TECHNICAL REPORT

Study of Rail Breaks: Associated Risks and Maintenance Strategies

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PREFACE

The study and research work presented in this report has been partly carried out at the Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden and School of Engineering Systems, Queensland University of Technology, Brisbane, Australia from March to July 2006. The main objective of this report is to provide a platform for research in 'Rail-Risk-Cost' area. The report also outlines the current issues and challenges in front of rail infrastructure owners. This report introduces the different rail defects and the risk analysis methods which can be used to analyze the risk involved with these defects.

I would like to express my gratitude to my supervisor, Professor Uday Kumar for motivating me to write this report and guiding me at different stages of this report. I wish to express my sincere thanks to Dr. Gopi Chattopadhyay of Queensland University of Technology, Australia for introducing me with the current issues in rail maintenance.

I am particularly grateful to Dr. Per-Olof Larsson-Kråik and Lars-Goran Hansson of Banverket, Professor Per-Anders Akersten and my colleagues Ulla Espling, Arne Nissen, Peter Söderholm, Ambika Patra and all the members of my division for sparing time for discussions and suggestions which gave valuable inputs to this report.

Thanks are also acknowledged to Mats Rhen, Dan Larsson and Rikard Granström of LTU, Venkatarami Reddy of QUT and Queensland Rail, Australia for providing photographs to make this report more explicit.

Saurabh Kumar
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Luleå, Sweden

ABSTRACT

Railways are large infrastructures and are the prime mode of transportation in many countries. As it is closely associated with passenger and cargo transportation, it owns high risk in terms of human lives and cost of assets. New technologies and better safety standards are constantly introduced but still accidents do occur. There will always be some risk associated with derailments and collisions but it can be reduced by elimination of the root causes. These causes necessitate an effective maintenance strategy to govern optimization of inspection frequency and/or improvement in skill and efficiency. A detailed study of the defects which emerge both on the rolling stock and rail infrastructure is essential to frame out the correct maintenance strategy.

Detection and rectification of rail defects are major issues for all rail players around the world. Some of the defects include worn out rails, weld problems, internal defects, corrugations and rolling contact fatigue (RCF) initiated problems such as surface cracks, head checks, squats, spalling and shelling. If undetected and/or untreated these defects can lead to rail breaks and derailments.

There are challenges to the infrastructure maintenance people to perform effective inspection and cost effective rectification decisions. If these issues are addressed properly, inspection and rectification decisions can reduce potential risk of rail breaks and derailments. In-spite of continuous efforts made by all rail operators around the world to reduce costs, a substantial amount of railway budget is spent on inspection and maintenance of rails. It is understood that the consequential cost due to derailment reduces with increase in inspection, lubrication and grinding costs. The challenge is to reduce the maintenance cost which consists of inspection, lubrication and grinding costs and at the same time prevent a rise in consequential cost due to derailment.

Risk evaluation has become an important parameter for the management to decide a better and cost effective solution that could meet the budgetary constraints regarding renewal, replacement and inspection frequency of rails and wheels. Thus, before development of any model or any empirical relationship associated with risk, familiarity with risk management tools is required. This study focuses on building up a basic knowledge required for establishing such a relationship. The aim is to reduce costs and risks related to rail operation by effective decisions related to rail inspection, grinding, lubrications, rectifications and rail replacements.

Different types of rail defects and degradation processes have been studied. From the literature survey and studies done by the author, it is interpreted that there is a need for better prediction of rail defects over a period of time based on operating conditions and maintenance strategies. The issues and challenges related to rail maintenance are outlined for further research in this area. The maintenance strategy followed by Banverket is also described.

Keywords: Rail Defects; Rail Breaks; Risk Methodologies; Cost; Maintenance Strategies.

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LIST OF ABBREVIATIONS

AREA – American Railway Engineering Association
ASCE – American Society of Civil Engineers
ASTM – American Society for Testing and Materials
BS – British Standards
CPR – Canadian Pacific Railways
CWR – Continuous Welded Rails
DB – Deutsche Bahn(German National Railway Operator)
ETA – Event Tree Analysis
FMEA – Failure Mode and Effects Analysis
FMECA – Failure Mode and Effects Criticality Analysis
FTA – Fault Tree Analysis
HAZOP – Hazard and Operability Study
HH1 – North American Heavy Haul Freight Railways
HH2 – North American Heavy Haul Freight Railways (Operating on the Eastern Side of North America)
HSPC – High-Speed Passenger Corridor (North America)
IEC – International Electrotechnical Commission, Geneva
IHHA – International Heavy Haul Association
MGT – Million Gross Tonnes
MIL-STD – Military Standard Procedures (Department of Defence, USA)
NDT – Non Destructive Testing
NS – Nederlandse Spoorwegen (Former Dutch/Netherlands Railways)
PHA – Preliminary Hazard Analysis
RCF – Rolling Contact Fatigue
RPN – Risk Priority Number
SNCF – Sociéte Nationale des Chemins de fer Français (French National Railway Company)
TM Model – Three Mechanism Model
UIC – Union Internationale des Chemins (International Union of Railways)

1. INTRODUCTION

Railways are large infrastructures and are the prime mode of transportation in many countries. As it is closely associated with passenger and cargo transportation, it owns high risk in terms of human lives and cost of assets. New technologies and better safety standards are constantly introduced but still accidents do occur. There will always be some risk associated with derailments and collisions but it can be reduced by detailed research of the root causes. Some of the causes require improvement in skill and efficiency, for example human error, (see Cacciabue, 2005) and some may be improved by optimization of inspection frequency (see for example, Podofillini *et al*, 2006; Chattopadhyay *et al*, 2005; Larsson, *et al*, 2005). Thus, a proper maintenance strategy is required to govern optimization of inspection frequency and/or improvement in skill and efficiency. A detailed study of the defects which emerge both on the rolling stock and rail infrastructure is essential to frame out the correct maintenance strategy.

Detection and rectification of rail defects are major issues for all rail players around the world. Some of the defects include worn out rails, weld problems, internal defects, corrugations and rolling contact fatigue (RCF) initiated problems such as surface cracks, head checks, squats, spalling and shelling. If undetected and/or untreated these defects can lead to rail breaks and derailments. There are challenges to the infrastructure maintenance people to perform effective inspection and cost effective maintenance decisions. If these issues are addressed properly, inspection and maintenance decisions can reduce potential risk of rail breaks and derailments. In-spite of continuous efforts made by all rail operators around the world to reduce costs, a substantial amount of railway budget is spent on inspection and maintenance of rails. The total cost of annual rail inspection for European Union is around € 375–850 million per year (Cannon et al., 2003). It is understood that the consequential cost due to derailment reduces with increase in inspection, lubrication and grinding costs. The challenge is to reduce the maintenance cost which consists of inspection, lubrication and grinding costs and at the same time prevent a rise in consequential cost due to derailment.

Many researchers are involved in developing cost effective maintenance models for railway infrastructure (see for example, Podofillini *et al*, 2006; Zarembski, 1991). Most of these models follow a cost based approach considering rail, sleepers, ballast, etc, as an integrated track structure (see, Larsson and Gunnarsson, 2001; Larsson, 2004 and Zhang *et al*, 1999; Martland *et al*, 1993). Some of the degradation models included both risk and cost for track assessment (see for example, Chattopadhyay *et al*, 2003). Risk evaluation has become an important parameter for the management to decide a better and cost effective solution that could meet the budgetary constraints regarding renewal, replacement, inspection frequency and policy development (Akersten and Espling, 2005). Risk in railways could be expressed in terms of cost, loss of human lives, infrastructure unavailability, traffic delay and environmental impact which may be caused due to derailment of a train carrying hazardous material.

In this report, different kinds of rail defects and maintenance procedures followed are described. An overview of crack development process in rails is described with a review of some of the crack growth models. Different risk assessment methods and the risk tools have been described briefly in this report. Some of the issues and challenges related to rail maintenance are also addressed with an aim to reduce the total cost and risks associated with rail operations.

2. OVERVIEW OF RAIL STRUCTURE

Rail is one of the most important components of the track structure. Usually a flat bottom rail is used in conventional railway track, which could be divided into 3 parts: rail head, rail web and rail foot. Figure 1 shows the rail profile. Many standards are used for rail profiles, which are classified into UIC, ASCE, AREA and BS, other profiles are used in Netherlands, Denmark, Germany, India, China, South Africa (SAR), etc. UIC 54 and UIC 60 are widely used in Europe. Maximum static axle loads in Europe range from about 21 to 25 Tonnes but in the USA they routinely reach almost 30 Tonnes and many coal trains running out of the Powder River Basin have axle loads of about 32.4 Tonnes. In Australia axle loads of about 37 Tonnes have been reported on iron-ore vehicles. All these axle loads are nominal values, assuming that vehicles are uniformly loaded. This need not be the case. Dynamic effects can significantly increase these static loads. Conversely, if dynamic effects can be reduced, and loads distributed more evenly, greater static loads can be carried. (Cannon *et al*, 2003). The iron-ore trains running in Sweden have axle loads of 30 Tonnes.

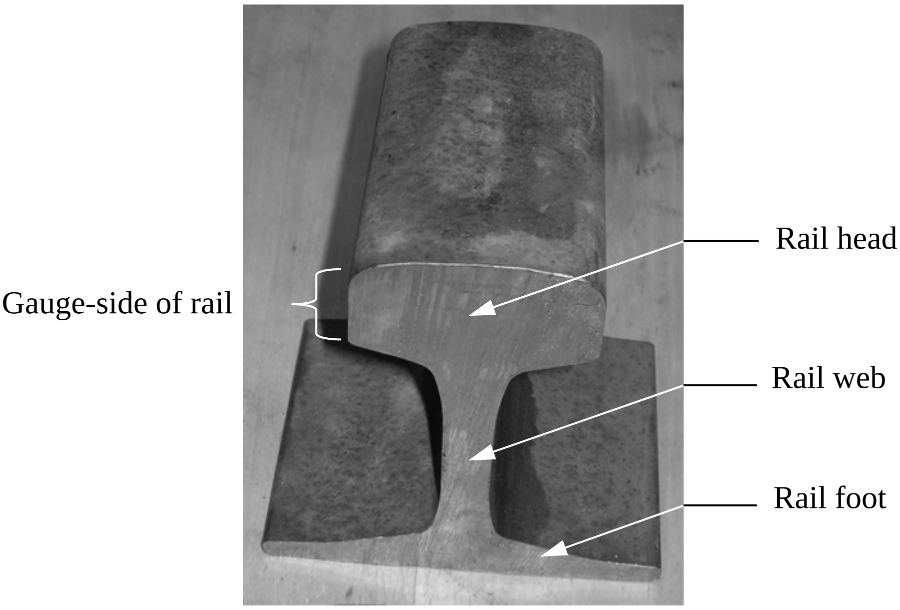


Figure 1: Flat bottom rail profile

Rails are longitudinal steel members that accommodate wheel loads and distribute these loads over the sleepers or supports, guiding the train wheels evenly and continuously (Esveld, 2001). The rails must possess sufficient stiffness so that they can act as beams and transfer the concentrated wheel loads to the spaced sleeper supports without excessive deflection between supports (Ernest and John, 1994). Rails are made from high carbon steel (up to 0.82 % of carbon), which provides high fatigue toughness. Higher quality steels are now being produced, which has lead to a significant improvement in rail fatigue performance and a considerable reduction in residual stress development (IHHA, 2001).

3. RAIL DEFECTS

Due to economic pressure there is a world-wide trend to increase axle loads, traffic density and speed to reduce the operating cost and increase the efficiency of railways. Axle loads around the world have increased in general from 22.5 to 32.5 Tonnes in last ten years (Allen, 1999). This has lead to increased rate of defect formation in rails.

Defects which occur due to RCF can be divided into subsurface initiated and surface initiated cracks. Subsurface cracks are often caused by metallurgical defects. On the other hand, surface initiated cracks are formed mostly due to increase in traffic density and axle load (Olofsson and Nilsson, 2002).

A critical defect is a rail defect that will affect the safety of train operations. Non-critical defects are the defects that occur in the rail but do not affect the structural integrity of the rail or the safety of the trains operating over the defect (US Railroad Track Standards, 1991). Some of the common defects are described in the following sections.

3.1 Shelling

Shelling is a defect caused by loss of material initiated by subsurface fatigue (Nielsen and Stensson, 1999). Shelling normally takes place at the gauge corner of high rails in curves. An elliptical shell like crack propagates in the subsurface parallel to the rail surface. When these cracks emerge on the surface, they cause the metal to come out from the crack area. Sometimes these cracks move in downward direction also, this may probably lead to a transverse fracture of rail. As it is subsurface initiated defect, steel metallurgy plays an important role in its initiation. Traces of oxide inclusion and residual stress formation during manufacturing contribute in shelling (Esveld, 2001). Figure 2 shows gauge corner shelling. It is generally eliminated by grinding.

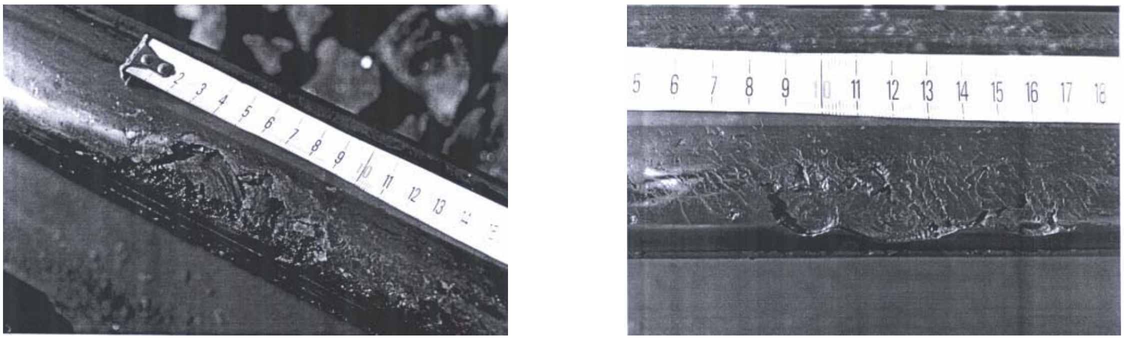


Figure 2: Gauge corner shelling in rails [Courtesy - Mats Rhen and Dan Larsson, LTU]

3.2 Head Checks

Contact stresses are generally low in the crown area as this has larger profile radius in comparison to the gauge side of rail. However, high contact stresses are generated on the gauge corner of the high rail, which generally has curve radius from 1000 to 1500 m. Head checks may also occur in tighter (less than 1000 m) curves near the gauge corner of the high rail (IHHA, 2001).

Head checks may also be found near the welds as welded profiles may have slight variations with actual rail profiles. A slight variation in profiles has a big effect on contact stresses. Head checks are surface initiated defects. Head checks generally occur at an angle of 30-60 degrees to the longitudinal axis of the rail (Figure 3). If head checks are not controlled, they can cause a rail break. Grinding is the most common practice to remove head checks. Severe head checks need rail section replacement.

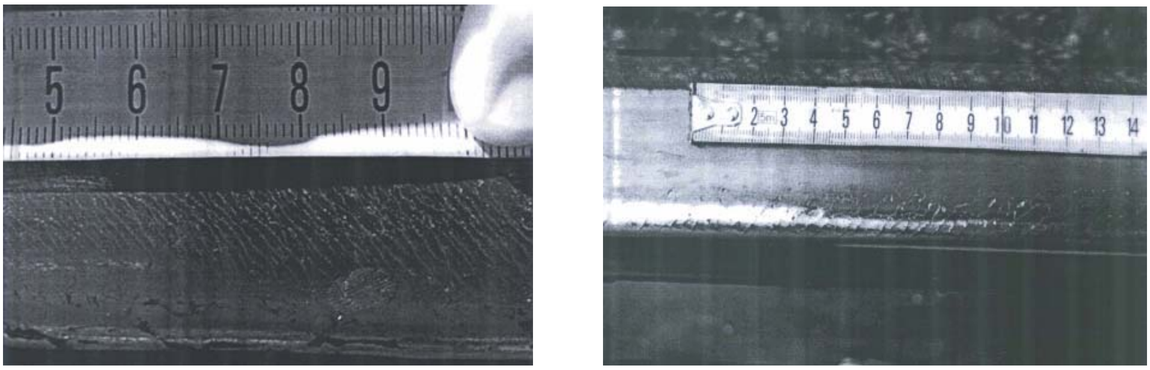


Figure 3: Head checks in rails [Courtesy - Mats Rhen and Dan Larsson, LTU]

3.3 Spalling

When the surface initiated crack development path is intersected by other similar shallow cracks on the rail head area, a shallow chip of rail material falls out. This is known as spalling (Figure 4). Spalling occurs at a much later stage of crack propagation phase if it is left uninspected (see for details Nielsen and Stensson, 1999; IHHA, 2001). Spalling is more frequent in cold climates as rail material stiffness increases.

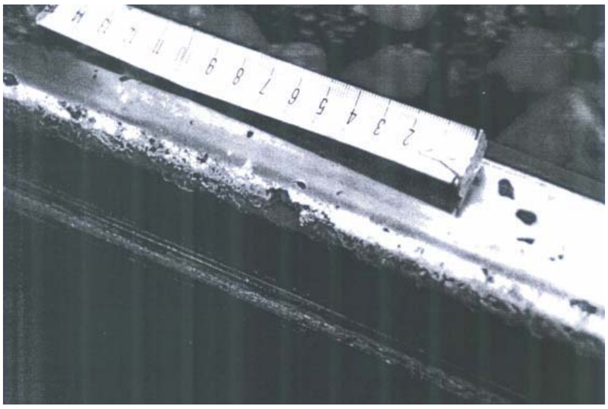


Figure 4: Spalling in rails [Courtesy - Mats Rhen and Dan Larsson, LTU]

3.4 Squats

Unlike shelling, squats appear in crown area of straight rail sections. They are surface initiated defects formed by RCF. A squat is formed by two cracks, a leading crack and a trailing crack. Both these cracks propagate in opposite direction. The leading crack proceeds in traffic direction, but the trailing crack propagates faster than the leading one. If preventive measures are not taken quickly, the trailing crack branches out and probably grow downward towards the rail web. Squats when seen initially look like a depression in the crown area (Figure 5). The depression is a result of crack which grows progressively and branches out horizontally just below the running surface, detaching it from the rail body. These defects could be prevented by grinding. Research has shown that rail grinding has an important role in reducing rail degradation, which can reduce rail brakes, early rail replacements and derailments (Kalousek and Magel, 1997).

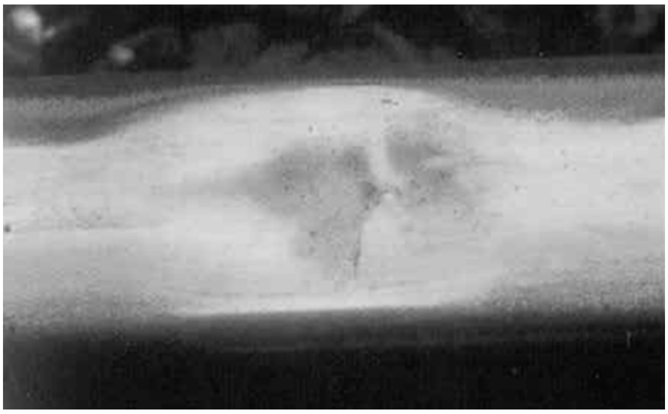


Figure 5: Squats in rails [Courtesy – V. Reddy, QUT, Australia]

3.5 Tache Ovale

Tache Ovale is a subsurface defect formed around 10-15 mm below the rail head surface (see Figure 6). This is caused by hydrogen accumulation during manufacturing of rail or when poor welding is done in rails. Thermal and residual stresses also contribute to form this defect.

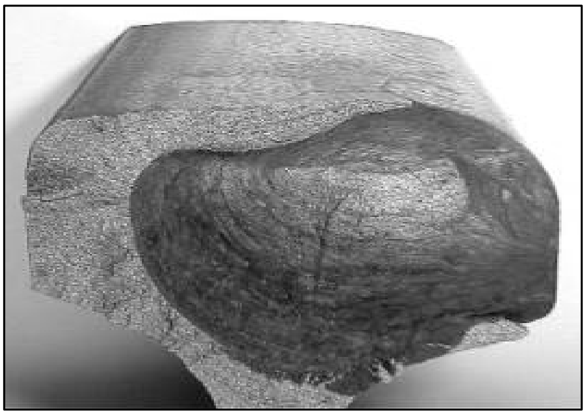


Figure 6: Tache Ovale [Courtesy - Queensland Rail, Australia, 2005]

3.6 Plastic Flow and Tongue Lipping

Plastic flow occurs in rail head area, the depth of which may be up to 15 mm. Plastic flow occurs on the field side of the low rail due to overloading. Plastic flow may also occur in low rail on the curves due to overloading (IHHA, 2001). Tongue lipping is also a form of plastic deformation, but it is initiated by surface cracks. These cracks partially separate a layer of material from the bulk of rail. Under high axial loads, these separated protrusions deform plastically as shown in Figure 7. Tongue lipping gives an indication of presence of cracks. This defect could be eliminated by grinding which would also bring back the original rail profile.

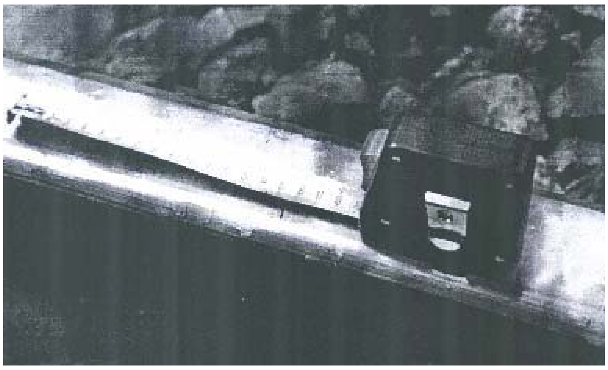


Figure 7: Tongue lipping [Courtesy - Mats Rhen and Dan Larsson, LTU]

3.7 Bolt Hole Crack

Bolt holes appear in the rail web often starting from the fastening point of fishplates. But these become weak points to resist crack initiation, as they face very high stress concentrations, and web shear stress. Usually these cracks propagate radially along the web plane at an angle of 45 degrees to the vertical plane (Esveld, 2001). These cracks have a very high potential to cause rail break and needs urgent replacement.

3.8 Longitudinal Vertical Crack

This is a manufacturing defect, which usually appears in the rail web and may extend in rail head also. If this crack is intersected by some other crack, it may lead to an early fracture or rail break. Chances of sudden fracture due to this type of crack become predominant in cold climate. Figure 8 shows a longitudinal vertical crack.

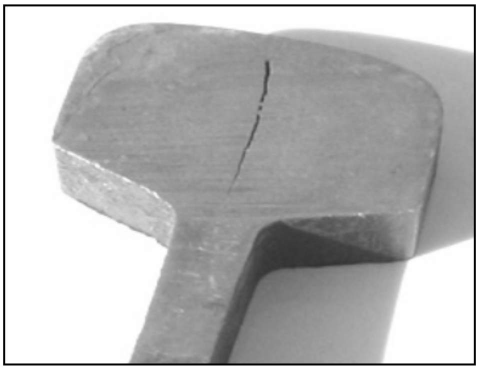
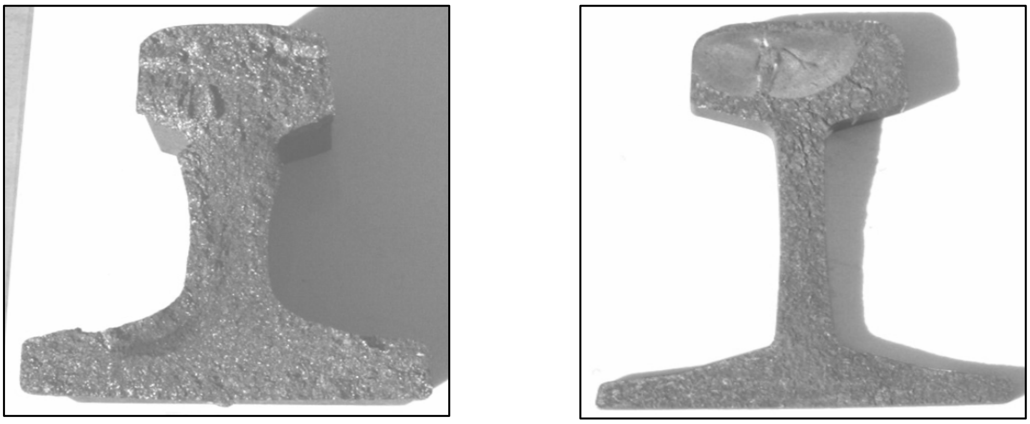


Figure8: Longitudinal vertical crack [Courtesy – Rikard Granström, LTU]

3.9 Transverse Crack

Transverse crack is mostly developed in the cross-sectional area of defective weld joints. A welding defect may be due to variation in weld material or rail manufacturing defect. Transverse cracks in weld joints have their defect origin from the welding processes such as pores, inclusions, misalignment, etc., Figure 9(a). Transverse crack develops from the centre of the rail head or the rail foot. It may be triggered by tache ovale as shown in Figure 9(b), having a kidney shaped impression. This crack develops in the subsurface and by the time it reaches the rail head surface, rail break becomes certain. Use of clean steel and deeper hardening of rail head may avoid its formation.



(a) (b)

Figure 9(a) and (b): Transverse crack [Courtesy – Rikard Granström, LTU]

3.10 Buckling

Lateral buckling in rails is a very common defect in which the rail bulges out on its either side due to expansion. As the temperature rises, longitudinal expansion in rail takes place (Zarembski, *et al.*, 2005). Both continuous welded rails (CWR) and non welded rails have their own advantages and disadvantages. Non welded rails are connected by joints to give them some space for longitudinal expansion. It is used in places where temperature may exist above 25 °C. This prevents lateral buckling in rails. However, the disadvantage of these rails is that accumulation of high stress concentration at joints becomes even higher in high speed rails. CWR do not have these drawbacks, the stress distribution is more uniform and less maintenance is required leading to reduction in life cycle cost. However, their use is limited to temperatures under which negligible longitudinal expansion takes place. Continuous welded rails (CWR) do not have any room to accommodate the expansion in rails, as a result, rail bulges out. This owns serious derailment risks. There is a need for risk based analysis of track buckling considering most of the important factors affecting track buckling. The risk approach can provide economic options for track maintenance to achieve the desirable buckling strength (Kish and Samavedam, 1999).

3.11 Corrugation

Corrugation is a rail flaw consisting of the wave-like wearing of the rail tread visualized as peaks and valleys, in other words, it is a periodic irregularity of the rail surface (IHHA, 2001), see Figure 10.

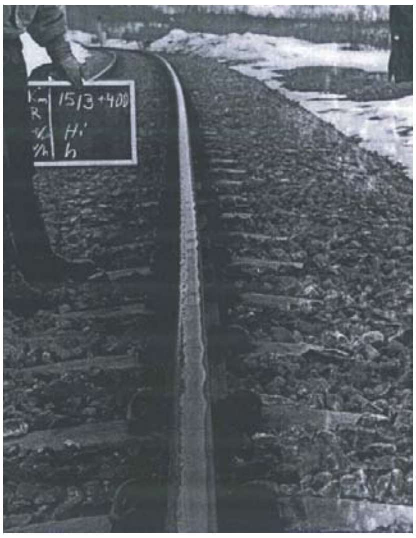


Figure 10: Corrugation in rails
[Courtesy - Mats Rhen and Dan Larsson, LTU]

Rail corrugations are the result of a damage mechanism, such as wear, fatigue or plastic flow operating at some characteristic frequency (Magel and Kalousek, 2002). Rail corrugations do not pose risk of immediate derailment, but they may be responsible for loosening of rail fastenings, ballast deterioration, increase in noise and vibration level leading to passenger discomfort, etc. Corrugation can be caused due to several reasons and it is difficult to correlate the causes of corrugation at different rail sections. Two main types of corrugations which generally occur in rails are:

- Short pitch corrugations
- Long pitch corrugation

3.11.1 Short Pitch Corrugations

Short pitch corrugations are considered to be self excited stick-slip vibration of a wheel set. Defective wheel or defective wheel setting and heavy traffic load may be some of the reasons for this type of corrugation. It is mainly seen in tracks under heavy haul operation. Short pitch corrugation varies between 3 cm to 8 cm (Grassie and Kalousek, 1993).

3.11.2 Long Pitch Corrugation

Long pitch corrugation is characterized by very shallow depth between peaks having very long waves of 8 cm to 30 cm (Esveld, 2001). They are mainly caused by manufacturing defect associated during rolling process of the rails. They are predominant in rails with high traffic density and high speed.

Grinding at an early stage, use of high strength rails and reduction in vertical stiffness characteristics may be some of the possible remedies to combat corrugation in rails. Recent research in understanding and reducing corrugation can be referred in (Ishida *et al.,* 2002; Matsumoto, *et al.*, 1996; Sato, *et al.*, 2002; Grassie and Kalousek, 1993 and Zhang, 2000).

Tables 1 and 2 show the percentage and type of defect detection by different rail infrastructure companies. Table 2 shows the critical defects which have led to development of rail breaks.

Table 1: Causes of defective rails (Sawley and Reiff, 2000)

Railway	First	Second	Third	Fourth
Rail track (1999/2000)	Squats 21.7%	Vertical/transverse 20.1%	Horiz./longitudinal 12.5%	Bolt holes 9.6%
SNCF (1999)	Squats 23.4%	Internal fatigue 11.5%	Shells 8.4%	Thermite welds 4.7%
HSPC (1999)	Thermite welds 31.5%	Wheel burns 17.2%	Horizontal split webs 13.3%	Bolt holes 11.3%
NS (1997)	Insulated Joints 59.4%	Transverse defects 18%	Thermite welds 15%	Fatigue Failure 5.2%
DB (1996)	Thermite welds 29%	Sudden fracture 18%	Fatigue Failure 16%	Electric bonds 4.0%
Banverket (1998)	Transverse fracture 55.1%	Welded joint 32.7%	Horizontal defect 6.1%	Vertical split 2.0%
HH1 (1999)	Vertical split heads 34.7%	Thermite welds 20.3%	Detail fractures 13.1%	Bolt holes 12.2%
HH2 (1999)	Transverse defects 23.6%	Thermite welds 15.5%	Wheel burns 13.2%	Shells 9.6%

Table 2: Causes of broken rails (Sawley and Reiff, 2000)

Railway	First	Second	Third	Fourth
Rail track (1999/2000)	Vertical/transverse 39.5%	Thermite welds 22.4%	Bolt holes 14.9%	Horiz./longitudinal 7.4%
SNCF (1999)	Thermite welds 35.3%	Internal fatigue 18.6%	Squats 8.8%	Rail manufacture 6.1%
Banverket (1998)	Transverse fracture 44.1%	Vertical split 19.4%	Welded joint 19.4%	Horizontal defect 17.2%
HH2 (1999)	Transverse defects 37.9%	Thermite welds 35.6%	Bolt holes 5.8%	Flash welds 5.6%

4. CRACK DEVELOPMENT PROCESS

When repeated stresses of sufficient magnitude are applied to a rail section, a crack is initiated after a certain number of cycles, which goes on propagating when stresses are repeatedly applied (Nishida, 1991). The direction of crack propagation depends on the rail material, the point of crack initiation and the kind of metallurgical processing or the heat treatment method adopted for that particular rail section. Analysis of RCF initiated defects have been studied by many researchers to understand the process of crack initiation and its propagation. [see, for example Ringsberg and Bergkvist (2003), Ishida, *et al* (2003), Fletcher and Beynon (2000), Sawley and Kristan (2003) and Jeong (2003)].

Crack development process consists of three phases:

- crack initiation,
- crack propagation and
- fracture or rail break

Rail break is the final result of the crack development process. The rail maintenance cost within the European Union is estimated to 300 Million Euros per year (Olofsson and Nilsson, 2002). The first two phases of crack development is critical for railway engineers, as it is this phase in which crack should be located by the inspection techniques followed by suitable implementation of maintenance or replacement action. The big task is to assess how frequently these cracks can initiate. Cracks will initiate as deterioration with use is the law of nature. However, by understanding the process clearly and then establishing risk based maintenance or inspection policy, reduction in the crack initiation process can be achieved and life of rails can be extended. The second important task is to find how much time it takes for the cracks once they have initiated, to propagate into a potential risk or rail break. By accomplishing these tasks, optimization of inspection frequency and prediction of maintenance schedules can be achieved, for example, interval between grinding campaigns. This would save a lot of maintenance cost and reduce the risk of derailments.

4.1 Crack Growth Models

Cracks initiate in a very thin surface layer of the rail and develop inside the rail head. Crack development is facilitated by the presence of water (Ishida, *et al,* 2003). If the crack propagation is in the upward direction towards the rail surface, pieces of rail material detach from the rail surface, but if these cracks propagate downwards, they may cause a railbreak. Cracks initiated by ratchetting (head checks) grow perpendicular to the direction of the resultant traction force (Grassie and Kalousek, 1997).

Many models have been developed to study crack initiation and its propagation. Miller (1997), proposed a model for crack growth in which he divided the crack propagation life into three phases:

Phase (i)	- shear stress driven initiation at the surface
Phase (ii)	- transient crack growth behaviour
Phase (iii)	- subsequent tensile and/or shear driven crack growth

Ringsberg (2001) explained those three phases with the help an illustration (Figure 11).

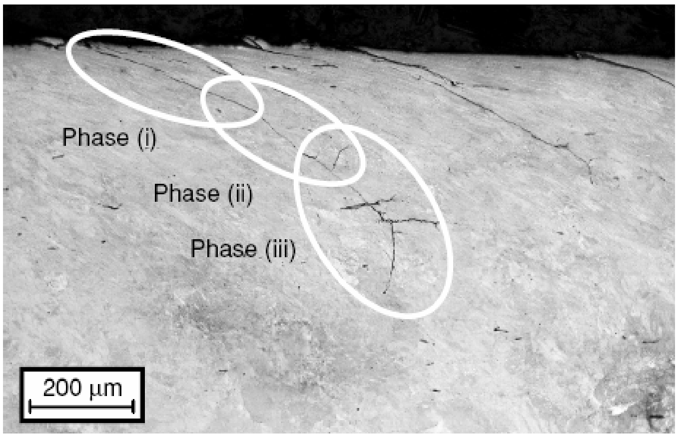


Figure 11: Three phases of RCF initiated crack propagation [Ringsberg, 2001]

The three mechanism model (TM Model) of RCF initiated crack growth proposed by Fletcher and Beynon (2000) is a prediction model for crack growth propagation mechanism. In this model, the tensile and shear stress intensity factors ($\Delta K_{\sigma,\tau}$) are compared for different modes: ratchetting, shear and tensile crack growth. Thereafter a decision is made whether or not crack growth will take place for a particular loading condition (see Figure 12).

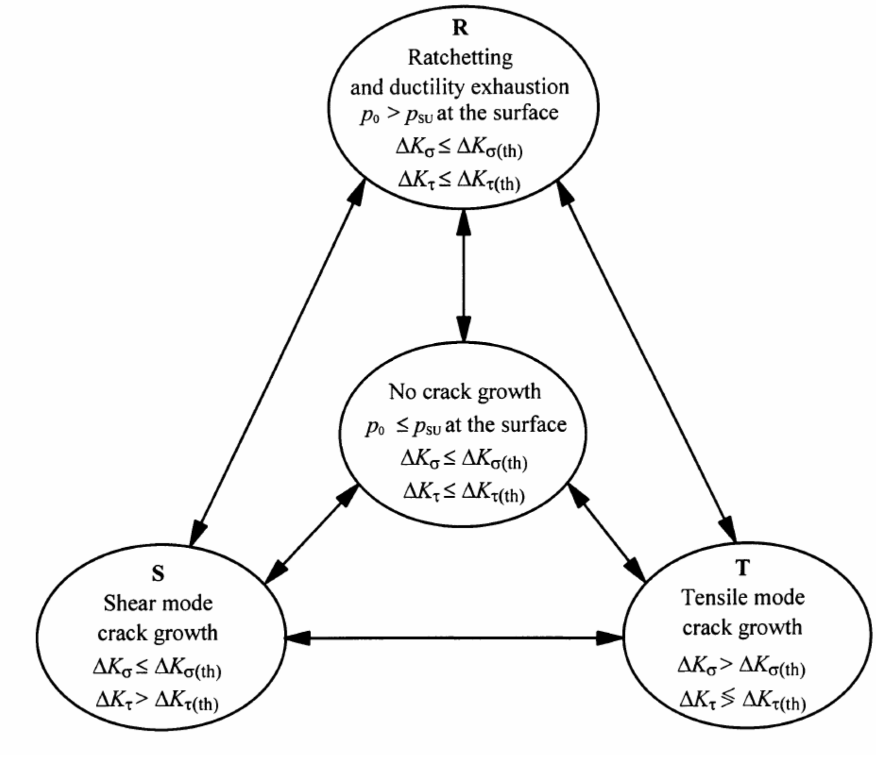


Figure 12: TM Model of RCF initiated crack growth [Fletcher and Beynon, 2000]

The model, as shown in Figure 13, explains the crack initiation and development process in a microscopic view of rail section. This model was proposed by Nishida (1991). When the wheel passes over the rail section considered here, the axial load goes on increasing and decreasing cyclically, this process continues for a certain number of cycles until plastic deformation begins, usually at a relatively weak location. This is shown by dotted lines in Figure 13 (a). These deformations take place by the effect of compressive and shear forces. The rail steel layers start sliding under high axial load. When release of axial load takes place, the layers resisting plastic deformation tries to regain their original positions, thus applying a reverse force. This process goes on for a few cycles until a micro-crack is formed in the rail surface, Figure 13 (b). These micro-cracks develop into cracks when stresses are repeatedly applied. Once a crack is initiated, stress concentration occurs at both ends of the crack and the crack may continue to grow. The micro-cracks may not always develop into cracks; this partly depends on the endurance limit of the rail material also [for details on fatigue crack growth and its initiation, refer Ellyin (1997), Taylor (1989) and ASTM (1977)].

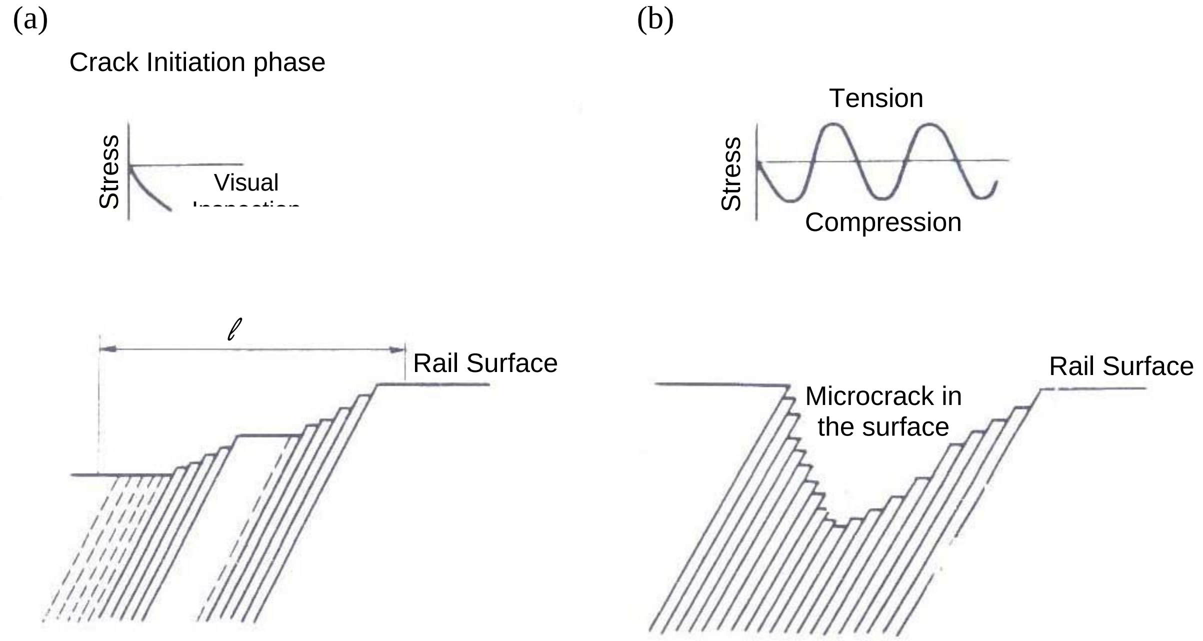


Figure 13: Model of RCF initiated crack development process [Adopted from Nishida, 1991]

The surface on which crack emerges looks very smooth, although when microscopically viewed, it is usually stepped (Figure 13). The microscopic crack once initiated, propagates through the heavily deformed surface layers of steel at a shallow angle to the rail running surface (about 10°) until it reaches a depth where the steel retains its original isotropic properties (Nishida, 1991). Fracture at one crack increases stress in the nearby rail, increasing the risk of further breaks and disintegration of the rail (Cannon *et al*, 2003).

4.2 Crack Propagation during Fluid Entrapment

Crack propagation which is the second phase of crack development process is accelerated by fluid entrapment during lubrication that leads to crack pressurization and reduces the crack face friction that allows relative shear of the crack faces (Figure 14). Presence of manufacturing defect in rail subsurface and the direction of the crack mouth on the rail surface are both responsible for guiding crack development direction (see Bower and Johnson, 1991 and Bogdanski *et al*, 1997).

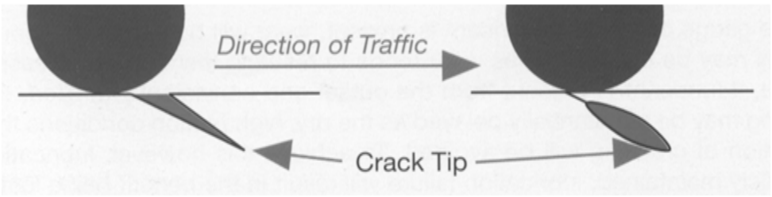


Figure 14: Fluid entrapment accelerates crack propagation [Courtesy – Queensland Rail, Australia, 2005]

Presence of water, snow or lubricant on the rails may increase crack propagation rate. When these minute head checks are filled with water or lubricants they do not dry up easily. During wheel rail contact, these liquids get trapped in the crack cavities and build up very high localized pressure, which may even be greater than the compressive stress. If head checks are in the direction of train traffic, crack growth takes place due to liquid entrapment, but when head checks are in opposite direction of train traffic, the liquid is forced out before its entrapment (Ringsberg, 2001).

4.3 Rail Deterioration and Rail Break

Wear and fatigue in rails are significant problems for rail industries. These are major contributors of rail deterioration depending on operational conditions such as train speed, axle load, rail-wheel material type, size and profile, track construction, characteristics of bogie type, Million Gross Tonnes (MGT), curvature, traffic type, weather and environment (see Chattopadhyay *et al*, 2006). Rails are so designed that they fit with the shape of the wheel forming a combination, which reduces contact stresses. They cause longitudinal compressive and tensile stresses, which are mainly concentrated in the head and foot of the rail whilst the shear forces produce shear stresses which occur mainly in the web. It is important to provide adequate resistance against the bending moment which determines the areas of the head and foot of the rail (Cope, 1993). The rail head gets worn away by wheels on its surface and worsened by abrasive contact with the base plate or sleeper on its underside. Corrosion leads to loss of rail section and the surface crack itself reduces the fatigue resistance of the rail. Rail wear, rolling contact fatigue and plastic flow are growing problems for modern railways. Increased speed, higher axle loads, increased traffic and freight leads to the surface initiated cracks on the rail (Reddy, 2004).

Rail break is the last phase of crack development process. As the crack goes on increasing in length as well as depth, stress concentration also goes on increasing and finally rail break occurs, but this does not happen in all cases. Sometimes spalling takes place and a portion of rail material comes out as crack develops. The end result of a crack is governed by its development path. It is very difficult to predict the crack development path as it depends on several factors. Some of the cracks are removed by wear process during initial stages of crack development while most of them are removed in grinding campaigns. Not all cracks impose derailment risk, but they are the major contributors to rail degradation.

One of the types of rail break is known as detailed fracture. A detail fracture is a progressive fracture starting from a longitudinal separation close to the running surface of the rail head, then turning downward to form a transverse separation substantially at right angles to the running surface. Detail fractures account for about 75 percent of the rail defect population in continuous welded rail track in North America (see Jeong, 2001).

5. RISKS RELATED TO RAILS

Rail breaks and derailments can cost the rail players in terms of loss of revenue, property, environmental damage or even loss of life. Estimation of these costs and analysis of risks are important in deciding effective maintenance strategies (Reddy, 2004). The risk methodology for rail defects requires not only the failure probability, but also the severity or the consequence of the failure (Kish and Samavedam, 1999).

As the consequential cost associated with derailments and rail breaks is very high, failure predictions have to be made by analyzing the risk involved with those failures. Some of the risk assessment methods are discussed in this section.

5.1 The Concept of Risk

In simple terms, risk can be defined as the chance or probability of loss, damage or injury. Risk has volatility in its definition and it depends upon the context in which it is being used. In the present context, risk is defined as a combination of frequency, or probability, of occurrence and the consequence of a specified hazardous event[1] (IEC60300-3-9, 1995). Apeland and Aven (2000) defined risk in terms of consequences and associated probabilities, where, they considered consequences related to humans, environment and assets/financial interests. The use of quantitative risk models over qualitative risk models gives more accurate picture to the management to take correct maintenance decisions (Aven, 1992; Kaplan, 1991). Risk can also be defined in terms of accidental events[2] (see Vatn 1998).

Risk can be reduced by capital investment but it often becomes very costly to avoid it entirely. Thus, a safe limit is evaluated based on the consequential losses, frequency of occurrence, investment in maintenance activities and operating and environmental conditions.

5.2 Types of Risks

According to Andrews and Moss (2002), risk can be classified into three main types:

- Occupational risk
- Community/Environmental risk
- Economical risk

Occupational risk is present in different industries; some occupation may presume a relatively low value of risk as very critical for its operations when compared to others. The criticality[3] here may be in terms of failures, operation and production losses, etc. Thus the criteria of acceptability of a safe limit for a particular occupation are decided by experience from that industry.

Community/Environmental risk is the risk involved in relation to human lives, damage to environment, pollution, etc. Petroleum or nuclear industry will involve higher risk as it has more potential to cause damage to life forms and environment than software or automobile industry.

Economical risk is related to the extent of damage to the assets, products, compensation and other costs. Economical risks are generally covered by insurance.

Thus it is seen that different kinds of risks have their importance under different situational context.

5.3 Risk Management

The main goal of risk management is to minimize the occurrence of accidents by reducing

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[1] Hazardous event: An event which can cause harm (IEC60300-3-9, 1995).

[2] An accidental event in the present context is an unplanned and uncontrolled event in which the action or reaction of an object, substance, person or radiation results or has the risk of personal injury (Heinrich, *et al.*, 1980).

[3] Criticality: A relative measure of the consequences of a failure mode and its frequency of occurrences (MIL-STD-1629A).

likelihood of occurrence, reducing the impact of occurrence (eg., by adopting emergency responses) and transfer risk (eg., by insurance coverage) (Modarres, 1993).

As shown in Figure 15, risk management consists of different stages, the initial stage being risk analysis, followed by its evaluation and finally deciding upon the alternatives to control it.

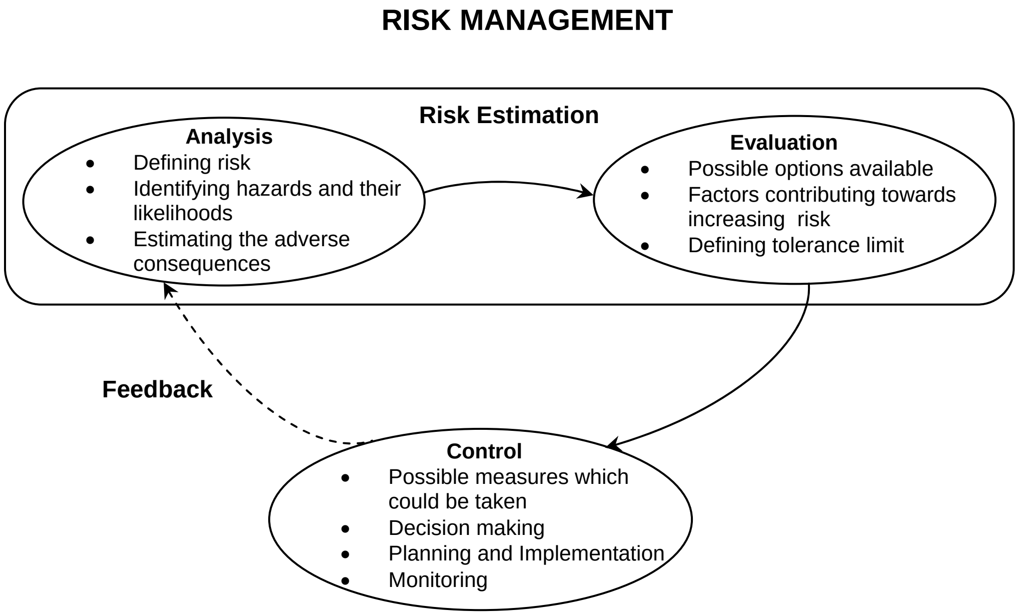

Figure 15: Risk management flow diagram

Risk analysis attempts to answer three fundamental questions (see for details, IEC60300-3-9, 1995; Kaplan and Garrick, 1981; Holmgren, 2003):

- What can go wrong?
- How likely is this to happen?
- If it happens, what are the consequences expected?

Risk analysis is a technique of identifying, characterizing, quantifying and estimating the hazards and consequences (Modarres, 1993). The possibility of different options available is estimated after risk analysis and evaluation. The different factors like cost, frequency, environmental and operating conditions, etc. which contributes towards increasing risk are also evaluated. These two stages together are known as risk estimation. In the third stage, possible measures are taken with which risk could be controlled or reduced. Once these policies for risk reduction are implemented, constant monitoring is done to assess the performance of the implemented policies.

5.4 Methodologies used in Risk Analysis

There are several methodologies available that can help a maintenance team to estimate the level of risk. Rasche and Wooley (2000) proposed that different risk analysis methods could be used depending on the requirements and the context in which it is being used. They classified these methods into qualitative and quantitative approaches. In most of the cases the complexity and cost effectiveness increases as the deterministic and probabilistic approaches are opted instead of traditional experience based approaches (Figure 16).

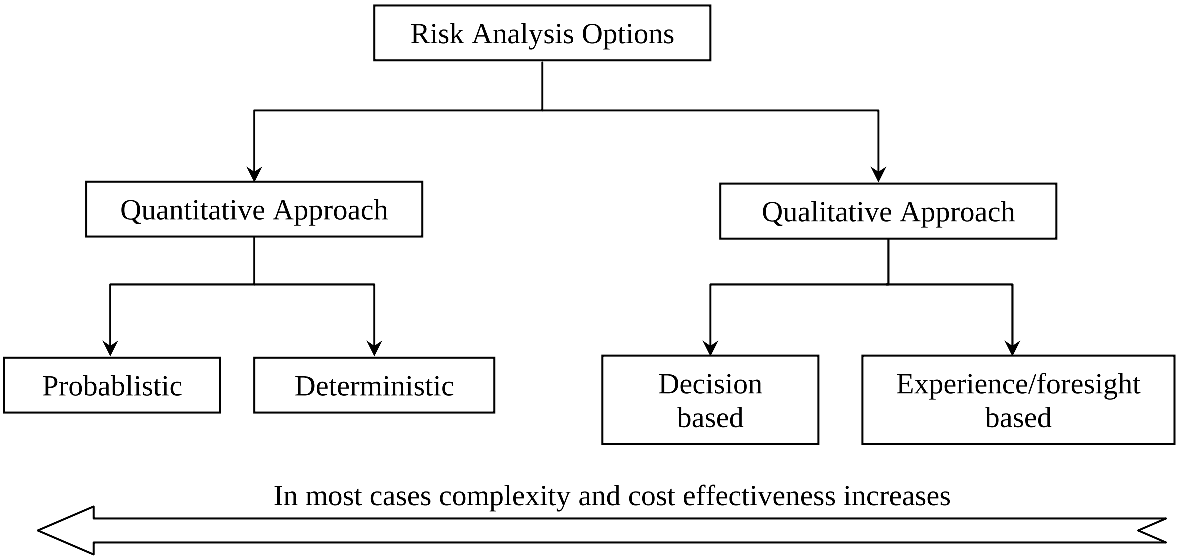

Figure 16: Risk Analysis Options [Adapted from Rasche and Wooley, 2000]

There are two analysis approaches which can be used to analyze the relationship between different failure modes, these are, inductive or forward analysis and deductive or backward analysis approach. An inductive analysis approach starts with a failure mode condition and finds out the possible consequences or effects of failure on system level. Qualitative and semi-quantitative reliability and risk analysis is usually performed using inductive analysis approaches, (for example FMEA/FMECA (Failure Mode and Effects [Criticality] Analysis), PHA (Preliminary Hazard Analysis) or HAZOP (Hazard and Operability Study) (Akersten, 2006). A deductive analysis approach tries to find out the causes of the failure.

5.4.1 Fault Tree Analysis (FTA)

The fault tree analysis (FTA) is one of the analysis techniques which are frequently used in reliability and risk analyses. It is a specialized methodology which requires good skill and experience so that it can be properly used. A fault tree is a logic diagram showing the connection between a system failure (i.e. unwanted events in the system), subsystems, and components failures (Markeset and Kumar, 2001). FTA is an example of deductive analysis approach. It is a graphical approach which starts with a failure and branches out showing possible causes (Andrews and Moss, 2002). Many different fault trees may be required on a subsystem level to evaluate the risk associated with a particular type of hazard in a system.

5.4.2 Event Tree Analysis (ETA)

ETA is a hazard identification and frequency analysis technique which employs inductive reasoning to translate different initiating events into possible outcomes (IEC60300-3-9, 1995). ETA is an inductive logic and diagrammatic method for identifying the various possible outcomes of a given initiating event (Huang, *et al*, 2001). An event tree identifies and quantifies possible outcomes following an initiating event. The event tree provides systematic coverage of the time sequence of event propagation. Event trees are frequently used to estimate the probability of events as well as to map the developments from the initiating event to all possible outcomes/consequences.

5.4.3 Failure Mode and Effects Analysis (FMEA)

FMEA is an inductive analysis approach by which each potential failure mode in a system is analyzed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity[4] (MIL-STD-1629A). FMEA is a step-by-step procedure for systematic evaluation of the severity of potential failure modes in a system. FEMA is mainly used for recommending improvement in a system during its design phase. Failure mode effects and criticality analysis (FMECA) is an extension of FMEA, which focuses on ranking the failure modes according to criticality based on various factors responsible in a particular context. FMECA is a powerful analysis method involving two elements of risk; namely, failure frequency and consequence (Markeset and Kumar, 2003). FMECA analysis concentrates on identification of the events and frequency resulting in failures and analysing their effects on the components and systems.

5.4.4 Hazard and Operability Study (HAZOP)

HAZOP is a fundamental hazard identification technique, which systematically evaluates each part of the system to see how deviations from the design intent can occur and whether they can cause problems (IEC 61882, 2001). The technique aims to stimulate the imagination of designers and operators in a systematic manner so that they can identify the cause of potential hazards in a design (Andrews and Moss, 2002).

5.4.5 Preliminary Hazard Analysis (PHA)

It is a technique that can be used early in the design stage to identify hazards and assess their criticality (IEC60300-3-9, 1995). It is used as a first step to understand risk present and the need for risk control. This method was initially applied to nuclear industry and is the basis of large number of formal risk assessment today (Modarres, 1993).

5.5 Frequently Used Tools for Quantification of Risk and Decision Making

Some of the tools which are frequently used for risk quantification and decision making are briefly described:

5.5.1 Delphi Technique

Delphi technique is a means of combining expert opinions that may support frequency analysis, consequence modeling and/or risk estimation (IEC60300-3-9, 1995). It is a widely used method for expert judgments. A set of questionnaires are prepared by a panel of experts and individual opinion on these questions are looked into as feedback to the expert panel. This refines the views of experts ending up to a general consensus (Akersten and Espling, 2005).

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4. Severity: The consequences of a failure mode. Severity considers the worst potential consequence of a failure, determined by the degree of injury, property damage, or system damage that could ultimately occur (MIL-STD-1629A).

5.5.2 Risk Priority Number (RPN)

Risk priority number (RPN) is a methodology for analyzing the risk associated with potential problems identified during a Failure Mode and Effects Analysis (FMEA) (for details refer Reliasoft, 2005).

Assigning RPN requires the analysis team to use past experience and engineering judgment to rate each potential problem according to three rating scales:

- **Severity**, which rates the severity of the potential effect of the failure.
- **Occurrence**, which rates the likelihood that the failure will occur.
- **Detection**, which rates the likelihood that the problem will not be detected before it reaches the end-user/customer.

These rating scale ranges from 1 to 5 or from 1 to 10; the higher number the more risk it involves and vice-versa. After the ratings have been assigned, the RPN for each issue is calculated as mentioned below,

RPN = Severity x **Occurrence** x **Detection**

The RPN value for each potential problem can then be used to compare the issues identified within the analysis. Typically, if the RPN falls within a pre-determined range, corrective action may be recommended or required to reduce the risk (*i.e.* to reduce the likelihood of occurrence, increase the likelihood of prior detection or, if possible, reduce the severity of the failure effect). When using this risk assessment technique, it is important to remember that RPN ratings are relative to a particular analysis (performed with a common set of rating scales and an analysis team that strives to make consistent rating assignments for all issues identified within the analysis). Therefore, an RPN in one analysis cannot be compared to RPNs in other analysis (Reliasoft, 2005). There are several interpretational problems connected with the use of RPN for risk estimation. Some of the RPN anomalies are described in (Kmenta & Ishii, 2004).

5.5.3 Risk Matrix

Many times, in actual practice it becomes difficult to analyze in detail each and every event having a certain potential of risk because of their very large numbers. In such situations, it becomes easier to rank these events qualitatively and put them in groups denoting different levels of risk. Risk matrix is such a tool for qualitative risk assessment to give an overall ranking for likelihood and consequences. The different blocks of the matrix define different levels of risk. Generally bottom left block is the lowest risk block and top right block is the highest, but it can vary depending on the convention used.

There are many more methods which could be applied efficiently in different context. The different methods could be evaluated based on Figure 17. A comparison of risk and expected cost is done. The methods like point P have solutions with less expected cost but on the other hand, become risky. Methods like point R give low risk solutions but they are a bit costly. Yet, those methods which lie on the risk efficient line are far better than methods which lie at point S. Point T represents those methods which are not feasible at all. But a reasonable method should give a solution denoted by point Q, which is a trade-off between risk and cost.

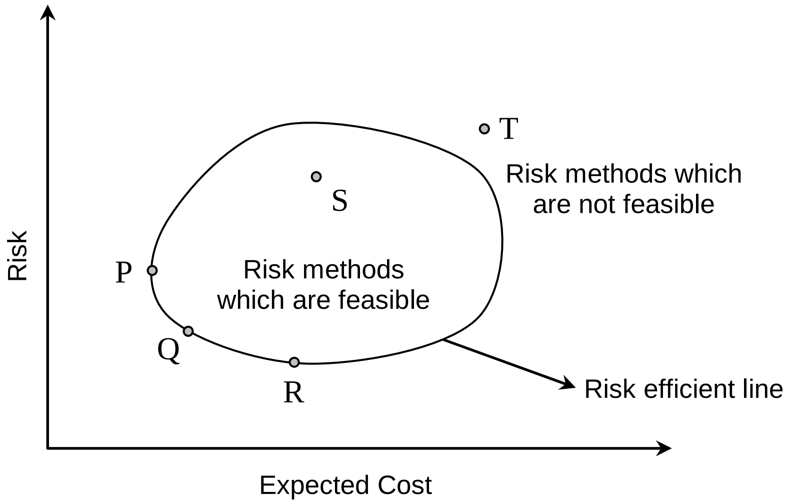

Figure 17: Risk efficient options [Adopted from Capman and Ward, 2004]

6. ISSUES RELATED TO RAIL MAINTENANCE

Rail maintenance issues can be broadly classified into:

- Inspection issues
- Issues related to rail wear, RCF and rail welding
- Rectification and replacement issues

6.1 Rail Inspection Issues

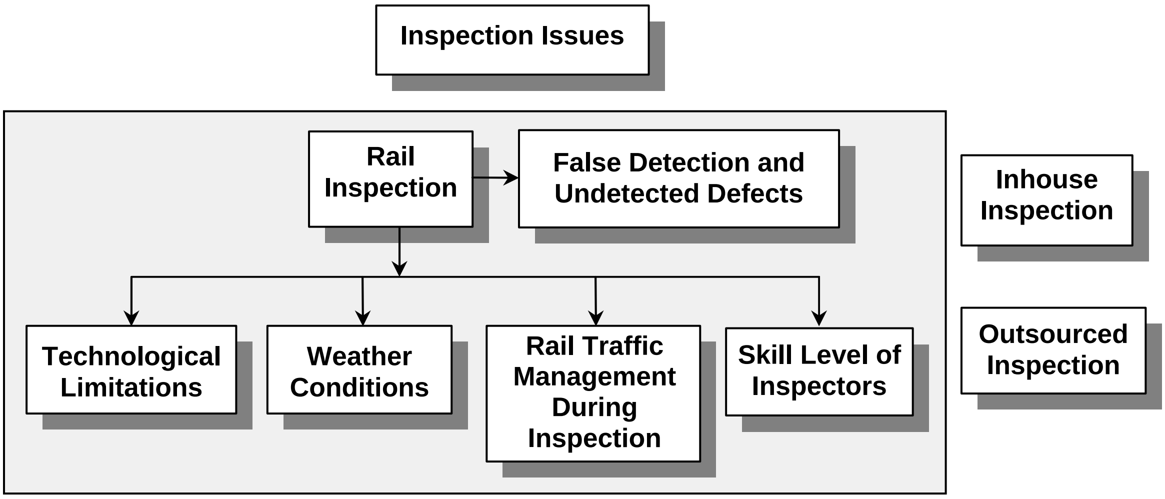

Figure 18: Rail inspection issues

The effectiveness of rail inspection depends on the efficiency and accuracy of the inspecting equipments. It also depends on the skill and experience of inspectors (Figure 18). Error in inspection is an important issue and its reduction is a big challenge. This mainly depends on the technological limitations of the inspection equipments and the skill level of the rail inspectors. Figure 19 shows the condition when some of the deeper cracks are left undetected due to the limitation of the ultrasonic probe, the sound of which cannot penetrate through the overlying cracks.

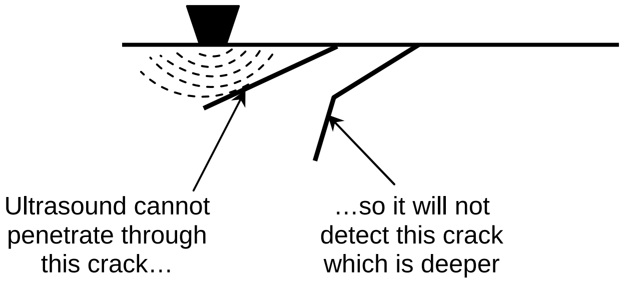

Figure 19: Shadowing of ultrasonic sound by head checks and squats [Adopted from Cannon, et al, 2003]

Figure 20 shows the Venn diagram of inspection, detection, rail breaks and derailments. The Venn diagram shows the percentage of defects detected by different inspection procedures. Rail break detection by signaling may not be a very effective procedure as the exact location of the rail break cannot be pin pointed, moreover by the time, the inspection team reaches the location, the gap in the rail break might shut down due to longitudinal expansion/contraction of rails. Thus it may take days to locate a rail break by this procedure. By improving the inspection techniques and using more efficient equipments, reduction in undetected and falsely detected defects is possible.

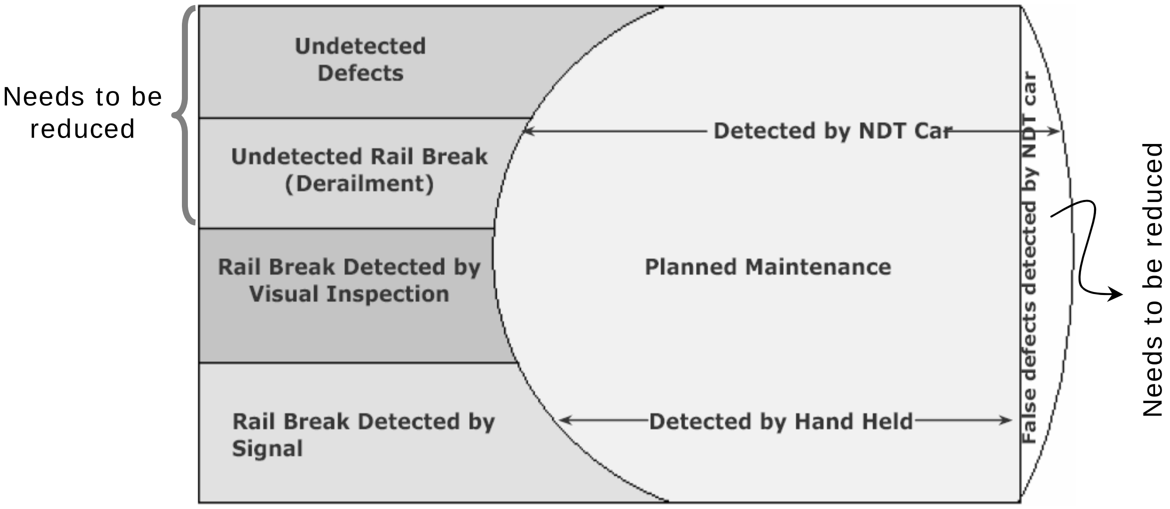

Figure 20: Venn diagram of inspection and detection, rail breaks and derailment [Chattopadhyay, et al, 2005]

Many rail players follow in-house inspection; in this inspection process the skilled personnel as well as required equipments are company employed/owned. Outsourced inspection is also followed widely, in which the inspection process is outsourced to various ancillary companies.

Inspection is also governed by weather conditions. In cold countries, like Sweden, inspection of rail becomes difficult and costly affair in winter. Another important issue is management of rail traffic during inspection. In Netherlands and Italy some of the rail routes are so busy that it becomes very difficult to stop train traffic and do rail inspection and maintenance, in these routes rail inspection and maintenance is done during night time (see Bocciolone *et al*, 2006). The workers and inspectors have to be paid more for working during night hours. Rail maintenance can be done more effectively during the day time provided the tracks are free. Keeping the tracks free depends on an efficient traffic management system. Still it is a challenge to effectively carry out inspection and maintenance procedures keeping optimal rail inspection and maintenance cost and minimal traffic disruption. Assuming annual vehicle ultrasonic inspections followed by manual verification of detected defects, inspection costs are estimated at about €70 million per year for a 0.5 million kilometer system (considering the total track length in the European Union is about 0.5 million kilometers) (Cannon *et al*, 2003). This indicates the importance of the inspection technology, frequency of inspection and the detection of undetected defects. Therefore, there is need for detail study and analysis of inspection techniques to detect rail defects.

6.2 Issues related to Rail Wear, RCF and Rail Welding

Figure 21 outlines the rail maintenance issues. The following sections briefly describe some of these issues.

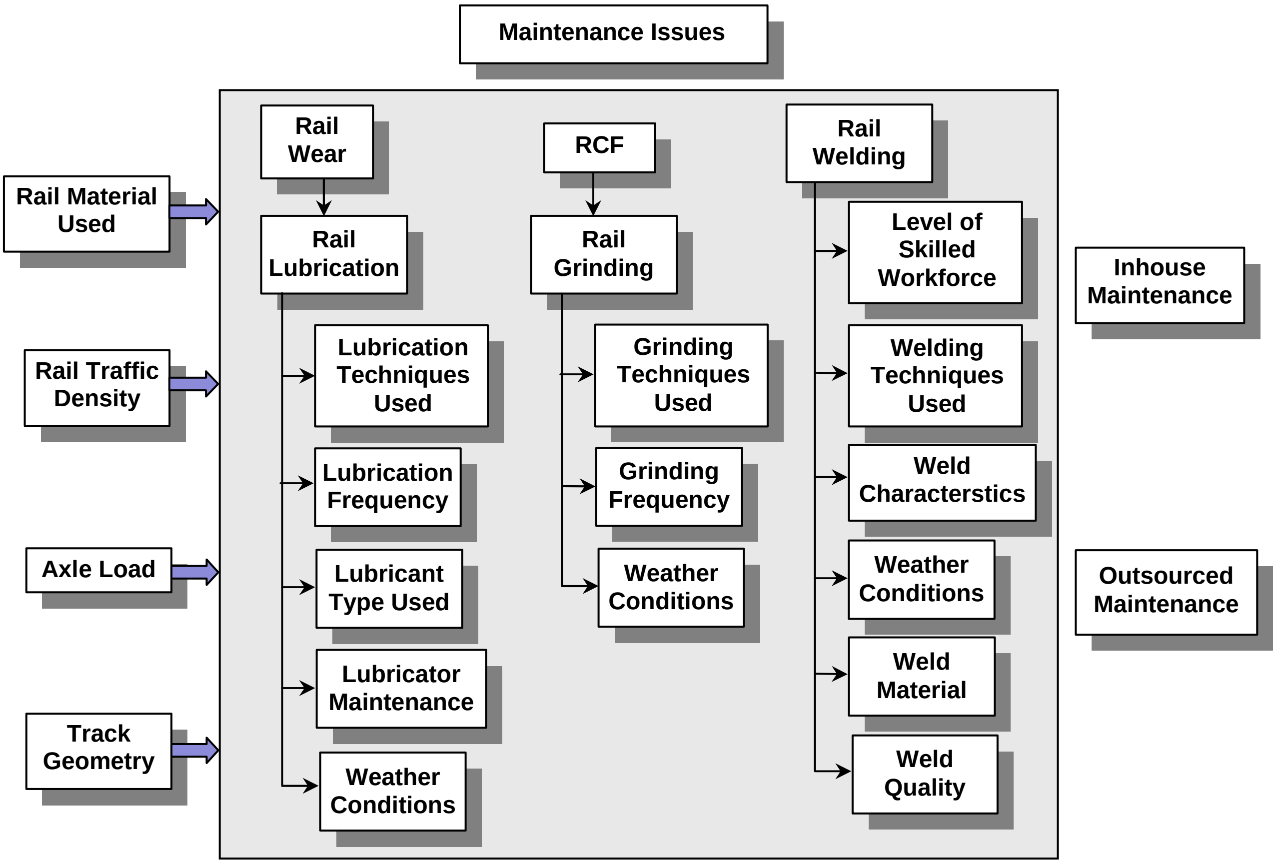

Figure 21: Rail maintenance issues

6.2.1 Rail Wear Issues

Wear occurs due to interaction of rail and wheel. It includes abrasive wear and adhesive wear. Jendel, (1999) defined the concept of mild and severe wear. Mild wear takes place slowly but severe wear is often much faster, similar to adhesive wear. Severe wear is predominant in curves and dry conditions (Olofsson and Nilsson, 2002). Mild wear is observed at the wheel tread and rail crown, and severe wear is observed at the wheel flange and gauge face. Zakharov, (2001) classified wear mode in rails as mild, severe and catastrophic. The basis of this classification was characterized by different wear rate, surface and wear debris form and size. Wear debris in the size range of 1000 μm, 500 μm and 300 μm are categorized into mild, severe and catastrophic wear respectively.

Four commonly used techniques which are followed for rail-wheel lubrication are:

- Top of rail lubricators
- Wheel flange lubricators
- Wayside lubricators
- On board lubricators

In Sweden, about 3000 wayside lubricators are installed, and the total investment cost excluding the annual maintenance cost is about US $ 7.9 million (Waara, 2000). Railways around the world are spending such high cost for rail lubrication because if it is neglected, rail replacement would be the ultimate solution, which is far more costly. Lubrication helps to reduce rail gauge face wear and reduces energy or fuel consumption along with noise reduction.

However, excessive lubrication leaves residue behind that builds up on the rails and wheels, resulting in potential environmental hazards. Excessive lubrication also reduces friction more than required which increases the train’s braking distance, this may build up risk in safe operation of trains. On the other hand, according to American Association of Railroads, US $ 2 billion are spent in excess on ineffective lubrication (Diamond and Wolf, 2002). The issue of effective lubrication of rails depends on the lubrication techniques used. Designing better and cost effective lubrication techniques and implementing them is a major challenge to the rail players around the world (Figure 21). In many of the wayside lubricators, optimum frequency of lubrication needs to be modeled based on detailed analysis so that it reduces derailment risk and rail/wheel damage and at the same time it is also cost effective. “Effective lubrication can only be enforced if adequate monitoring methods are available.” (Peters and Reiff, 1989), thus the sensors to actuate the lubricators should also be sensitive enough to optimize lubrication frequency. Weather conditions are of particular concern to these lubricators. The applicator nozzles when not used for a long time in summer starts clogging; this leads to improper functioning of the lubrication system. This problem is frequently faced in many parts of Australia, where summers are hot. Lubricators need to be cleaned before the start of winter in cold countries like Sweden as well. This procedure is important as the nozzles of these lubricators may clog in winter due to no lubrication during winter. It takes two persons one and half to two hours in Sweden to clean up a wayside lubricator. If it is done on the site then it costs US $ 360 /service (2 personnel x 2 hours and one car for transportation). If it is done at depot the cost can be different. The cost to maintain the lubricators cost around US $ 900 - US $ 1500 /year/apparatus (the lubricators are used only for six months as there is no lubrication during winter) this includes fill up and maintenance of lubricators (Chattopadhyay, *et al*, 2004). Biodegradable lubricants are also being used by various rail operators, but the economic side of their implementation is still an issue. Cost effectiveness of lubricants is analysed by condition monitoring of lubricant properties and prediction of remaining useful life of the lubricant so that frequent oil change is avoided (Kumar *et al*, 2005).

6.2.2 Rolling Contact Fatigue (RCF) Issues

In the late 1990s RCF defects accounted for about 60% of defects found by East Japan Railways, while in France (SNCF) and UK (Railtrack) the figures were about 25 and 15%, respectively. RCF is a major future concern as business demands for higher speed; higher axle loads, higher traffic density and higher tractive forces increase (see Cannon *et al*, 2003).

Rail grinding removes surface metal from the rail head. Grinding is done by a series of rotary abrasive grinding stones mounted at different angles on a rail car to give the rail head its required profile. It is done mainly with intensions to control RCF defects and rail wear. Rail grinding became increasingly recognized for controlling RCF defects from 1980 onwards, prior to that it was mainly focused on corrugation removal. At that time barely 15% of Canadian Pacific Railway's (CPR) grinding budget was devoted to treatment of RCF compared to 60% on control of corrugation. In the late 1990s, grinding as a treatment of RCF of rails became a more established approach and began to be adopted on some European railways. It is now widely followed in Europe. The annual grinding budget in North America for larger railways is about US $ 500 per kilometer of track, this means that on a system with 20 000 km of track, the grinding budget is about US $ 10 million. This figure includes all costs associated with grinding (Cannon *et al*, 2003).

Rail grinding has two approaches, corrective and preventive grinding. Corrective grinding requires deep and infrequent cuts where as preventive grinding requires thin but more frequent cuts (Kalousek, *et al*, 1989). Generally the minimum interval for rail grinding is in the range 10–15 million gross tones (MGT). The Swedish national rail administration, Banverket follows preventive grinding on new rails within one year or after 5 MGT of traffic load. Later on regrinding is done in a cyclic manner called maintenance grinding, when grinding is done specifically to remove severe irregularities or defects in certain areas of the rail section, it is termed as corrective grinding according to Banverket. But the issue of having optimal grinding frequency depending on weather conditions is still a challenge for rail players.

6.2.3 Rail Welding Issues

Small imperfection in welds can cause cracks to initiate. A defect free weld requires skilled workforce, better weld material and better welding techniques along with better welding equipments. In Sweden inspection, welding and rectification process becomes a costly affair due to snow and ice during winters. Most of the defects which do not pose immediate risk of damage to rail assets or derailment risk are deferred till the end of winter.

6.2.4 Other Issues affecting Rail Wear, RCF and Rail Welding

Rail players are always in difficulties to decide between outsourced maintenance or in-house maintenance, depending upon the capability, cost effectiveness, skill availability, availability of equipments and technology. Risk and cost are analyzed by rail infrastructure operators in maintenance decisions. It covers rail lubrication, rail grinding and rail weld.

Other important issues are:

- Rail material
- Rail traffic density and axle load
- Track geometry

6.3 Rail Rectification and Replacement Issues

Safety and integrity of rail sections are maintained by rail rectification, replacement and re-railing. Rail rectification is done where minimal repair is required, this may be in the form of small rail section replacement less than 110 meters of rail, rail welding, tamping, adjustment of rail sections mostly on curves and fastening of fish plates where required. If the rail is replaced for rail length greater than 110 meters then it is known as rail replacement. Major overhauling of rails, is known as re-railing.

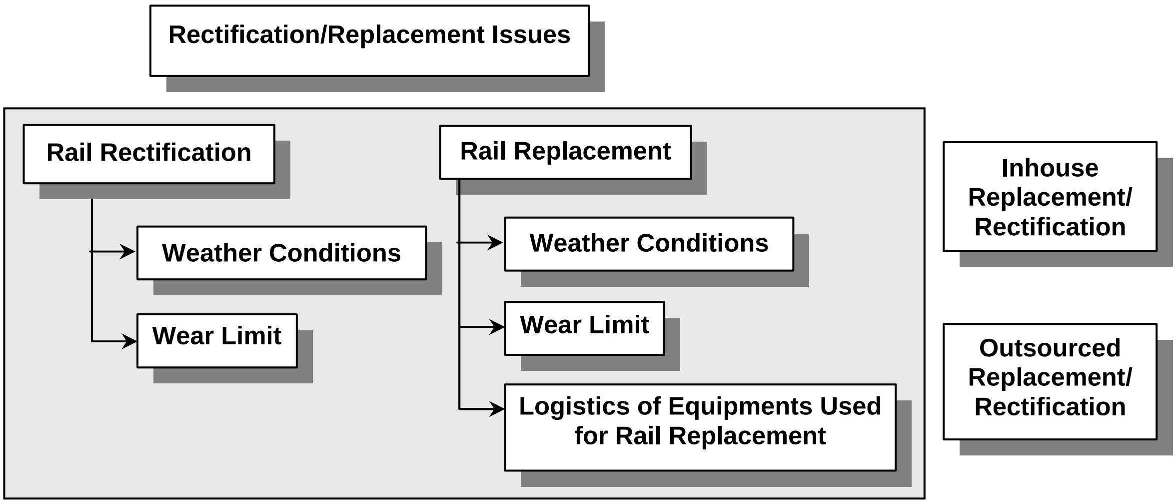

Figure 22: Rail rectification and replacement issues

Rail replacement is based on a number of responsible factors. Even now, rails are often replaced based on their life or MGT. Finding out optimal rail replacement interval which is an issue for rail players. This also depends on the wear limit and fatigue. Weather condition is also an important factor. In cold countries like Sweden, it is more economical to do rail replacement and re-railing in summers than in winters.

These issues are shown in Figure 22 and needs a detailed analysis to reach cost effective decisions in logistics planning related to rail track maintenance.

6.4 Rail Maintenance Strategy Followed at Banverket

The maintenance strategy used in Banverket is shown in Figure 23. Banverket currently uses Non destructive testing (NDT) cars, visual inspection and rail circuit detection by signals to inspect rails for identification of possible internal defects (see for details Larsson, *et al.*, 2005). The NDT Car inspection is again verified by hand held ultrasonic equipment. Visual inspection is carried out separately by rail inspector or track staff from time to time. At the same time rail circuit detection by signals (commonly known as signalling) is also carried out. The defects detected by NDT Car and verified by hand held equipment are recorded on the spot by an inspector in the form of a report. Severe defects which the inspector thinks are of high priority are immediately recommended for unplanned maintenance. Visually inspected defects are also recorded in a report. The data recorded in this report is further analyzed by an expert. Aid of historical data and information stored in a centralized database is also taken to correlate failure patterns. Finally, a decision is made to classify these defects according to priority. Priority of defects is based on several factors, such as track geometry, traffic type, traffic density, axle load, age of rails, defect history, rail material, curvature, MGT, and consequential cost and risk with a particular defect if derailment occurs due to that defect.

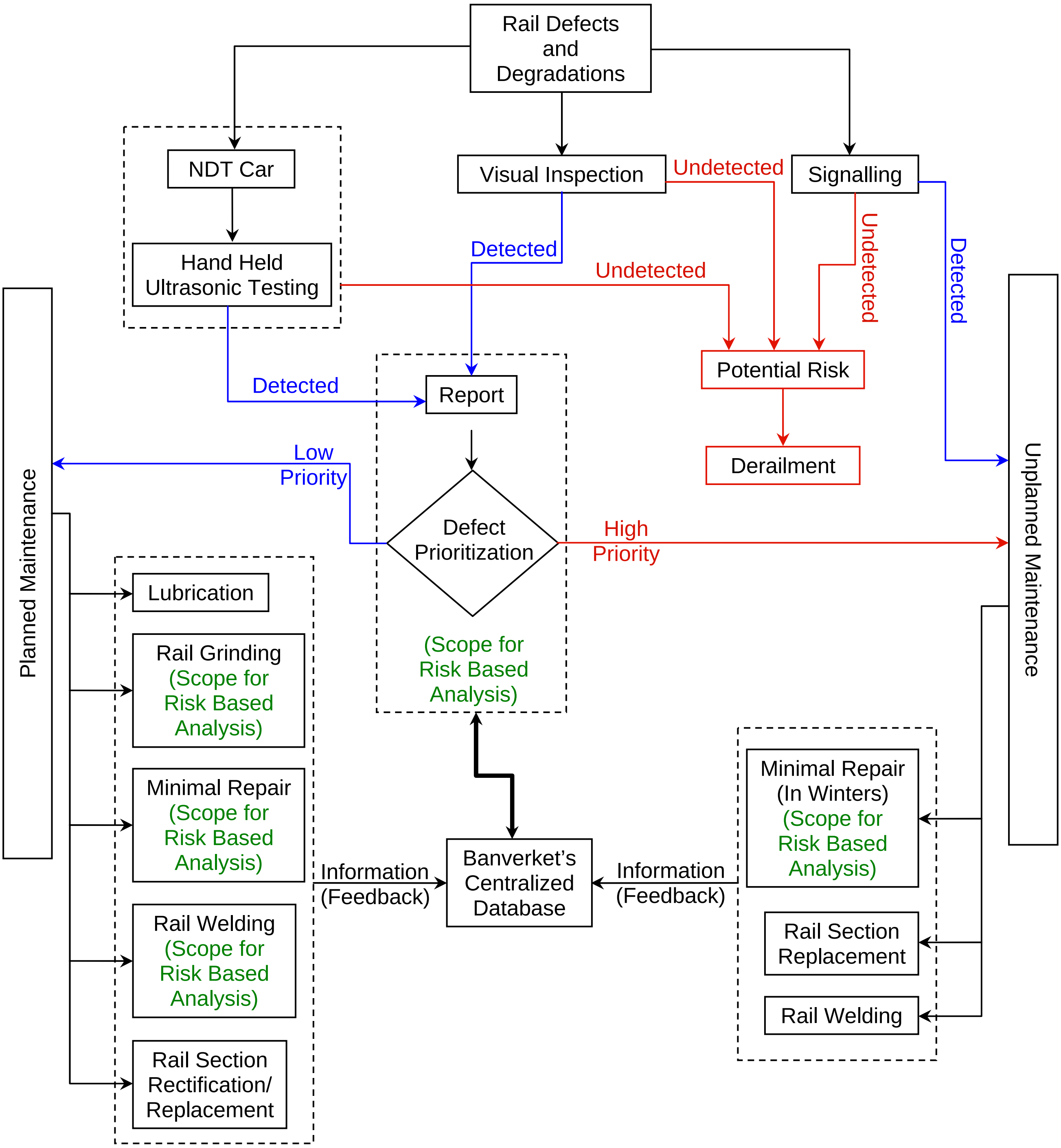

Figure 23: Banverket's rail maintenance strategy

The low priority defects are then recommended for planned maintenance which may be grinding, lubrication, minimal repair, rail welding or rail section rectification / replacement. The kind of planned maintenance adopted for a particular kind of defect depends on its need and severity.

The high priority defects are immediately recommended for unplanned maintenance which may be in the form of minimal repairs which is mostly carried out in winters, rail section replacement and/or welding. Minimal repair under unplanned maintenance is a temporary repair which is done in winters. The defects having minimal repair are later on repaired fully in summer. The defects detected by signaling is generally severe, often in the form of rail breaks or rail breaks in a developing stage and needs immediate attention, thus unplanned maintenance is carried out to counter these defects (Larsson, *et al*, 2005).

Figure 23 also illustrates those areas in Banverket’s maintenance strategy where the author feels a scope for risk based analysis.

Those defects which are undetected by these three inspection tools build up operational risk in rails, some of which may eventually be detected through derailments. However, the percentage of defects leading to derailments is very small. Figure 24 gives an idea of the percentage of potential rail breaks which are detected by different inspection tools (see for details, Larsson, *et al*, 2005)

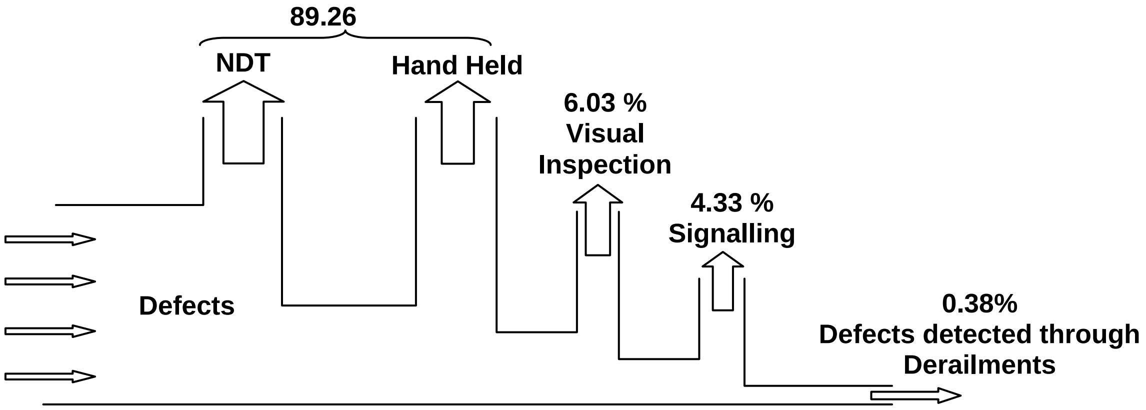

Figure 24: Percentage of potential rail breaks detected from different inspection tools [Adapted from Larsson, et al, 2005]

7. CONCLUSIONS

Different types of rail defects and degradation processes have been studied. From the literature survey and studies done by the author, it is interpreted that there is a need for better prediction of rail defects over a period of time based on operating conditions and maintenance strategies.

A good knowledge of risk along with an idea of the methods used for risk analysis is also required. Thus, before development of any model or any empirical relationship associated with risk, familiarity with risk management tools the different ways to link it with defects should be known. This study focuses on building up a basic knowledge required for establishing such a relationship.

The issues and challenges related to rail maintenance are discussed. The aim is to reduce costs and risks related to rail operation by effective decisions related to rail inspection, grinding, lubrications, rectifications and rail replacements. Some of the challenges in this area include development of cost effective maintenance decisions, reliability and availability of logistics support, which include availability of capable equipment, skilled personnel and availability of rail track. The analysis of these decisions needs to consider weather to go for inhousing or outsourcing of inspection, grinding, lubrication, rectification and rail replacements. Detailed study considering rail and wheel and economic models for safe and cost effective decisions is a big challenge now and also for the future. The author is currently working on these models along with important rail maintenance issues and the results will be published in the near future.

An overview of the maintenance strategy followed at Banverket has been described. Some of the areas having a scope of risk based analysis and prediction have also been pointed out.

8. SCOPE FOR FUTURE WORK

- Extraction of meaningful information from the data supplied and their classification based on various operational and climatic conditions.

- Development of a model for a trade off between maintenance investment and risk due to rail breaks by estimation of the parameters which influence rail defect formation and rail degradation.

- Experimental verification of the model from the data collected by simulating a crack growth pattern on rail specimens under assumed conditions.

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