LICENTIATE THESIS

Optimization of Track Geometry Maintenance

A Study of Track Geometry Degradation to Specify Optimal Inspection Intervals

Iman Arasteh khouy

LULEÅ
UNIVERSITY
OF TECHNOLOGY

Licentiate Thesis

Optimization of Track Geometry Maintenance

A Study of Track Geometry Degradation to Specify Optimal Inspection Intervals

by

Iman Arasteh khouy

Operation and Maintenance Engineering
Luleå University of Technology
971 87 Luleå, Sweden

Printed by Universitetstryckeriet, Luleå 2011

ISSN: 1402-1757
ISBN 978-91-7439-276-0

Luleå 2011

www.ltu.se

PREFACE

The research presented in this thesis has been carried out in the subject area of Operation and Maintenance Engineering at Luleå Railway Research Centre (Järnvägstekniskt Centrum, JVTC) at Luleå University of Technology and has been sponsored by Swedish Transport Administration (Trafikverket). I would like to thank Trafikverket for providing financial support during my research.

First of all, I would like to express my sincere gratitude to my supervisor, Associate Professor Håkan Schunnesson for his invaluable guidance, suggestions, encouragement and support during my study.

I am particularly grateful to Prof. Uday Kumar for his guidance and support. Special thanks go to my co-supervisor Dr. Ulla Juntti for her valuable suggestions and contribution to my research. I would also like to thank Dr. Arne Nissen, and Prof. Per-Olof Larsson-Kråik for their comments and supports.

Special thanks to Dr. Alireza Ahmadi and Dr. Behzad Ghodrati for their continuous help and guidance during the research.

I would like to thank all my colleagues and friends at the Division of Operation and Maintenance Engineering.

Finally, I would like to express my deepest gratitude to my parents (Mahmoud & Narges), brother (Ali) and sister (Ghazal) for their invaluable encouragement.

Iman Arasteh khouy

March, 2011

Luleå, Sweden

ABSTRACT

Railway infrastructure is a complex system which comprises different subsystems. Long useful life span is one of the important aspects of this prime mode of transport. The useful life length of its assets is highly dependent on the maintenance and renewal strategy used during its life cycle. Today's demands on the railway industry call for increased capacity, including more trains, travelling at higher speeds with higher axle loads. This increased usage will result in higher degradation of railway asset and higher maintenance costs. However, due to the competitive environment and limited budgets, railway infrastructure managers are compelled to optimize operation and maintenance procedures to decrease operation and maintenance costs while meeting high safety standards. To assure track safety and maintain high quality, a cost effective track maintenance strategy is required, one based not only on technical and/or safety limits but also on cost-effective maintenance thresholds. RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life Cycle Cost) analyses, which are derived from reliable track condition data, provide an approach to specify cost effective maintenance strategy to lessen corrective maintenance actions and downtimes.

One of the main parameters to assure railway safety and comfortable railway service is to maintain high quality of track geometry. Poor track geometry quality, directly or indirectly, may result in safety problems, speed reduction, traffic disruption, greater maintenance cost and higher degradation rate of the other railway components (e.g. rails, wheels, switch, crossings etc.). The aim of this study is to develop a methodology to optimize track geometry maintenance by using historical geometry data. The methodology is based on reliability and cost analysis and supports the maintenance decision-making process to identify cost-effective inspection interval. An important phase of track geometry maintenance optimization is to estimate the track degradation rate. Obtaining knowledge about degradation helps to properly schedule maintenance activities such as inspection and tamping.

The thesis provides a methodology to identify a cost-effective inspection interval based on track degradation rate and cost drivers. It contains state-of-the-art track geometry maintenance optimization. It describes Trafikverket's (Swedish Transport Administration) maintenance strategy regarding measurements, reporting on and improving track quality, and it evaluates the efficiency of this strategy. Finally, it includes a case study carried out on the iron ore line in north of Sweden that runs from Boden to Gällivare to evaluate track geometry degradation and analyze the probability distributions of failures. A cost model is developed in order to find optimal inspection interval.

Keywords: Track geometry degradation, Track maintenance optimization, Maintenance planning, Tamping

LIST OF APPENDED PAPERS

This thesis includes an extended summary and the following three papers appended in full.

Paper I	Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2011). Evaluation of track geometry maintenance (Tamping) in Swedish heavy haul railroad - A Case Study. Accepted in International Heavy Haul Association Conference, 19-22 June, Calgary, Canada.
Paper II	Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2011). Evaluation of track geometry degradation in Swedish heavy haul railroad - A Case Study. Accepted in COMADEM Special Issue in Railway.
Paper III	Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2011). Optimization of Track Geometry Inspection Interval. Submitted for publication in Journal of Rail and Rapid Transit.

CONTENTS

INTRODUCTION

Background

The railway is one of the prime modes of transportation for humans and materials. Safety, reliability, sufficient capacity and availability are main requirements of a railway network (Patra, 2009). With the advancement of technology and increasing competition in all sectors of transportation, railways must restructure and upgrade their management and technology (Profilidis, 2006). Due to the increased demands of operators and society in general, railway infrastructures must reduce operation and maintenance costs while improving network capacity. This can be accomplished by changing the culture within operation and maintenance departments by shifting from a reactive to a proactive strategy.

In Europe, the government usually owns railway systems. This means that the strategic objectives of railway networks often are based on political decisions (Espling, 2007). However, the European Union is moving toward an open access model for railroads in which track infrastructure administration is separated from train operations (Resor and Patel, 2002). In Sweden, Trafikverket (Swedish Transport Administration) is the government authority responsible for railway infrastructure administration as well as development of the railway sectors (Banverket, 2007; Espling, 2007). Trafikverket's main objective is to ensure cost-effective and long-term provision of transportation for citizens and the business sector (Granström, 2005). To increase the effectiveness and efficiency of Sweden's railway infrastructure, Traifkverket was divided into client/contractor organizations in 1998 (Espling, 2007).

The railway system is divided into rolling stock and infrastructure. Correspondingly, the infrastructure system is divided into subsystems including the track, signalling, electrical and telecom systems. The functional requirement of the track subsystem is to provide safe and economic movement of rail traffic (Bing & Gross, 1983). In terms of safety and operational expenditures, the track is one of the main parts of infrastructure. To exemplify, in the Netherlands in 2006, 65% of the maintenance cost was allocated to the track and platforms (Profillidis, 2006).

Track geometry is an important aspect of railway construction (Esveld, 2001), as indicated by Jovanovic (2004) in the following:

- The degradation of many other track components is closely related to track geometry condition;
- Track geometry is often used for triggering the entire range of track maintenance and renewals.

Track with good inherent quality provides a good ride and needs little maintenance; conversely, track with poor inherent quality results in poor ride comfort and requires much maintenance (Selig and Waters, 1994). The monitoring and evaluation of track geometry is imperative if the infrastructure administration is to control safety and meet the needs of track maintenance (Berggren et al., 2008).

Track maintenance consists of inspections and interventions (Lyngby et al, 2008). Inspections are carried out to ensure track safety by monitoring track condition and obtaining the information necessary to set up maintenance scheduling. The inspection methods are divided into manual and automated inspections by vehicle. Intervention refers to preventive and corrective maintenance, as well as renewal actions carried out to improve track quality.

In the past, railway maintenance procedures were usually planned based on the knowledge and experience of the company involved. The main goal was to provide a high level of safety, and there was little concern for economic issues (Lyngby et al, 2008; Carretero et al, 2003). Today, however, the competitive environment and budget limitations are forcing railway infrastructures to optimize operation and maintenance procedures. The primary goal of optimization is to reduce the operation and maintenance expenditures while still assuring high safety standards (Lyngby et al., 2008; Carretero et al., 2003).

Optimizing maintenance requires estimating track degradation and the consequence of this degradation, often in the form of cost (Lyngby et al., 2008). Obtaining knowledge about degradation helps a company estimate the right time for inspection, maintenance and renewal.

Track geometry degradation is a complex phenomenon affected by dynamic loads (Esveld, 2001). The rate of degradation is a function of time and/or usage intensity (Lyngby et al., 2008). According to Lichtberger (2001), the initial track quality, the initial settlement and the deterioration rate are the major parameters of track quality deterioration.

Several attempts have been made to better understand the track geometry degradation and make empirical models for degradation mostly by the Railway Research Institutes like ERRI - European Rail Research Institute in Netherlands, TTCI in USA, RTRl in Japan, TU Graz in Austria, etc.

Because early studies were carried out in the 1980s and 1990s when few condition data were available and computers were not powerful enough, the results ended up as simplified linear deterioration (Jovanovic, 2004). For instance, in 1987, Committee D161 of ORE (Office for Research and Experiments) conducted a comprehensive study of track geometry degradation based on historical data; it concluded that excluding sections with high deterioration rates, usually track quality deteriorates linearly with tonnage or time between maintenance operations after the first initial settlement (Esveld, 2001). However, a more recent study by the Austrian railway has revealed that the track deteriorates exponentially (UIC, 2008; Veit, 2003).

Some researchers have examined the effect of speed and axle loads on track deterioration, earlier studies concluded the speed of the train has a significant effect on track geometry deterioration (Kearsley and Vanas, 1993; Ferreira and Muray, 1997). More recently, Sadeghi and Askarinejad (2007) analyzed the influence of axle load, speed, rail type, subgrade condition, rail pad stiffness and sleeper spacing on the average growth of track irregularities. Sato (1997) proposed a degradation model from the super-structural aspect in which the degradation depends on tonnage, speed, types of rail connection (Jointed or continuously welded) and quality of the subgrade. The degradation model, which was developed by Bing & Gross (1983), predict how the track quality, as measured by Track Quality Indices (TQls) changes as a function of causal parameters, such as traffic, track type, and maintenance.

In addition, several attempts have been made to optimize track geometry maintenance. Vale et al. (2010) developed a model for scheduling tamping on ballasted tracks by considering the track degradation, the track layout, the dependency of track quality improvement on the quality of track at the time of maintenance operation and the track quality limits that depend on train speed. Zhao et al. (2006) developed a life cycle model to optimize ballast tamping and renewal. Their model was developed by incorporating the track deterioration model proposed by Riessberger (2001), and the tamping model. They presented three algorithms to obtain the optimal tamping and renewal strategy for three policies of fixed intervention level, constant interval of tamping and optimal non-constant intervals of tamping. Finally, Higgins (1998), proposed a model to determine the best allocation of maintenance activities and crews to minimize maintenance costs while keeping the track condition at an acceptable level.

In the optimization of track geometry inspection, more attention has been paid to optimizing the inspection procedure by correlating geometry irregularities to dynamic responses at wheel-rail interface. Due to the inability of current track standards to account for the performance of different vehicle types, or deal with combinations of track geometry perturbations, in the last few years, operating railroads shifted their focus to performance-based track geometry (PBTG) (Liu and Magel, 2009). Li et al. (2009) noted that current standards and assessment methods do not consider dynamic responses at the wheel-rail interface and may not be adequate for track maintenance and train speed setting. Therefore, they proposed a dynamic model to assess vertical track geometry quality based on simulation of dynamic track-vehicle interaction.

Limited research has considered the optimization of track geometry inspection intervals. Specifying a cost-effective inspection interval can help railway infrastructures perform maintenance before geometry irregularities reach intervention limits, thus reducing maintenance expenditures. Lyngby et al. (2008) studied the optimization of track geometry inspection intervals on the Norwegian railway network and showed that by optimizing inspection intervals about 20000 NOK per year could be saved on a specific track.

Summing up, a review of the literature indicates a need to optimize track geometry maintenance. Specifying a cost-effective maintenance strategy using RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life Cycle Cost) analyses can help infrastructure managers inspect assets and perform maintenance at the right time, thereby reducing operational expenditures and increasing the life span of the asset.

Problem definition

Today, the railway industry is required to increase its capacity: more trains go at greater speeds, with higher axle loads. This increased usage may result in the increased degradation of railway assets and higher maintenance costs. To assure the safety of the track and maintain high quality, an optimized and cost effective track maintenance strategy is required based on both technical and/or safety limits and cost-effective maintenance thresholds.

Aligned with European Commission, Trafikverket (Swedish Transport Administration) defined a vision till 2020 to increase capacity and market share of passenger and goods traffic and also to decrease the maintenance cost and emission of pollutants (White Paper, 2001). Thus, an optimal maintenance strategy will link maintenance strategy objectives to organisational objectives.

One of the main parameters to assure railway safety and comfortable railway service is to maintain high quality of track geometry. Poor track geometry quality, directly or indirectly, may result in safety problems, such as derailment, speed reduction, traffic disruption, greater maintenance costs and higher degradation rates in the other railway components (e.g. rails, wheels, switch, crossings, etc.).

Given limited maintenance budgets and short track access time for maintenance, it is essential to have an effective and efficient maintenance strategy that infrastructure managers can perform maintenance in a timely fashion. RAMS (Reliability, Availability, Maintainability and Safety) as well as LCC (Life Cycle Cost) analyses, which are derived from reliable track condition data, will help to specify cost effective maintenance intervals, thereby lessening corrective maintenance actions and downtimes.

The main objectives of track maintenance optimization are to decrease maintenance costs and increase life length of the asset while assuring high safety standards. The first step in optimizing track geometry maintenance is to estimate the track degradation rate. Obtaining knowledge about the degradation helps to properly schedule maintenance activities such as inspection and tamping.

Trafikverket outsources the inspection and tamping of each line to different contractors mostly in performance contracts. This means it is up to the contractor to select methods and plan for the work. The frequency of measurement varies from one to six times per year depending on the track inspection class. The condition data are used by the contractors to plan maintenance activities.

If the inspection interval is not selected properly, the track quality may deteriorate beyond the intervention limit; this can result in higher frequency of tamping and, consequently, greater maintenance costs. Furthermore, since tamping by itself can cause track deterioration, higher frequency of tamping leads to a higher degradation rate and shorter life length of the asset. In other words, the inspection interval should be specified based on reliability and LCC analysis.

This study develops a methodology to specify the optimal inspection interval for track geometry. For this purpose, track geometry data from a heavy haul line section between Boden and Gällivare, used by both passenger and freight trains, were collected to evaluate track geometry degradation and assess the effectiveness of current maintenance strategy.

Purpose of Research

The purpose of the study is to optimize track geometry maintenance by evaluating track geometry degradation, assessing the effectiveness of current maintenance strategy and developing a methodology to identify the optimal maintenance interval. The methodology is based on reliability and cost analysis and is used in the maintenance decision-making process to identify a cost-effective track geometry inspection interval.

Research Objectives

The objectives of this thesis are:

1. To assess track geometry degradation and its influencing parameters;
2. To evaluate the effectiveness of the present track geometry maintenance strategy of Trafikverket;
3. To develop a cost model to specify a cost-effective inspection interval.

Research questions

To fulfil the objectives of the study, the subsequent research questions must be answered:

1. What is the track geometry degradation rate and which factors dominate?
2. How effective is Trafikverket's current track geometry maintenance strategy?
3. How can geometry condition data be used to specify a cost-effective inspection interval?

Scope and Delimitations

The research seeks to optimize track geometry maintenance in terms of cost efficiency.

It has two limitations. Firstly, the evaluation of track geometry deterioration is mainly based on the longitudinal level degradation because the longitudinal level is the main parameter driving the need for tamping. Further study is required to evaluate the total effects of the other geometry parameters in specifying the optimal track geometry inspection interval. For example, the twist (both 3m and 6m) geometry parameter is used to assess the probability of safety failure occurrence.

Secondly, due to lack of data, the study assumes that the variation in longitudinal level value is based on dynamic loads. This means that it does not examine the effects of the other maintenance actions and factors in combination with the longitudinal level.

Structure of the thesis

The thesis structure is as follows:

Chapter 1, *Introduction and Background*, presents a brief introduction to the problem. It gives background information and explains the research problem. The objectives of the research, research questions and limitations are also discussed in this chapter.

Chapter 2, *Basic Concepts*, describes basic concepts of track geometry maintenance and provides Trafikverket's track geometry maintenance strategy.

Chapter 3, *Research Methodology*, presents different phases of the research: the purpose, approach, data collection, data analysis and assessment of research reliability and validity.

Chapter 4, *Results and Discussion*, summarizes the papers and discusses the findings of this research.

Chapter 5, *Contributions and Further Research*, as the title suggests, summarizes the research contributions and makes some suggestions for future research.

BASIC CONCEPTS AND DEFINITIONS

The following definitions were extracted from the European standard EN-13848 "Railway applications/Track - Track geometry quality", prepared by Technical Committee CEN/TC 256. "Railway applications" is divided into five parts:

- Part 1: Characterization of track geometry;
- Part 2: Measuring devices - Track recording vehicles;
- Part 3: Measuring systems — Track construction and maintenance machines;
- Part 4: Measuring systems — Manual and lightweight devices;
- Part 5: Geometric quality levels.

Track geometry quality

Track geometry quality is defined as "assessment of excursions from the mean or designed geometrical characteristics of specified parameters in the vertical and lateral planes which give rise to safety concerns or have a correlation with ride quality" (EN 13848-1).

Track geometry parameters

Track geometry is one of the main aspects of railroad construction; it consists of level, alignment, cant, twist and gauge.

Track gauge

This parameter is defined as the distance G between the gauge faces of the two adjacent running rails at a distance z_p=14 mm below the running surface (Figure 2.1). The nominal track gauge for a standard track is 1435 mm (EN 13848-1). The irregularity of this parameter is the deviation from the nominal value.

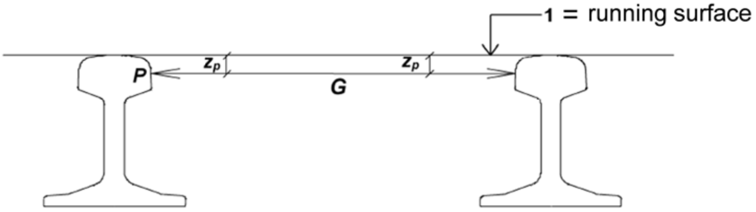


Figure 2.1 Definition of track gauge (EN 13848-1)

Alignment

In terms of alignment, "deviation y_p in y-direction of consecutive positions of point p (refer to 2.1.1) on any rail [is] expressed as an excursion from the mean horizontal position (reference line) covering the wavelength ranges stipulated below and calculated from successive measurements" (EN 13848-1) (Figure 2.2).

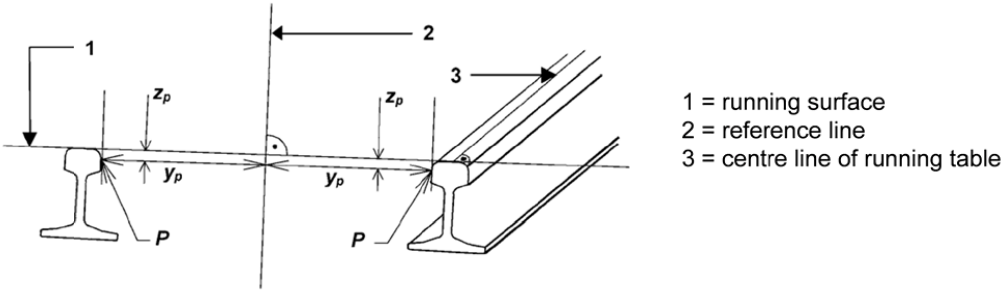


Figure 2.2 Alignment (EN 13848-1)

Longitudinal Level

For the longitudinal level, "deviation $z_{p'}$ in z-direction of consecutive running table levels on any rail [is] expressed as an excursion from the mean vertical position (reference line), covering the wavelength ranges stipulated below and is calculated from successive measurements" (EN 13848-1) (Figure 2.3).

This parameter is the principal determining factor in specifying track maintenance expenses (Profillidis, 2006).

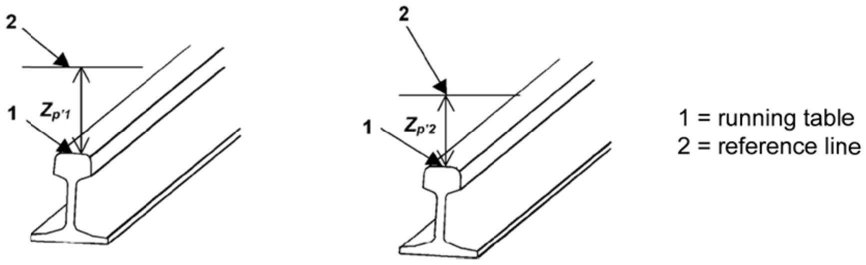
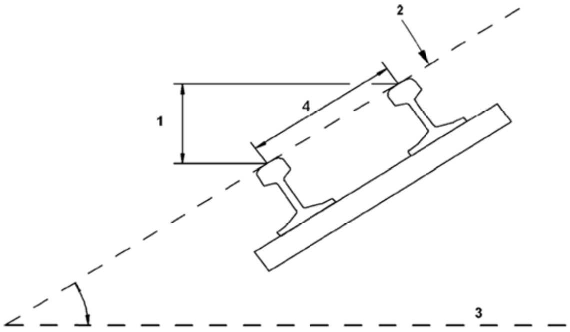


Figure 2.3 Longitudinal level (EN 13848-1)

Cant (Cross level)

"The difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane. It is expressed as the height of the vertical leg of the right-angled triangle having a hypotenuse that relates to the nominal track gauge plus the width of the rail head rounded to the nearest 10 mm" (EN 13848-1) (Figure 2.4).The hypotenuse for nominal gauge of 1435 mm is 1500 mm in length (EN 13848-1).



1 = cant
2 = running surface
3 = horizontal reference plane
4 = hypotenuse

Figure 2.4 Cant (EN 13848-1)

Twist

"Twist is the algebraic difference between two cross levels taken at a defined distance apart, usually expressed as a gradient between the two points of measurement" (EN 13848-1).

Assessment of track geometry quality

The quality of track geometry can be evaluated based on three different indicators (EN 13848-5):

- Extreme values of isolated defects;
- Standard deviation over a specified length, usually 200 m;
- Mean value.

Three maintenance levels are defined to evaluate the severity of the track geometry deviation (EN 13848-5):

- Intermediate Action Limit (IAL): this is a safety limit; if the deviation exceeds this limit, there is a risk of derailment. The risk can be reduced by closing the line, reducing the speed or correcting of track geometry.
- Intervention Limit (IL): this is a corrective maintenance limit; if the deviation goes beyond this limit, corrective maintenance should be performed so that the immediate action limit will not be reached before the next inspection.
- Alert Limit (AL): this is a preventive maintenance limit; if the deviation exceeds this limit, the track geometry condition should be analyzed and included in the regularly planned maintenance operations.

The values of these maintenance levels are given as a function of speed, which is a significant parameter for the assessment of track geometry quality (EN 13848-5).

Tamping

Tamping is a maintenance action performed to correct long wavelength faults caused by repeated traffic (Selig and Waters, 1994). Short wavelength faults cannot be removed by tamping; normally, only grinding or weld straightening are helpful for these kinds of defects. Tamping is only effective over wavelengths of 3 to 25 m in the smoothing mode and 25 m upwards in the design mode (Esveld, 2001).

According to Selig and Waters (1994), the sequence of tamping is the following (Figure 2.5):

(A) The tamping machine positions itself over the sleeper to be tamped.

(B) The lifting rollers raise the sleeper to be tamped to the target level and thereby create a space under the sleeper.

(C) The tamping tines are inserted into the ballast on either side of the sleeper.

(D) The tamping tines squeeze the ballast into the empty space beneath the sleeper, thereby retaining the sleeper in this raised position.

(E) The tamping tines are withdrawn from the ballast; the lifting rollers lower the track, and the tamper moves forward to the next sleeper.

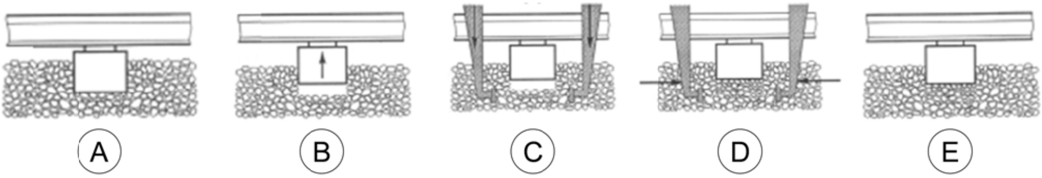


Figure 2.5 Sequence of Tamping (Selig and Waters, 1994)

After long service, ballast degrades, and its gradation changes. As a result, performance is reduced. This process is called "fouling" (Aursudkij, 2007).

Tamping is required when the threshold for action is reached. The execution of tamping execution causes the standard deviation of the track to decrease. As a result, track faults grow exponentially as ballast settles into a more compact position (Lichtberger, 2001). This settlement phenomenon is called "ballast memory" (Aursudkij, 2007). Selig and Waters (1994) have noted that the ballast memory effect can be reduced by changing the amount of sleeper lift; the higher lifts effected by the tamping machine lead to lasting improvement in the inherent track shape (Aursudkij, 2007).

The most significant parameters for determining the quality of tamping are frequency, amplitude, tamping pressure, squeezing time (0.8-1.2 s) and the squeezing speed of the tamping unit (Lichtberger, 2005). The tamping depth is also important to achieve high quality compaction of the ballast. To get the optimum compaction, there should be 15 mm free space between the top of the tamping tine plate and the sleeper base (Lichtberger, 2005).

Track Geometry Maintenance Strategy at Trafikverket

Trafikverket, which is owned by the Swedish government, is the railway infrastructure owner. In fact, around 80% of the railway network is owned by the government (Banverket annual report, 2006). Trafikverket's main objectives are to ensure system safety, reliable service, cost-effectiveness and sustainability (Granström, 2008).

Inspection Strategy

Trafikverket has outsourced its track geometry inspection and maintenance to various entrepreneurs. The frequency of measurement is regulated in BVF 807.2 (2005) and varies from one to six times per year depending on the track inspection class (BV, 2008).

Track geometry inspection is performed to control track irregularities and displacement from construction geometry. In track geometry monitoring, the vertical position, alignment, track gauge, rail elevation, twist (over 6 or 3 meters) and curvature are inspected (BVF 807.2).

Inspection train STRIX monitors the geometry of every 25 cm of the track continuously. STRIX uses a contactless measurement system, based on an inertial measurement system and an optical system. All measuring cars should meet the standards specified in EN 13848-2. The measurement procedures for vertical position, cant, track gauge and alignment are explained below.

Track vertical position measurement

The vertical position of the right and left rails is measured by a position sensor (HL) and an accelerometer (HA) (Figure 2.6). The accelerometer measures the vertical acceleration of the wagon. This measured acceleration should be integrated twice over time to determine the position of the wagon. Then, the result is summed to the value, which was measured by position sensor to identify the vertical position of each rail (formula 1) (Gripner, 2006).

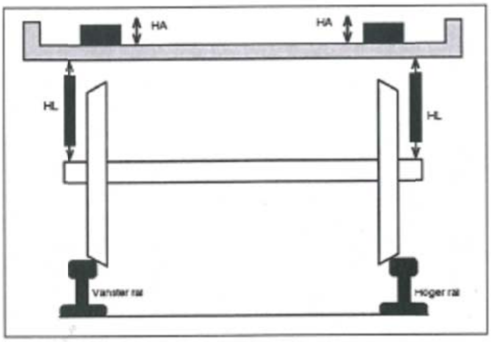


Figure 2.6 Vertical position measurement (Gripner, 2006)

$$\text{Vertical position} = \text{HL} + \iint \text{HA}\,dt^2 \qquad [1]$$

Since the recorded signals from the measuring car are the combination of long and short wavelengths, the long wavelength signals must be filtered. This can be done by selecting only signals in the range of 3 to 25 meters.

Cant measurement

Track cant is used to overcome centrifugal force in curves and is shown in Figure 2.7. Cant measurement is performed by a gyro which measures the angle between ground and wagon. Two vertical position sensors are used to measure the angle between the wagon and the wheel axle (HLh and HLv). The angle between the axle and the ground is computed by subtracting the angle between the wagon and the axle from the angle between the wagon and the ground.

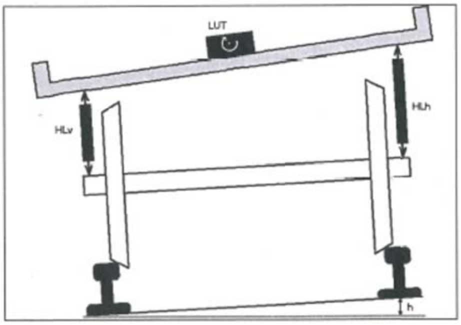


Figure 2.7 Cant measurement (Gripner, 2006)

Twist is defined as the variation of cant over 6 meters of track. STRIX measures the values of cant; based on this, the twist can be calculated.

Alignment and track gauge measurement

The track gauge is measured by two laser devices for the right and left rails (see Figure 2.8). This device sends a laser beam to the rail through a versatile mirror. The laser beam should illuminate a point 14 mm under the rail's upper edge. If the rail has been displaced in a lateral direction, the beam meets the rail at another point which will be detected by the camera. The camera sends the signal to the versatile mirror which turns the beam back to the correct position. The turning angle obtained by this process can be converted to the lateral displacement between the rail and wagon body. The track gauge is calculated without considering separate deviations of the right and left rail. The side deviation of the right and left rail is calculated by adding the side displacement of each rail to the relative movement of the wagon to the ground. This relative movement is computed by one accelerometer, as shown in Figure 2.8.

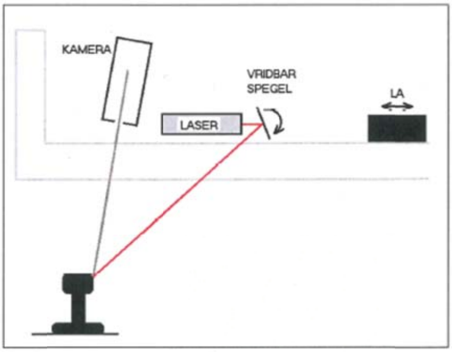


Figure 2.8 Measurement of track gauge and alignment (Gripner, 2006)

The inspection data are reported in the BESSY database; critical failures, which can cause derailment, should be reported immediately to the operation control centre.

BESSY is one of Trafikverket's asset databases; these databases will be described in Section 2.4.

Tamping strategy

Trafikverket uses several of condition indices to describe the condition of the track; the most important are the Q-value and K-value. These values are calculated based on the regular measurements of the track geometry.

The quality of the track is calculated based on two parameters:

- The standard deviation of vertical position (σ_H) from the geometric comfort limit set for a specific track class ($\sigma_{H\,\lim}$).
- The standard deviation of the sum of cant and lateral positions (σ_S) from the geometric comfort limit set for a specific track class ($\sigma_{S\,\lim}$).

The formula for calculating the Q-value is (BVF 587.02, 1997):

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H\lim}} + 2\frac{\sigma_S}{\sigma_{S\lim}}\right] /3 \qquad [2]$$

Where:

σ_S = the standard deviation of the sum of the monitored cant error and the monitored side position error over 200 meters (Figure 2.9). This value can be computed by formula [3]:

σ_S = standard dev. (cant error + (left side position error + right side position error)/2) [3]

$\sigma_{S\,\lim}$ = the limit for the standard deviation of the sum of the monitored cant error and the monitored side position error over 200 meters.

σ_H = the standard deviation of the average monitored height error for left and right rail over 200 meters.

$\sigma_{H\,\lim}$ = the limit for the standard deviation of the average monitored height error for left and right rail over 200 meters.

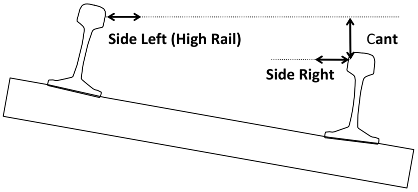


Figure 2.9 Calculation of σ_S

The other index, the K-value, is the ratio of the total length of the track with deviations below comfort limits (∑l) and the total length of the track (L). This index is used to obtain an overall picture of the track condition over a long distance and is calculated by the following equation:

$$K = \frac{\sum l}{L} \times 100\% \qquad [4]$$

At present, the Q value of the entire track section is the governing factor since this value is included in the contract between the rail administrator and the contractor (Espling et al., 2007).

The track geometry faults are classified as "B-faults" or "C-faults" (Espling et al., 2007). B-faults identify the limits for preventive maintenance while C-faults, which are corrective maintenance limits, identifies the maximum allowable deviation from the design position for 25 centimetre track sections.

Trafikverket outsources the tamping of each line to different contractors mostly on performance contracts. Outsourcing by performance contracts, means that it is up to the contractor to select methods and plan for the work.

In these performance contracts, two limits are specified for the Q value, a goal limit and a contractual limit. If the actual Q value of the track is higher than the goal limit, contractors receive a bonus; if it is under the contractual limit, they are penalized.

The execution of tamping is based on the calculated Q values and C-fault limits. Tamping due to C-fault deviations is considered corrective maintenance and is obligatory, while tamping due to a low Q value is considered preventive maintenance. If the inspection reveals C-fault(s) in the track, tamping is carried out within one or two weeks of the inspection. For track with a low Q value, planned tamping is performed within one month of the inspection.

Trafiverket asset databases

Trafikverket employs BIS (a track information system), BESSY (an inspection system), Ofelia (a fault analysis system) and Optram (a graphical track geometry data system) for maintenance planning (Patra, 2009). For the most part, the other systems use BIS as a reference system (Patra 2009, Andersson, 2002). Therefore, for efficient maintenance planning, it is best to integrate them.

BIS

BIS is the Transport Administration's computer system which stores and retrieves information about track facilities and events. BIS is a reference system, including descriptions of the railway system in the form of nodes and links, and also a classification system for areas and distances. It is searchable *via* a graphical user interface based in Sweden (Trafikverket website, Banportalen).

BESSY

BESSY is used for the safety and maintenance inspection of Trafikverket's fixed assets. Inspection Plan is a PC system for planning and monitoring inspections when using BESSY (Trafikverket website, Banportalen).

Ofelia

Data regarding symptoms of track faults are registered in Ofelia. Track Contractors report information, including the reason for faults, what action is performed, times of occurrence and fixing (Trafikverket website, Banportalen).

Optram

Optram is a web-based system used for data analysis. It coordinates the data from the recording car Strix and the measuring wagons. Managers and entrepreneurs use this system to analyse information from the track and overhead line. With this, they can optimize their maintenance practices (Trafikverket website, Banportalen).

Maintenance Optimization

Optimization is a process that, as its name implies, seeks the optimal solution by setting priorities and making compromises to achieve what is most important (Campbell & Jardine, 2001). The first step in optimization is to specify which objectives are most desirable, such as maximizing availability, minimizing cost, etc. In maintenance optimization, objectives are usually defined by maintenance purposes (Cui, 2008). All constraints should be considered before the optimal solution is determined (Cui, 2008). When it is not possible to achieve all objectives simultaneously, a trade-off should be made between the objectives to find the best solution.

The traditional approach in maintenance optimization is to determine an optimal maintenance strategy, minimizing the average cost per unit of time in the long run or the total expected discounted costs (Vatn and Aven, 2009). Techniques for maintenance optimization include the following (Cui, 2008):

- Conventional approaches such as the usual calculus method;
- Simulation approaches;
- Algorithms;
- Artificial neural networks;
- Programming methods such as linear programming;
- Fuzzy theory approaches.
- Maintenance optimization models are mathematical models which aim to find the optimum balance between the costs and benefits of maintenance (Dekker, 1996). These models may have different functions (Dekker, 1996):
- Evaluate maintenance policies with respect to cost-effectiveness and reliability;
- Specify the structure of optimal policies;
- Specify the optimal inspection or maintenance interval.

In this case, optimizing maintenance requires an estimation of the track degradation and the consequence of this degradation, often in form of cost (Lyngby et al., 2008). Obtaining knowledge of degradation helps to estimate the right time for inspection, maintenance and renewal, considering the total cost of maintenance and risk (Lyngby et al., 2008).

Degradation models can be classified as the following (Dekker, 1996; Sherif and Smith, 1981):

1. Deterministic Models
2. Stochastic Models:
    a. Under Risk
    b. Under Uncertainty

The difference between risk and uncertainty is that for risk, it is assumed that a probability distribution of the time to failure is known while in the case of uncertainty, it is unknown (Dekker, 1996).

RAMS in Railway

In railways, RAMS (Reliability, Availability, Maintainability and Safety) is a characteristic of a system's long-term operation and is obtained by the application of established engineering concepts, methods and techniques throughout the lifecycle of the system (EN 50126, 1999). By meeting the needs of RAMS, a railway can guarantee the achievement of its goals, namely, to reach a specific level of rail traffic in a given time, safely.

The system lifecycle is a sequence of phases, each with specified objectives, inputs and requirements, covering the total life of a system from initial concept through to decommissioning and disposal. It provides a structure for planning, managing, controlling and monitoring aspects of a system in order to deliver the right product at the right price within the agreed time (EN 50126, 1999). A system lifecycle that can be used in the context of railway is illustrated in Figure 2.10.

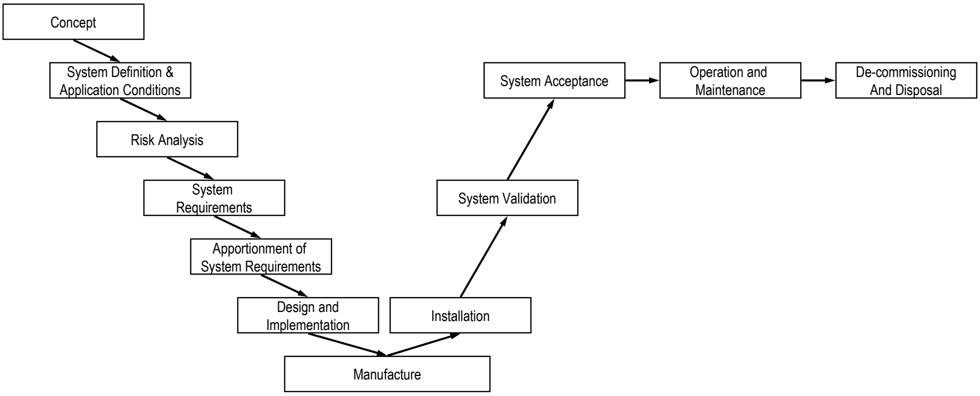


Figure 2.10 The "V" Representation of Railway Lifecycle (EN 50126, 1999)

The left side of this "V" representation of railway lifecycle is generally called development and is a refining process ending with the manufacturing of system components; the right side is related to the assembly, installation, receipt and operation of the whole system.

The RAMS of railway can be influenced by the following conditions (EN 50126, 1999):

- System condition: sources of failure introduced internally within the system at any phase of the lifecycle;
- Operating condition: sources of failure imposed on the system during operation;
- Maintenance condition: sources of failure imposed on the system during maintenance activities.

To optimise system performance, all factors which could affect railway RAMS need to be identified, their effect assessed and the cause of these effects managed throughout the lifecycle of the railway (see Figure 2.11).

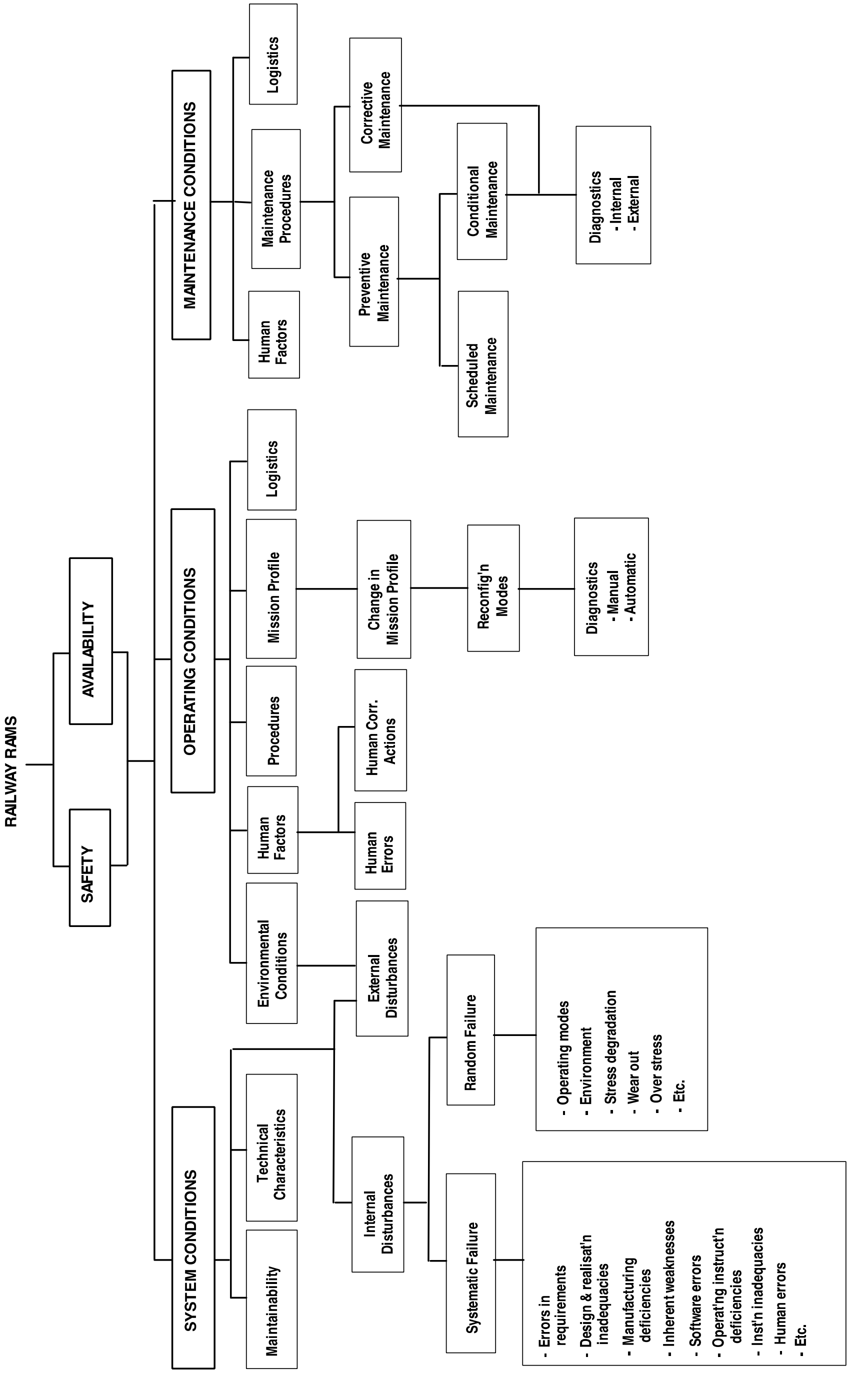


Figure 2.11 Factors Influencing Railway RAMS (EN 50126, 1999)

LCC in Railway

Since an investment in railway infrastructure is costly, and the infrastructure has a long lifespan, an optimal maintenance strategy should be developed through Life Cycle Cost (LCC) analysis. LCC analysis is a technique of decision-making using economic assessment and comparisons of alternative strategies and designs. It is a structured method of assessing all costs incurred within a given system using that system's technical life cycle (Nawabi, 2006).

The main steps of LCC analysis are the following (Andrade, 2008; IEC 60300-3-3, 2004):

1. Collect data for all cost elements which defined in the breakdown structure;
2. Perform LCC analysis for different product scenarios;
3. Identify the optimum scenario;
4. Identify cost drivers;
5. Specify any distinction in product performance, availability or any limitation that may affect the applicability of the scenarios considered;
6. Summarize LCC model outputs,
7. Perform sensitivity analysis to evaluate the robustness of the model;
8. Compare LCC model outputs to the objectives defined in the analysis plan.

There are two ways to distinguish the life cycle cost of railway track (Esveld, 2001):

1. Tangible versus intangible costs: In tangible costs, the exact costs are known, such as the costs of construction and maintenance (labour, materials and machines). For intangible costs, the precise costs are unknown. Intangible costs include loss of quality, reduction in transport services and reduced safety and comfort.
2. Initial (capital) costs versus running costs: Initial costs are the costs of acquisition and installation or construction; running costs are incurred during the operational period of a railway.

Some research has been done on the application of LCC to the railway industry. A guideline for LCC and RAMS analysis proposed by the INNOTRACK project applies to some European countries. The guideline explains principles, applications and advantages of LCC analysis. It was created using a survey on the rules and standards currently being used by infrastructure managers, as well as the tools and models implemented for RAMS and LCC analysis in Europe.

IMPROVERAIL (2003) is a European project, which discussed obstacles to the application of LCC in the railway industry. The project noted that although the need for LCC application has increased sharply due to the competitive business environment, knowledge at the technical-economical interface remains insufficient (Andrade, 2008)

Zoeteman (2001) developed a decision support system (DSS) for railway design and maintenance based on Life Cycle Costing. DSS considers four variables, which influence the performance of rail infrastructure and are considered cost drivers: steering, external, internal and effect variables. Steering variables are those factors which the infrastructure manager (IM) can directly influence; external variables all those not under IM's control. Internal variables are part of the maintenance and renewal process, specifying the volume of planned maintenance and failure performance.

Due to lack of data and indisputable renewal thresholds, uncertainties should be considered in any life cycle cost analysis. One of the main uncertainties in LCC analysis is the assessment of track quality decline (Esveld, 2001). The track quality degradation depends on many factors such as the initial quality of the construction, the quality of the substructure and the loads on the track.

Sensitivity analysis and Monte Carlo simulation are two methods of dealing with uncertainties in LCC analysis (Esveld, 2001; Norman et al, 1983). In sensitivity analysis, the input values are varied to test the robustness of the outcomes. The disadvantage of this method is that usually only one parameter at a time can be varied. Conversely, in a Monte Carlo simulation, all factors can be varied simultaneously.

RESEARCH METHODOLOGY

The term “research” has been defined in different ways. Kumar (2008) calls it an intensive and scientific activity undertaken to establish a fact, a theory, a principle or an application. In other words, research is a stepwise process of finding answers to questions (Neuman, 2003). Different research approaches require different steps; the most common research steps are shown in Figure 3.1.

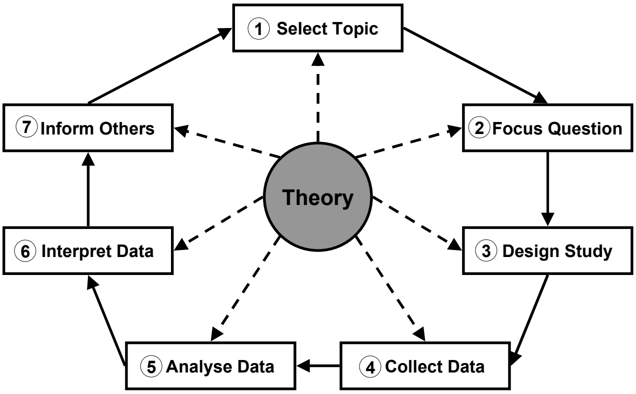


Figure 3.1 Steps in research process (Neuman, 2003)

Selecting an appropriate and clear methodology is a necessary requirement of conducting research. Research methodology, as defined by Kazdin (1992, 2003), refers to the principles, procedures and practices that govern research (Marczyk et al, 2005). Five major research methods are experiment, survey, archival analysis, history and case study (Yin, 2009). The selection of research methodology depends on three conditions (Yin, 2009):

- The type of research questions posed;
- The extent of control an investigator has over actual behavioural events;
- The degree of focus on contemporary as opposed to historical events.

The purpose of research can be organized into three groups: exploratory (explore a new topic), descriptive (describe a phenomenon) and explanatory (explain why something occurs) (Neuman, 2003). These are described in detail in Table 3.1.

Table 3.1 Different types of research goals (Neuman, 2003)

Exploratory	***Descriptive***	***Explanatory***
• Become familiar with the basic facts, setting, and concerns. • Create a general mental picture of conditions. • Formulate and focus questions for future research. • Generate new ideas, conjectures, or hypotheses. • Determine the feasibility of conducting research. • Develop techniques for measuring and locating future data.	• Provide a detailed, highly accurate picture. • Locate new data that contradict past data. • Create a set of categories or classify types. • Clarify a sequence of steps or stages. • Document a casual process or mechanism. • Report on the background or context of a situation	• Test a theory's predictions or principles. • Elaborate and enrich a theory's explanations. • Extend a theory to new issues or topics. • Support or refuse an explanation or prediction. • Link issues or topics with a general principle. • Determine which of several explanations is best

The methodology used in this research is the case study. The goals of the present research can be classified as both descriptive and exploratory. The research purpose is to describe the track geometry degradation phenomenon and explore a methodology to identify a cost-effective track geometry inspection interval based on historical condition data and various cost drivers.

Research Approach

Research can have different dimensions. The research style can be categorized as quantitative or qualitative. The main features of these styles are shown in Table 3.2.

Table 3.2 Quantitative style versus Qualitative style (Neuman, 2003)

Quantitative Style	***Qualitative Style***
• Measure objective facts • Focus on variables • Reliability is key • Value free • Independent of context • Many cases, subjects • Statistical analysis • Researcher is detached	• Construct social reality, cultural meaning • Focus on interactive processes, events • Authenticity is key • Values are present and explicit • Situationally constrained • Few cases, subjects • Thematic analysis • Researcher is involved

Research can be applied or basic (fundamental) based on its application. Basic research is conducted to determine or establish fundamental facts and relationships within a field of study with relatively little emphasis on its applications to "real-world" policy and management issues, while applied research is undertaken to solve a particular problem (Ethridge, 2004).

The research approach can be either inductive or deductive (Rubin and Babbie, 2009):

- In the inductive approach, the researcher begins with observations, seeks patterns in those observations, and creates tentative Conclusions;
- In the deductive approach, the researcher starts with hypotheses, which might come from a theory or from tentative conclusions, and then tests them.

In the present study, both quantitative and qualitative styles are used to optimize track geometry maintenance. The research problem has a direct application in the railway industry. The research also uses both inductive and deductive approaches. A deductive method is applied to develop a maintenance optimization process in railway infrastructure; an inductive approach is used to develop a model to specify the optimal inspection interval.

Data Collection

Data can be defined as the empirical evidence or information that scientists carefully collect according to rule or procedures to support or reject theories (Neuman, 2003). The data can be categorized as quantitative (i.e., expressed as numbers) or qualitative (i.e., expressed as words, objects or pictures) (Neuman, 2003).

In this research, qualitative data were collected from peer reviewed journal papers, conference proceedings articles, research and technical reports, Licentiate and PhD theses from a number of universities and railway magazines. Specific keywords were used to search both qualitative and quantitative data on well-known online databases, including IEEE Xplore, Elsevier Science Direct, Rail Rapid Transit and Emerald, etc. The reference lists of all relevant articles were searched to find other appropriate documents. Quantitative data (e.g. track geometry degradation, date and length of tamping) were collected from Trafikverket's Optram, BIS, BESSY and Ofelia databases. These quantitative data were related to a section of the iron ore railway line (Malmbanan). The databases are described in the following paragraphs. Cost-related data were collected by consulting Trafikverket's experts and examining a few scientific papers.

Some additional information regarding track geometry maintenance strategy (inspection and intervention) was obtained from InfraNord, the Trafikverket contractor for maintenance execution in the studied line.

To assess track geometry degradation, a section of the iron ore line in northern Sweden was selected. Since the parameter that usually drives the need for track geometry maintenance is the short wavelength longitudinal level (UIC, 2008) and given the reduction of the number of variables in the analysis, only the longitudinal level was considered in the evaluation of track geometry degradation. Furthermore, due to lack of data and to reduce the effect of track location, only tangent segments (each segment is 200 m) were used in the analysis with the aim of having similar segments.

Data Analysis

A railway track is a repairable system; hence, reliability analysis techniques for repairable systems should be applied for failure data analysis. The first step of analysis is to check whether the data are independently and identically distributed (IID). The trend and dependency characteristics of data can be checked by an IID test. Ascher and Feingold (1984) have proposed the steps of failure data analysis, which should be taken before choosing the best fitting distribution model (see Figure 3.2).

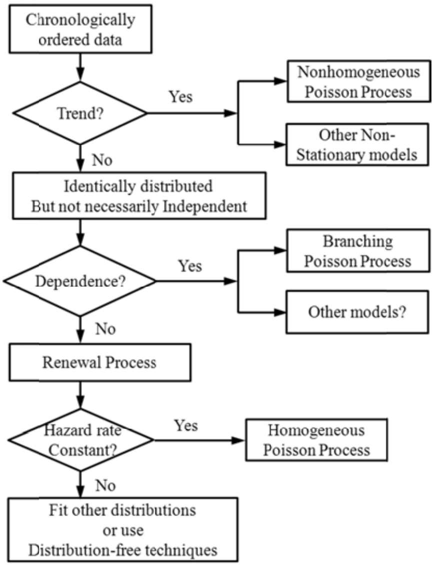


Figure 3.2 The steps of failure data analysis before selecting the best fitting model (Ascher and Feingold, 1984)

A railway track is a repairable system. It undergoes repair and can be restored by a method other than the replacement of the entire system. After a repair, the system may end up in one of the following possible states (Yañez et al., 2002):

- As good as new;
- As bad as old;
- Better than old but worse than new;
- Better than new;
- Worse than old.

Renewal Process (RP) and Non-Homogenous Poisson Process (NHPP) are two common probabilistic models used in repairable system analysis for the first two states respectively. The third state is more common in track geometry maintenance. As tamping is not entirely effective, the state of the system after maintenance execution will be better than old but worse than new.

This evaluation of track geometry degradation considered the following assumptions:

- Within each quality class all track segments (each segment is 200 meters) are assumed identical. This means that as well as being tangential, their superstructure characteristics, such as the rail profile, rail hardness and etc. are assumed to be the same.

- Additionally, it is assumed that April 2004, when tamping was performed on the entire line, is the start of the track life. This means that this date is the zero point for calculating the total transportation load in Million Gross Ton (MGT).
- The need for tamping execution is only derived from existence of longitudinal level failures.

Before finding the distribution of failures, it is necessary to define failure as it is used here. In this study, when the longitudinal level value goes beyond a corrective maintenance limit (Intervention Limit) it is considered a failure. This Intervention Limit (IL) can be defined either for isolated defects or for 200 m track segments. Since in Trafikverket, the IL is only defined for isolated defects and because the available data in this study belong to 200 m track segments, the UIC riding comfort limits graph ("Lines of constant riding comfort at different speeds") was applied to specify IL for the longitudinal level of 200 m track segments (Figure 3.3).

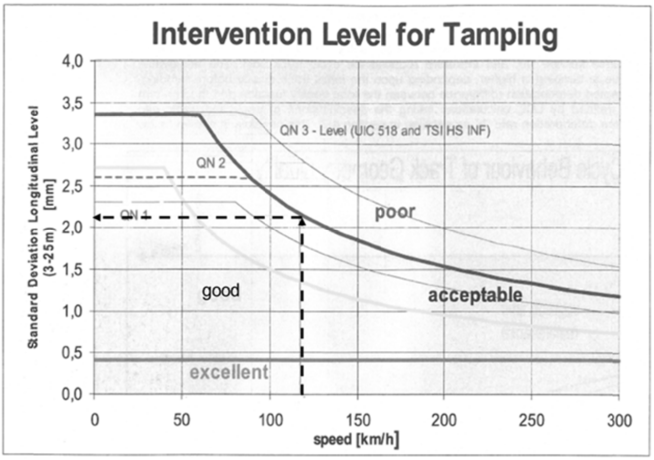


Figure 3.3 Lines of constant riding comfort at different speeds [UIC, 2008]

To find the best fitting probability distribution function, Weibull ++7 softwares was applied. To obtain applicable results from the analysis, only main distributions such as Weibull, normal/lognormal, exponential, etc. were considered, and the rest of the theoretical distribution was omitted.

Since the exact times of failure occurrence have not been determined, the failure time data were considered as interval censored data, which come from situations where the object of interest is not constantly monitored.

The P-value approach was used to measure the closeness of the fit. The P-value can be defined as the smallest level of significance that would lead to rejection of the null hypothesis (H_0) [16]. A small P-value means that H_0 is incorrect; a large P-value means that H_0 cannot be rejected. The null hypothesis, here, is the considered probability distribution function for failure occurrence.

The data analysis shows that each segment has a different degradation rate. The maintenance effectiveness in each segment is also different. By considering some assumptions and developing a cost model, the total maintenance cost per unit traffic load of different inspection strategies has been evaluated. The proposed model considers inspection time, the maintenance-planning horizon time after inspection and takes into account the costs associated with inspection, tamping and risk of accident costs due to poor track quality.

Reliability and Validity

Reliability and validity are two central research issues. Neuman (2003) has defined reliability as dependability or consistency. This means that if the research methodology is applied under identical or very similar conditions by another researcher, the same results should be obtained. Validity suggests truthfulness; it refers to the way a researcher conceptualizes an idea in a conceptualized definition. It is also a measure, as it denotes how well an idea about reality "fits" with actual reality (Neuman, 2003).

The information and data in this study have been extracted from peer reviewed journals, refereed conference proceedings in the field of railway operation and maintenance and Trafikvert's databases. These reliable sources, in addition to the application of well-established RAMS analysis techniques, consultations with railway experts about applied methodology and obtained results contribute to the study's validity.

RESULTS AND DISCUSSION

Railway infrastructure is a complex system comprised of a number of subsystems. Long useful life span is an important aspect of this prime mode of transport. The useful life length of an asset is highly dependent on the maintenance and renewal strategy used during its life cycle. Today's railway industry handles more and faster trains and deals with higher and higher axle loads. With increased usage comes the risk of faster degradation of railway assets, resulting in higher maintenance costs. However, due to a competitive environment and limited budgets, railway infrastructure managers are compelled to optimize operation and maintenance procedures in order to decrease operation and maintenance costs without endangering traffic safety. To assure the safety of the track and maintain a high standard of quality, a cost effective track maintenance strategy is required, one not only based on technical and/or safety limits but also on cost-effective maintenance thresholds. A cost effective maintenance strategy provides the lowest life cycle cost of the asset.

Optimizing maintenance requires estimating track degradation and the consequence of this degradation, often in the form of cost (Lyngby et al., 2008). Obtaining knowledge about degradation helps an infrastructure owner estimate the right time for inspection, maintenance and renewal.

In this research, track geometry data from the iron ore line (Malmbanan) in northern Sweden, used by both passenger and freight trains, were collected to calculate the degradation of track quality. To ensure comparable data, only tangent segments of 200 m from quality class K2 were considered; other parts of the track, such as curves and stations, were left out. Figure 4.1 presents the variability of the longitudinal level degradation rate in different tangent segments of the track between 2007 and 2009. The figure clearly shows the high variability of degradation rates for the track, with the majority of the section having a low rate of degradation that can be controlled by preventative tamping at infrequent intervals. However, the tail of the distribution has sections with very high degradation rates that need to be more frequently monitored and restored with corrective tamping to reduce risks. The balance between preventive and corrective tamping must be based on an appropriate cost analysis.

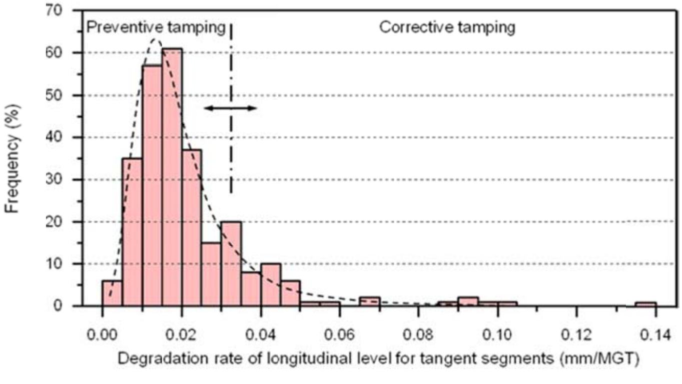


Figure 4.1 Histogram of longitudinal level degradation rates in tangent segments between 2007 and 2009

Paper II analyses the degradation rate of longitudinal level and twist 3m from 2004 to 2010. It examines the effects of climate and geometrical location on track geometry degradation and suggests possible reasons for the distribution of failures along the track and over different months. For this purpose, segments of 1000 m from both quality classes K2 and K3 were considered; stations as well as other parts of the track after or before stations with lengths shorter than 1000 m were left out.

Figure 4.2 shows the cumulative trends of number of C-failures for the longitudinal level and twist 3m. The longitudinal level failure rate has a clear linear trend over time (or MGT) during the period 2004-2010, while the C-failure for twist 3m increases over time, possibly indicating an aging effect. The rates of C-failure for cant, alignment and twist 6m show an aging trend similar to that shown by twist 3m. The curve trend indicates an aging effect, but the exact reason for this behaviour is not clear.

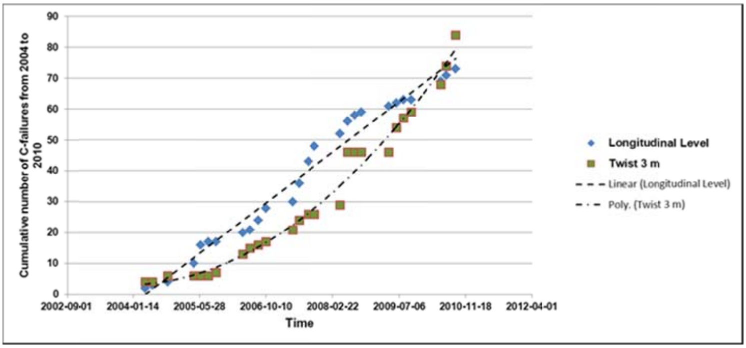


Figure 4.2 Cumulative trends of number of C-failures from 2004 to 2010

To optimize maintenance planning, it is necessary to assess the distribution of the occurrence of C-failures over a year. A histogram of the total number of C-failures occurring in different periods of the tamping season is presented in Figure 4.3. The data come from the selected track section for the time interval between 2004 and 2010. The figure shows the distribution of identified C-failures for two geometry parameters: longitudinal level and twist 3m. For the other geometry parameters, including cant, alignment and twist 6m, the trend is similar that shown by twist 3m.

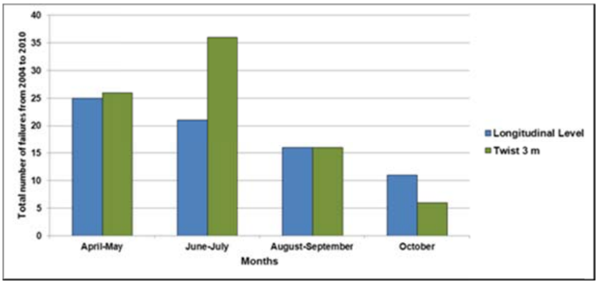


Figure 4.3 Number of detected C-failures on each inspection

To interpret the variation of failure occurrences in different seasons, factors such as climate and temperature, drainage and maintenance strategy should be considered. By the middle of May, the substructure temperature is usually above the freezing point; this causes the frost on the substructure to melt, resulting in reduced substructure stability. During June and July, the rate of geometry faults increases, identified by the increased quantity of detected twist 3m failures. One possible reason for this is the rising temperature. The soil is still frozen during the first measurement in April, but the rise in temperature starting in mid-May affects track geometry up to 30 cm below the sleepers. Frost heaves and drainage are two other possible reasons for the high rate of failure between April and July. Since drainage reduces track stability and twist usually occurs in track segments with soft subsoil (Lichtberger, 2005), the increase in detected twist faults during June and July can be explained. The effect of frost heaves on failure occurrence rate is visible in April/May, while the effect of drainage is noticeable in June/July.

To evaluate the entire section and identify subsections with a high probability of failure occurrence, the distribution of longitudinal level failure occurrence in different track segments has been evaluated (see Figure 4.4). Factors such as substructure characteristics, geometrical locations and maintenance history can possibly influence the rate of failure occurrence in different parts of the track. Combining Figure 4.4 and Figure 4.1, which indicates the high variability of degradation rates in different track segments, can help identify critical segments with high degradation rates.

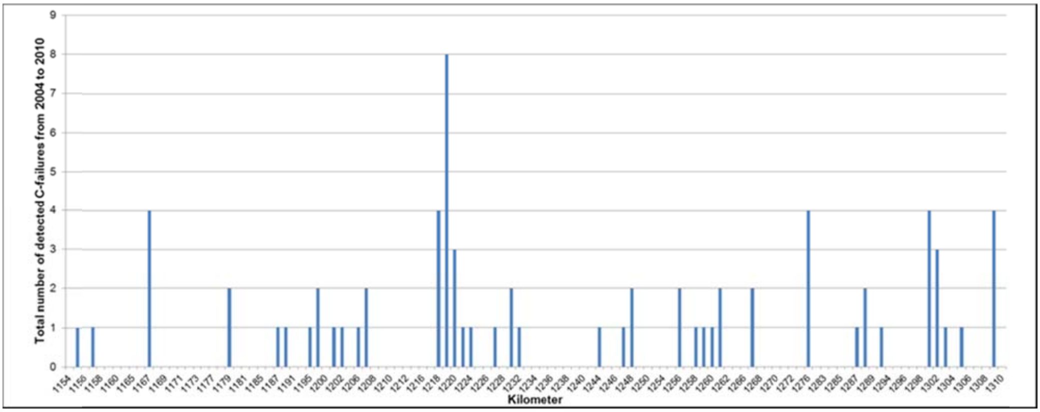


Figure 4.4 Total numbers of longitudinal level C-failures from 2004 to 2010

A study of the locations of failure occurrence in the track revealed that faults have repeatedly been registered in short sections of the track. As an example, Figure 4.5 shows the distribution of the occurrence of longitudinal level faults over kilometre 1218. In this case, only four main failures (see Figure 4.4) were registered 39 times between 2004 and 2010, over 45 m of a 1000 m track segment. The integration of failure locations within segments indicates that the root cause of failures has not been removed. Factors such as maintenance budget, contract budget or inadequate maintenance access time might be reasons for this.

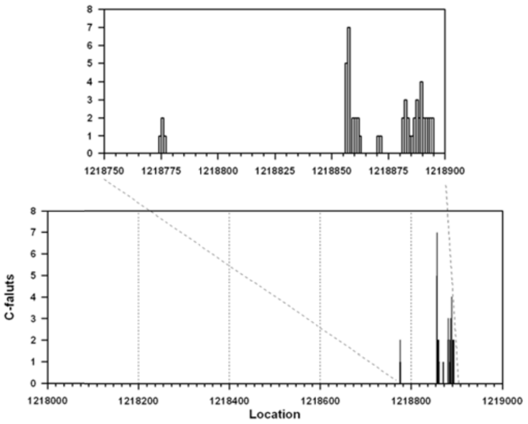


Figure 4.5 Locations of longitudinal level faults over kilometre 1218

The results above answer the first research question regarding the assessment of track geometry degradation and the specification of dominating factors.

Paper I describes Trafikverket's (Swedish Transport Administration) tamping strategy and evaluates its effectiveness in measuring, reporting and improving track quality. It also discusses the lack of data accuracy and notes the various factors involved in maintenance decisions. The analysis in this paper was based on longitudinal levels. When the longitudinal level value goes beyond the Intervention Limit, corrective maintenance should be performed. This Intervention Limit (IL) can be defined either for isolated defects or for a 200-m track segment. Trafikverket only defines IL for isolated defects. Since the studied data belong to 200-m track segments, the UIC riding comfort limits graph ("Lines of constant riding comfort at different speeds") is used to specify IL for the longitudinal level of 200-m track segments (UIC, 2008).

To provide an overview of the frequency of tamping, a histogram of the standard deviations of longitudinal level before tamping is shown in Figure 4.6. The red line represents the limit defined by UIC for poor riding comfort at 120 km/h, the maximum allowable speed in the track quality class K2. As shown in the figure, the majority of tamping is executed around the defined failure limits (2.1 mm), which is classified as poor track condition. However, a substantial amount of tamping is done at a much higher value than is expected from a riding comfort point of view.

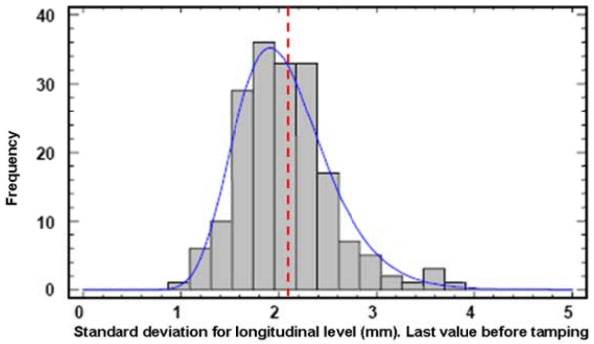


Figure 4.6 Probability density function of tamping execution at different level intervals

The standard deviation for the longitudinal level at which tamping is executed varies extensively during the period examined. Tamping is sometimes executed at a very low level and is, therefore, not motivated by riding comfort. On other occasions, tamping is conducted at levels exceeding the riding comfort limit; on still other occasions, tamping is not executed until almost double the level of the riding comfort limit for standard deviation of the longitudinal level is reached. Although tamping is not performed simply because of longitudinal level faults, this large variation indicates that its execution is not optimally planned.

An evaluation of tamping efficiency (Figure 4.7) that compares the longitudinal level before and after tamping execution reveals that efficiency in some segments is quite low. There are two possible reasons for this. The first is that only parts of the segment are tamped, not the entire section, but to confirm this, more information is required. Alternatively, these particular segments could have bad sub-structure conditions. However, it should be noted that the assessment of tamping efficiency is based on the Austrian railway results, which, in turn, are based on different substructure conditions and a dissimilar maintenance strategy.

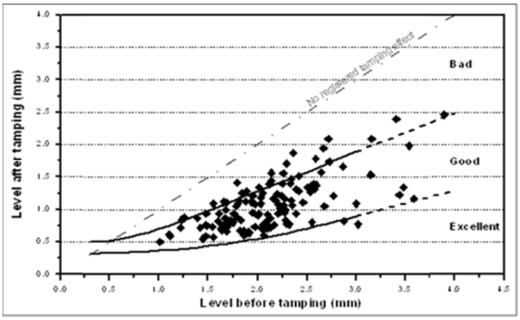


Figure 4.7 Efficiency of tamping

The analysis also revealed that some segments of the studied track continuously generate problems. Figure 4.8 shows the registered number of C-faults and the executed tamping activity between 2004 and 2008 for kilometre 1219 of the track. Almost all of the registered C-faults are concentrated in a very short section between 1219+600 and 1219+700. The same section has been subjected to tamping 6 times during the period. Without knowing the exact cause of the problems, it is obvious that tamping cannot prevent them. A root-cause analysis to reveal the underlying problem would be more beneficial in the long term.

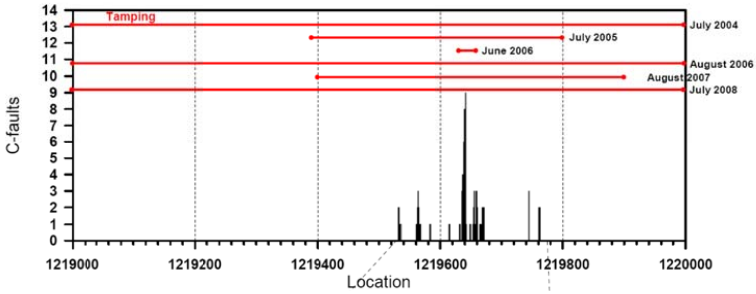
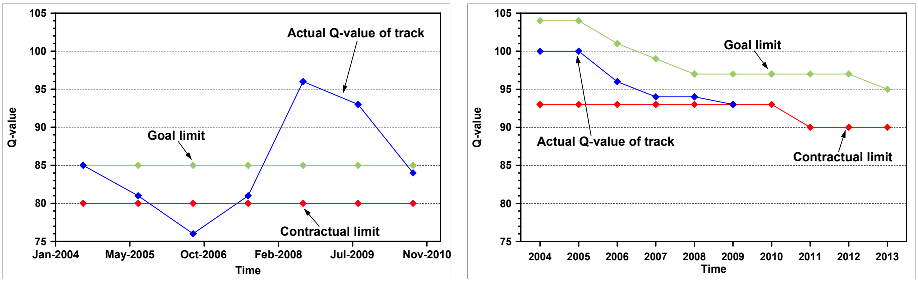


Figure 4.8 Efficiency of tamping in removing the root cause of failures in kilometre 1219

The contractor performance is evaluated in Paper I. Figure 4.9 (a and b) evaluates the contractor performance from 2004 to 2010 on the case study line (a) and a reference line in central Sweden (b). It is important to note that the contractor is the same for both lines, but the contracts are different.



a) The contractor's performance on the case study line.

b) The contractor's performance on a reference line in central Sweden.

Figure 4.9 Evaluation of the contractor's performance

The comparison of contractor's performance shows different maintenance policies. With the defined contractual and goal limits, the size of the associated penalties and bonuses will encourage the contractor either to be as close as possible to the lower contractual limit or to maintain a level above the goal limit. To interpret this, different factors such as maintenance budget, functional requirements stated in the contract, amount of bonus and penalties also mentioned in the contract, technical issues and maintenance decision criteria should be considered.

The study shows that although several condition indices have been defined to describe the condition of the track, at present, the decision to execute tamping is not based on all defined limits. The main triggering criteria in decision making for tamping execution are Q-value and C-fault. This study also reveals that there is no well-structured track degradation and LCC analysis that helps plan maintenance in the long term.

These findings answer research question two regarding the evaluation of the effectiveness of current track geometry maintenance strategy of Trafikverket.

Paper III discusses optimization of the track geometry inspection interval and aims to minimize the total ballast maintenance costs per unit traffic load. The proposed model considers inspection time and maintenance-planning horizon time after inspection and takes into account the costs associated with inspection and tamping, as well as possible accident costs due to poor track quality. The model is based on the assumptions that the track segments are identical and the maintenance effectiveness is perfect which means the track will be restored to as good as new state after maintenance execution. The model also assumes that based on the inspection data, corrective tamping is performed on a fixed ratio of the total track length while preventive tamping is executed at a fixed time interval (time-based maintenance). The time interval for preventive tamping execution is defined based on the infrastructure maintenance strategy.

Time-to-failure data collected from BIS and Optram databases have been inputted to calculate the probability of the distribution of failures. Since the exact times of failure occurrence cannot be determined, the failure time data were considered Interval Censored data. The optimal inspection interval was identified by considering probability distributions of C-faults and safety failures and cost factors. The best fitted probability distributions for B-fault, C-fault and safety failures occurrence were Weibull 2 parameter distributions. The values of the Weibull distribution parameters and the P-value of each distribution are shown in Table 4.1. As an example, the cumulative density function plot of C-faults appears in Figure 4.10.

Table 4.1 The characteristics of pdf of B-failures, C-failures and twist (3m and 6m)

Type of failures	Type of distribution	Values of distribution parameters		P-value
		Shape (β)	Scale (η)	
pdf of B-failures	Weibull 2parameters	1.606	31.99	0.968
pdf of C-failures	Weibull 2parameters	1.379	116.114	0.986
pdf of twist (3m and 6m)	Weibull 2parameters	1.857	329.771	0.971

Paper III shows that by expanding the inspection interval from every two months to every four months, the total maintenance cost per MGT will decrease but adequate track safety will be assured. The main reason is the slow degradation rate of the track, which results in the very low probability of occurrence of C-failures and safety failures (twist in this study) within a short time interval. The Weibull scale parameters (η) of C-failures and twist are 116.114 and 329.771 MGT respectively. η also known as characteristic life, means that 63.2 percent of the failures occur by the characteristic life point regardless of the value of shape parameter (β) (Dodson, 2006).

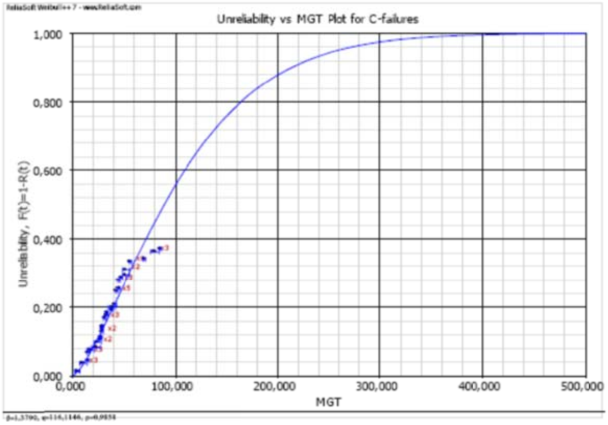


Figure 4.10 Cumulative density function plot of C-failures over MGT

The obtained result is based on some assumptions, which may not be completely valid. It is assumed that all track segments are identical regardless of geometrical characteristics, location (curve or tangent), substructure characteristics and construction time and maintenance history. However, as shown in Figure 4.1, even the degradation rates of the tangent segments vary significantly. To reduce the risk and assure the safety level, the sections with high degradation rates should be monitored and restored precisely. This means that more frequent inspections and preventive maintenance should be performed to control risk in segments with higher degradation rates.

In addition, the maintenance effectiveness was assumed to be perfect which is not true in reality. Nor has the so-called ballast memory, which results in sudden settling of ballast in a short interval after tamping, been considered in this model. As explained earlier, the probability distributions of failures used in the analysis were obtained based on the current maintenance strategy. Any change in maintenance strategy may result in different probability distributions of failures. Further study is required to analyze the effect of variation in probability distribution on the optimal inspection interval.

It should be considered that the outcome of this study is based on a model that consists of direct and quantitative cost parameters. Other indirect or qualitative cost parameters have not been included in the model, including cost due to loss of comfort or the cost effect for lower track quality due to the degradation rate of other components. Expanding the inspection interval will reduce the maintenance frequency, possibly resulting in lower comfort for passing trains. To ensure better comfort, inspection and maintenance actions should be more frequent. Low quality track may also affect the degradation rates of other parts such as wheelsets. By including the indirect and qualitative cost factors, more reliable results for specifying the most cost-effective inspection interval can be obtained.

These results answer research question three on specifying a cost-effective maintenance interval by using geometry condition data.

CONTRIBUTIONS AND FURTHER RESEARCH

Research Contributions

The research in this Licentiate thesis has focused on proposing an approach to convert condition-monitoring data into useful information for maintenance decision making for a railway infrastructure. The literature study shows that due to several factors such as different maintenance policy and strategy, regulations, and environmental and climate condition, dissimilar criteria for maintenance decision making are used by different infrastructure managers. It also finds that railway maintenance optimisation is still in its initial phase.

The research contributions can be summarized as follows:

- Evaluation the effect of track geometry degradation (Paper II)
- Evaluation the effect of climate on the failure occurrence (Paper II)
- Assessment of the efficiency of the current track geometry maintenance strategy (Paper I)
- Analysis of probability distribution of failure occurrence over time (MGT) (Paper III)
- Development of cost model to identify cost-effective inspection interval (Paper III)

Scope of Future Research

Based on the conducted research, the following areas are recommended for further research:

- The development of a Markov model for track geometry degradation which can be helpful in optimal maintenance planning;
- Comprehensive correlation analysis on the effect of substructure material type, geometry location, temperature, traffic, etc. on the degradation rate and probability of failure occurrence;
- The development of an approach to specify cost-effective maintenance thresholds for the maintenance strategy. Cost-effective maintenance thresholds obtained by applying RAMS and LCC methodologies can help infrastructure managers prolong the life length of the asset and reduce maintenance costs.

REFERENCES

Andersson, M. (2002). “Strategic Planning of Track Maintenance – State of the Art”, Research report, Division of Urban Studies, Department of Infrastructure, Royal Institute of Technology (KTH), ISSN: 165-0216.

Andrade, A. R. (2008). “Renewal decisions from a Life-cycle Cost Perspective in Railway Infrastructure: AN integrative approach using separate LCC models for rail and ballast components”, M.Sc thesis, Universidade Técnica de Lisboa, Portugal.

Ascher, H. and Feingold, H. (1984). “Repairable Systems Reliability: Modeling, Inference, Misconceptions and Their Causes”, Marcel Dekker Inc., New York, ISBN: 0-8247-7276-8.

Aursudkij, B. (2007). "A Laboratory Study of Railway Ballast Behaviour under Traffic Loading and Tamping Maintenance", University of Nottingham.

Banverket (2007). Goals. http://www.banverket.se/en-gb/Amnen/About-Banverket/Duties-and-organisation/Goals.aspx, 2007-11-03

Banverket. (2006), “Banverket annual report”, available at:http://www.banverket.se/pages/1493/BV_AR_06_WEBBx.pdf (accessed 10 September 2008).

Berggren, E. G., Li, M. X. D., Spännar, J. (2008). “A new approach to the analysis and presentation of vertical track geometry quality and rail roughness." Wear 265(9-10): 1488-1496.

Bing, A. J., Gross, A. (1983). “Development of railway track degradation models”, Transportation Research Record 939, 27-31.

BV. (2008). “Teknisk kravspecifikation – Periodisk Mätning”, Järnvägssystem / Tech. Department, Borlänge, Sweden.

BVF 587.02. (1997). “Spårlägeskontroll och Kvalitetsnormer Central Mätvagn STRIX”, CT, Borlänge, Sweden.

BVF 807.2. (2005). “Säkerhetsbesiktning av fasta anläggningar”, Banverket, Sweden.

Campbell, J. D. and Jardine, A. K. S. (2001), Maintenance Excellence – Optimizing Equipment Life-Cycle Decisions, MARCEL DEKKER, ISBN: 0-8247-0497-5

Carretero, J., Pe´rez, JM, Carci´a-Carballeira, F., Caldero´n, A., Ferna´ndez, J., Garci´a, JD, et al. (2003). “Applying RCM. In large scale systems: A case study with railway networks”, Reliability Engineering and System Safety.

Cui, L. (2008). "Handbook of Performability Engineering- Chapter 48: Maintenance Models and Optimizations", Springer, ISBN: 978-84800-130-5.

Dekker, R. (1996). “Applications of maintenance optimization models: a review and analysis”, Reliability Engineering and System Safety 51, 229-240.

Dodson, B. (2006). “The Weibull analysis handbook”, 2nd Edition, ASQ Quality Press, ISBN: 9780873896672, p.6

EN 13848-1 (2008), “Railway applications - Track-Track geometry quality- Part 1: Characterisation of track geometry”, Swedish Standard Institute.

EN 13848-2 (2006), “Railway applications - Track-Track geometry quality- Part 2: Measuring systems – Track recording vehicles”, Swedish Standard Institute.

EN 13848-5 (2008), “Railway applications - Track-Track geometry quality- Part 5: Geometric quality levels”, Swedish Standard Institute.

EN 50126 (1999), “Railway applications - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)”, Swedish Standard Institute.

Espling, U. (2007). "Maintenance strategy for a railway infrastructure in a regulated environment", Doctoral Thesis, Division of Operation and Maintenance, Luleå University of Technology, Luleå, Sweden.

Espling, U., Nissen, A., Larsson, D. (2007). “Underhållsgränser för fordon och bana”, JVTC – 196:2, Luleå University of Technology, Luleå, Sweden.

Esveld, C. (2001). "Modern railway track", MRT-Productions, ISBN: 90-800324-3-3.

Ethridge, D. E. (2004). “Research methodology in applied economics: organizing, planning, and conducting economic research”, Wiley-Blackwell, ISBN: 9780813829944.

Ferreira, L., Murray, M. (1997). “Modelling rail track deterioration and maintenance: Current practices and future needs”, Transport reviews, 17(3), 207-221.

Norman, G., Furbur, D. J., Flanagan, R. (1983). “Life cycle costing for construction”, RICS Books.

Granström, R. (2005). "Maintenance for improved punctuality : a study of condition monitoring technology for the Swedish railway sector", Licentiate Thesis, Division of Operation and Maintenance, Luleå University of Technology, Luleå, Sweden.

Granström, R. (2008). "Management of condition information from railway punctuality perspectives ", Doctoral Thesis, Division of Operation and Maintenance, Luleå University of Technology, Luleå, Sweden.

Gripner, S. (2006). “Datorbaserad spårlägesvärdering för optimerad spårriktning”, Chalmers University of Technology, Göteborg, Sweden.

Higgins, A. (1998). "Scheduling of Railway Track Maintenance and Crews." Journal of the Operational Research society, Vol.49, pp. 1026-1033.

IEC 60300-3-3 (2004). "Dependability Management: Part 3-3 Application guide – Life cycle costing", International Electro technical Commission, Second edition.

IMPROVERAIL (2003). "IMPROVEd tools for RAILway capacity and access management", Deliverable 10 Project Handbook, co-ordinated by TIS.PT.

Jovanovic, S. (2004). "Railway Track Quality Assessment and related Decision Making", IEEE International Conference on Systems, Man and Cybernetics. The Hague, Netherlands.

Kearsley, E. P., Vanas, S. C. (1993). "The effect of heavy haul traffic on traffic geometry deterioration", Fifth International Heavy Haul Railway Conference, Beijing.

Kumar, C. R. (2008). "Research Methodology". APH Publishing, New Delhi, India, ISBN: 9788131304228.

Li, M. X. D., Berggren, E. G. (2009). "Assessment of vertical track geometry quality based on simulations of dynamic track-vehicle interaction", Proceedings of the Institution of Mechanical Engineers; Part F; Journal of Rail and Rapid Transit 223(F2): 131.

Lichtberger, B. (2001). "Track maintenance strategies for ballasted track - a selection". Rail Engineering International, De Rooi Publications.

Lichtberger, B. (2005). "Track compendium: Formation, Permanent Way, Maintenance, Economics", Eurailpress, ISBN: 3-7771-0320-9., pp. 374

Liu, Y., Magel, E. (2009). "Performance-based track geometry and the track geometry interaction map", Proceedings of the Institution of Mechanical Engineers; Part F; Journal of Rail and Rapid Transit 223(F2): 111.

Lyngby, N., Hokstad, P., Vatn, J. (2008). "Handbook of Performability Engineering-Chapter 68: RAMS Management of Railway Track", Springer, ISBN: 978-84800-130-5.

Marczyc, G. R., et al. (2010). "Essentials of Research Design and Methodology", John Wiley and Sons, ISBN: 9780470893531.

McClave, S. (1990). "Probability and Statistics for Engineers", Third edition, PWS-KENT Publishing Company, Boston, USA, ISBN: 0-534-92184-1.

Nawabi, W. (2006). "Guide for LCC and RAMS Analysis", INNOTRACK (Innovative Track Systems), TIP5-CT-2006-031415.

ORE D161 (report no. 1). (1987). "General conditions for the evolution of track geometry based on historical information", Utrecht.

Patra, A. P. (2009). "Maintenance decision support models for railway infrastructure using RAMS & LCC analyses", Doctoral Thesis, Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden, ISBN: 9789174390230.

Pintelon, L., Puyvelde, F. V. (2006). "Maintenance Decision Making", Uitgeverij Acco, Belgium, ISBN: 90-334-6251-6, p. 19.

Profillidis, V. A. (2006). "Railway Management and Engineering", Ashgate Publishing Limited, Burlington, USA, ISBN: 0-7546-4854-0.

Resor, R. R., Patel, P. K. (2002). "Allocating Track Maintenance Costs on Shared Rail Facilities", Transportation Research Record: Journal of the Transportation Research Board, Vol. 1785.

Riessberger, K. (2001). "Extending Maintenance Cycles and Balasst Life". Proceeding of 7th International Heavy Haul Conference, Brisbane, Australia, pp. 193-197.

Rubin, A., Babbie, E. R. (2009). "Essential Research Methods for Social Work", Cengage Learning, ISBN: 9780495604372.

Sato, Y. (1997). "Optimum track structure considering track deterioration in ballasted track," in Proceedings Sixth International Heavy Haul Railway Conference, Cape Ton, South Africa.

Sadeghi, J., Askarinejad, H. (2007). "Influences of Track Structure, Geometry and Traffic Parameters on Railway Deterioration", International Journal of Engineering Transaction B: Application, Vol. 20, No.3.

Selig, E. T., Waters, J. M. (1994). "Track Geotechnology and Substructure Management", Thomas Telford Services Ltd., ISBN: 0 7277 2013 9.

Sherif, Y. S. and Smith, M. L. (1981). "Optimal maintenance models for systems subject to failure--a review", Nay. Res. Log. Quart. 28, 47-74.

UIC (International Union of Railways) (2008). "Best Practice Guide for Optimum Track Geometry Durability", Editions Techniques Ferroviaires.

Vale, C., Ribeiro, I., Calcada, R. (2010). "Application of a maintenance model for optimizing tamping on ballasted tracks: the influence of the model constraints", 2nd International Conference on Engineering Optimization, Lisbon, Porrtugal.

Veit, P. (2003). "Some thoughts concerning outsourcing of track maintenance", ProM@ain- Progress in Maintenance and Management of Railway Infrastructure.

White Paper. (2001), "European transport policy for 2010: time to decide", Office for Official Publications of the European Communities, Luxembourg, ISBN: 92-894-0341-1.

Yañez, M. et al. (2002), Generalized renewal process for analysis of repairable systems with limited failure experience, Journal of Reliability Engineering & System Safety, No. 77, 167-180.

Zhao, J., Joglar, F. and Modarres, M. (2006). "Optimizing Policies of Railway Ballast Tamping and Renewal", Transportation Research Record: Journal of the Transportation Research Board, No. 1943, pp. 50-56.

Zoeteman, A. (2001). “Life cycle cost analysis for managing rail infrastructure – Concept of a decision support system for railway design and maintenance”, European Journal of Transport and Infrastructure Research, pp. 391 – 413.

Websites:

Trafikverket website, Banportalen, http://www.trafikverket.se/Foretag/System-och-e-tjanster/System-och-verktyg/Transportera-och-trafikera/.

APPENDED PAPERS

PAPER I

Evaluation of track geometry maintenance (Tamping) in Swedish heavy haul railroad - A Case Study

Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2011). *Evaluation of track geometry maintenance (Tamping) in Swedish heavy haul railroad - A Case Study*. Accepted in International Heavy Haul Association Conference, 19-22 June, Calgary, Canada (Accepted)

Evaluation of track geometry maintenance (Tamping) in Swedish heavy haul railroad - A Case Study

I. Arasteh khouy[1], U. Juntti[1], A. Nissen[2], H. Schunnesson[1]

[1]*Luleå University of Technology, Luleå, Sweden,* [2]*Trafikverket, Luleå, Sweden*

Abstract

Track quality measurements and improvements is one of the prime issues in railroads in terms of planning time and related cost. Making decision concerning measurements interval and how to allocate limited resources for maintenance execution has an enormous influence on maintenance efficiency. Applying the efficient and optimal tamping strategy helps reduce maintenance costs, making operations more cost effective and leading to increased safety and passenger comfort. In this paper, track geometry data from the iron ore line (Malmbanan) in northern Sweden, which handles both passenger and freight trains, are used to calculate track quality degradation trend in a cold climate. The paper describes Trafikverket's (Swedish Transport Administration) tamping strategy and evaluates its effectiveness in measuring, reporting, and improving track quality. Finally, it discusses the lack of data accuracy and notes the various factors involved in maintenance decisions.

Index Terms: track geometry, maintenance, tamping

1. Introduction:

Today's railway industry handles more and faster trains and deals with higher axle loads, but this increased usage can result in faster degradation of railway assets and higher maintenance costs. To assure track safety and maintain high quality standards, we need to devise an optimized and cost-effective track maintenance strategy based on technical and/or safety limits that meet cost-effective maintenance thresholds.

Track geometry maintenance (tamping) is a maintenance action used to compact ballast and correct track geometry faults such as incorrect alignment (lateral deviation) or incorrect longitudinal level (vertical deviation). In Sweden, the annual tamping cost is about 100-120 MSEK, and the total amount of tamped track is approximately 1700 km, about 14% of the total track length [1].

Some researchers have developed empirical models of track geometry degradation with a view to better understanding the degradation [2, 3, 4, etc.]. Others have examined how different variables such as speed and axle load affect track deterioration [5, 6, 7, etc.]. However, a number of researchers claim that current standards and assessment methods may not be adequate for track maintenance, as these do not consider dynamic responses at the wheel-rail interface [8, 9, etc.].

In this paper, we describe the Swedish Transport Administration (Trafikverket) strategy for tamping, evaluate its efficiency and discuss about the quality and accuracy of data. To this end, we use track geometry data from a section of the iron ore line (Malmbanan) between Boden and Gällivare in northern Sweden. We find that time utilization in tamping is not very effective [1], with only about 25% of the available time being used for maintenance execution. The main reason for this low efficiency is limited access time to the track. This review reveals a need to optimize the track geometry maintenance strategy. Briefly stated, an estimation of track degradation and its consequences is required to optimize track maintenance [10]. With this knowledge, we can estimate the right time for inspection, maintenance and renewal.

2. Case study background:

On the "iron ore line", the Swedish mining company LKAB transports iron ore pellets from its mine in Kiruna to Narvik and from its mine in Vitåfors, near Malmberget, to Luleå. In 2000, LKAB increased the axle load on Malmbanan from 25 to 30 tonnes and the maximum speed of the loaded train from 50 to 60 km/h. This change is likely to result in higher track geometry degradation. In addition to iron ore transportation, the line is used by passenger trains and other freight trains. The train speeds vary from 50-60 km/h for loaded iron ore trains, to 60-70 km/h for unloaded ones and 80-135 km/h for passenger trains.

The annual passing tonnage on the track is about 13.8 MGT. The track consists of UIC 60 rails and concrete sleepers. The ballast type is M1 (Crushed Granite), and the track gauge is 1435 mm. The region is subject to harsh climate conditions: snow and extreme temperatures, ranging from -40˚C in winter to +25˚C in summer [11].

3. Track quality monitoring and maintenance:

To monitor track quality, Trafikverket regularly (every 1-2 months from April to October) uses an inspection car to measure the deviation of the track with an inertia measurement system and an optical system. An accelerometer measures the acceleration of the vehicle; based on the recorded accelerations, the vertical and lateral deviation of the track is calculated for consecutive 25-centimeter intervals.

Based on these 25-centimeter interval measurements, the standard deviation, σ_S, of the monitored cant error (C) and the average monitored lateral position error of the high rail (S_{High}) (see figure 1 and Eq. [1]) are calculated for 200-meter sections. The standard deviation of the average monitored vertical error for the left and right rail, σ_H, is also calculated for 200-meter sections.

$$\sigma_S = \sigma\left[C + S_{High}\right] \qquad \text{[Eq.1]}$$

The standard deviations for lateral and vertical errors (σ_S and σ_H) are calculated from short wavelength signals. Since the recorded signals from the measuring car are the combination of long and short wavelengths, filtering is required. This can be done by selecting only signals in the range of 1 to 25 meters.

Trafikverket uses several condition indices to describe the condition of the track, the most important of which are the Q-value and K-value. These are calculated based on the standard deviation of the vertical and lateral displacements, σ_H and σ_S, and the comfort limits that define the acceptable standard deviation of the longitudinal level for 200-meter track sections (see table 1).

The formula for calculating the Q-value is:

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H\,\mathrm{lim}}} + 2\frac{\sigma_S}{\sigma_{S\,\mathrm{lim}}}\right]/3 \qquad \text{[Eq.2]}$$

Where:

$\sigma_{S\ \mathrm{lim}}=$ The comfort limit for the σ_S value, defined for different track classes (see table 1).
$\sigma_{H\ \mathrm{lim}}=$ The comfort limit for the σ_H value, defined for different track classes (see table 1).

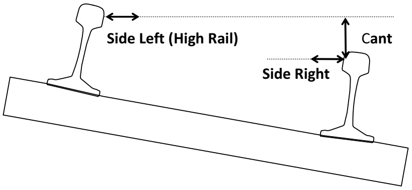


Figure 1: Calculation of σ_S

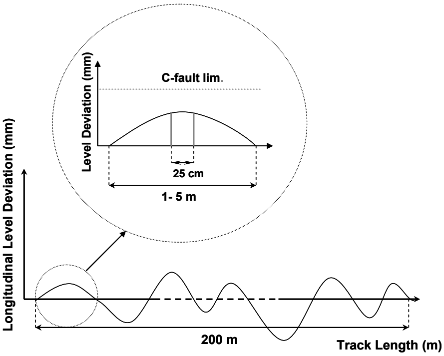


Figure 2: Illustration of C-fault limits

The other index, the K-value, is the ratio between (∑l), the total length of the track with standard deviations below the comfort limits, and the total length of track (L). This index is used to obtain an overall picture of the track condition over a long distance and is calculated by the equation:

$$K = \frac{\sum l}{L} \times 100\% \qquad \text{[Eq.3]}$$

In addition to the Q-value and the K-value, two fault limits are defined for 25-cm track sections, "B-faults" and "C-faults". C-faults, which are safety-related limits, identify the maximum allowable deviation from the design position (see figure 2), while B-faults identify the limits for the execution of preventive maintenance [12]. Although these limits are defined for "point failure" (25 cm), the fault normally occurs over a length of at least 1 to 5 meters due to rail stiffness.

The track of the iron ore line consists of two quality classes, K2 and K3, each with a different allowable speed, dissimilar fault thresholds and comfort limits for local trains (see table 1).

Table 1: comparison of the allowable limits between K2 and K3 [13]

Quality class	Maximum allowable speed for local trains	Comfort limits		B-fault limits	C-fault limits
		$\sigma_{H\ \mathrm{limit}}$ Standard deviation of vertical position	$\sigma_{S\ \mathrm{limit}}$ Standard deviation of the sum of vertical and lateral position	Maintenance Limit for vertical deviation for 25 cm interval (1-25m wavelength)	Maximum allowable vertical deviation for 25 cm interval (1-25m wavelength)
	Km/h	mm	mm	mm	mm
K2	105 - 120	1.5	1,9	7	12
K3	75 - 100	1.9	2,4	10	16

Trafikverket outsources the tamping of each line to different contractors, mostly using performance contracts. In this type of outsourcing, it is up to contractors to select appropriate methods and plan for the work. They are responsible for both regular measurements of track geometry and tamping, and they base their execution of tamping on the calculated Q-values and C-fault limits.

Tamping is executed as either preventive maintenance or corrective maintenance. Execution of tamping due to the C-fault is considered corrective maintenance; tamping due to the Q value is considered preventive maintenance. This means that if the Q value of the track section falls below the contractual limit and/or there is deviation in the track greater than the C-fault limits (safety limits), tamping should be performed. Tamping is obligatory (i.e., required by regulation) if the C-fault value exceeds the C-fault limit.

In the performance contracts, two limits are specified for the Q value, a goal limit and a contractual limit. If the actual Q value of the track is higher than the goal limit, contractors will receive a bonus, while if it is below the contractual limit, they must pay a penalty.

4. Methodology:

4.1. Data collection and data treatment

Track section 118, between Boden and Gällivare, was selected for the case study. To ensure comparable data, we considered tangent segments of 200 m from quality class K2 and left out other parts of the track, such as curves and stations.

The tamping information for the selected track section was extracted from two Trafikverket databases, BIS (track information system) and OPTRAM. BIS contains information on Trafikverket's infrastructure and facilities, agreements, the history of tamping (such as location of tamped section, length of tamping, date, etc.) and grinding and curves [14]. OPTRAM is a system implemented since 2007 by Trafikverket to show graphically the results of track position measurements. The system provides functionality for analysis and displays data trends [15]. To gain access to all information on tamping, however, it is essential to consider both systems [1].

In BIS, tamping information can be inaccurate, as corrective tamping is not always reported to the system by the contractors because it is not a contract requirement [1]. OPTRAM, which is based on inspection data, is more reliable; however, the data in this system have only been available since 2007. Therefore, a full overview of the long-term degradation of the track could not be obtained for this study.

The standard deviations for the longitudinal level before and after execution of tamping were selected from OPTRAM database, for the period 2007-2009. To evaluate the performed tamping efficiency, we used the tamping intervention graph developed by the Austrian railway (see reference [16]). Here, the tamping efficiency is classified as bad, good or excellent. In the original graph, the maximum value before tamping is 3 mm, and since some data in this case study are greater than 3 mm, the graph has been extended using trend regression analysis (see figure 5).

When the longitudinal level value goes beyond the Intervention Limit, corrective maintenance should be performed. This Intervention Limit (IL) can be defined either for isolated defects or for a 200-m track segment. Trafikverket only defines IL for isolated defects. When the studied data belong to 200-m track segments, the UIC riding comfort limits graph ("Lines of constant riding comfort at different speeds") is used to specify IL for the longitudinal level of 200-m track segments (figure 3) [16]. When the maximum allowable speed of quality class K2 (120 km/h), is considered, the IL equals 2.1 mm. When the maximum speed is considered, failure limit values become more conservative. In this way, all possible failures in the allowable speed range for each track class are considered.

To find the best fitted probability distribution function, we used STATGRAPHICS software. To obtain applicable results from our analysis, we only considered main distributions such as Weibull, normal/lognormal, exponential, etc., omitting other theoretical distributions.

We applied the Kolmogrov Smirnov "goodness of fit" test to measure the closeness of the fit. This test is used for continuous random variables and compares the empirical distribution function of a random sample with a hypothesized theoretical distribution function. The K-S test is based on the maximum vertical distance between the hypothesized and the empirical distribution function. If the K-S value is too large, the hypothesized distribution (null hypothesis) should be rejected [17].

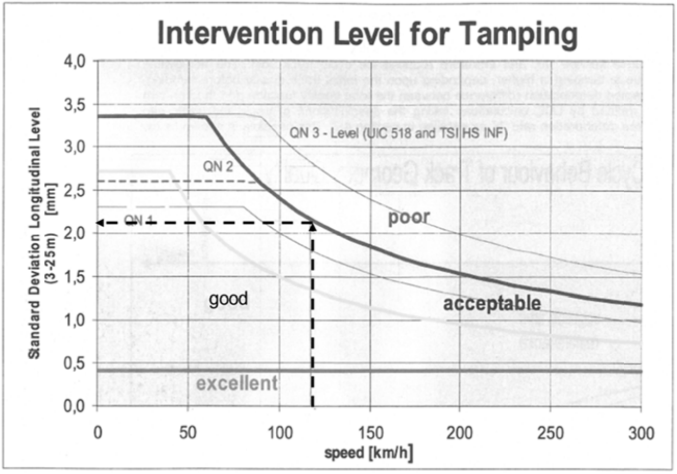


Figure 3: Lines of constant riding comfort at different speeds [16]

5. Results:

To provide an overview of the frequency of tamping, histogram of the standard deviations of longitudinal level before tamping is plotted in figure 4. The red line represent the limit defined by UIC for poor riding comfort at 120 km/h, the maximum allowable speed in the track quality class K2. Based on the data, we also determined the probability density function (pdf) (see figure 4). The probability density function of tamping execution in quality class K2 follows a lognormal distribution with a Kolmogorov Smirnov value of 0.051. As shown in the figure, the majority of tamping was executed around the defined failure limits (2.1 mm) which is classified as poor track condition in UIC. However, a substantial amount of tamping is done at a much higher value than is expected from a riding comfort point of view.

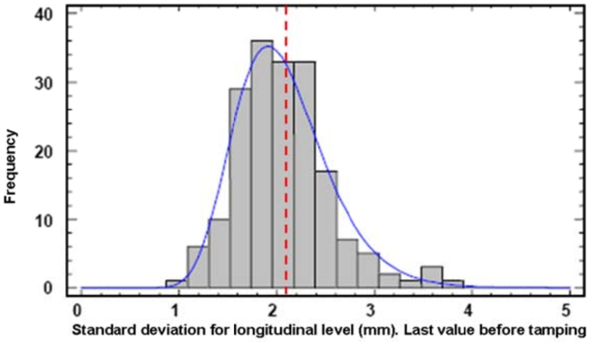


Figure 4: Probability density function of tamping execution at different level intervals

To evaluate tamping efficiency and to understand the reduction of longitudinal level deviations caused by tamping, we plotted all tamping points in the UIC "Tamping Intervention" graph; the result appears in figure 5. This evaluation shows that the tamping efficiency in the majority of the segments falls into the categories of either good or bad. However, a number of points are close to no registered tamping effect.

Figure 6 (a & b) evaluates the contractor performance from 2004 to 2010 on a case study line (a) and a reference line in central Sweden (b). It should be noted that the contractor is the same for both lines, but the contracts are different.

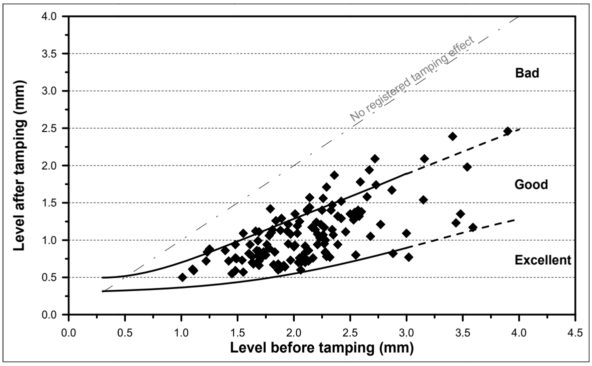
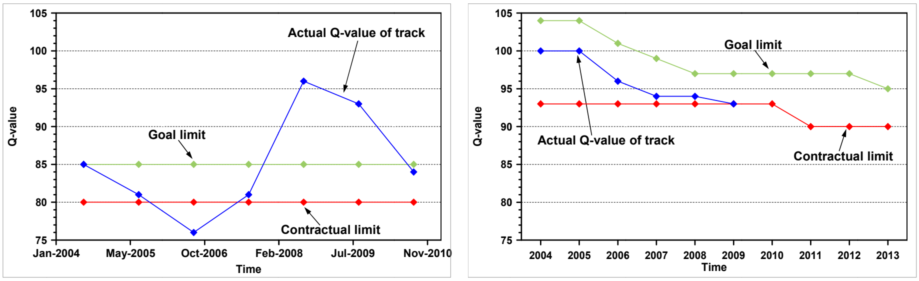


Figure 5: Efficiency of tamping



a) The contractor's performance on the "case study line".

b) The contractor's performance on a reference line in central Sweden.

Figure 6: Evaluation of the contractor's performance

6. Discussion:

The case study was designed to analyze the efficiency of track geometry maintenance in Trafikverket. While data were available from 2007 to 2009, for more precise evaluations, data for a longer period are required. Moreover, data should be reliable and accurate, and in this case, the contractor of the line had not reported all corrective tamping. To compensate for this, we used graphical inspection data and expert judgment.

The standard deviation for the longitudinal level at which tamping is executed varies extensively during the period examined (see figure 4). Tamping is sometimes executed at a very low level and is, therefore, not motivated by riding comfort. On other occasions, tamping has been conducted at levels exceeding the riding comfort limit; on still other occasions, tamping has not been executed until almost double the level of the riding comfort limit for standard deviation of the longitudinal level is reached. Although, tamping is not performed simply because of longitudinal level faults, this large variation indicates that its execution is not optimally planned.

The evaluation of tamping efficiency (figure 5) reveals that efficiency is quite low in some segments. Possibly, only parts of the segment are tamped, not the entire section, but to confirm this, we need more information. Alternatively, these particular segments could have bad sub-structure conditions. It should also be noted that the assessment of tamping efficiency is based on the Austrian railway results which, in turn, are based on different substructure conditions and a dissimilar maintenance strategy.

To explore the reasons for the high variability in tamping efficiency, we assessed the effects of a number of factors. The speed and axle load are the same for all track segments. To assess the effect of ballast age in tamping efficiency, we divided all sections into groups based on the ballast age. Then we evaluated the tamping efficiency of each group by plotting its data in tamping intervention graph, finding no clear effect from ballast age. A comparison of tamping efficiency between the ballast ages of 1987 and 1992 in class 2 appears in figure 7.

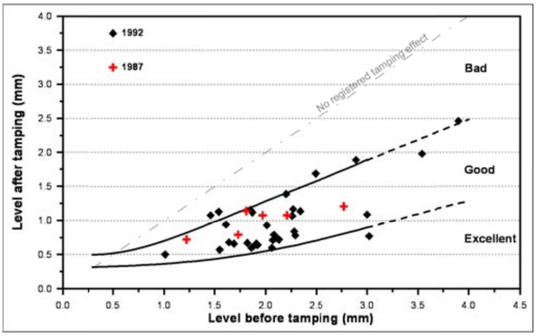


Figure 7: Comparison of ballast age in tamping efficiency

Tamping is carried out based on the Q index value and C-fault. Execution of tamping with no reliability and life cycle cost (LCC) analysis can be one possible reason for the lack of tamping efficiency. Reliability and LCC analysis can help to specify cost-effective maintenance limits, a main criterion for identifying optimal maintenance and inspection intervals. Assessment of the probability of failure occurrence over time can also help optimize maintenance planning and reduce maintenance cost.

The comparison of contractor's performance on two different lines (see figure 6) shows different maintenance policies. With the defined contractual and goal limits, the size of the associated penalties and bonuses will encourage the contractor either to be as close as possible to the lower contractual limit or to maintain a level above the goal limit. To interpret this, different factors such as maintenance budget, functional requirements stated in the contract, amount of bonus and penalties mentioned in the contract, technical issues, and maintenance decision criteria should be considered.

7. Conclusion:

The study concludes the following:

- Available and accurate data on geometry conditions and performed maintenance actions are the main requirements of track degradation analysis. However, the data available for this study are inadequate for precise degradation analysis;
- The decision-making process for the execution of tamping does not use all defined limits for geometry parameters;
- Evaluation of the standard deviation for the longitudinal level at which tamping is executed indicates that the execution of tamping is not optimally planned;
- Execution of tamping is highly dependent on the condition data and there is no well-structured track degradation analysis that helps to plan for maintenance in the long term;
- The structure of the contract, such as the maintenance budget, the defined goals and contractual limits, the size of the associated penalties and bonuses, can have a major effect on the efficiency of maintenance strategy.

References:

[1] Trafikverket document, Förstudie spårriktning, in Swedish, Borlänge, Sweden, 2009.

[2] A.J. Bing, A. Gross 1983. Development of railway track degradation models, Transportation Research Record 939 (1992) 27-31.

[3] Y. Sato, Optimum track structure considering track deterioration in ballasted track, Proceedings Sixth International Heavy Haul Railway Conference, Cape Town, 1997, pp. 576-590.

[4] p. Veit, M. Wogowitsch, Track Maintenance based on life-cycle cost calculations, Innovations for a cost effective Railway Track, ProM@ain- Progress in Maintenance and Management of Railway Infrastructure, 2002.

[5] J. Sadeghi, H. Askarinejad, An Investigation into the Effects of Track Structural Conditions on Railway Track Geometry Deviations, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 223 (4), (2009), 415-425.

[6] E.P. Kearsley, S.C. Vanas The effect of heavy haul traffic on traffic geometry deterioration, Proceedings Fifth International Heavy Haul Railway Conference, Beijing, 1993, pp. 369-378.

[7] D. Larsson, A study of the track degradation process related to changes in railway traffic, Licentiate thesis, Luleå University of Technology, 2004.

[8] Y. Liu, E. Magel, Performance-based track geometry and the track geometry interaction map, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 223 (2), (2009), pp. 111-119.

[9] D. Li, A. Meddah, K. Hass, S. Kalay, Relating track geometry to vehicle performance using neural network approach, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 220 (3), (2006), pp. 273-281.

[10] N. Lyngby, P. Hokstad, J. Vatn, RAMS Management of Railway Track, in: K.B. Misra, Handbook of Performability Engineering, Springer, London, 2008, pp. 1123-1145.

[11] S. Kumar, U. Espling, U. Kumar, A holistic procedure for rail maintenance in Sweden, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 222 (4) (2008) 331-344.

[12] U. Espling, A. Nissen, D. Larsson, Underhållsgränser för fordon och bana, in Swedish, JVTC, 2007.

[13] Trafikverket document, Spårlägeskontroll och kvalitetsnormer – Central mätvagn STRIX, in Swedish, Sweden, 1997.

[14] A. P. Patra, Maintenance decision support models for railway infrastructure using RAMS & LCC analyses, Doctoral Thesis, Luleå University of Technology, 2009.

[15] Trafikverket website, Banportalen, http://www.trafikverket.se, Access time: 2010-08-25.

[16] UIC (International Union of Railways), Best practice guide for optimum track geometry durability, 2008.

[17] S. McClave, Probability and Statistics for Engineers, Third edition, PWS-KENT Publishing Company, Boston, 1990.

PAPER II

Evaluation of track geometry degradation in Swedish heavy haul railroad - A Case Study

Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2011). *Evaluation of track geometry degradation in Swedish heavy haul railroad - A Case Study*. Accepted in COMADEM Special Issue in Railway.

Evaluation of track geometry degradation in Swedish heavy haul railroad - A Case Study

Iman Arasteh khouy[1], Håkan Schunnesson[1], Arne Nissen[2] and Ulla Juntti[1]
[1] Division of Operation & Maintenance Engineering
Luleå University of Technology, Sweden
[2] Trafikverket, Luleå, Sweden
Phone: +46 920 49 2071, E-Mail: iman.arastehkhouy@ltu.se

Mr. Iman Arasteh khouy obtained his M.Sc. in Maintenance Management and Engineering in 2008 from Luleå University of Technology (LTU) and Sharif University of Technology. He is currently a doctoral student at LTU in the area of operation and maintenance of railway infrastructure.

Håkan Schunnesson, PhD, has been working for a number of years for the Swedish mining equipment industry and as an independent consultant in the field of drill monitoring, exhaust purification, and vibration analysis for production control. In 2004, he joined Luleå University of Technology in the division of Operation and Maintenance Engineering as an associate professor. His main interests are mine automation, mining equipment monitoring, condition monitoring and maintenance of railway vehicles.

Dr. Arne Nissen did his PhD at the Division of Operation and Maintenance Engineering, Luleå University of Technology. His research deals with issues and question on performance of switches and crossings in railway systems. He is employed by Trafikverket at the Technical Support Unit, handling questions about track, superstructure, maintenance and reliability.

Dr. Ulla Juntti (ex Espling) did her PhD at the Division of Operation and Maintenance Engineering, Luleå University of Technology. Her research deals with maintenance strategies for railway infrastructure She is deputy director at Luleå Railway Research Center (JVTC) She has also background from Railway going back to 1984. Within the railway she has been working whit both traffic operation and planning, track engineer, design leader and as the head for a Track Area, giving her a broad experience from the Railway

Abstract

The measurement and improvement of track quality are key issues in determining both the time and cost of railway maintenance. Efficient track geometry maintenance ensures optimum allocation of limited maintenance resources and has an enormous effect on maintenance efficiency. Applying the appropriate tamping strategy also helps reduce maintenance costs, making operations more cost effective and leading to increased safety and passenger comfort. In this paper, track geometry data from the iron ore line in northern Sweden, which handles both passenger and freight trains, are used to calculate track quality degradation trend in a cold climate. The paper describes Trafikverket's (Swedish Transport Administration) tamping strategy and illustrates the distribution of safety failures in different seasons. It also analyses the track geometry degradation and discuss about the possible reasons for distribution of failures over a year and along the track.

Keywords: Track geometry degradation, Maintenance, Tamping

1 INTRODUCTION

Today's railway industry handles more and faster trains and deals with higher and higher axle loads. With increased usage comes the risk of faster degradation of railway assets, resulting in higher maintenance costs. However, the use of an optimized and cost-effective track maintenance strategy based on technical and/or safety limits that meet cost-effective maintenance thresholds will assure track safety and maintain high quality standards.

Track geometry maintenance (tamping) is a maintenance action used to compact ballast and correct track geometry faults, including incorrect alignment (lateral deviation) and incorrect longitudinal level (vertical deviation). In Sweden, annual tamping costs run in the neighbourhood of 11 to 13 M€, and the total amount of tamped track is approximately 1700 km, about 14% of the total track length [1].

To better understand track geometry degradation, some researchers have developed empirical models [2, 3, and 4]. The degradation model, which was developed by Bing & Gross (1983), predicts how the track quality, as measured by Track Quality Indices (TQls) changes as a function of causal parameters, such as traffic, track type and maintenance [2]. Sato (1997) proposed a degradation model that considers the super-structural aspect in which the degradation depends on tonnage, speed, types of rail connection (Jointed or continuously welded) and quality of the subgrade [3].
Others have examined how different variables such as speed and axle load affect track deterioration [5, 6, 7, etc.]. Still others claim that current standards and assessment methods may not be adequate for track maintenance, as they do not consider dynamic responses at the wheel-rail interface [8, 9, etc.].

Briefly stated, an estimation of track degradation and its consequences is required to optimize track maintenance [10]. With this knowledge, we can estimate the right time for inspection, maintenance and renewal.

This paper describes the Swedish Transport Administration (Trafikverket) strategy for tamping. It analyses track geometry degradation and discusses possible reasons for the distribution of failures along the track as well as distribution of failures over different months. For its case study, it draws on track geometry data from section 118 of the iron ore line (Malmbanan) between Boden and Gällivare in northern Sweden.

2 CASE STUDY BACKGROUND

On the selected track, the Swedish mining company LKAB transports iron ore pellets from its mine in Kiruna to Narvik and from its mine in Vitåfors, near Malmberget, to Luleå (see Figure 1). In 2000, LKAB increased the axle load on Malmbanan from 25 to 30 tonnes and the maximum speed of the loaded train from 50 to 60 km/h. These changes are likely to result in higher track geometry degradation. In addition to LKAB's transportation of iron ore, the line is used by passenger trains and other freight trains. Train speeds vary from 50-60 km/h for loaded iron ore trains, to 60-70 km/h for unloaded ones and 80-135 km/h for passenger trains.

The annual passing tonnage on the track between Boden and Gällivare is about 13.8 Million Gross Ton (MGT). The track consists of UIC 60 (UIC: International Union of Railways) rails and concrete sleepers. The ballast type is M1 (crushed granite), and the track gauge is 1435 mm. The region is subject to harsh climate conditions: winter snowfall and extreme temperatures, ranging from -40˚C in winter to +25˚C in summer [11].

Figure 1: Iron ore line from Luleå to Narvik [11]

3 Track quality monitoring and maintenance

To monitor track quality, infrastructure owner regularly (every 1-2 months from April to October) uses an inspection car to measure the deviation of the track with an inertia measurement system and an optical system. An accelerometer measures the acceleration of the vehicle; based on the recorded accelerations, the vertical and lateral deviation of the track is calculated for consecutive 25-centimetre intervals.

Based on these 25-centimetre interval measurements, the standard deviation, σ_S, of the monitored Cant error (C) and the average monitored lateral position error of the high rail (S_{High}) (see Figure 2 and Eq. [1]) are calculated for 200-metre sections. The standard deviation of the average monitored vertical error for the left and right rail, σ_H, is also calculated for 200-metre sections:

$$\sigma_S = \sigma_C + \sigma_{S_{\mathrm{High}}} \qquad \text{[Eq.1]}$$

The standard deviations for lateral and vertical errors (σ_S and σ_H) are calculated from short wavelength signals. Since the recorded signals from the measuring car combine long and short wavelengths, filtering is required. This can be done by selecting only signals in the range of 1 to 25 metres.

The infrastructure owner uses several condition indices to describe the condition of the track, the most important of which are the Q-value and the K-value. These are calculated based on the standard deviation of the vertical and lateral displacements, σ_H and σ_S, and the comfort limits that define the acceptable standard deviation of the longitudinal level for 200-metre track sections (see Table 1).

The formula for calculating the Q-value is

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H\lim}} + 2\frac{\sigma_S}{\sigma_{S\lim}}\right] /3 \qquad \text{[Eq.2]}$$

Where

$\sigma_{S\ \lim}$ = the comfort limit for the σ_S value, defined for different track classes (see Table 1); and

$\sigma_{H\ \lim}$ = the comfort limit for the σ_H value, defined for different track classes (see Table 1).

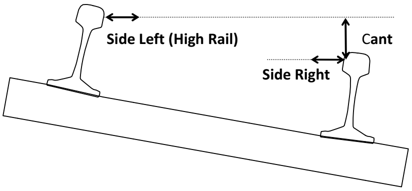


Figure 2: Calculation of σ_S

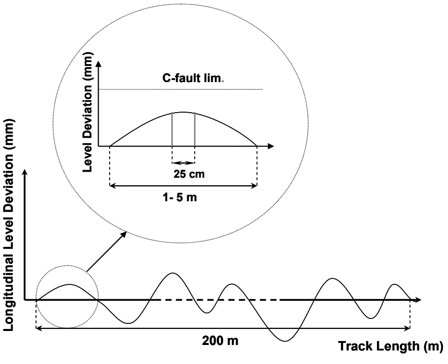


Figure 3: Illustration of C-fault limits

Table 1: Comparison of the allowable limits between K2 and K3 [13]

Quality class	Maximum allowable speed for local trains	Comfort limits		B-fault limits	C-fault limits
		$\sigma_{H\ limit}$ Standard deviation of vertical position	$\sigma_{S\ limit}$ Standard deviation of the sum of vertical and lateral position	Maintenance limit for vertical deviation for 25 cm interval (1-25m wavelength)	Maximum allowable vertical deviation for 25 cm interval (1-25m wavelength)
	km/h	mm	mm	mm	mm
K2	105 - 120	1.5	1.9	7	12
K3	75 - 100	1.9	2.4	10	16

The other index, the K-value, is the ratio of the total length of the track with deviations below comfort limits (∑l) and the total length of the track (L). This index is used to obtain an overall picture of the track condition over a long distance and is calculated by the equation

$$K = \frac{\sum l}{L} \times 100\% \qquad [Eq.3]$$

In addition to the Q-value and the K-value, two fault limits are defined for 25-cm track sections, “B-faults” and “C-faults”. C-faults, which are safety-related limits, identify the maximum allowable deviation from the design position (see Figure 3), while B-faults identify the limits for the execution of preventive maintenance [12]. Although these limits are defined for “point failures” (25 cm), since a failure is often caused by a movement in the substructure, it affects at least 1 metre of the track.

The iron or line’s track consists of two quality classes, K2 and K3, each with different allowable speeds; dissimilar fault thresholds and different comfort limits for local trains (see Table 1).

The infrastructure owner outsources the tamping of each line to different contractors, mostly using performance contracts with fixed budget. In this type of outsourcing, it is up to the contractors to select the most appropriate method. They are responsible for interpreting geometry measurements data, and tamping; they base their execution of tamping on their calculation of Q-values and detection of C-fault limits.

Since the end of 1990 the maintenance strategy changed from predetermined maintenance (time or tonnage based) to condition based maintenance. This means that tamping is performed due to the actual condition of track.

Tamping is done as either preventive or corrective maintenance. Execution of tamping due to the C-fault is considered corrective maintenance; tamping performed because of the Q value is preventive. This means that if the Q value of the track section falls below the contractual limit and/or there is a deviation in the track greater than the C-fault limits (safety limits), tamping is called for. Tamping is obligatory (i.e., regulation regulatory requirement) if the C-fault value exceeds the C-fault limit.

In the performance contracts, two limits are specified for the Q value, a goal limit and a contractual limit. If the actual Q value of the track is higher than the goal limit, contractors will receive a bonus; if it is below the contractual limit, they must pay a penalty.

4 Data collection and data treatment

To ensure comparable data for the selected track, we considered segments of 1000 m from both quality classes K2 and K3 and left out stations as well as other parts of the track after or before stations with lengths shorter than 1000 m.

The failure data for the selected track section were extracted from the inspection reporting system, STRIX. Inspection data reports have two levels. The first level indicates the Q value, the K value, the standard deviation of geometry parameters for each kilometre and different types of B and C failures detected in that segment. The second level contains more detailed information about C-failures such as type, location, size and length of failure. These critical failures which can cause derailment should be reported immediately to the operation control centre in order to restore them.

To collect data, two of Trafikverket's databases, BIS (Trafikverket asset register) and Optram were used. From BIS we obtained information about substructure characteristics; data on the geometry condition of segments were extracted from OPTRAM. BIS contains information on infrastructure and facilities, agreements, the history of tamping (such as location of tamped section, length of tamping, date, etc.) and grinding and curves [14]. OPTRAM is a system implemented since 2010 by the infrastructure owner to show graphically the results of track position measurements. While only the measurement data after 2007 are available in this database, the system provides functionality for analysis and displays data trends [15]. To gain access to all available information on tamping, it is essential to consider both systems [1].

5 Results and Discussion

To optimize maintenance planning, we should assess the distribution of the occurrence of C-failures over a year. Therefore, we created a histogram of the total number of C-failures occurring by month from 2004 to 2010 for the selected track section. To exemplify, Figure 4 illustrates the distribution of identified C-failures during the measurement season (summer) for two geometry parameters: longitudinal level and twist 3m. For the other geometry parameters, including cant, alignment and twist 6m, the trend is similar to the trend shown by twist 3m.

To interpret the variance of failure occurrence in different months, some factors such as climate and temperature, drainage and maintenance strategy should be considered. By the middle of May, the substructure temperature is usually above the freezing point; this causes the frost over the substructure to melt, resulting in reduced substructure stability. During June and July, the rate of geometry faults increases, as is clear from the quantity of detected twist 3m failures. One possible reason is the rising temperature. The soil is still frozen during the first measurement in April, but the rise in temperature starting in mid-May affects track geometry up to 30 cm below the sleepers. Frost heaves and drainage are two other possible reasons for the high rate of failure between April and July. Frost heave is a track displacement cause by the formation of pockets of ice within the upper surface of subgrade or within the ballast section [16]. Frozen water expansion by 9-10% in volume result in track surface distortion [16]. Since drainage reduce track stability and by considering that twist usually occurs in track segments with soft subsoil [17], the growth of detected twist faults during June and July can be explained.

The effect of frost heaves on failure occurrence rate is visible in April/May, while the effect of drainage is noticeable in June/July. Executing maintenance between April and October reduces the risk of such failures. Figure 5 shows the minimum, maximum and average temperature which has been observed in Gällivare on each month between 2004 and 2010.

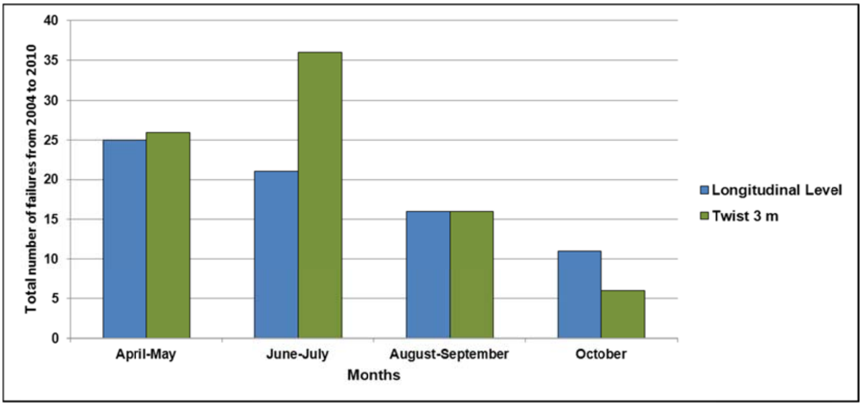


Figure 4: Number of detected C-failures on each inspection

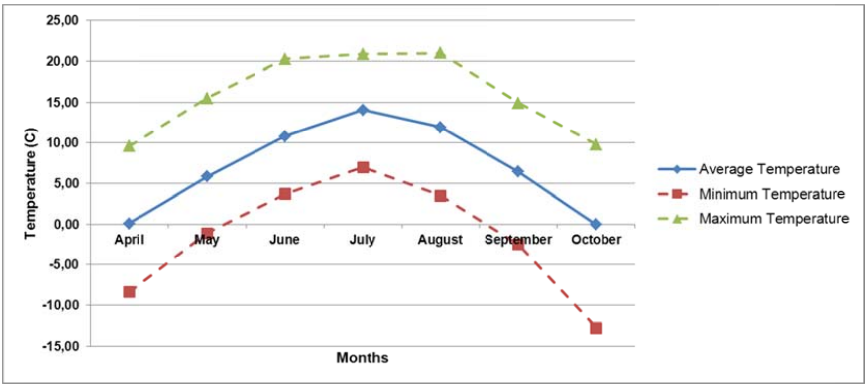


Figure 5: Temperature has been observed in Gällivare between 2004 and 2010

To evaluate the track geometry degradation and assess any aging irregularities for the geometry parameters, we calculated the cumulative number of C-failures. Figure 6 shows the cumulative number of C-failures for the longitudinal level and twist 3m. The longitudinal level failure rate has a clear linear trend over time (or MGT) during the period 2004-2010, while the C-failure for twist 3m increases over time, possibly indicating an aging effect. The rates of C-failure for cant, alignment and twist 6m show an aging trend similar to that shown by twist 3m. The curve trend indicates an aging effect, but the exact reason for this behaviour is not clear for the authors. Arguably, it could derive from a change in maintenance strategy when a new maintenance contract, struck in 2007, set out different maintenance objectives and dissimilar track requisites.

Another thing we note is that the contractor's response to longitudinal level faults is not the same as for other geometrical faults. Several detected longitudinal level faults were left without restoration action, while the contractor always performed corrective maintenance when twist was detected (either over 3 metre or 6 metre). This can be related to the dissimilar criticality of each parameter fault in terms of risk of derailment. If the size of twist 3m faults goes beyond 15 mm, the infrastructure owner should either reduce speed or close the track due to high risk of derailment. This safety limits for twist 6m faults and track gauge faults are 25 mm and 1470 mm respectively.

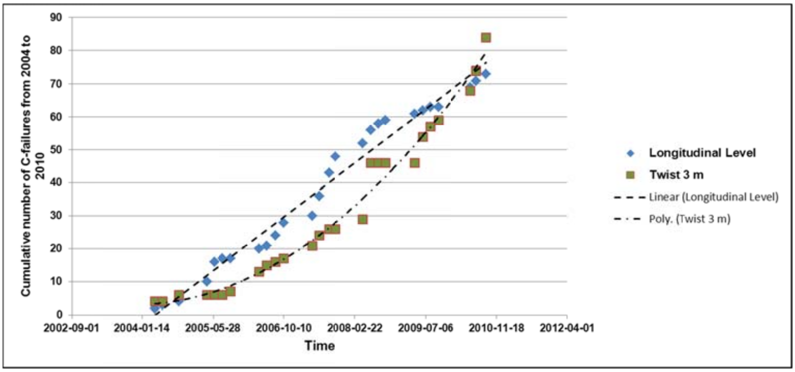


Figure 6: Cumulative number of C-failures from 2004 to 2010

To evaluate the entire section and identify problem sections with high probability of failure occurrence, we evaluated the distribution of longitudinal level failure occurrence in different track segments (see Figure 7). Factors such as substructure characteristics, geometrical locations and maintenance history can possibly influence the rate of failure occurrence in different parts of the track.

Unexpectedly, our evaluation of the failure occurrence locations over segments with the greatest number of failures revealed that faults took place repeatedly over a short length of track within the segments. As an example, Figure 8 shows the distribution of the occurrence of longitudinal level faults over kilometre 1219 of the track. In this case, four main un-restored failures (see Figure 7) were detected 39 times over only 45 m of a 1000 m track segment from 2004 to 2010. The figure also shows the frequency of performed tamping on the segment and indicates that tamping execution is not effective to remove the root cause of failures since the failures re-occurred repeatedly. Factors such as maintenance budget, contract budget or inadequate maintenance access time might be reasons for this kind of maintenance strategy. Removing the root cause of failures could be beneficial for the infrastructure owner by reducing maintenance costs and increasing track availability. In contrast, cutting the capital cost required for fixing the root cause of failures may result in large maintenance cost for years afterwards to compensate for the track substructure shortcomings. However, the LCC analysis should be conducted in order to select the cost effective maintenance strategy.

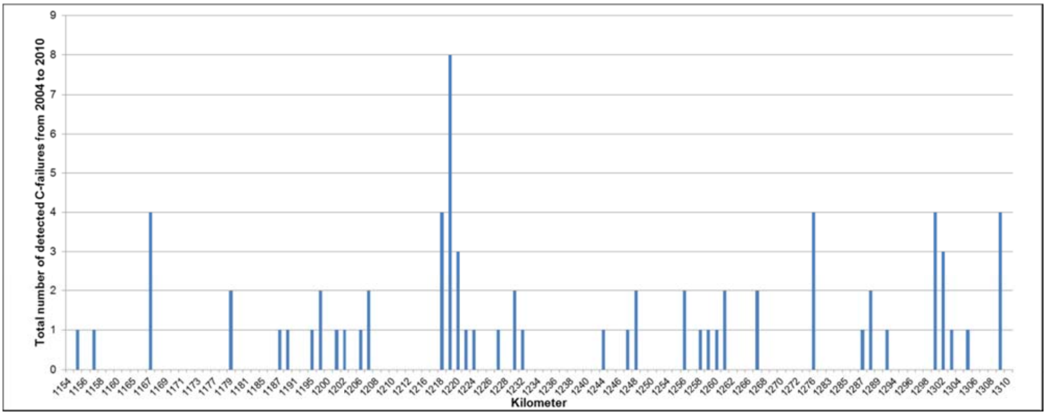


Figure 7: Total number of longitudinal level C-failures from 2004 to 2010

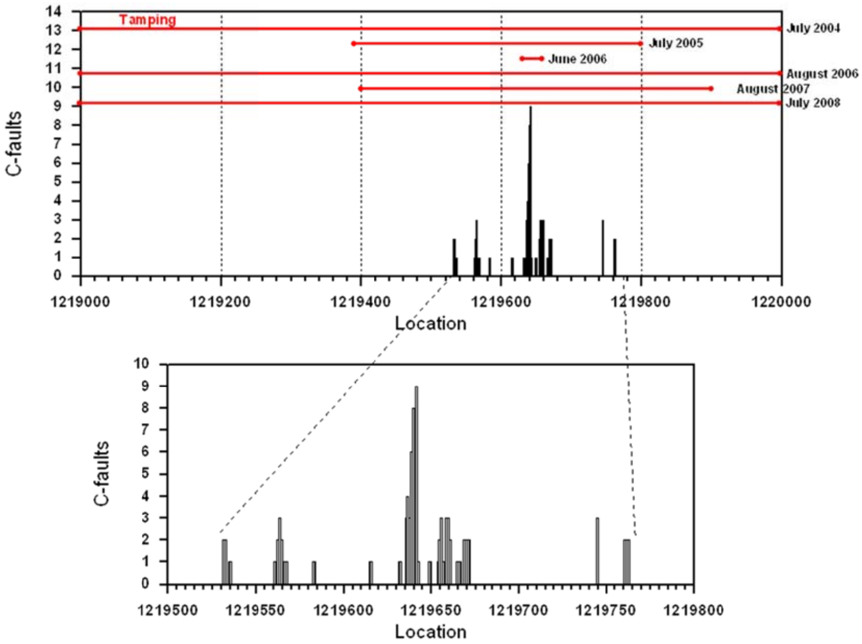


Figure 8: Locations of longitudinal level faults over kilometre 1219

6 Conclusion

The study concludes the following:

- The results show that seasonal climate and temperature has an effect on failure rate. However, to optimize maintenance planning, the effects of climate and temperature on failure rate should be evaluated accurately.
- The cumulative trend of failure occurrence over time is not similar for different geometry parameters. The analysis shows that the longitudinal level failure rate has a clear linear trend over time (or MGT) during the period 2004-2010, while the failure rate of the other geometrical parameters such as twist 3m increases over time, possibly indicating an aging effect.
- The result show that the failure occurrence rate different in segments is not uniform. The possible reasons can be different substructure characteristics, dissimilar geometrical locations and unlike maintenance history.
- The response of the contractor to detection of failure in different geometry parameters is not the same. For example, our analysis found that several detected longitudinal level faults were left without restoration, while the contractor always performed corrective maintenance when twist was detected (either over 3metres or 6 metres).
- The analysis reveals that in some segments tamping execution is not effective to remove the root cause of failures since the failures re-occurred repeatedly. Removing the root cause of integrated failures can be more beneficial for the infrastructure owner by reducing maintenance costs and increasing track availability.

References

[1] Trafikverket document, Förstudie spårriktning, in Swedish, Borlänge, Sweden, 2009.

[2] Bing, A. J. and Gross, A. 1983. Development of railway track degradation models, Transportation Research Record 939 (1992) 27-31.

[3] Sato, Y., Optimum track structure considering track deterioration in ballasted track, Proceedings Sixth International Heavy Haul Railway Conference, Cape Town, 1997, pp. 576-590.

[4] Veit, P. and Wogowitsch, M. Track Maintenance based on life-cycle cost calculations, Innovations for a cost effective Railway Track, ProM@ain-Progress in Maintenance and Management of Railway Infrastructure, 2002.

[5] Sadeghi, J. and Askarinejad, H. An Investigation into the Effects of Track Structural Conditions on Railway Track Geometry Deviations, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 223 (4), (2009), 415-425.

[6] Kearsley, E. P. and Vanas, S. C. The effect of heavy haul traffic on traffic geometry deterioration, Proceedings Fifth International Heavy Haul Railway Conference, Beijing, 1993, pp. 369-378.

[7] Larsson, D. A study of the track degradation process related to changes in railway traffic, Licentiate thesis, Luleå University of Technology, 2004.

[8] Liu, Y. and Magel, E. Performance-based track geometry and the track geometry interaction map, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 223 (2), (2009), pp. 111-119.

[9] Li, D., Meddah, A., Hass, K. and Kalay, S. Relating track geometry to vehicle performance using neural network approach, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Vol. 220 (3), (2006), pp. 273-281.

[10] Lyngby, N., Hokstad, P. and Vatn, J. RAMS Management of Railway Track, in: K.B. Misra, Handbook of Performability Engineering, Springer, London, 2008, pp. 1123-1145.

[11] Kumar, S., Espling, U. and Kumar, U. A holistic procedure for rail maintenance in Sweden, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 222 (4) (2008) 331-344.

[12] Espling, U., Nissen, A. and Larsson, D. Underhållsgränser för fordon och bana, in Swedish, JVTC, 2007.

[13] Trafikverket document, Spårlägeskontroll och kvalitetsnormer – Central mätvagn STRIX, in Swedish, Sweden, 1997.

[14] Patra, A. P. Maintenance decision support models for railway infrastructure using RAMS & LCC analyses, Doctoral Thesis, Luleå University of Technology, 2009.

[15] Trafikverket website, Banportalen, http://www.trafikverket.se, Access time: 2010-08-25.

[16] Hay, W.W. Railroad Engineering, John Wiley and Sons, ISBN: 0-471-36400-2, 1982, pp. 374

[17] Lichtberger, B. Track Compendium: Formation, Permanent Way, Maintenance, Economics, Eurailpress, ISBN: 3-7771-0320-9, pp. 274

PAPER III

Optimization of Track Geometry Inspection Interval

Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2011). *Optimization of Track Geometry Inspection Interval*. Submitted for publication in Journal of Rail and Rapid Transit.

Optimization of Track Geometry Inspection Interval

Iman Arasteh khouy, Ulla Juntti, Arne Nissen, Håkan Schunnesson

Division of Operation and Maintenance, Luleå University of Technology,
SE- 971 87 Luleå, Sweden
Iman.arastehkhouy@ltu.se

Abstract:

The measurement and improvement of track quality are key issues in determining the time and cost of railway maintenance. Efficient track maintenance ensures optimum allocation of limited maintenance resources and has an enormous effect on maintenance efficiency. Applying an appropriate tamping strategy helps reduce maintenance costs, making operations more cost effective and leading to increased safety and passenger comfort. This paper discusses optimization of the track geometry inspection interval with a view to minimizing the total ballast maintenance costs per unit traffic load. The proposed model considers inspection time, the maintenance-planning horizon time after inspection and takes into account the costs associated with inspection, tamping and risk of accident costs due to poor track quality. It draws on track geometry data from the iron ore line (Malmbanan) in northern Sweden, used by both passenger and freight trains, to find the probability distribution of failures.

Keywords: Track geometry degradation, Maintenance, Inspection interval, Optimization, Tamping.

1. Introduction

Today's railway industry handles more and faster trains and deals with higher and higher axle loads. With increased usage comes the risk of faster degradation of railway assets, resulting in higher maintenance costs. However, by shifting the criteria of maintenance strategy from meeting safety limits to discerning cost-effective maintenance thresholds through reliability and life cycle cost analyses, high quality track standards can be maintained.

The quality of the track geometry is highly dependent on ballast conditions. Today, railways frequently use ballasted track, incurring high annual expenses for ballast maintenance and renewal. Track geometry maintenance (tamping) is used to compact ballast and correct track geometry faults, including incorrect alignment (lateral deviation) and incorrect longitudinal level (vertical deviation). Planning of this maintenance is usually based on performance, and no economic analysis is involved [1]. In Sweden, annual tamping costs are in the neighbourhood of 11 to 13 M€, and the total tamped track is approximately 1700 km, about 14% of the total track length [2].

A number of railway research institutes and researchers have attempted to develop a track geometry deterioration model; these include the European Rail Research Institute (ERRI) in the Netherlands, Transportation Technology Center Inc. (TTCI) in the USA and Graz University of Technology (TU Graz) in Austria. Sato (1997) proposed a degradation model that considers the super-structural aspect in which the degradation depends on tonnage, speed, types of rail connection (jointed or continuously welded) and quality of the subgrade [3]. The model, developed by Bing & Gross (1983), predicts how the track quality, as measured by Track Quality Indices (TQls) changes as a function of causal parameters, such as traffic, track type and maintenance [4].

Vale et al. (2010) developed a model for scheduling tamping on ballasted tracks by considering the track degradation, the track layout, the dependency of track quality improvement on the quality of track at the time of maintenance operation and the track quality limits that depend on train speed [5]. Zhao et al. (2006) developed a life cycle model to optimize ballast tamping and renewal by incorporating a track deterioration model proposed by [6] and a tamping model [1]. They used three algorithms to obtain the optimal tamping and renewal strategy for fixed intervention levels, constant intervals of tamping and optimal non-constant intervals of tamping. Higgins (1998) proposed a model to determine the best allocation of maintenance activities and crews to minimize maintenance costs while keeping the track condition at an acceptable level [7].

In the optimization of track geometry inspection, more attention has been paid to optimizing the inspection procedure by correlating geometry irregularities to dynamic responses at the wheel-rail interface [8, 9]. However, little research has considered the optimization of track geometry inspection intervals. Using a genetic algorithm, Podofillini et al. (2005) developed a model to calculate the risks and costs associated with an inspection strategy to determine an optimal inspection strategy [10]. Specifying a cost-effective inspection interval can help railway infrastructures perform maintenance before geometry irregularities reach intervention limits, thus reducing maintenance expenditures.

This paper aims to minimize the total ballast maintenance costs per unit traffic load by identifying the optimal inspection interval for particular track geometry.

2. Studied Line Background

On the railway line from Narvik to Luleå, “the iron ore line,” the Swedish mining company LKAB transports iron ore pellets from its mine in Kiruna to Narvik and from its mine in Vitåfors, near Malmberget, to Luleå (see Figure 1). In 2000, LKAB increased the axle load on Malmbanan from 25 to 30 tonnes and the maximum speed of the loaded train from 50 to 60 km/h. These changes are likely to result in higher track geometry degradation. In addition to LKAB’s transportation of iron ore, the line is used by passenger trains and other freight trains. Train speeds vary from 50-60 km/h for loaded iron ore trains to 60-70 km/h for unloaded ones and 80-135 km/h for passenger trains.

On the selected track section, section 118 between Boden and Gällivare, the annual passing tonnage is about 13.8 MGT. The track consists of UIC 60 rails (UIC stands for International Union of Railways) and concrete sleepers. The ballast type is M1 (crushed granite), and the track gauge is 1435 mm. The region is subject to harsh climate conditions: winter snowfall and extreme temperatures, ranging from -40˚C in winter to +25˚C in summer [11].

Figure 1: Iron ore line from Luleå to Narvik [11]

3. Track Quality Monitoring and Maintenance

To monitor track quality, the infrastructure owner (Trafikverket) regularly (every 1-2 months from April to October) uses an inspection car (STRIX) to measure the deviation of the track with an inertia measurement system and an optical system. An accelerometer measures the acceleration of the vehicle; based on the recorded accelerations, the vertical and lateral deviation of the track is calculated for consecutive 25-centimetre intervals.

Based on these 25-centimetre interval measurements, the standard deviation, σ_S, of the monitored cant error (C) and the average monitored lateral position error of the high rail (S_{High}) (see Figure 2 and Eq. [1]) are calculated for 200-metre sections. The standard deviation of the average monitored vertical error for the left and right rail, σ_H, is also calculated for 200-metre sections:

$$\sigma_S = \sigma_C + \sigma_{S_{\mathrm{High}}} \qquad \text{[Eq.1]}$$

The standard deviations for lateral and vertical errors (σ_S and σ_H) are calculated from short wavelength signals. Since the recorded signals from the measuring car combine long and short wavelengths, filtering is required. This can be done by selecting only signals in the range of 1 to 25 metres.

Several condition indices are used to describe the condition of the track; the most important are the Q-value and the K-value. These are calculated based on the standard deviation of the vertical and lateral displacements, σ_H and σ_S, and the comfort limits that define the acceptable standard deviation of the longitudinal level for 200-metre track sections (see Table 1).

The formula for calculating the Q-value is

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H\,\mathrm{lim}}} + 2\frac{\sigma_S}{\sigma_{S\,\mathrm{lim}}}\right] /3 \qquad \text{[Eq.2]}$$

Where

$\sigma_{S\,\mathrm{lim}}$ = the comfort limit for the σ_S value, defined for different track classes (see Table 1); and

$\sigma_{H\,\mathrm{lim}}$ = the comfort limit for the σ_H value, defined for different track classes (see Table 1).

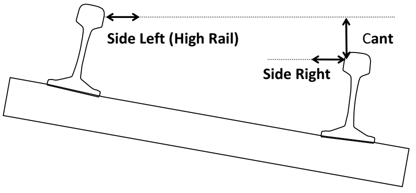


Figure 2: Calculation of σ_S

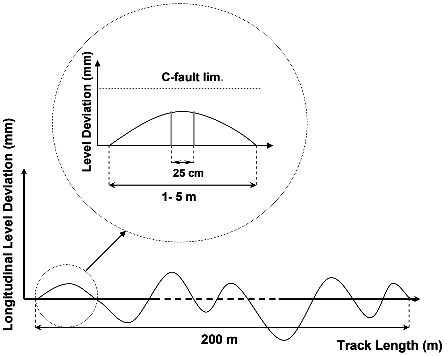


Figure 3: Illustration of C-fault limits

Table 1: Comparison of the allowable limits between K2 and K3 [12]

Quality class	Maximum allowable speed for local trains	Comfort limits		B-fault limits	C-fault limits
		$\sigma_{H\ limit}$ Standard deviation of vertical position	$\sigma_{S\ limit}$ Standard deviation of the sum of vertical and lateral position	Maintenance limit for vertical deviation for 25 cm interval (1-25m wavelength)	Maximum allowable vertical deviation for 25 cm interval (1-25m wavelength)
	km/h	mm	mm	mm	mm
K2	105 - 120	1.5	1.9	7	12
K3	75 - 100	1.9	2.4	10	16

The other index, the K-value, is the ratio of the total length of the track with deviations below comfort limits (∑l) and the total length of the track (L). This index is used to obtain an overall picture of the track condition over a long distance and is calculated by the equation

$$K = \frac{\sum l}{L} \times 100\% \qquad \text{[Eq.3]}$$

In addition to the Q-value and the K-value, two fault limits are defined for 25-cm track sections (isolated defects), "B-faults" and "C-faults". C-faults, which are safety-related limits, identify the maximum allowable deviation from the design position (see Figure 3), while B-faults identify the limits for the execution of preventive maintenance [13]. Although these limits are defined for "point failures" (25 cm), since a failure is often caused by a movement in the substructure, it affects at least 1 metre of the track.

The selected track consists of two quality classes, K2 and K3, each with different allowable speeds, dissimilar fault thresholds and varying comfort limits for local trains (see Table 1).

The infrastructure owner outsources the tamping of each line to different contractors, mostly using performance contracts with a fixed budget. In this type of outsourcing, it is up to the contractors to select the most appropriate method. They are responsible for interpreting geometry measurements data and executing tamping based on calculation of Q-values and detection of C-fault limits.

In 1990, the maintenance strategy changed from predetermined maintenance (time or tonnage based) to condition-based maintenance. This means that tamping is performed based on the actual condition of the track.

Tamping is done as either preventive or corrective maintenance. Execution of tamping due to the C-fault is considered corrective maintenance; tamping performed because of the Q value is preventive. This means that if the Q value of the track section falls below the contractual limit and/or there is a deviation in the track greater than the C-fault limits (safety limits), tamping is called for. Tamping is obligatory (i.e., regulation regulatory requirement) if the C-fault value exceeds the C-fault limit.

In the performance contracts, two limits are specified for the Q value, a goal limit and a contractual limit. If the actual Q value of the track is higher than the goal limit, contractors will receive a bonus; if it is below the contractual limit, they must pay a penalty.

4. Data Collection and Data Treatment

To ensure comparable data from the selected track section, segments of 1000 m from both quality classes K2 and K3 were selected. Stations and other parts of the track before or after stations with lengths shorter than 1000 m where left out.

The failure data for the selected track section were extracted from the inspection reporting system, STRIX. Inspection data reports have two levels. The first level indicates the Q value, the K value, the standard deviation of geometry parameters for each kilometre and different types of B and C failures detected in that segment. The second level contains more detailed information about C-failures such as type, location, size and length of failure. These critical failures, which can cause derailment, are reported immediately to the operation control centre so that the track can be restored.

The study uses two of Trafikverket’s databases: Ban InformationsSystem (BIS) (Trafikverket asset register) and Optram. Information about substructure characteristics was obtained from BIS, and data for the geometry condition of segments were extracted from OPTRAM. BIS contains information on infrastructure and facilities, agreements, the history of tamping (such as location of tamped section, length of tamping, date, etc.) and grinding and curves [14]. OPTRAM is a system implemented in 2010 to graphically show the results of track position measurements. Only measurement data after 2007 are available in this database. The system also provides functionality for analysis and displays data trends [15]. To gain access to all available information on tamping, it is essential to consider both systems [2].

The collected data from these databases were used to find the probability distributions of failures. To find the best fitted probability distribution function, the study used the software Weibull++7. To obtain applicable results from the analysis, only main distributions such as Weibull, normal/lognormal, exponential, etc. were considered; other theoretical distributions were omitted.

Since the exact times of failure occurrence have not been determined, the failure time data were considered as interval censored data, which come from situations where the object of interest is not constantly monitored.

The P-value approach was used to measure the closeness of the fit. The P-value can be defined as the smallest level of significance that would lead to rejection of the null hypothesis (H_0) [16]. A small P-value means that H_0 is incorrect; a large P-value means that H_0 cannot be rejected. The null hypothesis, here, is the considered probability distribution function for failure occurrence.

5. Track Geometry degradation

Track geometry degradation is a complex phenomenon occurring under the influence of dynamic loads and is normally calculated as a function of traffic in mm/MGT, or of time in mm/year [17]. For a track section with similar traffic, the rate of degradation also varies depending on construction and differences in substructure. Figure 4 shows the variability of longitudinal level degradation rate in different tangent segments of the studied track for the time interval 2007-2009. The figure clearly shows the high variability of degradation rates for the track with the majority of the section having low rate of degradation that can be controlled by tamping at infrequent intervals. However, the tail of the distribution consists of sections with very high degradation rates that need to be accurately monitored and restored with corrective tamping to reduce risks. The balance between preventive and corrective tamping must be based on an appropriate cost analysis, as suggested in this paper.

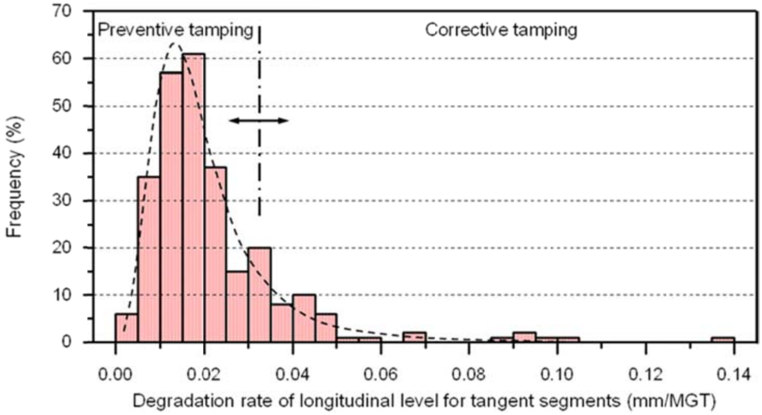


Figure 4: Histogram of longitudinal level degradation rates in tangent segments between 2007 and 2009

The data of B-failures and C-failures of longitudinal level between 2004 and 2010 have been collected to find the probability of failure occurrence over time. The probability density functions (pdf) of B-failures and C-failures are used to indicate the probability that preventive tamping and corrective tamping are required at a specified time.

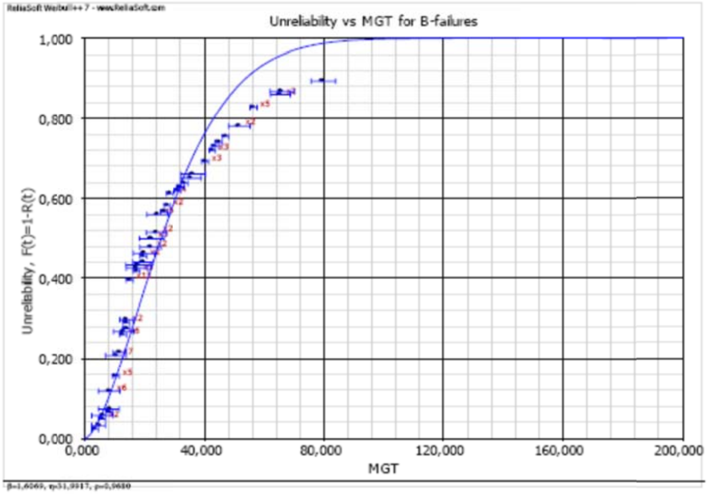
Since the occurrence of twist 3m fault greater than 15 mm and twist 6m fault greater than 25 mm are critical in terms of risk of derailment, the data of occurrence of these failures between 2004 and 2010 have been used to find the probability density function (pdf) of their occurrences. This probability function is used to find the probability of accident at a specified interval.

The types of distribution of B-failure, C-failure and twist (3m and 6m), values of the distribution parameters and the P-value of each distribution are shown in Table2.

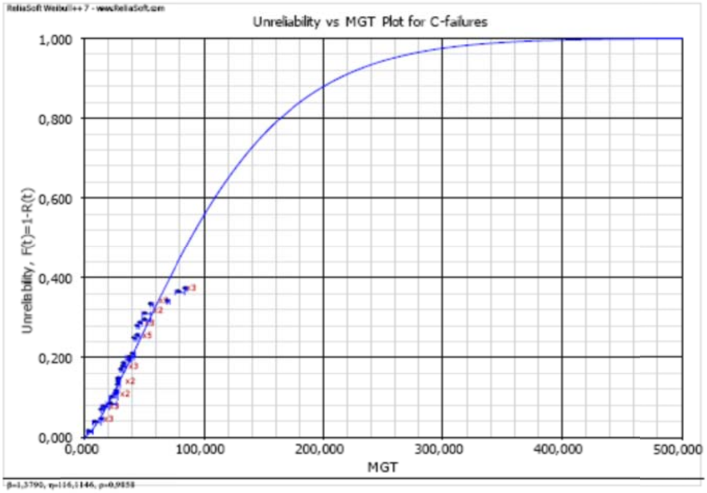
Table 2: The characteristics of pdf of B-failures, C-failures and twist (3m and 6m)

Type of failures	Type of distribution	Values of distribution parameters		P-value
		Shape (β)	Scale (η)	
pdf of B-failures	Weibull 2parameters	1.606	31.99	0.968
pdf of C-failures	Weibull 2parameters	1.379	116.114	0.986
pdf of twist (3m and 6m)	Weibull 2parameters	1.857	329.771	0.971

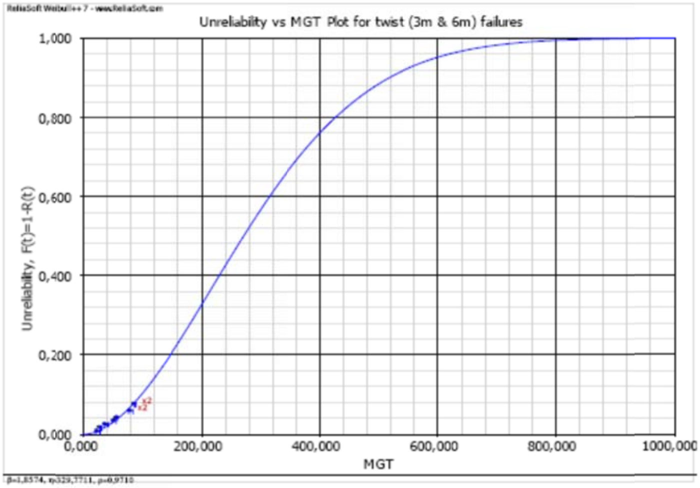
The cumulative density functions (cdf) of B-failure, C-failures and twist (3m and 6m) are shown in Figures 5-a, 5-b and 5-c respectively.



a: cdf (cdf) of B-failures versus MGT



b: cdf of C-failures versus MGT



c: cdf of twist (3m & 6m) failures versus MGT

Figure5: Cumulative density function (cdf) versus MGT

6. Proposed inspection model

Figure 6 contains a schematic description of the maintenance events.

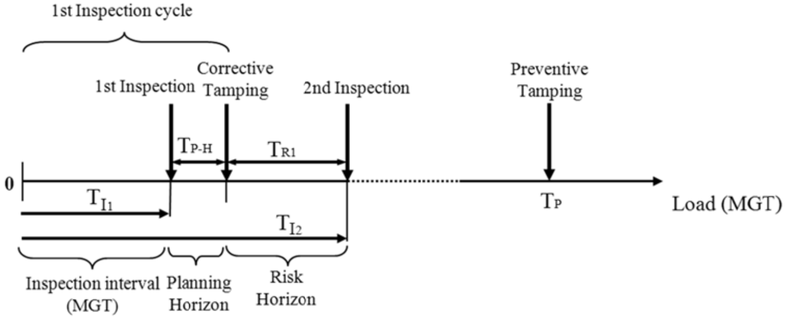


Figure 6: Schematic model of inspection cycles

Where:

T_{I1}: is the operational interval for the first inspection.
T_{I2}: is the operational interval for the second inspection.
$T_{P\text{-}H}$: is the maintenance planning horizon time interval during which the track can be operated until deferred maintenance takes place.
T_{R1}: is the risk horizon time. This means that in the time interval between maintenance execution and the next inspection, there is a risk of a safety failure occurrence that can cause derailment.
T_P: is the time for the execution of preventive tamping.

In the model, it is assumed that based on the inspection data, corrective tamping is performed on a fixed ratio of the total track length, while preventive tamping is executed at fixed time intervals (time based maintenance). The time interval for preventive tamping execution is defined based on the infrastructure maintenance strategy. Therefore, the frequency of corrective tamping depends on the frequency of inspections. The aim is to identify the optimal maintenance inspection interval (T) and frequency (K) that will minimize the total cost per unit of traffic load (MGT). In other words, an inspection should be performed only when its cost is offset by a resulting reduction in expected future cost.

The other assumptions of the proposed model are:

- The execution of inspection and maintenance has no effect on the availability and capacity of the line. Therefore, the cost of unavailability of the line due to inspection or maintenance execution is not considered.
- The whole track is considered as system consisting of identical segments.
- The maintenance effectiveness is perfect, which means that the condition of the track after maintenance will be restored to as good as new.
- The probability of failure occurrence at the planning horizon interval is considered zero.
- The ratio of total length of the track that should be tamped correctively after each inspection is constant and is independent of the frequency of tamping.
- Any change in maintenance strategy has no effect on the probability of failure occurrence, and the probability of failure occurrence is the same for all inspection strategies.

The following cost parameters are considered for cost modelling:

1. Inspection cost: The inspection cost (C_i) is a deterministic value and is constant in consecutive inspection cycles.
2. Corrective tamping cost: This can be calculated by multiplying the cost of corrective tamping ($C_{C.T}$), the probability of C-failure occurrence at the specified time interval ($P_C(T_I)$) and the ratio of total length of track section (A) that needs corrective tamping. However, since corrective tamping is performed on only part of the track, just that portion will be restored to as good as new; the rest will be as bad as old. Therefore, the probability of failure detection during each inspection should be subtracted from probability of failure in the previous inspection when a part of the track was restored to as good as new by corrective tamping. Hence, $A\ C_{C.T}\ [P_C(T_{I\ i}) - P_C(T_{I\ i\text{-}1})]$.
3. Preventive tamping cost: This is the cost of preventive tamping ($C_{P.T}$) which is executed at a fixed time interval.
4. Risk of accident cost: This cost can be estimated by multiplying the cost of derailment ($C_{Acc.}$) by the probability of safety failure occurrence that can cause derailment in the interval between maintenance execution and the next inspection ($P_{S.F}(T_R)$). Hence, $C_{Acc.}\ P_{S.F}(T_R)$.

Since it is assumed that the entire track will be restored to as good as new after preventive maintenance, the cost model should be defined for the interval between two consecutive executions of preventive tamping. Consequently, the cost model for the "K" series of inspection cycles can be expressed as:

$$Total\ Cost = \frac{\sum_{i=1}^{k} C_I + \sum_{i=1}^{k} A\ C_{C.T}\left[P_C\left(T_{I_i}\right) - P_C\left(T_{I_{i-1}}\right)\right] + \sum_{i=1}^{k} C_{Acc.} P_{S.F}\left(T_{R_i}\right) + C_{P.T}}{T_P}$$

[Eq.5]

7. Application of the model on the studied line

As mentioned, the studied line is usually inspected every two months. However, according to regulations, this inspection interval can be expanded to every four months. By applying the proposed model, three scenarios of inspections – every two months, every three months and every four months – are compared to find the optimal alternative with the lowest total maintenance cost.

The costs of inspection, preventive tamping and corrective tamping per kilometer were collected from Trafikverket experts. The cost of accidents was adopted from Podofillini's study on the optimization of railway track inspection and maintenance procedures [10]. The costs used in the model are shown in Table 3.

Table 3: The considered costs in the model

Type	Cost (SEK)
Inspection per kilometer	1200
Preventive tamping per kilometer	20000
Corrective tamping per kilometer	50000
Accident	15000000
1€ ≈ 9 SEK	

The study assumes that preventive tamping is performed every two years on the entire line and based on this assumption has analyzed total maintenance costs for the three scenarios mentioned above. It should be noted that the contractor of the line performs corrective tamping within one to two weeks after each inspection. During winter (November to March) no inspection or maintenance actions take place. In April, the temperature rises; the melting snow results in a change in track stability. Therefore, the first inspection every year is performed in April.

To illustrate the method of calculation, the schematic model of the third scenario (inspection every four months) is shown in Figure 7.

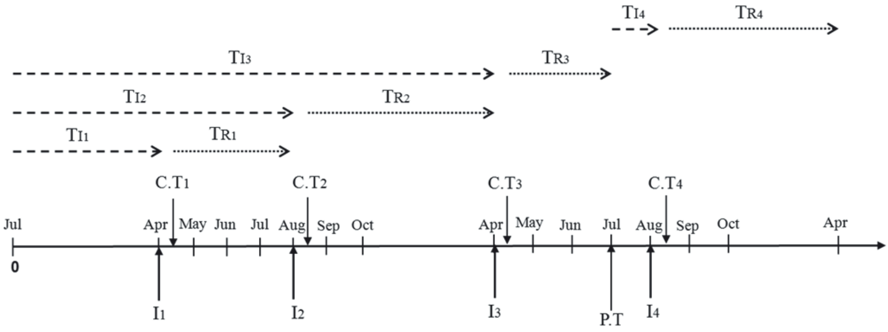


Figure 7: Schematic illustration of third scenario (inspection every four months)

As it is assumed that state of the entire track will be restored to as good as new after preventive maintenance, the time (T) starts from zero again, as shown in the figure. In this study, the operational load (MGT) is considered as time.

The total maintenance cost per MGT for each scenario appears in Figure 8. As can be seen, the third scenario (inspection every four months) is the optimal alternative in terms of lowest maintenance cost.

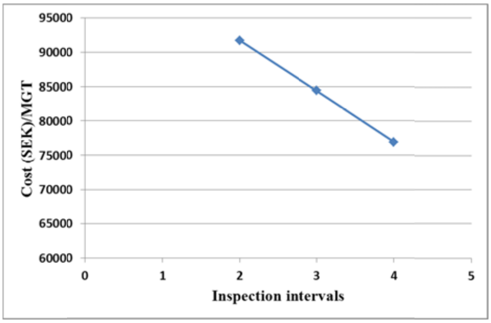


Figure 8: Comparison of maintenance cost per MGT for different inspection intervals

8. Discussion

The results show that by expanding the inspection interval from every two months to every four months, the total maintenance cost per MGT will decrease, while track safety is preserved. The slow degradation rate in majority segments of the track results in the very low probability of the occurrence of C-failures and safety failures (twist in this study) within short time intervals. The probability distribution of occurrence of both types of failures is Weibull 2 parameters. The Weibull scale parameters (η) of C-failures and twist are 116.114 and 329.771 MGT respectively. η is also known as characteristic life; this means that 63.2 percent of the failures occur by the characteristic life point, regardless of the value of shape parameter (β) [18]. This means that 63.2 percent of C-faults and twist failures occur at around 116 and 329 MGT load cycles respectively.

The obtained results are based on certain assumptions, which may not be valid. For example, it is assumed that all track segments are identical regardless of geometrical characteristics, location (curve or tangent), substructure characteristics and construction time and maintenance history. However, as shown in Figure 4, the degradation rates of the tangent segments vary significantly. To reduce the risk and assure the safety level, the sections with high degradation rates should be carefully monitored and restored. In other words, more frequent inspections and preventive maintenance should be performed in segments with higher degradation rates.

The maintenance effectiveness is also assumed to be perfect. But when the tamping intervention graph developed by the Austrian railway [19] was used to evaluate the efficiency of tamping on 200-meter tangent segments, results showed high variability of efficiency in different segments (see Figure 9).

Nor has “track memory” which results in sudden settling of the ballast in a short interval after tamping execution been considered in this model. As explained earlier, the probability distributions of failures used in the analysis were obtained based on the current maintenance strategy. Any change in maintenance strategy may result in different probability distributions of failures. Further study is required to analyze the effect of variation in probability distribution on the optimal inspection interval.

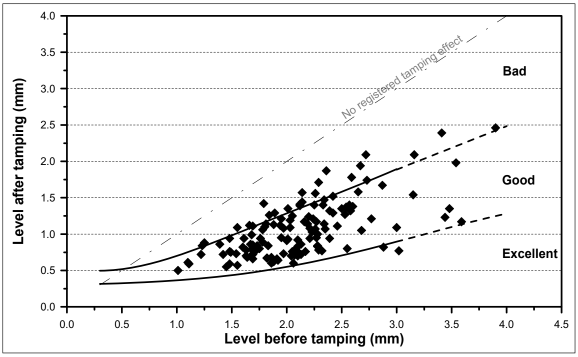


Figure 9: Efficiency of tamping on 200m tangent segments

The outcome of this study is based on a model that consists of direct and quantitative cost parameters. Indirect or qualitative cost parameters have not been included in the model; these include costs incurred by loss of comfort or the cost effect of lower track quality on the degradation rate of the other components. This means that Expansion of the inspection interval and reducing the maintenance frequency might result in less comfort; to provide more comfort, inspection and maintenance should be performed more frequently. Likewise, low quality track may affect the degradation rates of other parts such as wheelsets. By including the indirect and qualitative cost factors, a more reliable specification of the most cost-effective inspection interval can be obtained.

9. Conclusion

The study concludes the following:

- In the current maintenance strategy, the probability of failure occurrence in short time intervals is quite low since the majority segments of the track have slow degradation rates.
- Degradation rates and the efficiency of tamping on different tangent segments of the track vary considerably.
- To reduce risk and assure the safety level, track sections with high degradation rates should be monitored and restored more frequently; this requires shorter inspection intervals.
- To obtain more comprehensive results, indirect and qualitative cost parameters such as loss of comfort and the effect of lower track quality on the degradation of other components should be included in the model.

References

1 Zhao, J., Joglar, F., and Modarres, M., Optimizing Policies of Railway Ballast Tamping and Renewal. Transportation Research Record: Journal of the Transportation Research Board 2006, 1943, 50-56.
2 Trafikverket document, Förstudie spårriktning, in Swedish, Borlänge, Sweden, 2009.
3 Sato, Y. Optimum track structure considering track deterioration in ballasted track. In Proc. Sixth International Heavy Haul Railway Conference, Cape Ton, South Africa, 6-10 April 1997, pp. 576-590.
4 Bing, A. J., and Gross, A., Development of railway track degradation models, Transportation Research Record: Journal of the Transportation Research Board 1983, 939, 27-31.
5 Vale, C., Ribeiro, I., and Calcada, R. Application of a maintenance model for optimizing tamping on ballasted tracks: the influence of the model constraints. In 2nd International Conference on Engineering Optimization, Lisbon, Porrtugal, 6-9 September 2010.
6 Riessberger, K. Extending Maintenance Cycles and Balasst Life. In Proc. of 7th International Heavy Haul Conference, Brisbane, Australia, 10 - 14 June 2001, pp. 193-197.
7 Higgins, A., Scheduling of Railway Track Maintenance and Crews, Journal of the Operational Research society 1998, 49, pp. 1026-1033.
8 Liu, Y., and Magel, E., Performance-based track geometry and the track geometry interaction map, Proc. of the IMechE, Part F: J. Rail and Rapid Transit 2009, 223(F2): 111.
9 Li, M. X. D., and Berggren, E. G., Assessment of vertical track geometry quality based on simulations of dynamic track-vehicle interaction, Proc. of the IMechE, Part F: J. Rail and Rapid Transit 2009, 223(F2): 131.
10 Podofillini, L., Zio, E., and Vatn, J., Risk-informed optimisation of railway tracks inspection and maintenance procedures, Journal of Reliability Engineering and System Safety 2006, 91, 20–35.
11 Kumar, S., Espling, U., and Kumar, U., A holistic procedure for rail maintenance in Sweden, Proc. of the IMechE, Part F: J. Rail and Rapid Transit 2008, 222 (4), 331-344.
12 Trafikverket document, Spårlägeskontroll och kvalitetsnormer – Central mätvagn STRIX, in Swedish, Sweden, 1997.
13 Espling, U., Nissen, A., and Larsson, D., Underhållsgränser för fordon och bana, in Swedish, JVTC, 2007.
14 Patra, A. P., Maintenance decision support models for railway infrastructure using RAMS & LCC analyses, Doctoral Thesis, Luleå University of Technology, 2009.
15 Trafikverket website, Banportalen, http://www.trafikverket.se, Access time: 2010-08-25.
16 Montgomery, D. C., Design and Analysis of Experiments, 7th Edition, Jhone Wiley & Sons, 2009, ISBN: 978-0-470-39882-1, p.38.
17 Esveld, C., Modern railway track, MRT-Productions, 2001, ISBN: 90-800324-3-3, p. 402.
18 Dodson, B., The Weibull analysis handbook, 2nd Edition, ASQ Quality Press, 2006, ISBN: 9780873896672, p.6
19 UIC (International Union of Railways), Best practice guide for optimum track geometry durability, 2008.