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A Study of the Rail Degradation Process to Predict Rail Breaks

Saurabh Kumar

Luleå University of Technology
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PREFACE

The study and research work presented in this thesis has been carried out both 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.

First of all, I would like to express my sincere gratitude to my supervisor, Professor Uday Kumar for his invaluable guidance, thought provoking discussions and continuous support during the research.

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I wish to express my sincere thanks to Banverket for providing the data for analysis and Luleå Railway Research Centre (JVTC) for all the support required in completing the thesis.

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Finally, I wish to express my gratitude to my loving wife, Ruchika, for her patience and support during the work.

Saurabh Kumar

August, 2006
Luleå, Sweden

ABSTRACT

Rail infrastructure is a large and costly investment, and has a long life. To realize the benefits from this investment, effective maintenance is required. Railways are one of the prime modes of transportation in many countries and as they are closely associated with passenger and cargo transportation, they own high risk in terms of potential loss of human life and damage/destruction of assets. New technologies and stringent safety standards are constantly being introduced, but accidents still occur. There will always be some risk associated with derailments and collisions, but it can be reduced by elimination of the root causes by means of an effective maintenance strategy to govern optimization of inspection, lubrication and grinding frequency and/or improvement in skill and efficiency. A detailed study of the defects which emerge both in the rolling stock and the rail infrastructure is essential to identify the correct maintenance strategy.

Detection and rectification of rail defects/degradations are major issues for all rail players around the world. Some of the rail degradations 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. Efficient maintenance strategies can reduce potential risk of rail breaks and derailments. A potential risk is the risk which accumulates in the form of rail degradation over a period of time.

In spite of continuous efforts made by all rail infrastructure operators around the world to reduce costs, a substantial proportion of railway budget is spent on rail maintenance. It is understood that the consequential costs due to derailment reduces with increase in inspection, lubrication, grinding and replacement costs. The challenge is to find a balance between the maintenance costs which consists of inspection, lubrication and grinding costs, and consequential costs due to derailments. The consequences of derailment in terms of loss of human life, damage/destruction of assets and loss of company trust and reputation justify maintaining stringent safety standards, which require massive rail maintenance investments in order to be met. Reduction in maintenance investments may increase the rate of rail degradation, which may increase the risk of derailments.

The aim is to develop an approach to predict rail failures, which will help to optimize maintenance activities (inspection, grinding, rectification/replacement and/or welding). Generally, there is a trade-off between maintenance investment and the risk involved in rail degradation in order to develop a rail maintenance procedure. Failure prediction of rail sections undergoing degradation will help to estimate the risk of derailment. Thus, prediction of the rail failure rate is a requirement for the development of an effective rail maintenance procedure.

Different types of rail degradation processes leading to various rail defects have been studied. The performed literature studies indicate a need for better prediction of rail failure over a period of time based on the factors influencing rail degradation. The maintenance strategy followed by the Swedish National Rail Administration (Banverket), Sweden’s rail infrastructure operator, is described and the issues related to rail degradation and maintenance are outlined for further research in this area.

Rail failure data has been extracted from different Banverket’s databases, classified according to a classification framework developed and analyzed over a period of time based on Million Gross Tonnes (MGT) of traffic using Weibull distribution. During the process of data evaluation and analysis, a method of extracting useful information from incomplete data has been identified.

Keywords: Rail degradation, rail defect, effective maintenance procedure, risk, rail break, rail maintenance issues, data classification, maintenance investment.

LIST OF FIGURES

LIST OF ABBREVIATIONS

AAR – *Association of American Railroads*
Amtrak – *National Railroad Passenger Corporation and Subsidiaries*
AREA – *American Railway Engineering Association*
ASCE – *American Society of Civil Engineers*
ASTM – *American Society for Testing and Materials*
BN – *Burlington Northern Railroads*
BS – *British Standards*
BV – *Banverket (Swedish National Rail Administration)*
CPR – *Canadian Pacific Railways*
CWR – *Continuous Welded Rails*
DB – *Deutsche Bahn (German National Railway Operator)*
DECOTRACK – *Degradation Cost on Track*
ECOTRACK – *Economical Track Maintenance*
ERRI – *European Railway Research Institute*
FBW – *Flash Butt Weld*
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)*
IHHA – *International Heavy Haul Association*
ITDM – *Integrated Track Degradation Model*
JVTC – *Järnvägstekniskt Centrum (Luleå Railway Research Centre)*
MIT – *Massachusetts Institute of Technology, USA*
MGT – *Million Gross Tonnes*
NDT – *Non-Destructive Testing*
NS – *Nederlandse Spoorwegen (Former Dutch/Netherlands Railways)*
ORR – *Office of Rail Regulation*
QUT – *Queensland University of Technology, Australia*
RCF – *Rolling Contact Fatigue*
REPOMAN – *Rail Expert Planning, Organization and Maintenance*
SJ – *Statens Järnvägar (Swedish State Railways)*
SNCF – *Sociéte Nationale des Chemins de fer Français (French National Railway Company)*
TM Model – *Three Mechanism Model*
TRACS – *Total Right-of-Way Analysis and Costing System*
TW – *Thermit Weld*
UIC – *Union Internationale des Chemins (International Union of Railways)*

LIST OF RELATED PUBLICATIONS

Kumar, S., Chattopadhyay, G., Reddy, V. and Kumar, U. (2006) Issues and Challenges with Logistics of Rail Maintenance, *Conference proceedings of 2nd International Intelligent Logistics Systems Conference*, Brisbane, Australia, Feb 22-23rd, 2006, pp. 16.1-16.9, ISBN: (CD-Rom) 0-9596291-9-X.

Chattopadhyay, G., Kumar, S., Larsson-Kråik, P.O. and Kumar, U. (2006) Estimation of Parameter for Degradation of Rails, *Conference proceedings of 19th International Congress on Condition Monitoring and Diagnostic Engineering Management*, *(COMADEM)*, Luleå, SWEDEN, 12th -15th June, 2006, pp. 605 – 612, ISBN: 978-91-631-8806-0.

Kumar, S. (2006) Study of Rail Breaks: Associated Risks and Maintenance Strategies. *Technical Report*, Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden. ISSN: 1402-1536; 2006:07.

Kumar,S., Chattopadhyay, G. and Kumar, U., Reliability Improvement through Alternative Designs – A Case Study, *(Accepted for publication in Reliability Engineering and System Safety).*

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1 INTRODUCTION AND BACKGROUND

Railways are one of the prime modes of transportation in many countries. As they are closely associated with passenger and cargo transportation, there is a high risk in terms of the potential loss of human lives life and assets. New technologies and better safety standards are constantly being introduced, but accidents still occur. There will always be some risk associated with derailments and collisions, but it can be reduced by detailed research into the root causes. Some of the causes require improvement in skill and efficiency, for example human error, (see Cacciabue, 2005) while some may be improved by optimization of inspection frequencies, grinding campaigns and lubrication intervals (see for example, Podofillini *et al.*, 2006; Chattopadhyay *et al.*, 2005a & b; Waara, 2006). Thus, an effective maintenance procedure is required for optimization of inspection frequency and/or improvement in skill and efficiency. A detailed study of the defects which emerge on the rail infrastructure is essential to design an effective rail maintenance procedure.

Detection and rectification of rail defects are major issues for all rail players around the world. A rail defect may call for safety measures to be taken by rail players (for example: the imposition of speed restrictions), leading to considerable traffic disruption and ultimately passenger dissatisfaction. Possible 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. Infrastructure maintenance personnel face the challenge of performing effective inspection and taking cost-effective maintenance decisions. If these issues are addressed properly, inspection and maintenance decisions can reduce the potential risk of rail breaks and derailments. A potential risk is the risk which accumulates in the form of rail degradation over a period of time. In spite of continuous efforts made by all rail infrastructure operators around the world to reduce costs, a substantial amount of their railway budgets is spent on inspection and maintenance of rails. The total cost of annual rail inspection in the European Union is around € 375–850 million per year (Cannon *et al.*, 2003). It is understood that the consequential costs of derailment decrease as inspection, lubrication and grinding costs increase. The challenge is to find a balance between the maintenance costs (for inspection, lubrication and grinding activities), on one hand and the consequential costs of derailments on the other.

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.*, 2003a). Risk evaluation has become an important tool for the management to decide a better and more cost-effective solution that could meet budgetary constraints regarding renewal, replacement, inspection frequency and policy development (Akersten and Espling, 2005). Risk in railways is a very important aspect, the consequences of which can be expressed in terms of loss of human life, infrastructure unavailability, traffic delay, penalty imposed by transport authority, loss of assets and environmental impact which may be caused by the derailment of a train carrying hazardous material.

To see the previous work done to develop cost effective maintenance solutions and reduction of rail/track degradation, a review of the previous literature was undertaken.

1.1 Review of Previous Literature

If we wish to realize the benefits from an investment, maintenance is the prerequisite (Andersson, 2002). Rail infrastructure is an expensive investment, but it has a long life with low operating cost compared to other modes of transportation. The asset value is very high, which probably makes maintenance efforts of high value (Larsson, 2004). Reasonably structured track maintenance planning started to develop in the early 1980's. Fazio and Prybella (1980) described a track maintenance approach in which they highlighted some of the prerequisites for track maintenance. Hargrove (1985) proposed a track degradation model considering degradation in different components of the track. Separate degradation models of all the components together form the track degradation model. His approach has been applied to a certain extent in this thesis. He further calculated track maintenance cost by life cycle estimation of different components of the track. But Hargrove's model lacked the prioritisation of different activities which should be done in order to control the degradation rates in different components of the track.

By the beginning of 1990's, many researchers and rail players felt the need for a rail infrastructure maintenance model which was both economical and efficient. Considerable work was done during the 1990's on the development of effective maintenance strategies for rail infrastructure. REPOMAN (Rail Expert Planning, Organization and Maintenance) and TRACS (Total Right-of-Way Analysis and Costing System) were developed in the early 1990's at Massachusetts Institute of Technology (MIT), USA, with the aid of rail players like Burlington Northern Railroads (BN) and the Association of American Railroads (AAR). REPOMAN was based on maintenance planning while TRACS was based on track degradation analysis and life-cycle costing. (see Martland and Hargrove, 1993; Martland, *et al.,* 1994; Acharya, *et al.,* 1991 for details). Rail players in collaboration with academic/research institutions became actively involved in the development of rail infrastructure maintenance strategies which further produced useful track maintenance models like ECOTRACK (developed jointly by UIC, ERRI and other rail companies), ITDM (developed at Queensland University of Technology, Australia) and DECOTRACK (developed jointly by Damill AB, Banverket (Swedish National Rail Administration) and JVTC (Järnvägstekniskt Centrum) at Luleå University of Technology). (see ERRI, 1995; Zhang, 2000; Zhang, *et al.,* 1999; Larsson, 2004).

Ebersöhn (1997) discussed the need for track maintenance management and outlined some of the prerequisites for the track maintenance decision-making process such as traffic data, cost information, asset inventory and historical data. Ebersöhn's approach provided useful data for the development of track maintenance strategies. His approach has been implemented in AMTRAK (see, Ebersöhn, *et al.*, 2001). Zarembski (1998) emphasized the use of automated inspection systems and well-structured databases, which should provide all the information required and enable proper planning to improve the efficiency of rail infrastructure management systems. Zarembski (1998) tried to give a general view on developing an effective track maintenance strategy. But his approach lacked some of the factors affecting rail degradation, like axle load and characteristics of bogie type.

This thesis is based on the development of an approach to rail failure prediction. One of the objectives has been to identify the issues in rail maintenance. There are issues which need to be resolved concerning rail inspection, the rail degradation process, rail replacement as well as the inhousing and outsourcing of maintenance activities. Cannon, *et al.,* (2003) described the shadowing effect of ultrasonic sound waves by head checks and squats. Some of the defects which are left undetected by non-destructive testing (NDT) techniques are due to the problem described by Cannon. Chattopadhyay, *et al.,* (2005) emphasized the need for a reduction in undetected defects and wrongly detected defects. One of the main issues in rail maintenance is reduction in rail wear. A detailed study of the process of rail wear can be found in the articles of Jendel, (1999), Zakharov, (2001), Olofsson and Nilsson, (2002) and Chen *et al.,* (2005). Wear is a form of degradation which cannot be completely eliminated but can be reduced by lubrication. Effective lubrication can only be achieved if adequate monitoring methods are available (Peters and Reiff, 1989). Online lubricant condition monitoring is one of the possible alternatives (see Tomeoka, *et al.,* 2002; Suda, *et al.,* 2005; Kumar *et al.,* 2005). Another important issue is reducing defects originating mainly from rolling contact fatigue (RCF). Analysis and modelling of RCF initiated defects have been done by many researchers, (see, Ringsberg and Bergkvist, 2003; Ishida, *et al.,* 2003; Fletcher and Beynon, 2000; Sawley and Kristan, 2003; Ekberg *et al.,* 2001; Jeong, 2003) to find out ways of reducing the initiation and propagation of these defects. A small reduction in the initiation of these defects will save a lot of maintenance, replacement and consequential costs (in case of derailments caused by RCF initiated defects), but an appreciable level of reduction has still not been achieved. Rail grinding is done mainly to control RCF defects and rail wear and became increasingly recognized as a way of reducing RCF defects from 1980 onwards, prior to that it was mainly focused on corrugation removal (Cannon, *et al.,* 2003). A noticeable contribution on the rail grinding process and strategy can be found in (Kalousek, *et al.*, 1989). (also see, Kalousek and Magel, 1997; Magel and Kalousek, 2002; Magel, *et al.*, 2003). In the author's perception, rail infrastructure owners like the Swedish National Rail Administration (Banverket) are increasing investment in preventive maintenance and reinvesting in rail infrastructure as they start to understand the issues related to rail maintenance and the consequences of negligence (see Banverket, 2000, 2003 and 2005; Chattopadhyay, *et al.*, 2005b; Andersson, 2002).

As rail degradation is one of the prime issues for rail infrastructure owners and several other issues depend on rail degradation, it becomes important to understand the rail degradation process. Rail degradation is a failure process which leads to a rail defect (a fault). Olofsson and Nilsson, (2002) classified rail defects which occur due to RCF into surface initiated and subsurface initiated defects (also see Zerbst *et al.*, 2005). Other classifications were given by Cannon *et al.*, (2003) and Marais and Mistry, (2003). Detailed study on the different types of rail defects has been performed by a number of researchers over the years (see Grassie and Kalousek, 1993; Matsumoto, *et al.*, 1996; Kalousek and Magel, 1997; Nielsen and Stensson, 1999; Zhang, 2000; Esveld, 2001; Ishida *et al.*, 2002; Zarembski, *et al.*, 2005; Zerbst *et al.*, 2005). Residual stress accumulation is also an important factor which accelerates the rail degradation process. Use of improved welding technology and post-weld heat treatment considerably decrease the extent of weld initiated residual stress (for details, see Esveld, 2001; IHHA, 2001). Most of the critical defects manifest themselves in the form of cracks which finally leads to a rail break. An interesting insight into the phenomenon of crack propagation during fluid entrapment was given by Bower and Johnson in 1991 (also see Bogdanski *et al.*, 1997). Some of the crack growth models have also been discussed here (see Nishida 1991; Miller 1997; Fletcher and Beynon 2000; Ringsberg 2001; Kapoor *et al.*, 2002; Magel *el al.*, 2003).

From the review of previous literature, it was found that there is a need to reduce track degradation and defect formation rate which requires failure prediction of different components of the track in order to develop an effective track maintenance strategy. The next section describes the problem and the need for studying it.

1.2 Problem Statement and Need for the Study

Rail players have well-defined business objectives based on customer demands which in turn create a foundation for track maintenance objectives. Rail maintenance objectives can be considered as a part of track maintenance objectives. Safety, passenger comfort and satisfaction are examples of overall business objectives which require reliable track with increased availability in order to minimize traffic disruption (track maintenance objectives). Track reliability, availability and reduced risk of derailments can be achieved by reducing the rate of rail degradation (rail maintenance objective) which requires a well-structured and effective rail maintenance procedure (Figure 1).

Predicting the failure rate for a rail section helps to properly schedule maintenance activities (inspection, grinding, rectification/replacement and/or welding) in an optimal way. Generally, a trade-off is made between maintenance investment and the risk involved with rail degradation in order to develop a rail maintenance procedure. Predicting the failure of a degrading rail section will facilitate risk estimation. Thus, predicting rail failure rate is a requirement for the development of an effective rail maintenance procedure.

If a maintenance procedure is not well-structured and effective, proper maintenance action may not be taken within the required time or a defect may be left uninspected, as a result, rail degradations and defects may develop into rail breaks. A rail break can cause derailments which may have catastrophic consequences. The Hatfield derailment (UK) in October 2000 killed 4 and injured 34 people. The damages in terms of consequential costs to Railtrack Company (acquired by Network Rail since 2002) were about £733 million (The Guardian, 2005). According to the Office of Rail Regulation's interim report (2002) on the Hatfield crash, the derailment happened because a rail, in which there were multiple cracks and fractures due to rolling contact fatigue (RCF), fragmented when a high speed train passed over it.

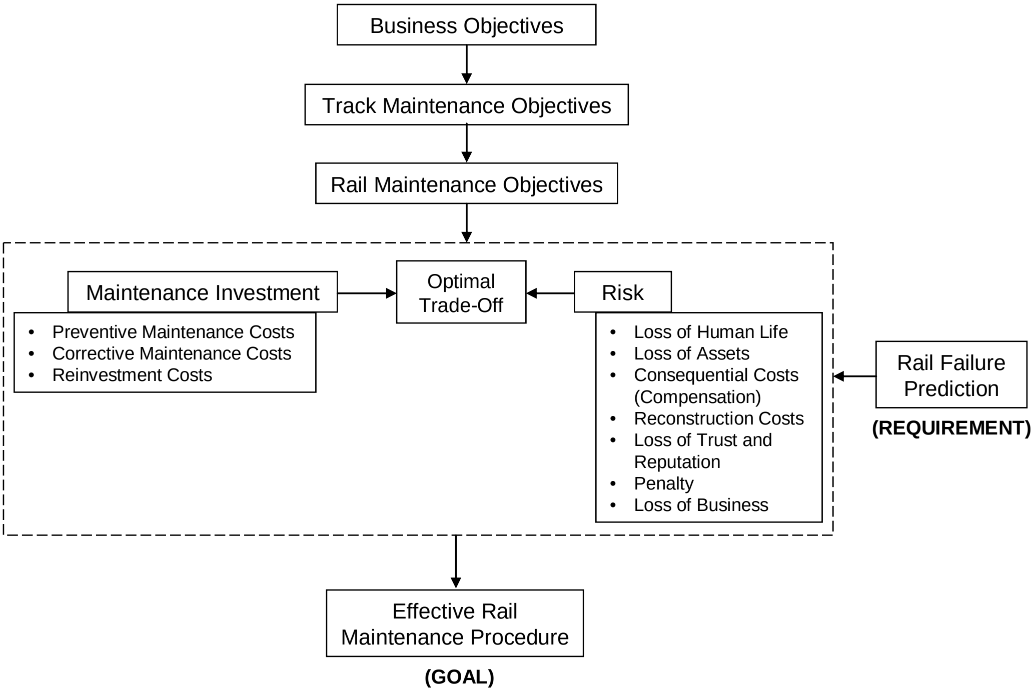

Figure 1: Process of goal formulation

The consequences of derailment in terms of loss of human life, assets and company trust and reputation, as well as fines, compensation and reconstruction costs call for stringent safety standards which require massive rail maintenance investments to be met. There will always be some risk associated with derailments and the condition of rails, but it can be reduced by increasing maintenance investment. The investment limit depends on the availability of funds and the level of risk acceptable under the given operating conditions. An effective maintenance strategy should be able to strike the optimum balance between the risk and the required investment.

Extensive literature study, discussions and consultations with maintenance experts from Banverket, JVTC, Queensland Rail and QUT, Australia led to the development of an approach to predicting rail failures.

Some of the other points elaborating the need for the current research are:

- Effective utilization of rail budgets for rail maintenance activities
- Better prediction of inspection, grinding, lubrication and replacement intervals for the development of an effective rail maintenance procedure
- Better prediction of expected number of rail breaks over a period of time based on Million Gross Tonnes (MGT) traffic and the factors influencing the formation of rail breaks

1.3 Purpose of the Study

The purpose of the study is to develop an approach for rail failure prediction based on the factors influencing the rail degradation process.

This will help to better estimate the risk associated with rails, better understand the existing rail maintenance procedure, prevent the occurrence of rail failures by taking the required action at the right time and extending rail life expectancy by developing an effective rail maintenance procedure.

1.4 Objectives

The objectives of the thesis are to:

1. Study the different types of rail defects and rail degradation processes
2. Identify the different factors influencing the rail degradation process
3. Identify the current issues in rail maintenance

1.5 Research Questions

In order to fulfill the purpose of the study and the objectives, the following research questions need to be answered:

1. What are the current issues in rail maintenance?
2. What are the factors influencing the rail degradation process?
3. How can we develop an approach to rail failure prediction?

1.6 Delimitations

Two main delimitations are made in this thesis. Firstly, the research is focussed on developing an approach to rail failure prediction instead of track failure prediction as a whole. The reason for this limitation is the vastness and complexity of the research area. A track consists of different components namely, rails, switches, fasteners, sleepers, tie plates, rail anchors, ballast and subgrade (see Esveld, 2001). Each of these components will be affected by different factors influencing rail degradation. It will be very complex and difficult to predict failure for all track components considering all the factors responsible for their degradation.

Secondly, all the factors influencing rail degradation could not be considered for rail failure data analysis and classification because sufficient and complete information about the influence of some of these factors was not available in the database. Data were provided by Banverket (north region), from its BIS, BESSY and 0felia databases, and Banverket employees on the Malmbanan iron ore line (Section 111) from Kiruna to Riksgränsen (see Section 6.3.1 in the thesis for details).

1.7 Structure of the Thesis

The thesis consists of seven chapters. Chapter 1 starts with an introduction giving a brief background of the research area followed by a review of previous literature and problem description. The purpose of the study, objectives, research questions and the delimitations have also been outlined in this chapter.

Chapter 2 describes the methodology that has been used in this research. It explains the different phases of research, which include the research purpose, the research approach, the research strategy, data collection, data analysis and evaluation of research quality.

Chapter 3 describes Banverket's rail infrastructure maintenance procedure giving an idea of their overall maintenance strategy. In this chapter maintenance and reinvestment expenditure of Banverket over the last decade has been looked into. A rail maintenance procedure followed at Banverket has also been described. The basic aim of introducing this chapter in the thesis is to give an idea of the current maintenance practices followed at Banverket as the analysis part of the thesis uses data provided by Banverket.

Chapter 4 presents the theoretical framework related to the different types of rail defects. This chapter also looks into the crack development process and the different crack growth models.

Chapter 5 outlines the issues related to rail maintenance which can be broadly classified into rail inspection, degradation rate in rails and rail rectification and replacement.

Chapter 6 is the core of the thesis which describes the development of an approach for prediction of rail breaks. In this chapter various factors influencing the rail degradation process has been identified followed by data collection, classification, analysis and prediction of the results. A framework for classification of data has also been developed which is one of the contributions of this thesis.

Chapter 7 contains the conclusions, contributions and recommendations for future research.

2 RESEARCH METHODOLOGY

Research is a way of thinking; critically examining the various aspects of our day-to-day professional work; understanding and formulating the guiding principles that govern a particular procedure; and developing and testing new theories for the enhancement of our practice (Kumar, 2005). In other words, research is a systematic examination of the observed information to find answers to problems. Research methodology is the link between thinking and evidence (Sumser, 2000). Good research generates dependable data and information that are derived by professionally conducted practices and that can be used reliably for decision-making (Cooper and Schindler, 2006).

2.1 Research Purpose

There are three different ways of doing research in terms of its purpose, viz exploratory, descriptive and explanatory research.

- Exploratory research is useful when researchers lack a clear idea of the problems they will meet during the research (Cooper and Schindler, 2006).
- Descriptive research is used when the knowledge level is moderate and it is possible to categorize the existing knowledge into models or approaches. The aim of this kind of research is to describe a few aspects either one by one or together in the area of interest by using more or less the same technique.
- Explanatory research is done to examine and explain the existence of an observed pattern. This type of research is used to analyze the relationships and causes of a certain phenomenon. (Sullivan, 2001).

The chosen research methodologies in this thesis are exploratory and descriptive as the purpose of the research is developed by exploring of the different issues in the field of rail maintenance. Exploratory research helped in building up the knowledge needed to identify the different factors influencing rail degradation. The development of an approach to rail failure prediction is the result of descriptive research.

2.2 Research Approach

Research may be fundamental or applied in nature depending upon the knowledge about a certain area and the solution intended. Fundamental research aims to widen knowledge of a particular subject so that future research initiatives could be based on it. It is research which is designed to solve problems of a theoretical nature with little direct impact on strategic decisions. Applied research addresses existing problems or opportunities. (Cooper and Schindler, 2006).

This thesis is applied research, the purpose of which is to develop an approach to rail failure prediction based on the factors influencing the rail degradation process. The knowledge gathered from extensive literature study, discussions and consultations with maintenance experts from Banverket, JVTC, Queensland Rail and QUT, Australia was applied to develop an approach to predicting rail failure which will help to better estimate the risks associated with rails, better understand the existing rail maintenance procedure, prevent the occurrence of rail failures by taking the required action at the right time and extending rail life expectancy by developing an effective rail maintenance procedure.

Research approach can be categorized into induction or deduction (Sullivan, 2001).

- Induction approach uses observations, knowledge base and empirical data to explain and develop theories. The approach involves inferring something about a whole group or class of objects from our knowledge of one or a few members of that group or class.
- Deduction approach can be applied to generate hypothesis based on existing theories, the results of which are derived by logical conclusions.

Research approach can be quantitative or qualitative. In simple terms, quantitative research uses numbers, counts and measures of things whereas qualitative research adopts questioning and verbal analysis (Sullivan, 2001).

In this thesis both deduction and induction research approaches have been applied. Deduction approach is applied initially to build up the theoretical frame of reference for the research and later on, induction approach is applied for rail failure prediction (Figure 2). Both quantitative and qualitative research methodologies have been used in this research.

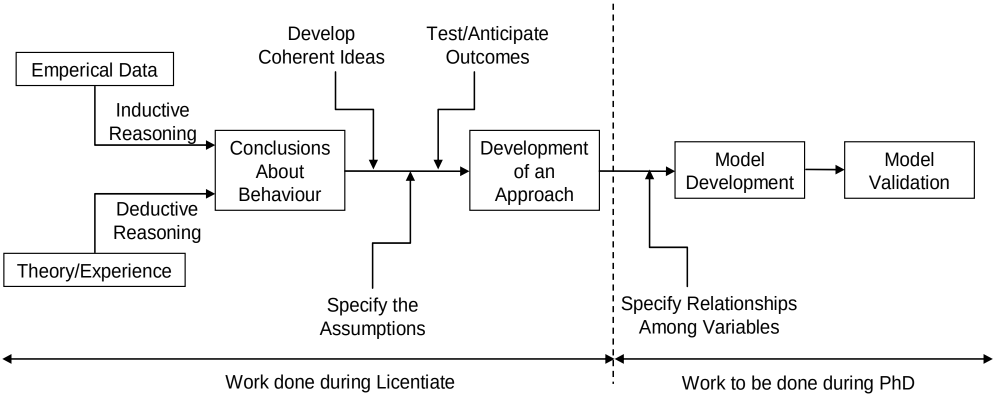

Figure 2: The process of model development and its validation [Adopted from Cooper and Schindler, 2006]

In the present context, it becomes essential to have a clear concept of a model. A model is defined as a representation of a system that is constructed to study some aspects of that system or the system as a whole. Models are important means of advancing theories and aiding decision makers (Cooper and Schindler, 2006).

An approach to rail failure prediction has been developed during the Licentiate period. The scope for future work is to develop an empirical model based on the establishment of relationships between different factors influencing rail degradation.

2.3 Data Collection

Most of the rail players collect huge amounts of data when carrying out inspection and maintenance procedures. Analyzing these data to obtain meaningful information is a tedious job. At present, the rail maintenance data is interpreted through the experience of the technical people based on non-destructive testing and visual checks (Clark, 2003). The skill level of inspectors is important for assessing the criticality of the problem and taking appropriate maintenance decisions.

In the present context data can be defined as the facts presented to the researcher from the study's environment. Data may be divided into primary and secondary types. Data collected by the researcher for the purpose of the study through various experiments or onsite data recording are called primary data. Primary data are sought for their proximity to the truth and control over error. Data collected by other people/organizations and used by the researcher are called secondary data. They have at least one level of interpretation inserted between the event and its recording. (Cooper and Schindler, 2006).

Different databases were searched to extract both qualitative and quantitative data. Relevant scientific papers and articles were extracted from online databases, such as, Elsevier Science Direct, Blackwell Synergy, Emerald and Compendex. Some of the articles were searched from the references of other relevant articles. Different keywords were used for searching these articles, such as, rail defects, rail degradation, derailment, crack propagation, rail maintenance, inspection and grinding, corrugation, rolling contact fatigue, etc. Different combinations of these keywords were tried to narrow down the number of hits. Some of the known articles were directly searched from the journal databases. Technical journals like European Railway Review were also examined. Some of the rail investigation reports (for example, the Hatfield investigation report) were downloaded from the website of the Office of Rail Regulation (ORR), UK.

Relevant books were searched from Lucia (Luleå university library's catalogue) and relevant reports, licentiate and PhD theses from various universities were also studied.

Data was collected from Banverket's (north region) BIS, BESSY and 0felia databases for Malmbanan (iron ore line) from Kiruna to Riksgränsen (Section 111) from the year 1997 to 2005, (see section 6.3.1 for details).

2.4 Data Analysis

Data analysis is an important step in the research process which includes the aspects of examining, categorizing, tabulating, or recombining the evidence to address the propositions of a study (Yin, 2003). Data analysis usually involves reduction of accumulated data to a manageable size, developing summaries, looking for patterns, and applying statistical techniques. Further, the researcher must interpret these findings in the light of the client's research questions or determine if the results are consistent with the hypotheses and theories (Cooper & Schindler, 2006).

In this thesis, failure analysis has been done considering rail break as a failure state (see section 6.3.2 for details). In practice, components are subjected to different design, manufacturing, maintenance and operating conditions and will fail at different time intervals in future. Consequently, these times-to-failure obey a probability distribution which may, or may not be known and which describes the probability that a given component fails within a certain specified time or survives beyond a certain specified time (Billinton and Allan, 1983). Different probability distributions are used for failure analysis and prediction.

In this thesis, an analysis of failure data for best fitting distribution was carried out (see section 6.3.4 for details). 2-parameter Weibull distribution and normal distribution were the best fitted distributions. Weibull distribution has been used in this thesis to analyze the data and predict the rail failure rate as it has the ability to provide reasonably accurate failure analysis and prediction with extremely small sample size (Abernethy, 2003). As the Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation (Billinton and Allan, 1983). A detailed analysis procedure has been described in Chapter 6, section 6.3.4.

Weibull distribution has a very important property; the distribution has no specific characteristic shape and depending upon the values of the parameters in its reliability functions, it can be shaped to represent many distributions (Billinton and Allan, 1983). Great adaptability of Weibull distribution results in accurate failure analysis and prediction. The slope or shape parameter β has an effect on the failure rate of a component. The value of β being less than one indicates infant mortality stage, while β being equal to one means random failures (follows exponential distribution). This stage is the normal operating or useful life of the component. If β is greater than one, it indicates the wear-out stage of the component. The scale parameter η is also known as the characteristic life of the component and is defined as the age at which 63.2 percent of the units will have failed (Abernethy, 2003).

2.5 Evaluation of Research Quality

Research quality can be evaluated in terms of reliability of procedures and data collection techniques adopted. A good explanation of the techniques and the procedures adopted adds to the quality of the research done.

2.5.1 Reliability and Validity

A reliable operation means that the procedures when repeated in a very similar or identical manner, will give the same results. One condition for high reliability is that the methodology used for data collection is clearly described (Yin, 2003). Validity is concerned with whether or not the item actually produces or explains the intended information.

This research can be assumed as a reliable one because the data and information used in this thesis are collected either from reputed journals, refereed conference proceedings and reports or from Banverket’s databases. The failure distribution used for analyzing the data is a well known distribution which has been effectively used over the years for failure predictions.

3 RAIL INFRASTRUCTURE MAINTENANCE AT BANVERKET

3.1 Introduction

Maintenance is defined as a combination of all technical, administrative and managerial actions during the life-cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (SIS, 2001). The purpose of maintenance is to reduce business risk. Business risk for managers becomes an issue due to non-availability of track or poor track performance. This can ultimately lead to customers changing their preference to other modes of transportation or loss of revenue due to non-availability of track. (Espling and Kumar, 2004).

3.2 Banverket's Overall Maintenance Strategy

The purpose of Banverket's overall maintenance strategy is to share a common view within the organization of what is to be achieved. Banverket's overall maintenance strategy is to conduct cost-effective maintenance operations that result in safety, reliability and comfort for the customers. There are well-defined values that will ensure the results of maintenance actions/operations can be measured in a satisfactory way. (Karlsson, 2005). Figure 3 shows Banverket's railway infrastructure maintenance process, which starts during the conceptual stages of developing a new infrastructure (comprising of new facilities, systems, components, etc.) and continues until the infrastructure has been phased out, decommissioned or recycled.

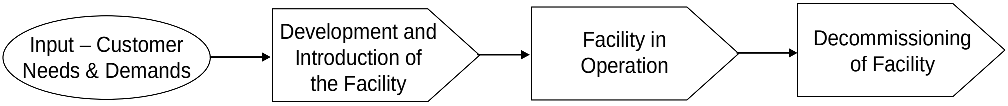

Figure 3: Life cycle of a facility [Karlsson, 2005]

Banverket's strategy leads to its overall aim of rail maintenance, which is to provide a rail that meets functional demands for frequency of train service and loading capacity, travelling time, comfort, reliability (accessibility and punctuality), safety and environmental impact; and all these requirements are to be fulfilled as cost efficiently as possible (Banverket, 2006).

3.3 Maintenance Process Followed at Banverket

A process may be defined as an activity or a set of orderly linked activities transforming input to output for customers in a repetitive flow (Rentzhog, 1996). Figure 4 shows the process view of maintenance in relation to operation and modification processes. In railways for example, track is a system, the function of which is transportation of freight and passengers. The gap between the actual performance and the required performance level illustrates the degree of stakeholder satisfaction with the delivered service. This gap can be minimized by increasing the availability and reliability of track which requires effective operation and maintenance activities. Adequate modification is done (if required) to maintain track

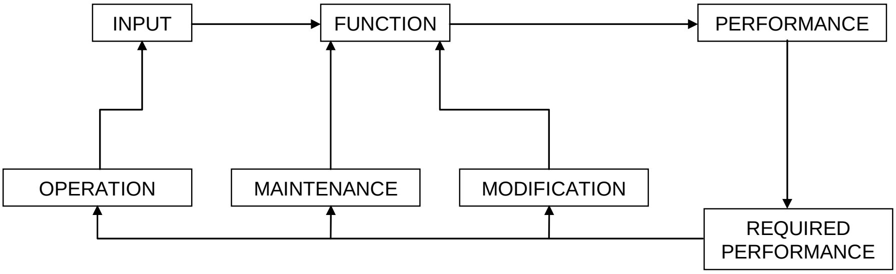

Figure 4: A process view of maintenance in relation to operation and modification processes

performance. This process continues in a repetitive flow to ensure stakeholder satisfaction (see for reference, Söderholm, *et al.*, 2006).

The life-cycle of an infrastructure facility in Banverket is divided into four stages: operation, maintenance, upgradation and decommissioning (Figure 5) (Karlsson, 2005). According to the European standard (EN 13306), the maintenance process is divided into corrective maintenance and preventive maintenance, which is subdivided into condition-based and predetermined maintenance (SIS, 2001).

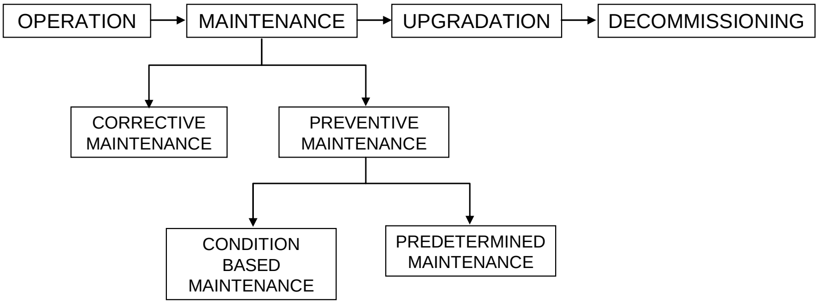

Figure 5: Maintenance definition followed by Banverket [Adopted from SIS, 2001; Andersson,2002; Ahren, 2005 and Karlsson, 2005]

According to the current strategy, the emphasis should be on minimizing corrective maintenance and as far as preventive maintenance is concerned, predetermined maintenance should, to the extent possible, be changed to condition-based maintenance (Karlsson, 2005).

3.4 Maintenance and Reinvestment Expenditure at Banverket

Banverket’s annual maintenance expenditure is divided into costs for corrective maintenance, preventive maintenance and reinvestments (Banverket, 2000). Corrective maintenance includes procedures such as emergency fault rectification, post-inspection measures and damage repair. In terms of rail maintenance, emergency fault rectification is required when severe defects, such as rail breaks, are detected. The concept of post-inspection measures was introduced in 1999 in order to keep track of the measures implemented immediately after inspection. Before 1999 some of these measures were included in preventive maintenance (Banverket, 2000). Andersson (2002) stated that the procedures under corrective maintenance, such as emergency fault rectification and post-inspection measures, are too broadly defined and need to be specified more precisely since they account for a large share of the total costs. Preventive maintenance is maintenance that is carried out at predetermined intervals or adhering to prescribed criteria and is intended to reduce the probability of failure or the degradation of the functioning of an item (SIS, 2001). Preventive maintenance consists of procedures like safety and maintenance inspection, overhauling, replacement and track straightening (Banverket, 2000). Reinvestments carried out have in principle the same objective as preventive maintenance, i.e. restoring the condition of the track (Banverket, 2000). Reinvestments are made when the assets reach the end of their useful life or become uneconomical to maintain. Banverket distinguishes between maintenance costs and reinvestment costs. The distinction lies in the amount of money spent per given object. For objects relating to track, component replacement per given track length must cost at least two million SEK to be regarded as a reinvestment. For other assets, 300,000 SEK is the minimum limit to be regarded as a reinvestment. (Banverket, 2001).

Figure 6 shows Banverket's maintenance and reinvestment expenditure from 1998 to 2005. Deductions about the reasons behind the expenditures have been made on the basis of Banverket's documents, reports and personal communication with Banverket staff at various levels.

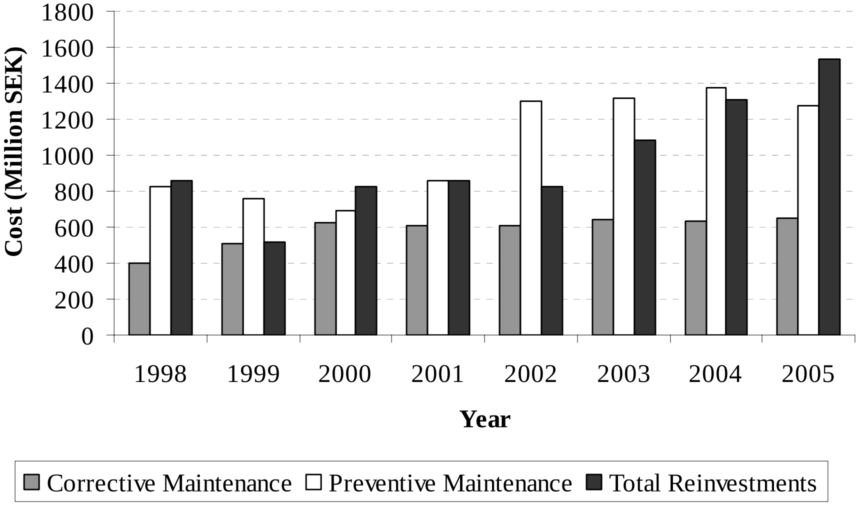

Figure 6: Banverket's maintenance and reinvestment expenditure (1998-2005)

The graph shows that both preventive maintenance and the reinvestment budget have increased considerably in recent years. In 2005, 1.274 billion SEK was allocated for preventive maintenance, which is an increase of 450 million SEK compared to 1998

(Banverket, 2000, 2003 and 2005). This trend can be interpreted in different ways. First of all, definitions may have changed over time, and may have caused the trend. During the period 1998–2000, there was a rise in corrective maintenance costs. This may be due to the introduction of a new accounting concept "Post-inspection measures" in 1999, which included the majority of the measures implemented immediately after inspection. Previously, some of these measures were included in preventive maintenance (see Banverket, 2000 for details).

Preventive maintenance costs had fallen continuously from 1998 to 2000 (as shown in Figure 6) from 824 million SEK in 1998 to 694 million SEK in 2000 (Banverket, 2000). This may be at the expense of an increase in inspections and corrective maintenance costs (Andersson, 2002)). Corrective maintenance is up to three times more expensive than preventive maintenance, for example, in the case of early warning systems for turnouts and bulbs in signaling system (Espling and Kumar, 2004). From 2001, there has been a rise in preventive maintenance expenditure owing to the increased cost of replacing defective sleepers (Banverket, 2003). The rise in preventive maintenance expenditure may also be due to the winter investigation report for better infrastructure management, which was compiled as a result of extensive train delays due to bad weather conditions with heavy snowfalls during the winter of 2001-2002 (Banverket, 2002). This led to bad train punctuality and customer dissatisfaction. A total of 200 million SEK was allocated for improving punctuality driven tasks with an extra allocation of 100 million SEK and 50 million SEK was allocated for increasing the availability of maintenance repair resources (Banverket, 2002).

Banverket's present strategy is to minimize corrective maintenance and as far as preventive maintenance is concerned, to change from scheduled (predetermined) maintenance to status-based (condition-based) maintenance (Karlsson, 2005).

According to the author's opinion, the increase in speed and traffic density and higher axle loads over the years has caused more rapid track degradation and defect formation. But to counter this, Banverket has reinvested considerably in new and better rail materials and preventive maintenance of rails. This has managed to keep the defect formation and degradation rate constant over the last ten years. Thus, we see that the expenditure for corrective maintenance (which is a maintenance procedure applied after a defect is detected) has remained relatively constant during the last decade.

3.4.1 Rail Maintenance Procedure followed at Banverket

Banverket uses different guidelines for monitoring track and track components. They specify minimum requirements for the infrastructure maintainer. Monitoring and maintenance include the functions of inspection and testing; assessment of inspection and test results, and the execution of corrective or preventive actions. The objectives are to inspect the critical elements of the track to determine its condition; record defects which might affect, or have the potential to affect the capability of the track to safely perform its required function; carry out assessments to determine the capacity of the track and finally, take actions where the track is unable to carry out the required function safely (for example, where conditions are outside acceptable limits).

The procedure described below is the author’s perception of the rail maintenance procedure followed at Banverket. This perception has been developed after an intensive literature survey of related articles, reports, discussions and consultations with rail maintenance experts from Banverket and JVTC.

The rail maintenance procedure used at Banverket is shown in Figure 7. Banverket currently uses non-destructive testing (NDT) cars and visual inspection to inspect rails to identify possible internal defects (see Chattopadhyay, *et al.*, 2005b for details). To confirm, validate and estimate potential risk, each rail failure detected by the NDT cars is reverified by hand-held ultrasonic equipment. The defects detected by the NDT cars and verified by hand-held equipment are recorded on the spot by an inspector in the form of a report. Severe defects which the inspectors thinks are of high priority are immediately recommended for unplanned maintenance, i.e. corrective maintenance (also see Andersson, 2002).

Visual inspection is carried out separately by rail inspectors according to an inspection plan (known as planned visual inspection), recorded in a report and stored in a database. Visual inspection may also be carried out in an unplanned manner by the inspector to check the track condition between planned inspection intervals. Finally, track inspectors are obligated to report if they detect any deviation from normal rail condition, as they perform their daily maintenance work along the track. These reports are also stored in a database.

The signaling system, with its traffic control safety mechanisms, will detect any deviation that could be linked to a rail failure. However, this signaling system is not used as a maintenance planning/identification tool; it is a safety system for operating trains. If the signaling system detects any deviation from the norm, traffic control reports this to the maintenance contractor. The contractor then performs an inspection or repair if necessary, and reports the action to a database.

All data recorded from the different systems are further analyzed by an expert. Historical data and information stored in a centralized database is also used to correlate failure patterns. Finally, a decision is made to prioritize these defects. 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, yearly and total accumulated MGT. The consequential costs and risks associated with a particular defect are also taken into consideration, if derailment occurs due to that defect.

Low-priority defects are then recommended for planned maintenance in the form of e.g. grinding, 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.

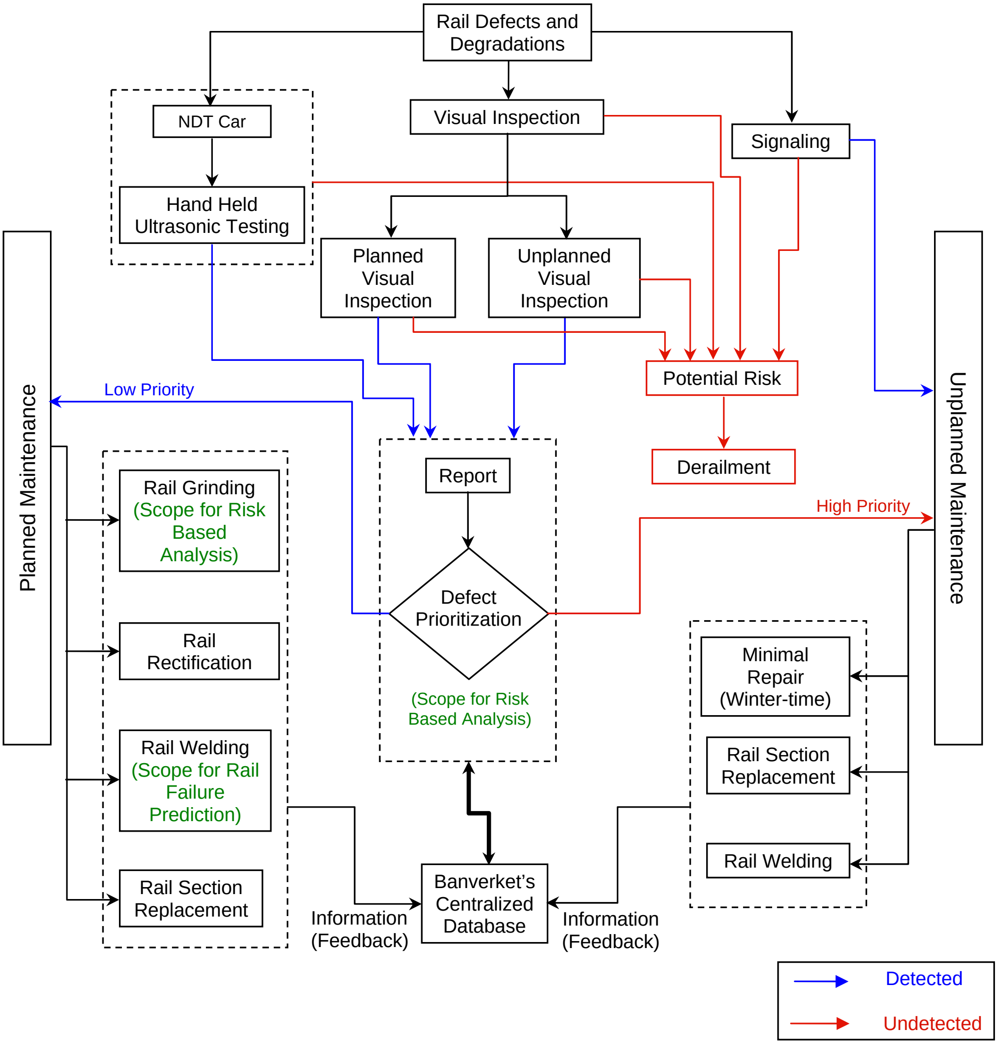

Figure 7: Banverket's track maintenance procedure

High-priority defects are immediately recommended for unplanned maintenance which may be in the form of minimal repairs (mostly carried out during the winter), rail section replacement and/or welding. Immediate maintenance is a procedure whereby emergency measures are either carried out immediately or traffic restrictions are imposed (Andersson, 2002). Minimal repairs as a form of unplanned maintenance are temporary repairs carried out during the winter. Defects that undergo minimal repair are later repaired fully in summer. The defects detected by signaling are generally severe, often in the form of rail breaks or rail breaks in a developing stage and need immediate attention, thus unplanned maintenance is carried out to counter these defects (Chattopadhyay, *et al*, 2005b).

Figure 7 also illustrates those areas in Banverket’s track maintenance procedure where the author feels there is scope for risk-based analysis. Rail failure prediction can help the maintenance expert to make better decisions as regards recommending a defect for planned or unplanned maintenance by assessing the risk of each defect. A limit for permissible risk can be standardized for defects falling under different specifications. If the risk associated with a particular type of defect is more than the maximum permissible limit, the defect will be recommended for high-priority, unplanned maintenance and vice versa. This requires the development of an effective track maintenance procedure. Similarly, rail failure prediction and risk estimation will help in deciding on cost-effective grinding intervals. Rail failure prediction will also help in cost-effective welding procedures.

Defects left undetected by the above mentioned 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.

3.5 Swedish Heavy Haul Iron Ore Line (Malmbanan)

The iron ore line (Malmbanan) runs from Narvik in Norway, situated on the coast of the Norwegian Sea, to Luleå in Sweden, which is situated on the coast of the Gulf of Bothnia. Construction of the standard gauge rail line of Ofotenban (in Norway) and Malmbanan, the Swedish ore line, began in 1898, taking the extreme northern climate and remote location into consideration. The heavy haul line was completed and became operational by 1902 and was later on electrified. Unlike its global counterparts, the ore transportation company MTAB, neither owns nor manages the track infrastructure; these are under the control of two national railway authorities; Banverket in Sweden and Jernbaneverket in Norway. Work on upgrading the iron ore line for a 30-tonne axle load was recently completed. Overall, this implies that each car will be able to carry 100 tonnes instead of 80, and that each train will consist of 68 cars instead of today’s 52. The total train weight has increased from 5,200 to 8,160 tonnes. (see Chattopadhyay, *et al.*, 2005b).

Figure 8 gives an idea of the percentage of potential rail breaks on the Swedish heavy haul iron ore line (Malmbanan) which are detected using different inspection tools (see for details, Chattopadhyay, *et al*, 2005b). There is a need to reduce the undetected defects which may lead to derailments. False detection of defects is an important inspection issue and has been later explained in Figure 26. It should be mentioned here that the analysis had been done on 50 Kg Rails, which has now been renewed with 60 Kg rails.

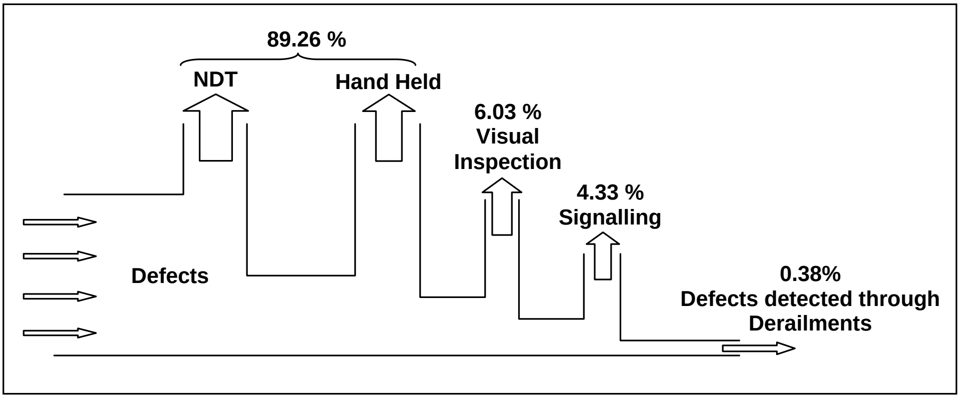

Figure 8: Percentage of potential rail breaks detected by the use of different inspection tools [Courtesy – P.O. Larsson-Kråik, 2005]

4 THEORETICAL FRAME OF REFERENCE

4.1 Overview of Rail Structure

The rail is one of the most important components of the track structure. Usually a flat-bottom rail is used in conventional railway track, which can be divided into three parts: the rail head, rail web and rail foot. Figure 9 shows the rail profile. Many standards are used for rail profiles, which are classified into UIC, ASCE, AREA and BS and 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 and 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.

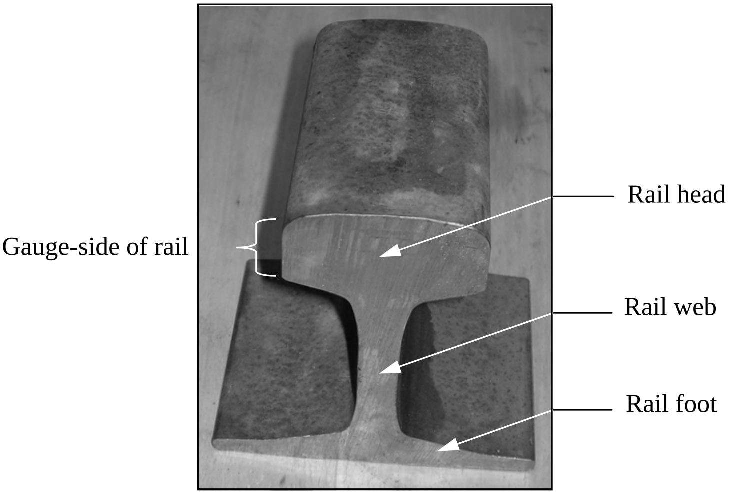

Figure 9: Flat bottom rail profile

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% 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).

4.2 Rail Defects

Due to economic pressure there is a world-wide trend to increase axle loads, traffic density and speed to reduce operating costs and increase the efficiency of railways. Axle loads around the world have increased in general from 22.5 to 32.5 tonnes in the last 10 years (Allen, 1999). This has lead to an increased rate of rail defect formation.

Rail defects occur due to a number of causes, which have been used as a basis for rail defect classification by many researchers.

Olofsson and Nilsson, (2002) classified rail defects which occur due to RCF into surface-initiated and subsurface-initiated defects (also see Zerbst *et al.*, 2005). Surface-initiated defects are formed mostly due to an increase in traffic density and axle load (for example: head checks and squats). On the other hand, subsurface defects are often caused by metallurgical faults (for example: shelling, tache ovale and longitudinal vertical crack).

Cannon *et al.*, (2003), divided rail defects into three broad groups:

- Defects originating from rail manufacture (for example: tache ovale)
- Defects originating from damage caused by inappropriate handling, installation and use (for example: the wheel burn defect, which is caused by spinning wheels)
- Defects caused by the exhaustion of the rail steel's inherent resistance to fatigue damage. Many forms of RCF-initiated defects are within this group (for example: head checking and squats)

whereas Marais and Mistry (2003) classified rail defects into two groups:

- Defects related to the rail joints (for example: flash butt weld (FBW) defects, thermit weld (TW) defects) and,
- Defects related to rail quality (for example: horizontal head cracks, tache ovale)

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

4.2.1 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 also move in a downward direction, leading to a likely transverse fracture of the rail. As this is a subsurface-initiated defect, steel metallurgy plays an important role in its initiation. Traces of oxide inclusion and residual stress formation during manufacture contribute to shelling (Esveld, 2001). Sometimes, extended shellings are misleading and are designated as spallings (Zerbst *et al.*, 2005). Figure 10 shows gauge corner shelling, which is generally eliminated by grinding.

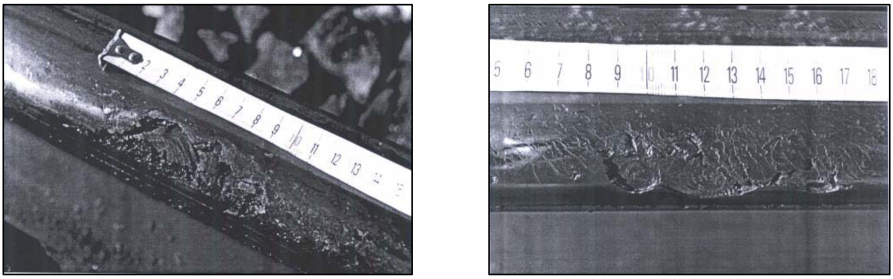

Figure 10: Gauge corner shelling in rails [Courtesy - Mats Rhen and Dan Larsson, LTU]

4.2.2 Head Checks

Head Checks are groups of fine surface cracks at the gauge corner separated by a distance of 0.5–7 mm (Zerbst *et al.*, 2005). Generally, contact stresses are low in the crown area as this has a 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 a curve radius of between 1,000 and 1,500 m. Head checks may also occur in tighter (less than 1,000 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 vary slightly in comparison with actual rail profiles. A slight variation in profiles has a major 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 11). If head checks are not controlled, they can cause a rail break. Grinding is the most common practice employed to remove head checks. Severe head checks require rail section replacement.

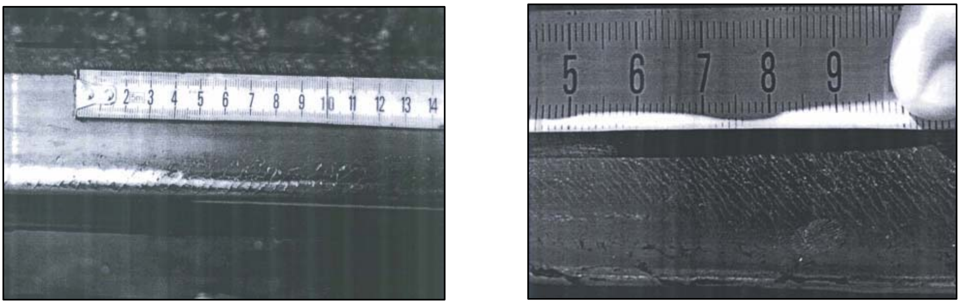

Figure 11: Head checks in rails [Courtesy - Mats Rhen and Dan Larsson, LTU]

4.2.3 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 12). Spalling occurs at a much later stage of the crack propagation phase if it is left undetected (see for details Nielsen and Stensson, 1999; IHHA, 2001). Spalling is more frequent in cold climates as rail material stiffness increases.

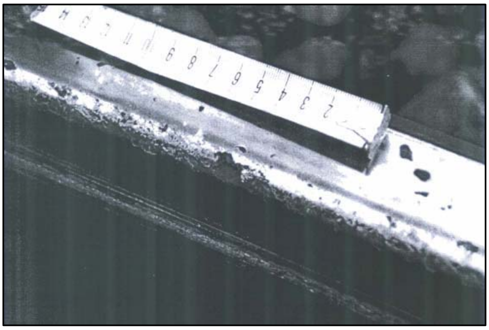

Figure 12: Spalling in rails [Courtesy - Mats Rhen and Dan Larsson, LTU]

4.2.4 Squats

Unlike shelling, squats appear in the 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 directions. The leading crack proceeds in the traffic direction, but the trailing crack propagates faster than the leading one. If preventive measures are not taken quickly, the trailing crack will branch out and probably grow downward towards the rail web. In their intial stage, squats look like depressions in the crown area (Figure 13). The depression is a result of a crack which grows progressively and branches out horizontally just below the running surface, detaching it from the rail body. These defects can 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).

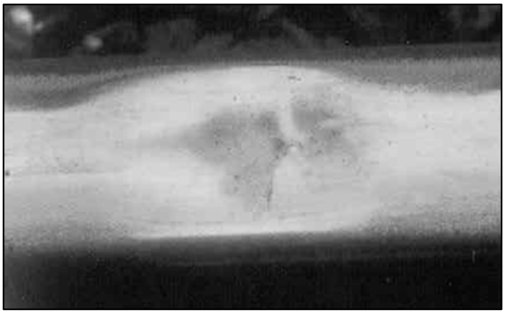

Figure 13: Squats in rails [Courtesy – V. Reddy, QUT, Australia]

4.2.5 Tache Ovale

Tache Ovale is a subsurface defect formed around 10-15 mm below the rail head surface (see Figure 14). This is caused by hydrogen accumulation during manufacture of the rail or due to poor welding. Thermal and residual stresses also contribute to the formation of this defect.

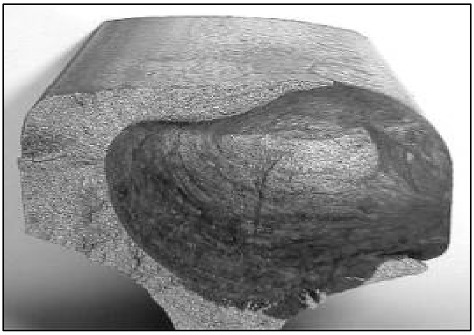

Figure 14: Tache Ovale [Courtesy - Queensland Rail, Australia, 2005]

4.2.6 Plastic Flow and Tongue Lipping

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

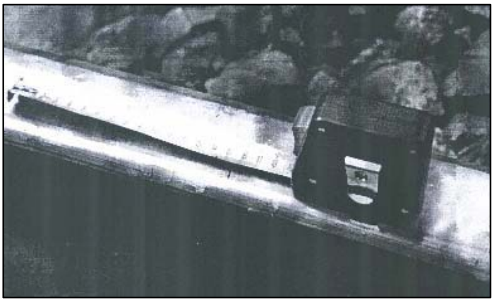

Figure 15: Tongue lipping [Courtesy - Mats Rhen and Dan Larsson, LTU]

4.2.7 Bolt Hole Crack

Bolt holes appear in the rail web often starting from fishplate fastening points. These become weak points and are left vulnerable to 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), are very likely to cause rail breaks and require urgent rail section replacement.

4.2.8 Longitudinal Vertical Crack

This is a manufacturing defect, which usually appears in the rail web and may extend into rail head also. If intersected by another crack, it may lead to an early fracture or rail break. The risk of sudden fracture due to this type of crack is elevated in cold climates. Figure 16 shows a longitudinal vertical crack.

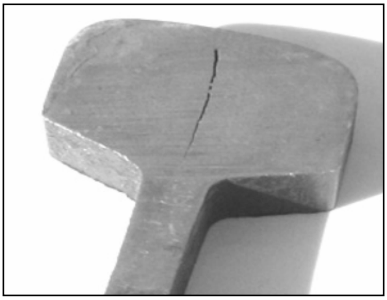

Figure 16: Longitudinal vertical crack [Courtesy – Rikard Granström, LTU]

4.2.9 Transverse Crack

Transverse cracks mostly develop in the cross-sectional area of defective weld joints. A welding defect may be due to a variation in weld material or a rail manufacturing defect. Transverse cracks in weld joints have their defect origin from the welding processes such as pores, inclusions, misalignment, etc., Figure 17(a).

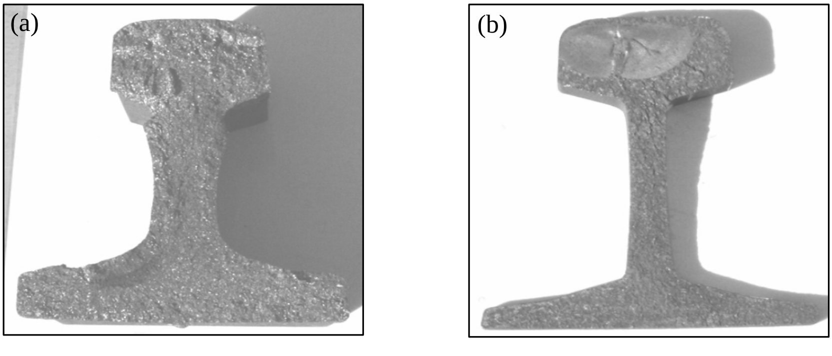

Figure 17: Transverse crack [Courtesy – Rikard Granström, LTU]

Transverse cracks develop from the centre of the rail head or the rail foot. It may be triggered by tache ovale as shown in Figure 17(b), forming a kidney shaped impression. The crack develops in the subsurface and when it reaches the rail head surface, rail break becomes inevitable. Use of clean steel and deeper hardening of rail head may avoid its formation.

4.2.10 Buckling

Lateral buckling in rails is a very common defect in which the rail bulges out on either side due to expansion. As the temperature rises, longitudinal expansion in the rail takes place (Zarembski, *et al.*, 2005). Both continuous welded rails (CWRs) 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 the ambient temperature may exceed 25°C and prevents lateral buckling in rails. However, the disadvantage of these rails is that the accumulation of high stress concentration at joints becomes even higher in high-speed rails. CWRs do not have these drawbacks as the stress distribution is more uniform and less maintenance is required leading in turn to lower life-cycle costs. However, their use is limited to temperatures under which only negligible longitudinal expansion takes place. CWRs do not accommodate rail expansion and, as a result, the rail bulges out. This leads to a serious derailment risk. There is a need for risk-based analysis of track buckling considering its most important contributory factors. A risk-based approach can provide economic options for track maintenance to achieve the desirable buckling strength (Kish and Samavedam, 1999).

4.2.11 Corrugation

Corrugation is a rail flaw in the form of wave-like wearing of the rail tread and manifests itself as peaks and valleys, in other words, a periodic irregularity of the rail surface (IHHA, 2001), see Figure 18.

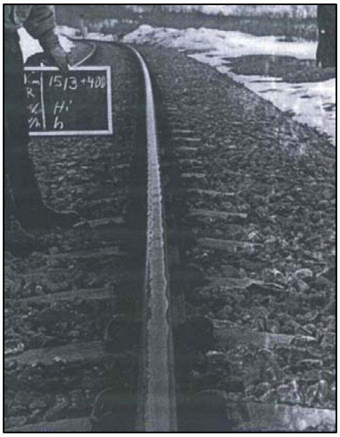

Figure 18: Corrugation in rails [Courtesy - Mats Rhen and Dan Larsson, LTU]

Rail corrugation is the result of a damage mechanism, such as wear, fatigue or plastic flow operating at some characteristic frequency (Magel and Kalousek, 2002). Rail corrugation does not pose a risk of immediate derailment, but may cause loose rail fastenings, ballast deterioration, an increase in noise and vibration levels leading to passenger discomfort, etc. Corrugation can have several causes, which are difficult to correlate at different rail sections.

Two commonly occurring types of corrugations are:

- Short pitch corrugation
- Long pitch corrugation

4.2.11.1 Short Pitch Corrugation

Short pitch corrugation is thought to be caused by self-excited stick-slip vibration of a wheel set. Defective wheels or wheel settings and heavy traffic load may cause this type of corrugation. It is mainly seen in tracks subject to heavy haul operation. Short pitch corrugation varies between 3 cm to 8 cm (Grassie and Kalousek, 1993).

4.2.11.2 Long Pitch Corrugation

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

Grinding at an early stage, use of high-strength rails and less vertical stiffness constitute some of the possible remedies for combating corrugation in rails. Research into understanding and reducing corrugation has been performed by (Ishida *et al.,* 2002; Matsumoto, *et al.,* 1996; Sato, *et al.*, 2002; Grassie and Kalousek, 1993 and Zhang, 2000).

4.3 Accumulation of Residual Stress in Rails

Residual stress builds up in rails during the manufacturing process, rail welding process or as a result of contact stress generated by the wheels rolling on the rails. Residual stress formation can accelerate defect initiation and propagation.

When new red hot rails are placed on the cooling bed, deformation/bending takes place. A time difference in the phase transformations in the railhead, web, and foot causes deformation/bending of rails. It takes about 3-4 hours for the rails to cool down from 800˚C to 100˚C. Once the rails are cool enough, a roller straightening process is carried out. A cold roller straightening process provides excellent straightness in rails but introduces unwanted residual stress which can be as much as 100-300 N/mm^2, depending on the yield stress of the rail steel. Tensile stress develops in the rail head and foot while compressive stress develops in the rail web. The maximum longitudinal, tensile residual stress in the rail foot, formed during manufacture, should be less than 250 MPa (Cannon *et al.*, 2003). Stresses induced by wheels rolling on the rails are found on the rail surface layer. These stresses protect the surface layer by preventing fatigue crack depth propagation. Residual stress formation due to rail welding is a very complex phenomenon. This is caused by an irregular heating or cooling rate of the weld metal and the rail-ends to be joined. In many cases, these stresses are the cause of rail web failure. Use of improved welding technology and post-weld heat treatment considerably decrease the extent of weld-initiated residual stresses (for details see, Esveld, 2001; IHHA, 2001).

4.4 Comparison of the causes of broken and defective rails in different railway companies

Tables 1 and 2 show a comparison of different railway companies in terms of percentage and type of defect detection. Table 1 shows the critical defects which have led to development of rail breaks for different railway companies.

Rail degradation depends on many factors; the climate, operational environment and track construction being some of the factors that vary in all the four companies shown in Table 1. A trend can nevertheless be seen. For defects leading to broken rails, welded joints (particularly thermite welds) are a particular problem, being one of the top three causes of broken rails for all four companies (Table 1), (Sawley and Reiff, 2000).

Table 1: 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%

Table 2 shows a comparison between different railway companies having four different types of defects which lead to defective rails. According to the table, three of the major passenger railways report RCF defects (shells and squats) as the number one cause of defective rails. This suggests a rise in RCF initiated defects on high-speed rail networks (Sawley and Reiff, 2000). The heavy freight railways, on the other hand, report transverse defects as the major cause of a defective rail. In the author’s opinion, axle load may be one of the primary contributory causes of transverse defects.

Table 2: 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%

4.5 Crack Development Process

When a rail section is subjected to repeated stresses of sufficient magnitude, a crack is initiated after a certain number of cycles and continues to propagate 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 has been made by many researchers in order to understand the process of crack initiation and propagation (see for example, Ringsberg and Bergkvist 2003; Ishida, *et al.*, 2003; Fletcher and Beynon, 2000; Sawley and Kristan, 2003; Jeong, 2003).

The crack development process consists of three phases:

- crack initiation,
- crack propagation and
- rail break

Rail break is the final result of the crack development process. The first two phases of crack development are critical for railway engineers, as it is during these phase that the crack should be detected by the inspection techniques and subsequently rectified by the suitable implementation of maintenance or replacement measures. The major challenge 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 an effective rail maintenance procedure, reduction in the crack initiation process can be achieved and rail life expectancy can be extended. The second important task is to find how much time it takes for the cracks, once they have initiated, to become a potential rail break. By accomplishing these tasks, inspection frequency and maintenance schedules can be optimized, for example, an appropriate interval between grinding operations can be established. This would save considerable maintenance costs and reduce the risk of derailments.

4.5.1 Crack Growth Models

Many models have been developed to study crack initiation and its propagation. The model depicted in Figure 19 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, the axial load continues to increase and decrease 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 19 (a). These deformations take place as a result of compressive and shear forces. The rail steel layers start sliding when subjected to high axial load. When release of axial load takes place, the layers resisting plastic deformation try 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 19 (b). These micro-cracks develop into cracks when stress is repeatedly applied. Once a crack is initiated, stress concentration occurs at both ends of the crack causing it to continue to grow. Micro-cracks may not always develop into cracks; partly due to the endurance limit of the rail material (for details on fatigue crack growth and its initiation, please see Ellyin, 1997; Taylor, 1989; ASTM, 1977).

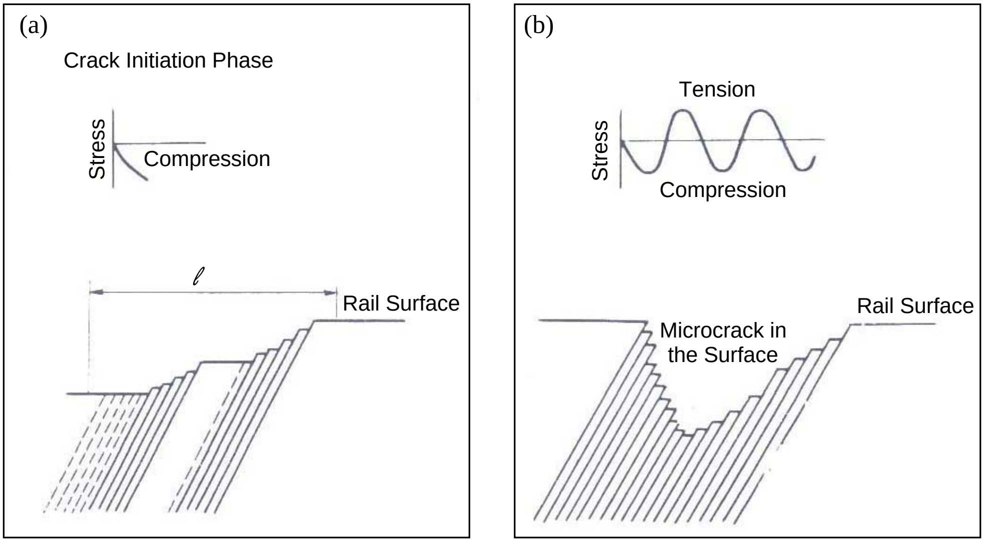

Figure 19: Model of RCF initiated crack development process [Adopted from Nishida, 1991]

The surface on which the crack emerges looks very smooth, although when microscopically viewed, it is usually stepped (Figure 19). Once initiated, the microscopic crack, 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 of one crack increases stress in the nearby rail, increasing the risk of further breaks and disintegration of the rail (Cannon *et al.*, 2003).

Cracks initiate in a very thin surface layer of the rail and develop inside the rail head. Crack propagation rate is accelerated by fluid entrapment. This is further explained in the next section. If the crack propagation is in an 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 rail break. Cracks initiated by ratchetting (head checks) grow perpendicular to the direction of the resultant traction force (see Grassie and Kalousek, 1997, for details).

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 stress-driven crack growth

Ringsberg (2001) explained these three phases with the help an illustration (Figure 20).

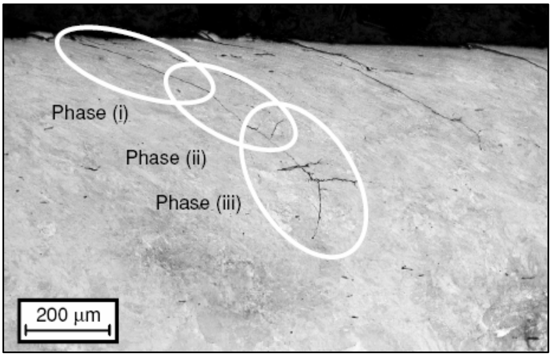

Figure 20: Three phases of RCF initiated crack propagation [Ringsberg, 2001]

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. 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 as to whether or not crack growth will take place under particular loading conditions (see Figure 21).

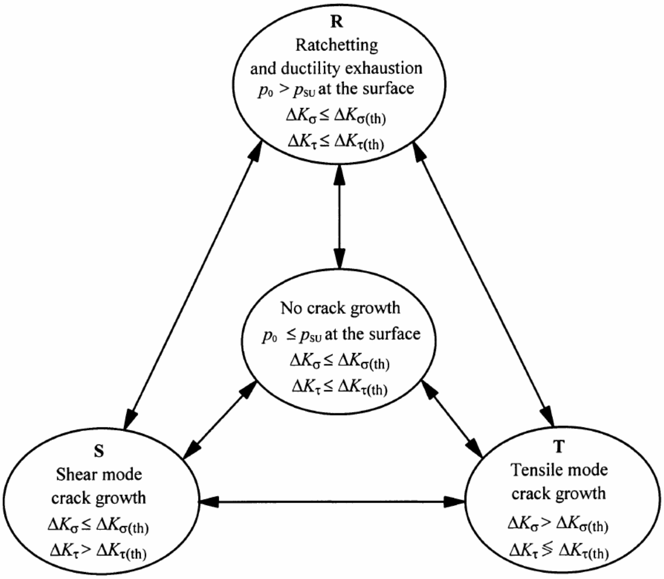

Figure 21: TM Model of RCF initiated crack growth [Fletcher and Beynon, 2000]

Figure 22 describes the crack growth prediction model presented by Kapoor *et al.,* (2002). The model states that cracks initiate early in the life of rails as a result of ratchetting (phase I), and then propagate at an increasing rate until they extend through the depth of maximum shear stress (first half of phase II). Cracks then proceed at a relatively slow rate thereafter as they grow outside the region influenced by rolling contact stresses (unless lubrication or moisture is present). Kapoor *et al.,* (2002) described this phase as the second half of phase II. The crack growth after phase II is dependent largely on the pattern of combined bending and residual stresses, which dictate whether the cracks will propagate up to the surface or down into the rail head (phase III)

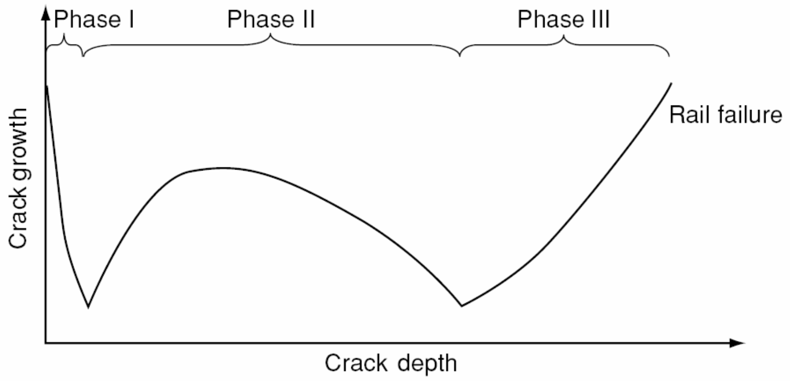

Figure 22: Crack initiation and fatigue model by Kapoor et al., (2002)

According to Magel *el al.,* (2003), most of the crack growth models lack generality and help only in understanding some of the properties of rail material or wheel/rail contact phenomenon. But they make a valuable contribution to existing best practices adhered to in rail maintenance. A model should be more general, covering most of the factors influencing crack initiation and its propagation. Magel *el al.*, (2003) also proposed a crack growth model considering the effect of different environments. The model divides crack initiation and propagation into four phases:

Phase 1: wheel-rail interaction leads to ratcheting due to high contact stress generation and a surface crack initiates. The process occurs over a period of 3–6 MGT and cracks starts propagating at an angle of 5-15 degrees with respect to the surface.

Phase 2: Cracks in this phase are termed “micro-cracks” and their growth rate slowly increases. In this phase, the crack depth is around 1mm in a high traction environment and 2–4 mm in a heavy haul environment.

Phase 3: In this phase, the crack growth rate also depends on moisture. A dry environment slows down the crack growth process whereas a moist environment or alternate wet and dry environment accelerates it. The length of crack in this phase is around 15mm with a depth of 4-8mm.

Phase 4: Further propagation depends on a combination of bending, thermal and residual stresses. Cracks which divert downwards may eventually lead to a rail break and cracks which propagate towards the surface leads to shelling. Most of the cracks propagate towards the surface. Shelling is not considered a safe operating condition as it may contribute to corrugation and ballast damage.

4.5.2 Crack Propagation during Fluid Entrapment

Crack propagation, which is the second phase of the crack development process, is accelerated by fluid entrapment during lubrication that leads to crack pressurization and reduces the crack face friction causing relative shear of the crack faces (Figure 23). Manufacturing defects in the rail subsurface and the direction of the crack mouth on the rail surface both dictate the crack development direction (see, Bower and Johnson, 1991; Bogdanski *et al.*, 1997).

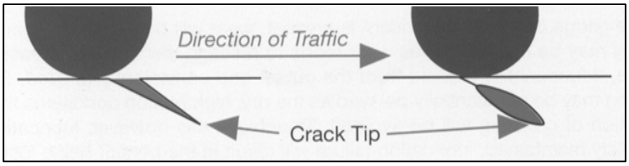

Figure 23: Fluid entrapment accelerates crack propagation [Courtesy – Queensland Rail, Australia, 2005]

The presence of water, snow or lubricant on the rails may increase the 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 the opposite direction of train traffic, the liquid is forced out before its entrapment (Ringsberg, 2001).

4.6 Rail Deterioration and Rail Break

Wear and fatigue in rails are significant problems for the railway industry. They are major contributors to 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, climate and operational environment (see Chattopadhyay *et al.*, 2006). Rails are designed so that they fit the shape of the wheel, thereby reducing 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 is worn away by wheels on its surface and deteriorates due to 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 lead to the surface-initiated cracks on the rail (Reddy, 2004).

Rail break is the last phase of the crack development process. As the crack continues to increase in length as well as depth, stress concentration also increases and finally rail break occurs. This does not happen in all cases, however. Sometimes spalling takes place and a portion of rail material comes out as the 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 disappear early on in their development as a result of wear and tear, while most of them are removed by grinding operations. Not all cracks pose a derailment risk, but they are major contributors to rail degradation.

One type 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 at right angles to the running surface. Detail fractures account for about 75 percent of rail defects in continuously welded rail track in North America (see, Jeong, 2001).

5 ISSUES RELATED TO RAIL MAINTENANCE

In order to identify the current issues related to rail maintenance, various knowledge bases have been looked into. These included literature survey, inputs from various railway-related conferences attended and discussions and consultations with rail maintenance experts from Banverket working at various levels, JVTC, QUT and QR.

Rail maintenance issues can be broadly classified into the areas of:

- Rail inspection
- Rail degradation rate
  - Reduction in rail wear,
  - RCF initiated defects reduction
  - Reduction in rail weld defects
- Rail rectification and replacement
- Outsourcing or inhousing of maintenance activities

5.1 Rail Inspection

The effectiveness of rail inspection depends on the efficiency and accuracy of the inspection equipment. It also depends on the skill and experience of the inspectors (Figure 24). Inspection error is an important issue and its reduction is a major challenge. This mainly depends on the technological limitations of the inspection equipment and the skill level of the rail inspectors.

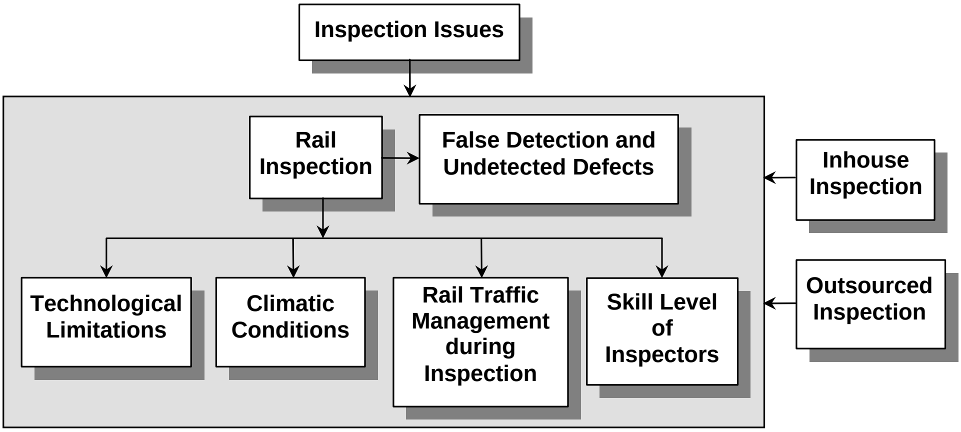

Figure 24: Rail inspection issues

Figure 25 shows a situation when some of the deeper cracks remain undetected due to limitations of the ultrasonic probe, the sound of which cannot penetrate through the overlying cracks. Better ultrasonic probes are being investigated as a possible solution (Cannon *et al.*, 2003).

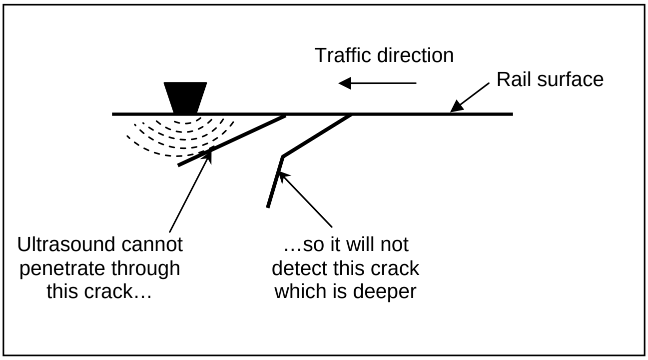

Figure 25: Shadowing of ultrasonic sound by head checks and squats [Adopted from Cannon, et al, 2003]

Figure 26 shows the Venn diagram of inspection, detection, rail breaks and derailments. The Venn diagram shows the percentage of defects detected by different inspection procedures. The signaling system is primarily a traffic control safety system. Rail break detection by signaling may not be a very effective procedure as the exact location of the rail break cannot be pinpointed. Moreover, by the time the inspection team reaches the location, the gap in the rail break might disappear due to longitudinal expansion/contraction of the rails. Thus, it may take several days to locate a rail break using this procedure. By improving inspection techniques and using more efficient equipment, it is possible to reduce the number of undetected and falsely detected defects.

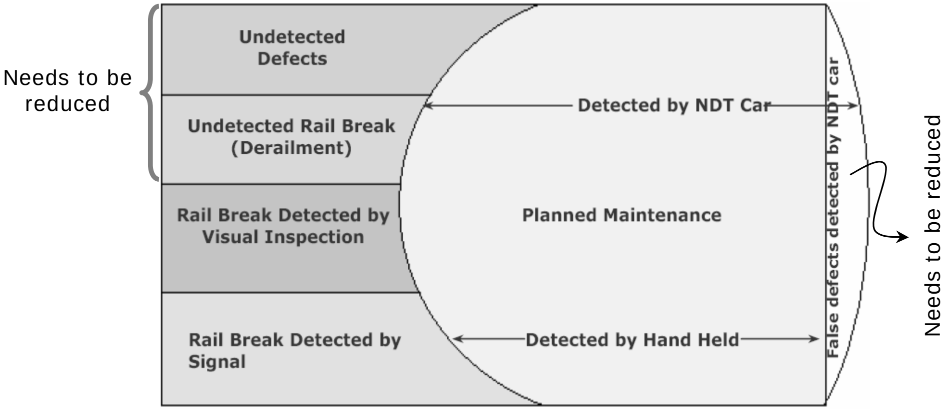

Figure 26: Venn diagram of inspection and detection, rail breaks and derailment [Chattopadhyay, et al., 2005b]

Many rail players perform inhouse inspection; in other words the skilled personnel and the required equipment are employed/owned by the operator. Outsourced inspection is also commonly practiced, in which the inspection process is outsourced to various ancillary companies. Whether to perform inspections inhouse or outsource it is a difficult decision to make and is still an issue for many rail players.

Inspection is also governed by climatic conditions. In cold countries, like Sweden, rail inspection becomes difficult and costly in the winter. Another important issue is rail traffic management during inspection. In The Netherlands and Italy, some of the rail routes are so busy that it becomes very difficult to stop train traffic to carry out rail inspection and maintenance; consequently, inspection and maintenance are often done during the night (see Bocciolone *et al.*, 2006) and workers and inspectors have to be paid more to compensate them for unsociable working hours. Rail maintenance can therefore be done more effectively during the day time provided the tracks are free. Keeping the tracks free depends on an efficient traffic management system. It is nevertheless a challenge to carry out effective inspection and maintenance procedures while at the same time keeping rail inspection and maintenance cost down and traffic disruption to a minimum. Assuming vehicle ultrasonic inspections followed by manual verification of detected defects are performed once a year, 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 defect detection methods. Therefore, there is need for detail study and analysis of inspection techniques to detect rail defects.

5.2 Reduction in the Rail Degradation Rate

Reducing the rate of rail degradation is one of the prime concerns of rail infrastructure operators. Rail wear, RCF initiated defects and welded defects are some of the prime contributors to rail degradation. Preventive maintenance procedures, such as rail lubrication and grinding, are performed to reduce the rail degradation process and defect formation rate, but in turn these maintenance procedures have some issues (as outlined in Figure 27) due to which expected results are not fully achieved in a cost-effective way. The following sections briefly describe some of these issues. There are other factors influencing the rail degradation rate which have been identified and explained in the next chapter.

5.2.1 Rail Wear Reduction

Wear occurs due to the 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 on the wheel tread and rail crown area, while, severe wear is observed on the wheel flange and gauge face. Zakharov, (2001) classified wear modes in rails as mild, severe and catastrophic.

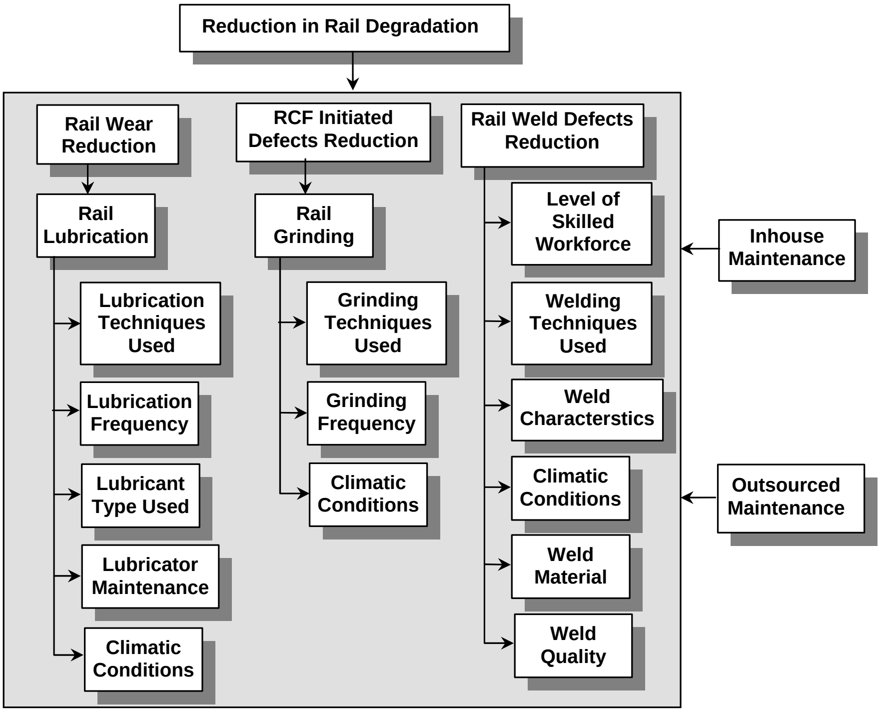

Figure 27: Issues related to reduction in rail degradation

This classification was based on 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 as mild, severe and catastrophic wear respectively.

Applying lubricant at the wheel/rail interface significantly reduces wheel and rail wear as well as dramatically decreases locomotive fuel consumption (Diamond and Wolf, 2002). Four commonly used techniques used for rail-wheel lubrication are:

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

About 3,000 wayside lubricators have been installed in Sweden, and the total investment costs, excluding annual maintenance costs, are about € 6.17 million (Waara, 2000). Railways around the world are spending substantial amounts of money on rail lubrication because if it is neglected, rail replacement would be the ultimate solution, which is far more costly. As stated above, lubrication helps to reduce rail gauge face wear and reduces energy or fuel consumption as well as noise.

However, excessive lubrication leaves residue behind that builds up on the rails and wheels, resulting in a potential environmental hazard. Excessive lubrication also reduces friction more than required which increases the train's braking distance, elevating the risk of railway accidents. On the other hand, according to the American Association of Railroads, € 1.56 billion is spent on ineffective lubrication (Diamond and Wolf, 2002). The issue of effective rail lubrication depends on the techniques used. Designing better and more cost-effective lubrication techniques and implementing them is a major challenge to rail players around the world. In many of the wayside lubricators, optimum frequency of lubrication needs to be modeled on detailed analysis so that it reduces derailment risk and rail/wheel damage and at the same time is also cost-effective. Effective lubrication can only be achieved if adequate monitoring methods are available (Peters and Reiff, 1989), thus the sensors that activate the lubricators should also be sensitive enough to optimize lubrication frequency. Climatic conditions are of particular concern to these lubricators. When idle for long periods during the summer, lubricator nozzles start to clog up, causing the system to malfunction. This problem is frequently faced in many parts of Australia, which have hot summers. Lubricators need to be cleaned before the start of winter in cold countries like Sweden as well. This procedure is important as lubricator nozzles may also clog up in the winter due to inactivity. It takes two people one and half to two hours to clean up a wayside lubricator in Sweden. If cleaned on site, the operation costs € 280 (2 personnel x 2 hours and one car for transportation). If cleaned at a depot, the cost can be different. The cost of maintaining lubricators is around € 700 - € 1200 /year/device (the lubricators are used only for six months as there is no lubrication during the winter) this includes fill up and maintenance of lubricators (Chattopadhyay, et al., 2004). Biodegradable lubricants are also being used by various rail infrastructure operators, but the economics of their implementation is still an issue. The cost-effectiveness of lubricants is analyzed by condition monitoring of lubricant properties and prediction of remaining useful life of the lubricant to avoid frequent oil change (Kumar et al., 2005).inactivity. It takes two people one and half to two hours to clean up a wayside lubricator in Sweden. If cleaned on site, the operation costs € 280 (2 personnel x 2 hours and one car for transportation). If cleaned at a depot, the cost can be different. The cost of maintaining lubricators is around € 700 - € 1200 /year/device (the lubricators are used only for six months as there is no lubrication during the winter) this includes fill up and maintenance of lubricators (Chattopadhyay, et al., 2004). Biodegradable lubricants are also being used by various rail infrastructure operators, but the economics of their implementation is still an issue. The cost-effectiveness of lubricants is analyzed by condition monitoring of lubricant properties and prediction of remaining useful life of the lubricant to avoid frequent oil change (Kumar et al., 2005).

5.2.2 Reduction in Rolling Contact Fatigue (RCF) Initiated Defects

In the late 1990s, RCF defects accounted for about 60 percent of the defects found by East Japan Railways, while in France (SNCF) and the UK (Railtrack), the figures were about 25 and 15 percent, respectively. RCF is a major future concern due to the rail industry's ever increasing demands for higher speed, higher axle loads, higher traffic density and a higher tractive force, which increase the rate of RCF initiated defects (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 to combat RCF initiated defects and rail wear. Rail grinding became increasingly accepted as a way of controlling RCF defects from 1980 onwards, prior to that it was mainly used to remove corrugation. At that time, barely 15 percent of Canadian Pacific Railway's (CPR) grinding budget was devoted to treatment of RCF compared to 60 per cent being spent on corrugation removal. In the late 1990s, grinding as a treatment for RCF defects became a more established approach and began to be adopted on some European railways. It is now widely used in Europe. The annual grinding budget in North America for larger railways is about € 390 per kilometer of track, this means that on a system with 20,000 km of track, the grinding budget is about € 7.81 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 for heavy haul railways, the minimum interval for rail grinding is in the range 10–15 million gross tones (MGT) (Cannon et al., 2003). Banverket follows preventive grinding on new rails within one year or after 5 MGT of traffic load (Banverket, 2004). Later on, regrinding is done in a cyclic manner and is termed “maintenance grinding”. When grinding is done specifically to remove severe irregularities or defects in certain areas of the rail section, it is termed “corrective grinding” according to Banverket. But the issue of optimum grinding frequency depending on climatic conditions, operational environment and other factors affecting rail degradation is still a challenge for rail players.

5.2.3 Reduction in Rail Weld-Initiated Defects

Small imperfection in welds can cause cracks to initiate. A defect-free weld requires skilled workmanship as well as, better weld material, welding techniques and welding equipments. In Sweden, inspection, welding and rectification are costly due to the presence of snow and ice during the winter. Most defects that do not pose an immediate risk of damage to rail assets or derailment are deferred until the end of winter.

5.3 Rail Rectification and Replacement

Safety and integrity of rail sections are maintained by rail rectification, replacement and re-railing. Rail rectification is performed when only minimum repair is required, be in the form of e.g. small rail section replacement, rail welding, tamping, adjustment of rail sections mostly on curves and the fastening of fish plates where required. Replacing more substantial rail sections is known as “rail replacement” and major overhauling of rails is known as “re-railing”. Different rail players employ different criteria when classifying rail repair activities into rail rectification, replacement or re-railing depending on repair costs, time required and availability of funds.

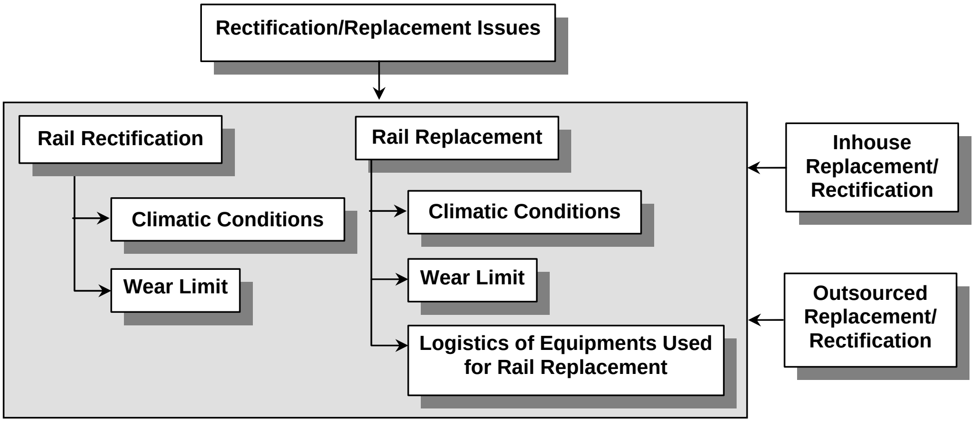

Figure 28: Rail rectification and replacement issues

Rail replacement is based on a number of responsible factors. Even now, rails are often replaced based on their life expectancy or MGT. Establishing the optimum rail replacement interval is an issue for rail players. Factors such as wear limit, fatigue and climate are also important. In cold countries like Sweden, it is more economical to do rail replacement and re-railing in the summer than in the winter.

These issues are shown in Figure 28 and need detailed analysis to enable cost-effective decisions in logistics planning related to rail track maintenance.

5.4 Outsourcing or Inhousing of Maintenance Activities

Rail players always find it difficult to decide between outsourced maintenance and in-house maintenance, depending upon capability, cost-effectiveness and the availability of skilled personnel, equipment and technology. Risks and costs have to be analyzed by rail infrastructure owners while making decisions about maintenance issues. These decisions should cover rail lubrication, rail grinding and rail welding issues.

Outsourcing and inhousing of maintenance activities in railways is a very complex issue and has not been looked in detail in the thesis.

6 DEVELOPMENT OF AN APPROACH TO RAIL BREAK PREDICTION

6.1 Introduction

As it is discussed in Chapter 5, reducing rail degradation is an important issue for rail players. In order to develop an effective rail maintenance procedure, being able to predict rail failure is essential. Failure is the termination of the ability of an item to perform a required function (IEV-191-04-01). Rail degradation is a failure process, an event, which may result in a rail break, a fault – a state. (A fault may also occur without prior failure, IEV-191-04-01). A fault is a state of an item characterized by inability to perform a required function, excluding inability during preventive maintenance or other planned actions, or due to lack of external resources (IEV-191-04-01). Rail break is considered as a fault and is explained later in Section 6.3.2. Identification and consideration of the different factors influencing the rail degradation process will help to improve the prediction of rail breaks.

6.2 Identification of the Factors Influencing Rail Degradation

In order to identify the factors influencing the rail degradation process, various sources of information have been examined. These included a literature survey, inputs from various railway-related conferences attended and discussions and consultations with rail maintenance experts from Banverket working on various levels, JVTC, QUT , QR and colleagues working at the Division of Operation and Maintenance Engineering, Luleå University of Technology.

The identified factors are:

- Condition of Assets: Poor condition of asset (for example: sleepers, fastenings, ballast, etc.) accelerates the rail degradation rate. Fishplates having a degraded condition or loose fishbolts will cause the rail joint gap to close or fully open, even at minor temperature changes (Lichtberger, 2005). This may result in rail buckling or rail end degradation.
- Age of Rails: Sometimes rail replacement becomes essential due to degradation in its material properties over a period of time and usage. This is known as ageing in rails and replacement is required as aged rails may degrade the wheel material during rail-wheel interaction or vice-versa.
- Axle load: This is a measure of the deterioration of track quality and as such provides an indication of when maintenance and renewal are necessary (Esveld, 2001). Heavy axle load causes static and dynamic stress at the rail-wheel contact patch which may accelerate rail degradation (IHHA, 2001).
- Speed: Vehicle speed can adversely influence the curving performance of the vehicle and, in turn, lead to wear and stresses in rail and wheel (IHHA, 2001). The running speed does, however, have a certain influence on the dynamic interaction between vehicle and track because the point of application of the load moves with the running speed.

- Tamping: This is a process whereby the ballast under the ties (sleepers) is compacted to provide proper load bearing (IHHA, 2001). Ties are the portion of the track structure generally placed perpendicular to the rail to maintain the track gauge, distribute the weight of the rails and rolling stock, and keep the track properly aligned. The majority of ties are made of wood. Other materials used in their manufacture include concrete and steel (IHHA, 2001).
- Ballast Cleaning: Despite identical track structure, the same year of construction and the same traffic load, the rates of deterioration differ widely even between adjacent sections. One of the reasons is the non-homogeneity of the ballast beds (Lichtberger, 2005). Infrequent ballast cleaning may result in undesirable changes in track position which may cause more stress generation and more wear.
- Traffic Density: The more frequently trains pass over a rail section, the more rail wheel interaction takes place leading to more wear and RCF generation.
- Traffic Type: The type of traffic passing over the rail (passenger or freight) defines the axle load and thus influences the rail degradation rate.
- Characteristics of Bogie Type: In Sweden, railway operators and maintenance contractors have been deregulated, which has led to a tendency for operators to introduce low-cost rolling stock to reduce their cost. This might increase track degradation (Larsson, 2004). Thus characteristics of bogie type influence rail degradation.
- Grinding Frequency: Preventive grinding leads to a significant increase in the service life of rails, delay in the occurrence of rail corrugation and a decrease in traffic noise levels (Van Den Bosch, 2002). An optimal grinding frequency helps to increase rail life (Chattopadhyay, et al., 2005b).
- Rail-Wheel Interaction: Rail-wheel interaction is a very complex phenomenon. Repetitive wheel loads on the rail results in rolling contact fatigue (RCF). Rail wear occurs due to rail-wheel interaction and is more common on curves where maximum rail wheel shearing occurs (IHHA, 2001).
- Million Gross Tonnes (MGT): All types of track degradation features, such as increase in geometrical deviations, increase in rail fractures and rail wear, can be expressed as a function of tonnage and is often expressed as Million Gross Tonnes (MGT). It is used to express the intensity or capacity of rail traffic on a specific line. (Esveld, 2001).
- Track Curvature: Optimal wear rate depends on differences in traffic type and density, axle load, rail metallurgy, and track curvature (IHHA, 2001). (For example, the rail degradation rate on a curve with a curve radius of 500 metres will be different from a curve with a 1200-metre curve radius)
- Track Elevation: More traction force is required to overcome gravitational force when vehicles travel in an uphill direction. Limited lubrication is required to avoid slippage on uphill tracks causing more wear on this section of track.

- Inspection Interval: More frequent ultrasonic inspection is required to manage/reduce the risk of internal defects (IHHA, 2001).
- Superelevation: This is the difference in elevation between the two edges of the track; it allows vehicles travelling through the turn to go at higher speeds than would normally be possible. Superelevation helps prevent overturning of the vehicle (IHHA, 2001). It is provided to overcome the centrifugal force of the vehicle on curves. Degradation on either the high rail or low rail lying in the same curve radius depends on the speed of the vehicle. If the vehicle speed is higher than the designated speed limit of the curved track, considering the superelevation, more degradation will take place on the high rail. This is because the wheel flange is more in contact with the inner surface of the high rail than the inner surface of the low rail due to centrifugal force acting on the vehicle. If the vehicle speed is lower than the designated speed limit of the curved track, considering the superelevation, more degradation will take place on the low rail.
- Operational Environment: Wear is highly dependent on third-body properties, which are strongly influenced by lubrication, environmental conditions (humidity, rain and snow), and the presence of sand. During winter in North America and Russia, there is more wheel shelling damage than in the summer time. This is evident because of an increase in track stiffness and thus impact of track distortions on forces between the wheel and the rail. Another cause of this phenomenon is the influence of liquid. Water in the form of rain or melted snow considerably enhances the crack propagation rate due to the hydrostatic effect of liquid trapped in the crack. The worst conditions occur when a dry period (when cracks are initiating) is followed by a wet period, when water enhances crack propagation (see, IHHA, 2001). Dust and a corrosive environment accelerate rail wear. High ambient temperature (greater than 25°C) may cause the longitudinal expansion of rails, which may result in track buckling. This poses a serious risk of derailment.
- Rail-Wheel Material Type: Rail-wheel material plays a very important role in rail degradation. The mechanical properties of a pearlitic rail steel structure are governed by the distance between the cementite (Fe_3C) layers and the grain size. These are controlled by the cooling rate of the steel. The yield point and tensile strength are inversely proportional to the distance between the cementite layers and grain size. There are different types of heat-treated, alloyed or plain carbon steel rails being used around the world. Apart from the usual manufacturing process of the rails, tensile strength and toughness are increased by heat treatment. Heat treatment is usually carried out on the rail head, turnouts and at the ends of non-welded rails to address the issue of maximum stress concentration. (Esveld, 2001).
- Rail Hardening: Rail hardening aims to reduce wear and to increase resistance to RCF of rails in operation, particularly in tight and medium curves (Lichtberger, 2005). A head-hardened rail is a rail where only the rail head has been heat treated to provide harder steel for locations of extreme service, such as curves (IHHA, 2001).

- Inclusion of Residual Stress: Residual stresses could be built up in rails during the rail manufacturing process, during the rail welding process or as a result of contact stresses generated by the wheels rolling on the rails (Esveld, 2001; IHHA, 2001). (See Section 4.3 for details).
- Formation of Blowholes: Blowholes are possible defects formed during rail manufacturing. The presence of blowholes weakens the rail section causing further development of other types of defects. Today, new rails have to pass through several quality checks, including ultrasonic inspection before their commissioning. Thus it is very rare to find blowholes or other manufacturing defects in rails.
- Rail Size: The weight of rail in kilograms per meter denotes the rail size (Esveld, 2001). Rails of different sizes will have different degradation rates.
- Rail Profile: Many different rail profiles are in use. Different rail infrastructure owners use different standards for rail profiles. Different rail profiles are designed according to their operational requirements (see Section 4.1 for details)
- Track Construction: A track is constructed according to the requirements of axle load, speed, required service life time, amount of maintenance to be done, operating conditions and availability of basic material (Esveld, 2001). For example, the condition of the subgrade and soil properties should be analyzed during track construction.
- Lubrication Frequency: Lubrication can be optimized for rails to effect a reduction in flange wear so that maintenance resources are minimized and the rail/wheel life maximized (Wilson, 2006).
- Rail Welding: Rail welding results in residual stresses that are distributed in a very complex manner with respect to their magnitude and direction. In many cases, these stresses are the cause of rail web failure. Use of improved welding technology and post-weld heat treatment considerably decrease the extent of weld-initiated residual stresses. (IHHA, 2001)
- Track Accessibility: Poor track accessibility leads to delayed maintenance which causes more degradation.

The identified factors responsible for rail degradation have been described by Ishikawa diagram in Figure 29. Four broad classification areas denoting the different phases (design, manufacturing, operation and maintenance) of rail life have been identified while constructing the Ishikawa diagram. During the design stage, selection of rail/wheel material type, rail size and rail profile depends on the required operating conditions such as axle load, speed, traffic type, traffic density, etc. Similarly, track is constructed according to the requirements of track geometry (elevation and curvature). Better track design will lead to less degradation and longer rail life.

Defects may be generated during rail manufacture. Other manufacturing aspects along with many of operational and maintenance factors (as shown in Figure 29) will also influence rail degradation.

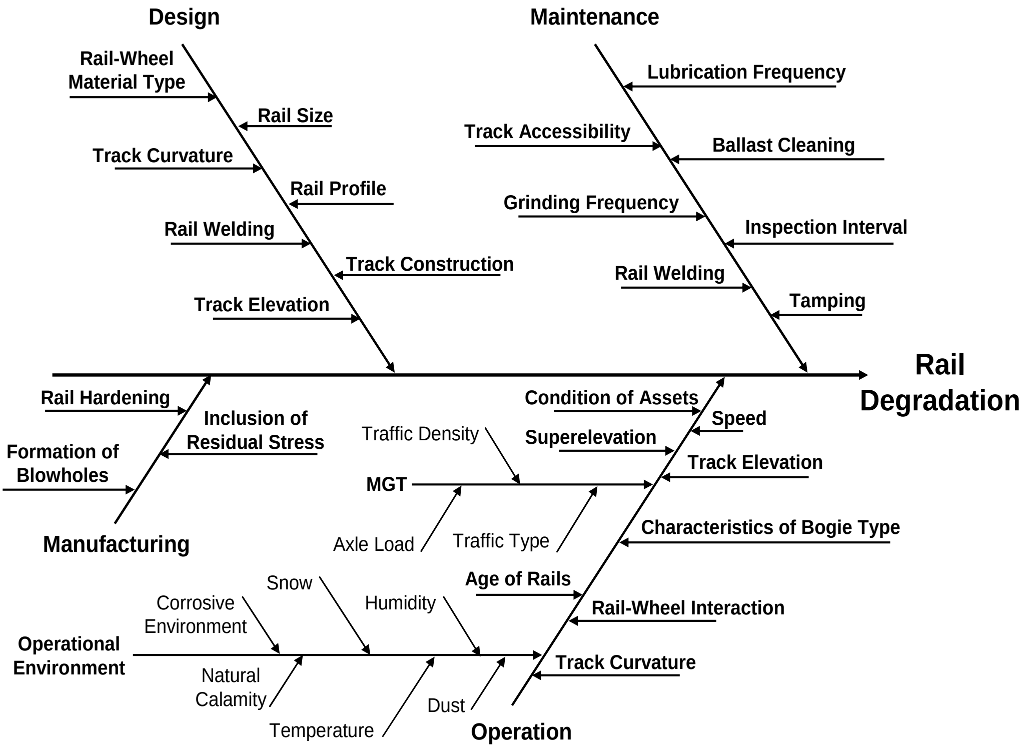

Figure 29: Ishikawa diagram (cause and effect diagram) for the factors influencing rail degradation

6.3 An Approach to Rail Break Prediction

The factors influencing rail degradation are shown in Figure 30. The rail degradation process leads to the formation of rail defects. There are many types of rail defects, some of them may not be severe enough to cause a derailment. The potential for some defects, like rail buckling, rail break and corrugation, to cause a derailment or damage to assets is, however, much greater. Potential in this context means the possibility (risk) of an event (failure) developing into an accident[1] under requisite conditions. Figure 30 shows an approach to predicting rail breaks.

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[1] An accident is here defined as an undesired event that causes damage or injury (Harms and Ringdahl, 2001).

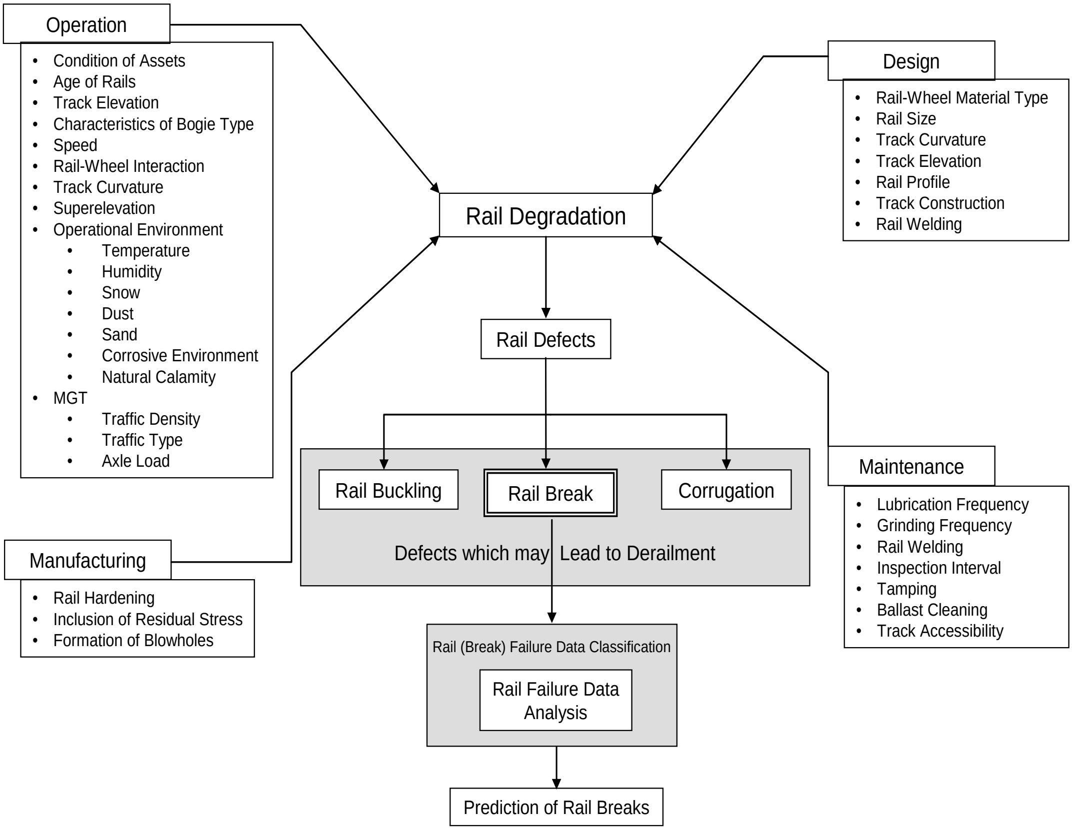


Figure 30: An approach to rail break prediction

6.3.1 Data Collection from Banverket's Database

Data was provided by Banverket (north region), from its BIS, BESSY and 0felia databases for Malmbanan (iron ore line) from Kiruna to Riksgränsen (Section 111) from the year 1997 to 2005.

<u>BIS:</u> This is Banverket's infrastructure register (computerised database) containing information about infrastructure or facilities, arranged geographically in accordance with Banverket's facility structure. In BIS, for example, information is collected prior to work on train timetables and before work in connection with inspections (Karlsson, 2005). Apart from this, information about agreements, accident reports, history of tamping, grinding, curv-info, can also be obtained.

<u>BESSY:</u> This is an inspection system in which comments are registered per facility on completion of inspection. The data are registered directly during the course of inspection with the aid of a palm computer.

0felia: This is a database containing information on all faults in the infrastructure that have been registered on a particular railway facility. The faults are sorted on the basis of the structure used in BIS. (Karlsson, 2005)

Apart from data collection via the above mentioned databases, information was also collected from discussions and consultations with experts from Banverket, JVTC, Queensland Rail and Queensland University of Technology, Australia. Onsite trips were also made to Malmbanan (iron ore line), Section 111, to gain a better understanding of the rail degradation process and rail maintenance procedures followed. Some of Banverket's documents and reports were also studied to understand some of the causes behind the confusing data.

6.3.2 Rail Break Data Classification

Due to a lack of information, all the factors influencing rail degradation could not be considered in the rail failure data analysis. Based on the available information, a data classification framework was developed as shown in Figure 31.

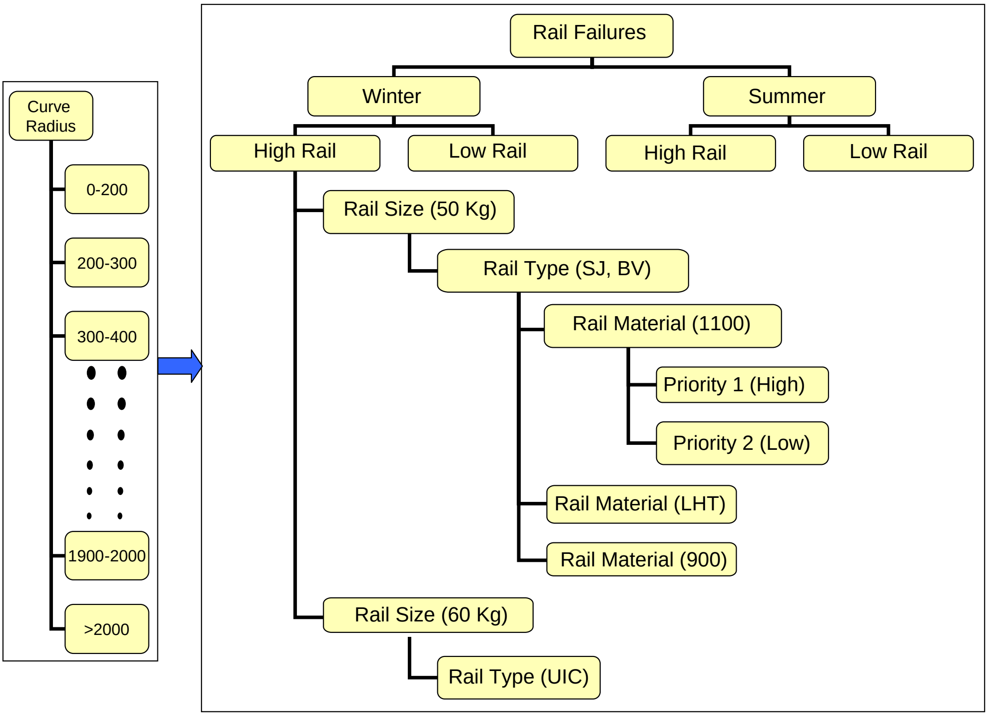


Figure 31: Framework for rail failure/break data classification

The data collected from the above mentioned Banverket's sources were entered into an Excel spread sheet for classification and analysis. Inspection data were then classified according to the incident, date of inspection of that incident, position and section of the incident and year of replacement of the rail segment on which the incident occurred. Only rail break incidents were considered for data analysis. This is because a rail break is a rail defect that can be considered as a definite failure state. Other defects such as cracks, shelling or spalling are considered as part of an ongoing degradation process.

According to the UIC code on rail defects 712R (2002),

- A damaged rail is any rail which is neither cracked nor broken, but which has other defects, generally on the rail surface.
- A cracked rail is any rail which, anywhere along its length and irrespective of the parts of the profile concerned, has one or more gaps of no set pattern, apparent or not, the progression of which could lead to breakage of the rail fairly rapidly.
- A broken rail is any rail which has separated into two or more pieces, or a rail from which a piece of metal becomes detached, causing a gap of more than 50 mm in length and more than 10mm in depth in the running surface.

As ageing in rails takes place due to tonnage accumulation on the track resulting from traffic movement, rail break data analysis was based on Million Gross Tomes (MGT) of traffic flow. Rail segments are used as per the database of rail replacements and ageing is estimated by assuming 25 MGT per year of traffic flow (also see, Chattopadhyay, *et al.*, 2005b). The age of rail segments having a rail break was calculated by multiplying the annual MGT of traffic flow with the difference between the year the rail segment was inspected for rail break and the year it was last replaced.

Banverket’s rail break data (Section 111) were collected from 1997 to 2005 and analyzed according to the factors classified in Figure 31. The data classification framework has been developed based on curve radius, climate, rail position according to superelevation (high rail and low rail), rail size, rail type, rail-wheel material type and defect priority level (for rail break data, all defects are high priority) for analysis and prediction of rail breaks.

The classification sequence of rail break data is as follows:

Rail break data are classified as winter or summer data in the first level. The next level of classification is high rail or low rail data categorization. Further levels of classification are carried out based on rail size, rail type, rail material and priority of rail failure along with different curve radius classification. Summer rail failure/break data will also have the same levels of classification, which is not shown in Figure 31.

Rail break data collected from Banverket North Region (Section 111) are shown in Appendix (Tables 1 to 4) in line with the proposed classification framework. The values entered in the cells of these tables are the total MGT of the rail segments in which rail break occurred. Many cells in the tables have been left empty because the rail break data associated with these cells were not found.

6.3.2.1 Assumptions

The following assumptions were made due to the unavailability of correct and complete data:

- Northern Sweden has long winters and short summers. Since data were collected from Malmbanan (iron ore line) between Kiruna and Riksgränsen (Section 111), which is located in the far north of Sweden, “winter” is considered to be from November to May and “summer” from June to October.
- Rail sizes were limited to 50 kg and 60 kg.
- As regards Section 111, rails from two different sources have been used. The two different sources, SJ and BV, adhere to the same rail size specifications (i.e. 50 kg). After 1990, the rail specification SJ was known as BV due to the formation of Banverket (in 1988) as the rail infrastructure owner (Banverket, 1998).
- Rail break data are not specified with exact curve radius, which was assumed to be in a range of 100 metres. For example, 302 meters was considered to be in the 200-300 range.
- Annual MGT for Section 111, Kiruna to Riksgränsen, is assumed to be 25 on average and is multiplied by the number of years that the portion of rail in question has been in operation since it was last replaced. (The assumption is based on the fact that freight trains going from Kiruna to Narvik are loaded and those coming back from Narvik to Kiruna are empty).

6.3.3 Rail Failure Prediction

Rail failures/breaks can be modelled as a point process with an intensity function $\Lambda(m)$ where m represents Millions of Gross Tonnes (MGT) and $\Lambda(m)$ is an increasing function of m indicating that the number of failures in a statistical sense increases with MGT. That means more used rails with higher cumulative MGT passed through the section is expected to have more probability of initiating defects and if undetected then through further passing of traffic can lead to rail failures/breaks. Chattopadhyay *et al.*, (2005b) proposed the number of failures for an accumulated MGT, m, as a random variable and modelled using Weibull distribution.

Let cumulative MGT of rail, m, be known and $F_n(m)$ and $f(m)$ denote the cumulative rail failure distribution and density function respectively, and be modelled as a Weibull distribution given by:

$$F_n(m) = 1 - \exp(-(\lambda m)^{\beta}) \qquad (1)$$

and

$$f(m) = \lambda\beta(\lambda m)^{\beta-1} \exp(-(\lambda m)^{\beta}) \qquad (2)$$

with the parameters β (known as shape parameter of the distribution)
λ (Known as inverse of characteristic function for the distribution)

In the degradation process, β greater than 1, which indicates an increasing failure rate of the item under study and ageing is predominant in the failure mechanism.

Then failure intensity function *Λ(m)* as derived from (1) and (2) is given by:

$$\Lambda(t) = \frac{f(m)}{1-F(m)} = \frac{\lambda\beta(\lambda m)^{\beta-1}\exp(-(\lambda m)^{\beta})}{1-(1-\exp(-(\lambda m)^{\beta})} = \lambda\beta(\lambda m)^{\beta-1} \qquad (3)$$

Rail track is normally made operational by means of repair or replacement of the failed segment and no action is taken with regards to the remaining length of the whole track. Since the length of failed segment replaced at each failure is very small relative to the whole track, the rectification action can be viewed as having negligible impact on the failure rate of the track as a whole, see Barlow and Hunter (1960).

Then the expected number of failures over period *i* and (*i+1*) is given by:

$$E[N(M_{i+1}, M_i)] = \lambda^{\beta}((M_{i+1})^{\beta} - (M_i)^{\beta}) \qquad (4)$$

where the total accumulated MGT up to ith inspection, M_i, is given by:

$$M_i = \sum_{j=0}^{i} m_j \qquad (5)$$

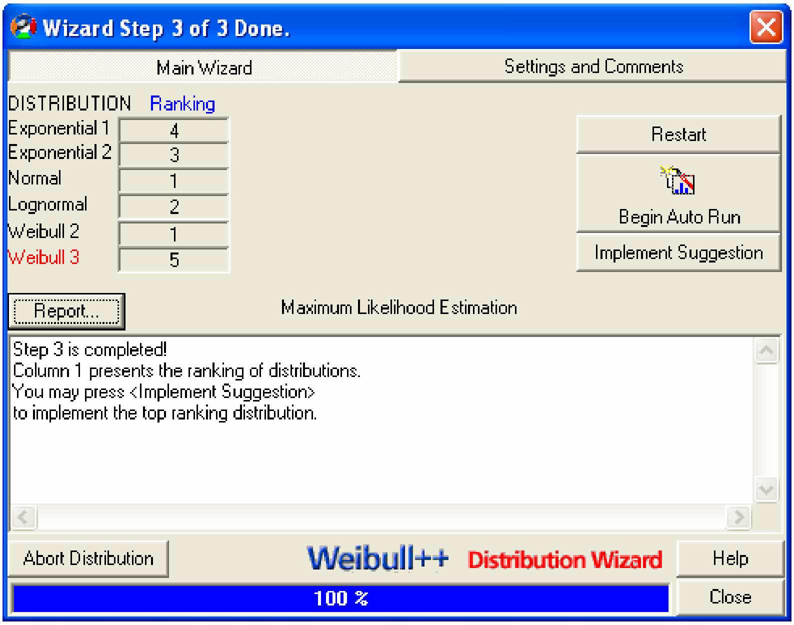
Failure data are analyzed for estimating the probability of detecting defects that have the potential to cause a rail break before the next inspection. Defects developing later in-between inspections or going undetected during inspections can result in rail failures/breaks. Some rail breaks are detected by the signalling system. Some of the previously undetected breaks are detected by visual checks. Balance of undetected rail failures/breaks can result in derailment (for details, see Chattopadhyay *et. al.*, 2003b).

The probability of rail break in-between inspections depends on the likelihood of detectable defects, present at the time of inspection, going undetected and/or the defect increasing to a critical level resulting in rail failure/break before the next inspection. Other important factors that may affect rail degradation have been mentioned in Section 6.2. This led to the development of the above-mentioned data classification framework based on these. The analysis of data after their classification and comparison of the results obtained is a process to ascertain whether the identified factors are influencing rail degradation along with rail failure rate prediction. This will help in finding a possible relationship between the identified factors and rail degradation.

6.3.4 Rail Break Data Analysis

Once rail break data were segregated from the databases, information about other factors affecting rail degradation were extracted from them, such as rail size, rail material used, rail type, curve radius, etc. After classification of the data as shown in Appendix (Tables 1, 2, 3 and 4), they were then analyzed using reliability analysis software (ReliaSoft Weibull 6++ and Matlab) to predict rail break.

Due to inadequate rail break data for other ranges of curve radius, only one curve radius (500-600 metres) has been analyzed. In this thesis, an analysis of failure data for best fit distribution was carried out using Weibull++6 (Reliasoft, 2006) software as shown in Figure 32. 2-parameter Weibull distribution and normal distribution were the best fitted distributions. Weibull distribution has been used in this thesis to analyze the data and predict the rail failure rate as it has the ability to provide reasonably accurate failure analysis and prediction with extremely small sample size (Abernethy, 2003). Another reason is because Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation (Billinton and Allan, 1983). Basic facts about Weibull distribution has been discussed in Chapter 2, section 2.4. Winter, high and low rails, 50kg, 1100 steel type, high priority data for curve radius between 500 to 600 m (Appendix: Table 1 and 2) are analyzed using 2-parameter Weibull distribution. Maximum likelihood estimation has been used to analyze and predict rail failure/break.



DISTRIBUTION	Ranking
Exponential 1	4
Exponential 2	3
Normal	1
Lognormal	2
Weibull 2	1
Weibull 3	5

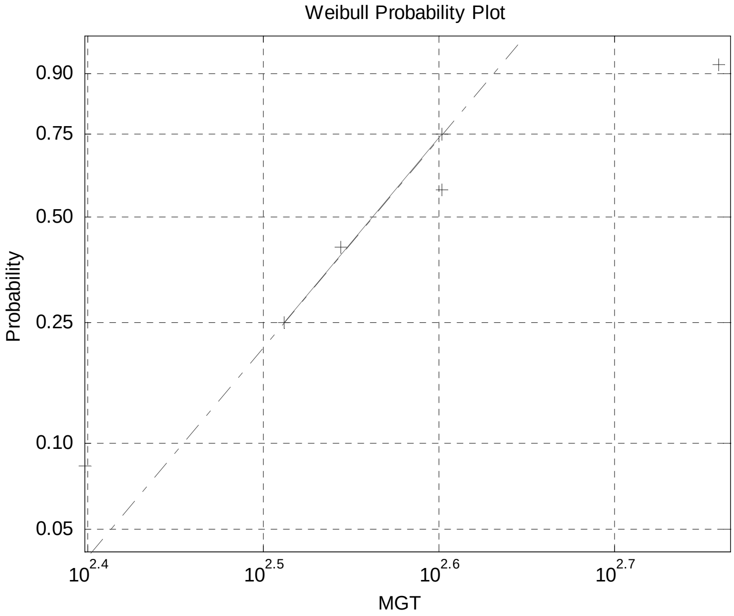
Maximum Likelihood Estimation

Step 3 is completed!
Column 1 presents the ranking of distributions.
You may press <Implement Suggestion>
to implement the top ranking distribution.

Figure 32: Best fitting distribution test by Weibull++6 Software

6.3.5 Results and Discussions

The results of the analysis are shown in Figures 33, 34, 35 and 36. Two different software programs (Matlab and Weibull 6++) are used for the analysis of rail break data in order to verify that the values of β and η are correct.



β= 3.9951 and
η= 422.1029

Figure 33: Winter, high rail, 50kg, 1100 steel type, SJ and BV rail type rail break data for curve radius 500-600 metres analyzed using Matlab Software

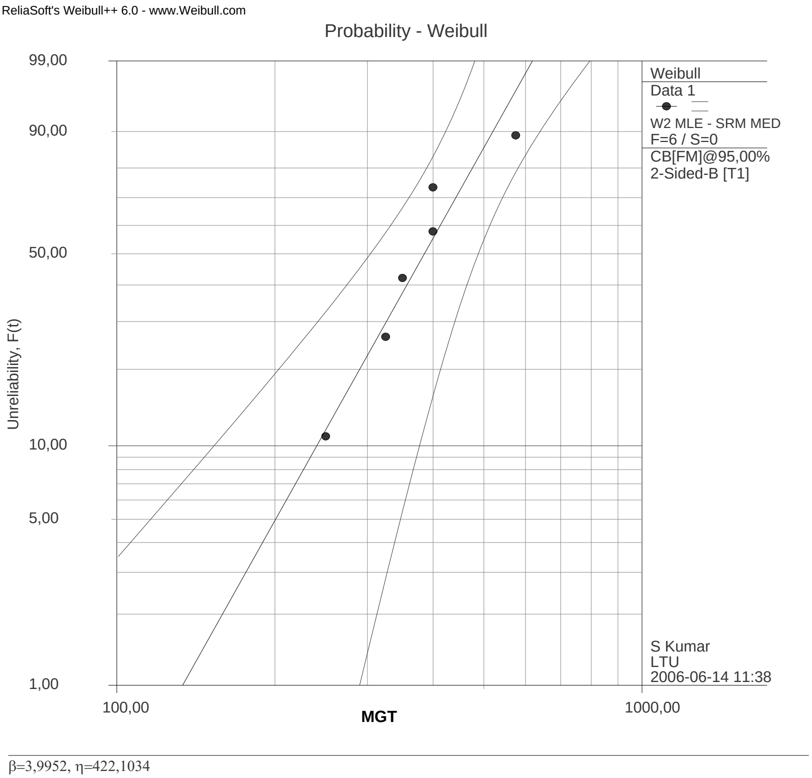
Figure 33 and 34 shows a Weibull plot for high rail, winter rail break data having 1100 steel type, 50kg rail size. The data analyzed above contain rail breaks on different segments (having the same curve radius of 500-600m) located on different curves of Section 111. Rail break data have been plotted at a 95-percent confidence interval. The values of β and η are approximately the same from both the software programs.

From the values of β and η obtained, the mean time to failure can be calculated, where,

$$MTTF \quad = \eta \Gamma\left(\frac{1}{\beta} + 1\right)$$

$$= 422.103\Gamma\left(\frac{1}{3.995} + 1\right) = 382.55 \text{ MGT}$$

This means that, based on the data used for analysis, the predicted mean rail life is 382.55 MGT in high rail segments having a curve radius of 500-600 metres, rail size of 50 kg, rail type SJ or BV, and rail steel type 1100 under the assumed winter conditions.

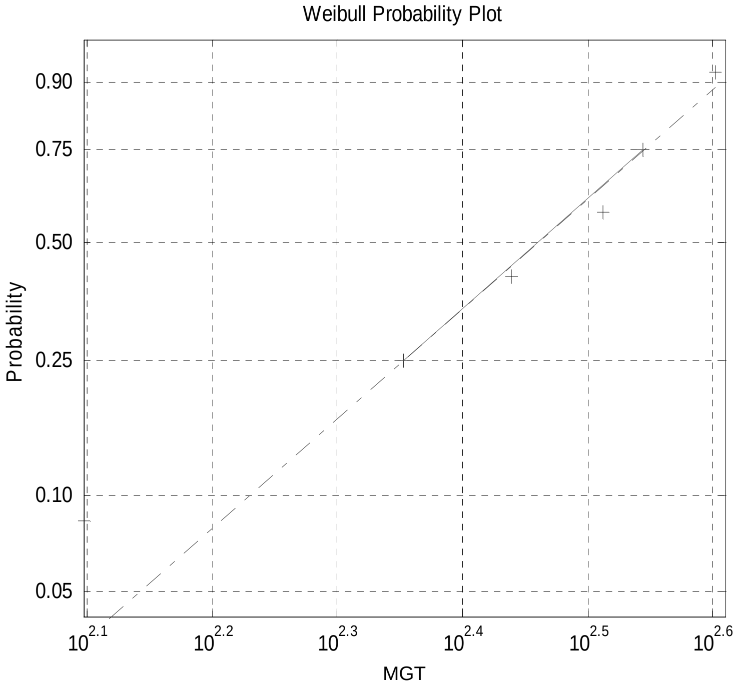


β= 3.9952 and
η= 422.1034

Figure 34: Winter, high rail, 50kg, 1100 steel type, SJ and BV rail type rail break data for curve radius 500-600 metres analyzed using Weibull++6 software

In order to arrive at a reasonably good conclusion about the predicted results, more rail break data are required (i.e., the sample size should be large enough for accurate prediction). Data accuracy also depends on the data collection and recording process (see for details, Chattopadhyay, *et al.*, 2005b). As the present data are secondary data, there may have been some misinterpretations during data recording or while extracting the data from the databases. The above analysis procedure is an approach to rail failure prediction. More detailed and accurate prediction can be made using the above mentioned classification framework and analysis procedure. This approach can similarly be applied for rail break data falling under the classification of different influencing factors.

A similar analysis was performed using a Weibull plot for low rail, winter rail break data on 1100 steel type, 50kg rail size. The data analyzed, as shown in Figure 35 and 36, contain rail breaks on different segments (having the same curve radius of 500-600m) located on different curves of Section 111.



β= 3.7592 and
η= 314.7048

Figure 35: Winter, low rail, 50kg, 1100 steel type, SJ and BV rail type rail break data for curve radius 500-600 metres analyzed using Matlab Software

Rail break data have been plotted at a 95-percent confidence interval. The values of β and η are approximately the same from both the software programs.

The mean time to failure (β = 3.759 and η = 314.705) $= 314.705\,\Gamma\left(\frac{1}{3.759}+1\right)$

$$= 284.24 \text{ MGT}$$

This means that based on the data used for analysis, the predicted mean rail life is 284.24 MGT in low rail segments having a curve radius of 500-600 metres, rail size of 50 kg, rail type SJ or BV, and rail steel type 1100 under the assumed winter conditions.

Further, if we compare the values of shape parameter β (also known as the slope) and scale parameter η in Figure 34 and 36 and their respective Mean Time To Failure (MTTF), results show that low rail is more prone to failures with a higher aging rate compared to high rail under the same conditions and factors influencing rail break data (as stated above) for Malmbanan (iron ore line) from Kiruna to Riksgränsen (Section 111).

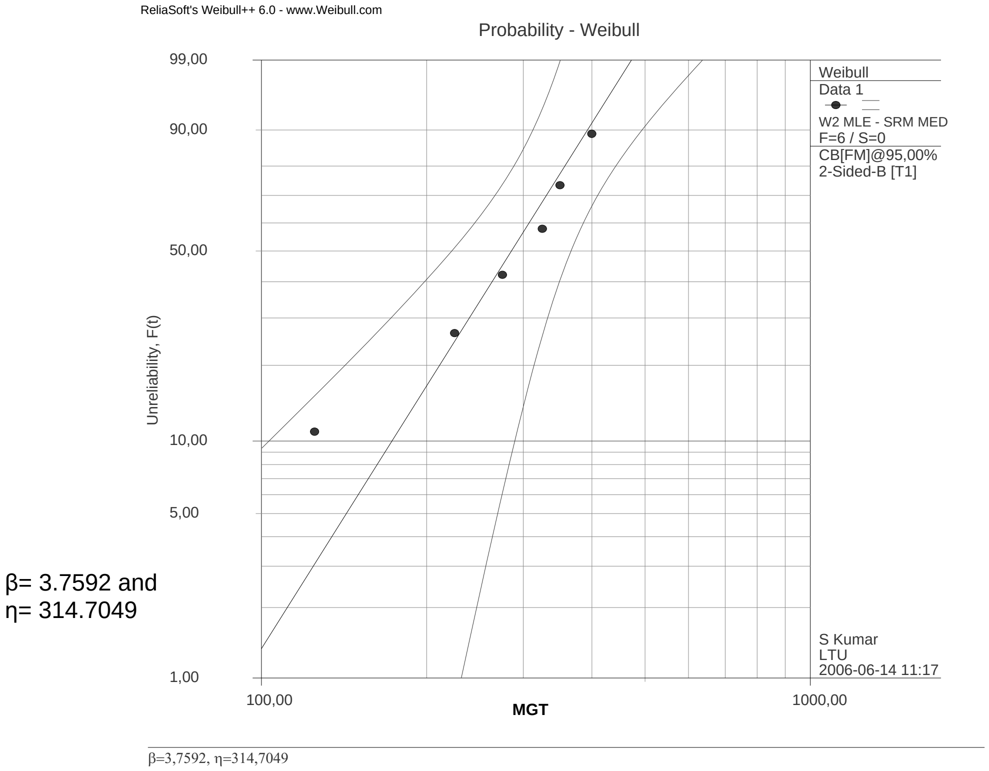


Figure 36: Winter, low rail, 50kg, 1100 steel type, SJ and BV rail type rail break data for curve radius 500-600 metres analyzed using Weibull++6 software

A possible explanation in my opinion can be speeds maintained lower than the prescribed speed limits of trains passing through the curve segments with a curve radius of 500-600 metres as the track will be having the required superelevation. Moreover, the Kiruna to Riksgränsen iron ore line has mixed traffic, with different vehicle speeds, thus the superelevation designed for curve radius 500 to 600 metres may be a compromise to balance freight as well as passenger traffic, loads and speeds. Hence, a relationship can be found out between superelevation and rail degradation. Analysis of the rail break data for different curve radii and under similar stated conditions will give a relationship between the curve radius and rail failure rate in high and low rails. More rail break data in each cell will give more accurate predictions. Similarly, a relationship between rail failure rate and other identified factors can be established. This will help in the development of a rail degradation model. The estimated failure rate can also be useful for planning inspection, grinding, rectification and replacement intervals and planning maintenance actions based on the needs of various segments of the rail network.

7 CONCLUSIONS, CONTRIBUTIONS AND SCOPE FOR FUTURE WORK

The purpose of this study is to develop an approach for rail failure prediction based on the factors influencing the rail degradation process.

The thesis focuses on the following research questions:

1. What are the current issues in rail maintenance?
2. What are the factors influencing the rail degradation process?
3. How can we develop an approach to rail failure prediction?

7.1 Conclusions

Some of the conclusions are drawn from the present research based on the research questions.

The issues related to rail maintenance are discussed. The aim is to reduce costs related to rail operation by effective decisions on rail inspection, grinding, lubrication, rectification and rail replacement. Some of the inspection issues include inspection in adverse climatic conditions, management of rail traffic during inspection and error in inspection. Issues related to wear reduction, RCF initiated defect reduction and weld problems have been discussed. Rail players always find it difficult to decide between outsourced maintenance and in-house maintenance, depending upon the capability, cost-effectiveness, skill availability, availability of equipments and technology.

Different types of rail defects and degradation processes have been studied. From the literature survey, discussions and consultations with rail maintenance experts and studies done, it is interpreted that there is a need for better prediction of rail defects over a period of time based on existing maintenance procedures. Thus, the factors influencing rail degradation have been identified.

An approach to rail break prediction has been developed and described. Rail break data have been extracted from different Banverket’s databases, classified according to a classification framework developed and analyzed over a period of time based on Million Gross Tonnes (MGT) of traffic using Weibull distribution. During the process of data evaluation and analysis, a method of extracting useful information from incomplete data has been identified.

This will help to better estimate risk in rails, better understand existing rail maintenance procedures, prevent occurrence of the predicted rail failures by taking the required actions at the right time and extend rail life by developing an effective rail maintenance procedure.

7.2 Contributions

The contributions, in short can be mentioned as:

- The factors influencing rail degradation process have been identified
- An approach to rail break prediction has been developed
- A framework for data classification based on the identified factors influencing rail degradation process has been developed
- Result analysis show that low rail is more prone to failures with a higher aging rate compared to high rail, having a curve radius of 500-600 metres, rail size of 50 kg, rail type SJ or BV, and rail steel type 1100 under the assumed winter conditions for Malmbanan (iron ore line) from Kiruna to Riksgränsen (Section 111)

7.3 Scope for Future Work

- A more generalized relationship can be found out between superelevation, curve radius and rail breakage rate in high and low rail by analyzing rail break data for different curve radii and under similar stated conditions.
- A more detailed and careful extraction of rail break data and information regarding each rail break should be done. Many of the factors affecting the rail degradation process have not been considered during data analysis and classification. Information about these factors should be extracted by conducting interviews and discussions with on-site inspectors. This will help to develop a better prediction approach.
- A relationship between rail failure rate and other identified factors can be established based on the approach developed for rail failure prediction. This will help in the development of a rail degradation model.
- This approach could be extended to predict rail breaks in other track sections belonging to Banverket or other rail infrastructure owners.
- The issues highlighted during the discussion about rail inspection, degradation and replacement processes can be used as a basis for further research in this area.

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APPENDIX

Table 1: Winter data (high rail)

	Kgs	50		
	Rail Type	SJ , BV		
	Steel Grade	1100	LHT	900
	Priority	High	High	High
Curve Radius	0-200			
	200-300	500, 500*		
	300-400			
	400-500			
	500-600	400, 250, 325, 575, 400, 350		
	600-700			
	700-800	325, 250		
	800-900			
	900-1000			725, 750
	1000-1100			
	1100-1200			
	1200-1300			
	1300-1400			
	1400-1500	275		
	1500-1600			
	1600-1700			
	1700-1800			
	1800-1900			
	1900-2000			
	>2000			

***** The values entered in the cells of Tables 1, 2, 3 and 4 are the total MGT of the rail segments in which rail breaks occurred.

Total MGT is the age of the rail segment having a rail break which is calculated by multiplying the annual average MGT of traffic flow by the difference between the inspection year of a particular rail segment in which the rail break developed and the year the same rail segment was last replaced (refer to Section 2.3 and 2.4 for details). Many cells in the tables have been left empty due to a lack of rail break data.

Many cells in the tables have been left empty because the rail break data associated with these cells were not found. Banverket's rail break data (Section 111) were collected from 1997 to 2005.

Table 2: Winter data (low rail)

	Kgs	**50**			**60**	
	Rail Type	**SJ,BV**			**UIC**	
	Steel Grade	**1100**	**LHT**	**900**	**1100**	**LHT**
	Priority	**High**	**High**	**High**	**High**	**High**
Curve Radius	**0-200**					
	200-300					
	300-400					
	400-500					
	500-600	325, 350, 275, 125, 400, 225				600
	600-700	375 300				
	700-800	325				
	800-900	250				
	900-1000	275				
	1000-1100					
	1100-1200					
	1200-1300					
	1300-1400					
	1400-1500					
	1500-1600					
	1600-1700					
	1700-1800					
	1800-1900					
	1900-2000					
	>2000					

Table 3: Summer data (high rail)

	Kgs	50		
	Rail Type	**SJ,BV**		
	Steel Grade	**1100**	**LHT**	**900**
	Priority	**High**	**High**	**High**
Curve Radius	**0-200**			
	200-300			
	300-400			
	400-500			
	500-600	275		
	600-700	300		
	700-800	375		
	800-900			
	900-1000			
	1000-1100			
	1100-1200			
	1200-1300			
	1300-1400			
	1400-1500	350		
	1500-1600			
	1600-1700			
	1700-1800			
	1800-1900			
	1900-2000			
	>2000			

Table 4: Summer data (low rail)

	Kgs	**50**		
	Rail Type	**SJ,BV**		
	Steel Grade	**1100**	**LHT**	**900**
	Priority	**High**	**High**	**High**
Curve Radius	**0-200**			
	200-300			
	300-400			
	400-500			
	500-600			
	600-700			
	700-800			
	800-900			
	900-1000			
	1000-1100	325, 400		
	1100-1200			
	1200-1300			
	1300-1400			
	1400-1500			
	1500-1600			
	1600-1700			
	1700-1800			
	1800-1900			
	1900-2000			
	>2000			