: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the low rail at R621m, L = locomotive, W = wagon.

Looking at the shear stress diagrams in figure 4.7 the stress gradually increases with its beginning at 1441mm, with a similar plateau as in figure 4.6 up to 1449mm, where the accumulated shear stress starts to increase rapidly. Another observation that can be made by looking at the line plot in figure 4.7, is that the curve pulling away at the largest track gauges is the unloaded wagons, suggesting that the larger cant excess is influencing the behaviour of the unloaded wagons negatively. This agrees well with the same plot in figure 4.3, although more extreme in this case.
4.2.4 Curve 4, Radius 683m, Cant deficiency 1.3mm

The next curve at 683m radius shows a big change. Two of the more obvious observations that can be made is that, firstly, virtually no change in the amount of MGT with RCF is registered from 1435mm to 1445mm in track gauge. From 1449mm and beyond the pattern is familiar from earlier pictures. Secondly, the limit value is now only breached by the very largest gauge simulated at 1455mm. The line plot showing the percentage of the traffic which induces RCF is similar to what was seen in the previous curves.
Figure 4.8: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the low rail at R683m, L = locomotive, W = wagon.

The same trends that could be seen in the previous figure can be observed in the accumulated shear stress results in figure 4.9. The absence of the fall of point is clearly visible in the line plot, as the rate of accumulated shear stress between track gauges remain stable beyond 1447mm. It was briefly mentioned in the previous curving case that cant excess seems to negatively impact the unloaded wagons. This statement is further supported as in this case there is only a small difference between the unloaded and loaded wagons at 30t axle load.
4.2.5 Curve 5, Radius 724m, Cant deficiency 7.4mm

For the largest curve investigated in this thesis, the trend from the previous cases continues. Visible in figure 4.10, it shows how there is a constant level of RCF up until 1445 mm track gauge, where there is a change in how it develops toward the higher gauges. From 1447mm, the rate of change between gauges steady, before reaching the aforementioned fall-off point at 1451mm, where the appearance of RCF inducing conditions dramatically increase. The line plot reveals that the three running configurations are indistinguishable until 1445mm gauge, where the unloaded wagons start growing ahead of the two loaded configurations. Another significant change is that this is the first curve, that with regard to the reference case in terms of MGT, does not reach the calculated limit value in 105 days of traffic.
Figure 4.10: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the low rail at R724m, L = locomotive, W = wagon.

The accumulated shear stress plots (figure 4.11) align with the observations made above. Also this method of calculation reveals no breach of the limit value for the set 105 day period. As has been previously seen, there is no significant difference between the loaded and unloaded case looking to the line plot. There is still a significant increase in the rate of change in accumulated shear stress between gauges after 1451mm.
Figure 4.11: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the low rail at R724m, L = locomotive, W = wagon.
4.2.6 Comparison of the damage in the five curving cases

Figure 4.12 shows a comparison between the five curving cases, in terms of how many days it takes to reach the limit value calculated in the validation case, at five of the track gauges simulated (1435mm, 1441mm, 1445mm, 1451mm & 1455mm). Studying the graph highlights the dramatic change in wear rate from gauges below and above 1450mm. It then becomes evident that there is a difference in terms of the behaviour on the vehicles above and below the limit, indicating that the currently set maintenance limit coincides well with this gauge width.

Figure 4.12: Number of days to reach the damage limit at five track gauges (1435mm, 1441mm, 1445mm, 1451mm & 1455mm), for each of the five curving cases.
4.3 The influence of cant deficiency on RCF

As was discussed with regard to figure 4.9 an observed influence of cant deficiency can be seen in figure 4.13, highlighted by the red circle in the two curve cases. Here, the shear stress plots from curves three and four are shown. What can be seen is that, at the highest track gauge, the amount of accumulated shear stress for the vehicles with unloaded wagons rises significantly faster than the vehicles with standard load wagons (30t axle load). The former case at radius 621m has a cant deficiency of -21.3mm, or a cant excess of 21.3mm, while the latter case at 683m has a cant deficiency of 1.3mm, very close to equilibrium cant.

Figure 4.13: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the low rail at (a) R621m and (b) R683m, L = locomotive, W = wagon.
4.4 Rail damage contact bands

In figure 4.15, the location of the rail RCF damage at each of the track gauges after 105 days is plotted. There is no scale as this only serves as a visual aid to the plots presented earlier. This type of plot allows for an overview of where damage can be expected depending on the current gauge width on the line. The same skew to the plot as was mentioned with regard to figure 4.1a is true here as well. What can be seen is a clear pattern in all curves that the damage concentration is the highest at the center of the rail with the majority of the damage appearing at track gauges above 1445mm. At the wider gauges, the plotted RCF contact points see similar intensities, and it is in the lower range that there is a clear difference between the five curves. As an example, the first curve at 508m has both more intense and wider band of RCF contact at the narrower gauges.

Comparing the damage locations for the smallest curve at R508m, with the contact band which was photographed in May of 2020 in the same curve, where spalling damage can be seen (see figure 4.14), a good agreement between simulations and real-life experience is seen. As was mentioned in association with figure 4.1, the top of rail in the simulation plot lies around the -5 point, which corresponds to the lower edge of the contact band in the picture of the rail.

Figure 4.14: Comparison between simulated damage points on the low rail in curve one with actual damage on the rail.
Figure 4.15: The damage contact band on the low rail after 105 days at each gauge on each curve radius, brighter colour indicates more load cases with RCF (X-axis: Track gauge [mm], Y-axis: Lateral position[mm]).
Chapter 5

Discussion

In this chapter, the results as presented in Chapter 4 will be discussed in order to attempt to better understand the studied effects and its consequences.

Firstly, it is worth noting that in relation to the results, the current, empirically developed gauge width maintenance limit of 1450mm, compares favourably to them. Especially in the smallest curve radii, there is a clear trend of the contact conditions worsening considerably after 1451mm. If one also considers the margin of error that has to be accounted for within any simulation built on simplified theory and the limited parameters used to calculate the reference value, it is possible that it might occur slightly earlier, although not visible in the results.

Secondly, it is interesting to observe that the trains running with unloaded wagons seem to perform worse in terms of the number of unique load cases that experience contact conditions facilitating RCF. Naturally, any difference between the two cases can be attributed to the difference in wagon loading, as the locomotives have the same axle load regardless of the wagons. This result could possibly stem from the fact that the wagons, which are using three-piece bogies with friction dampening have a different dynamic behaviour. In essence, the wagons steering ability is worsened at lower loads, which increases wheel-rail wear. This is increased further with high wheel-rail friction, something that is abnormally apparent on the iron ore line where temperatures are normally low and humidity as well. In addition to this, it was also noted that the empty wagons performed worse in curves with cant excess (see figure 4.13), suggesting that limiting the cant excess would reduce the damage caused by the unloaded wagons. Here it must be noted that there is a higher permissible speed for unloaded wagons, which should mitigate this effect in practice, but the speed logs used for the simulations here have been from loaded vehicles.
Another item which is of great interest to the rail operator LKAB is of course the prospect of running traffic regularly at 32.5t axle load regularly, as is already being done on the southern loop. Although there are no significant differences when looking at the relative amount of the traffic running with RCF, how this translates in accumulated shear stress values is varying. For example, in the line plot in figure 4.5 it is possible to note that the accumulated shear stress at 32.5t axle load is slightly larger than one fourth of the same value at 30t. This is easiest seen by looking at the largest gauge of 1455mm. This is somewhat in disagreement with observations made by Trafikverket, which states that the damages increase significantly when heavier trains are used.

Finally, the results show a good agreement in contact band RCF prediction when compared to real life observations. The damage contact band begins relatively far toward the gauge side at narrower gauges, moving toward the top of rail band with increasing gauge width. The main damage have been observed on the center of the rail (see figure 1.3) and this is also where the highest concentration of damage is found, especially at the wider gauges. It is also further supported by the currently taken pictures of the track (see figure 4.14), where the damage location in the simulation shows a good agreement with the actual damage (which is a lot less severe than in figure 1.3).
Chapter 6

Conclusions and future work

6.1 Conclusions

The Swedish transport administration, Trafikverket, are responsible for the up-keeping of a majority of the railways in Sweden, including the Heavy-haul Iron-ore line northern Sweden. As such, Trafikverket has experienced issues in the form of surface initiated rolling contact fatigue damage on the low rail of small radii corners. It is believed that track gauge widening is a driving underlying factor, and wished to investigate if their current maintenance limit is set appropriately. By applying current state of the art in vehicle simulation and contact mechanics an investigation has been made at eleven track gauge widths and a total of five corners, as well as a number of vehicle and rail parameters.

Validity of the current gauge width maintenance limit of 1450mm

Based on the results from these simulations, it can be concluded that the current maintenance limit set at 1450mm is appropriate for the current running conditions. The most important change that could occur in the future, namely an increase in the permissible axle load to 32.5t has to consider that the maintenance limit possibly would have to be lowered in order to not have the track deteriorate at a rate higher than what is currently expected. Something that it crucial to note is that this work as has been stated only focuses on the Swedish side of the line, and that there is another 43km of rail running from the border to the Norwegian harbour city of Narvik that also would affect any decision to run heavier trains.
6.2 Future work

Enhanced parameter study

One of the major limitations in the work of this thesis has been the exclusion of studying the effect of cant deficiency/excess on the running performance in detail. Since the results show evidence of different behavior based on the cant deficiency/excess in the corner, it is something that would be interesting to study going forward, especially considering the potential support it could lend to allow an increase in the permissible axle load on the line.

It is also suggested that to evaluate the damage rate better, track inspections could be performed at a higher frequency, allowing for a better understanding of how damage develops. The current figure is based on observations, but the normal inspection interval, which runs parallel with the grinding campaigns, is twice per year. Which, with a limit in this thesis of 105 days leaves gaps in which damage grows unobserved.

Wheel-rail profile optimization

The current rails are very much designed to mitigate damage on the high rail gauge corner, which is achieved by heavily reducing the gauge corner of the rail. What it does not achieve is to create a favorable contact condition on the low rail. Although similar experimentation with rail profiles have been conducted, no update for the low rail has been introduced. Another important factor to look at is hollow wear wheel profiles on the wagons which are believed to cause a large amount of damage. These have not been included in this study, which included a worn profile without hollow wear. These wheels damage the field side of the low rail, and perhaps by optimizing the wheel and rail profile on the low rail, this type of wear can be reduced and thus the track condition improve.
Bibliography


Appendix A

A.1 High rail result plots

A.1.1 Curve 1, Radius 508m, Cant deficiency -11.2mm

Figure A.1: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the high rail at R508m, L = locomotive, W = wagon.
Figure A.2: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the high rail at R508m, L = locomotive, W = wagon.
A.1.2 Curve 2, Radius 594m, Cant deficiency -1.3mm

Figure A.3: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the high rail at R594m, L = locomotive, W = wagon.
Figure A.4: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the high rail at R594m, L = locomotive, W = wagon.
A.1.3 Curve 3, Radius 621m, Cant deficiency -21.3mm

Figure A.5: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the high rail at R621m, L = locomotive, W = wagon.
Figure A.6: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the high rail at R621m, L = locomotive, W = wagon.
A.1.4 Curve 4, Radius 683m, Cant deficiency 1.3mm

Figure A.7: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the high rail at R683m, L = locomotive, W = wagon.
Figure A.8: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the high rail at R683m, L = locomotive, W = wagon.
A.1.5  Curve 5, Radius 724m, Cant deficiency 7.4mm

Figure A.9: MGT passing with RCF in 3.5 months traffic and relative amount of load cases with RCF at each gauge on the high rail at R724m, L = locomotive, W = wagon.
Figure A.10: Accumulated shear stress above the shear yield limit in 3.5 months traffic on the high rail at R724m, L = locomotive, W = wagon.
Figure A.11: The damage contact band on the high rail after 105 days at each gauge on each curve radius, brighter colour indicates more load cases with RCF.