DOCTORAL THESIS

Cost-Effective Maintenance of Railway Track Geometry

A Shift from Safety Limits to Maintenance Limits

Iman Arasteh Khouy

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UNIVERSITY
OF TECHNOLOGY

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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 (JVTC). The research project was sponsored by Swedish Transport Administration (Trafikverket). I would like to thank Trafikverket for providing financial support during my research.

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Iman Arasteh Khouy

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ABSTRACT

Railway infrastructure is a complex system which comprises different subsystems. Long life span is one of the important aspects of this prime mode of transport. However, the useful life of its assets is highly dependent on the maintenance and renewal strategy used during the assets' 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 results in higher degradation of railway assets and higher maintenance costs. Formerly, railway maintenance procedures were usually planned based on the knowledge and experience of the infrastructure owner. The main goal was to provide a high level of safety, and there was little concern for economic issues. Today, however, the deregulated competitive environment and budget limitations are forcing railway infrastructures to move from safety limits to cost-effective maintenance limits to optimise operation and maintenance procedures. The goal is to make operation and maintenance cost-effective while still meeting high safety standards.

One of the main parameters to assure railway safety and comfortable railway service is to maintain high quality of track geometry. Poor quality of track geometry, 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, switches and crossings etc.). The aim of this study is to develop a methodology to optimise track geometry maintenance by specifying cost-effective maintenance limits. The methodology is based on reliability and cost analysis and supports the maintenance decision-making process.

The thesis presents a state-of-the-art review of track geometry degradation and maintenance optimisation models. It also includes a case study carried out on the iron ore line in the north of Sweden to analyse the track geometry degradation and discuss possible reasons for the distribution of failures along the track over a year. It describes Trafikverket's (Swedish Transport Administration) maintenance strategy regarding measuring, reporting on and improving track quality, and it evaluates the efficiency of this strategy. It introduces two new approaches to analyse the geometrical degradation of turnouts due to dynamic forces generated from train traffic. In the first approach, the recorded measurements are adjusted at crossing point and then the relative geometrical degradation of turnouts is evaluated by using two defined parameters, the absolute residual area (AR_a) and the maximum settlement (S_{max}). In the second approach, various geometry parameters are defined to estimate the degradation in each measurement separately. It also discusses optimisation of the track geometry inspection interval with a view to minimising the total ballast maintenance costs per unit traffic load. The proposed model considers inspection time and the maintenance-planning horizon time after inspection and takes into account the costs associated with inspection, tamping and risk of accidents due to poor track quality. Finally, it proposes a cost model to identify the cost-effective maintenance limit for track geometry maintenance. The model considers the actual longitudinal level degradation rates of different track sections as a function of million gross tonnes (MGT) / time and the observed maintenance efficiency.

Keywords: Track geometry, Track quality, Geometry degradation, Track maintenance optimisation, Cost-effective maintenance, Maintenance planning, Tamping.

LIST OF APPENDED PAPERS

Paper I	Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2012). Evaluation of track geometry degradation in Swedish heavy haul railroad - A Case Study. *Published in International Journal of COMADEM*, 15(1), 11-16.
Paper II	Arasteh khouy, I., Schunnesson, H., Juntti, U., Nissen, A. and Larsson-Kråik, P-O. (2013). Evaluation of track geometry maintenance for a heavy haul railroad in Sweden - A Case Study. *Published in Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.*
Paper III	Arasteh khouy, I., Larsson-Kråik, P-O, Nissen, A., Lundberg, J. and. Kumar, U. (2013). Geometrical degradation of railway turnouts - A Case Study from a Swedish heavy haul railroad. *Accepted for publication in Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.*
Paper IV	Arasteh khouy, I., Larsson-Kråik, P-O., Nissen, A., Juntti, U., and Schunnesson, H. (2013). Optimisation of track geometry inspection interval. *Published in Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.*
Paper V	Arasteh khouy, I., Larsson-Kråik, P-O., Nissen, A., and Kumar, U. (2013). Cost-effective track geometry maintenance limits. *Submitted for publication.*

NOMENCLATURE LIST

Definitions & Acronyms

AL	Alert Limit
BESSY	Trafikverket’s Inspection Report System
BIS	Trafikverket’s Asset Register System
CRF	Cost Rate Function
DSS	Decision Support System
FMECA	Failure Mode Effects and Criticality Analysis
IID	Independently and Identically Distributed
IL	Intervention Limit
IAL	Intermediate Action Limit
IM	Infrastructure Manager
LCC	Life Cycle Cost
MGT	Million Gross Tonne
NHPP	Non-Homogenous Poisson Process
NOK	Norwegian Krone
Optram	Trafikverket’s Track Geometry Maintenance Database
PBTG	Performance-Based Track Geometry
RAMS	Reliability, Availability, Maintainability and Safety
RCF	Rolling Contact Fatigue
RP	Renewal Process
SEK	Swedish Krona
TQIs	Track Quality Indices
UIC	International Union of Railways
0felia	Trafikverket’s Failure Report System (name adopted from the concept of zero failure)

Symbols

A	Distance [m] between the peaks after and before crossing valley
AR_a	Absolute residual area [m^2]
B-fault	Preventive maintenance limit [mm] in Trafikverket
Bfs 2	Turnout's name
Bln 2	Turnout's name
C (only in page 19)	Cant error [mm]
C	Slope of the measurement line 1 metre before the crossing point
C-fault	Corrective maintenance limit [mm] in Trafikverket
D	Slope of the measurement line 1 metre after the crossing point
E	Longitudinal level value [mm] at the first peak (before crossing point)
E'	Difference of longitudinal level values [mm] between the first peak (before crossing) and the valley before it
F	Longitudinal level value [mm] at the second peak (after crossing point)
F(t)	Cumulative distribution function
F'	Difference of longitudinal level values [mm] between the second peak (after crossing) and the valley after it
G	Difference of longitudinal level values [mm] between the first peak (before crossing) and the crossing valley
G (only in page 7)	Track gauge [mm]
h	Cant value [mm]
H	Difference of longitudinal level values [mm] between the second peak (after crossing) and the crossing valley
HA	Accelerometer
HL	Position sensor
HLh	Right position sensor
HLv	Left position sensor
K-value	Ratio between ($\sum l$), the total length of the track with standard deviations below the comfort limits, and the total length of track (L)
K2	Track quality class 2
K3	Track quality class 3
l	Length [m or km] of the track with standard deviation below the comfort limit

L	Total Length [m or km] of the track
LA	Lateral displacement sensor
LUT	Gyro measuring the angle between the ground and the wagon
m	Metre
P	Gauge face contact point (EN 13848-1)
Q	Track quality
QN 1	Quality level QN 1: "necessitates observing a track section or taking maintenance measures within the frame of normal operations scheduling" (EN 14363)
QN 2	Quality level QN 2: "necessitates taking short-term maintenance measures" (EN 14363)
QN 3	Quality level QN 3: "characterises track sections which do not exhibit the usual track geometry quality" (EN 14363)
Rsn 1	Turnout's name
Rsn 2	Turnout's name
R(t)	Reliability function
s	Second
Sbk 1	Turnout's name
S_{max}	Maximum settlement [mm]
Soa 2	Turnout's name
y_P	Distance [mm] between point P and a reference line, used to measure Alignment (EN 13848-1)
Z_P	Limit [mm] of the range below the running surface within which the gauge is measured; "Zp is always 14 mm" (EN 13848-1)
$Z_{P'1}$	Deviation [mm] in the direction of consecutive running table levels on left hand rail, used to measure Longitudinal Level (EN 13848-1)
$Z_{P'2}$	Deviation [mm] in the direction of consecutive running table levels on right hand rail, used to measure Longitudinal Level (EN 13848-1)
β	Shape parameter of the Weibull distribution
η	Scale parameter of the Weibull distribution
μ	Mean value
ρ	Correlation coefficient parameter
σ	Standard deviation
σ_C	Standard deviation of the cant error
σ_H	Standard deviation of the average vertical error for the left and right rail
$\sigma_{H\ lim.}$	Comfort limit for the σ_H value

σ_S	Sum of standard deviations of cant error (C) and the lateral position error of the high rail (S_{High})
$\sigma_{S\ High}$	Standard deviation of the lateral position error of the high rail
$\sigma_{S\ lim.}$	Comfort limit for the σ_S value

CONTENTS

INTRODUCTION

1.1 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 (Profillidis, 2006). In today's competitive market, they are called upon to reduce operating 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 operation (Resor and Patel, 2002). In Sweden, Trafikverket (Swedish Transport Administration) is the government authority responsible for railway infrastructure administration as well as the development of the railway sectors (Espling, 2007). Trafikverket was established in 2010 by merging Swedish National Rail Administration (Banverket) and Swedish National Road Administration (Vägverket) into one organisation. 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 its effectiveness and efficiency, Banverket was divided into client/contractor organisations in 1998 (Espling, 2007).

The railway system is divided into rolling stock and infrastructure. 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 economical movement of rail traffic (Bing & Gross, 1983). In terms of safety and operating expenses, the track is one of the main parts of infrastructure. For example, in the Netherlands in 2006, 65% of the maintenance cost was allocated to the track and platforms (Profillidis, 2006).

Turnouts are an important part of the track subsystem in terms of safety, operation punctuality and maintenance cost. A study of train delay statistics for the period 2001-2003 in the Swedish railway system shows that the share of turnout failures in the total number of infrastructure-related delays is about 14% (Granström, 2005). In 2009, the maintenance cost of turnouts in Sweden was around 8% of the total maintenance cost (Trafikverket report, 2011).

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

- The degradation of many other track components is closely related to the track geometry condition;

- Track geometry is often used to trigger 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). For example, Karttunen et al. (2012) show the influence of lateral geometry irregularities on the mechanical deterioration of freight tracks.

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. Inspections are manual or automated using a 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 infrastructure owner. 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 optimise operation and maintenance procedures. The primary goal of optimisation is to reduce the operation and maintenance expenditures while still assuring high safety standards (Lyngby et al., 2008; Carretero et al., 2003).

Optimising 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. The monitoring and evaluation of track geometry allow the infrastructure administration to control safety and plan track maintenance (Berggren et al., 2008).

A number of railway research institutes have attempted to analyse the deterioration of track geometry, including the Office for Research and Experiments (ORE) of the International Union of Railways (UIC), European Rail Research Institute (ERRI) in the Netherlands, Transportation Technology Centre Inc. (TTCI) in the USA and Graz University of Technology in Austria.

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 with the exception of sections with high deterioration rates, track quality deteriorates linearly with tonnage or time between maintenance operations after the first initial settlement (Esveld, 2001). However, a more recent study has revealed that the track quality deteriorates exponentially (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) noted 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. Bing and Gross (1983) presented a model that could be used to predict how the track quality, measured in terms of track quality indices (TQIs), changes as a function of causal parameters, such as traffic, track type and maintenance. Nurmikolu (2013) identified factors affecting the performance of track substructures subjected to cold climates. Finally, Audley and Andrews (2013) analysed the effects of tamping on track geometry degradation.

However, most studies have been conducted for plain tracks, i.e. straights and curves. In the case of turnouts, for example, only a few attempts have been made to model degradation in addition to optimising maintenance. An exception is Zwanenburg (2009) who modelled the degradation process of turnouts for maintenance and renewal planning on the Swiss railway network. The European project, INNOTRACK (2008) has specified the key parameters for monitoring turnouts using the FMECA (Failure Mode Effects and Criticality Analysis) method. It has also advocated the optimisation of turnouts by optimising the geometry and track stiffness (INNOTRACK, 2010).

Some researchers have examined the dynamic interaction between the train and the turnout to simulate the wear, rolling contact fatigue (RCF) and plastic deformation in turnout components (Nicklisch et al., 2010; Kasa and Johansson, 2006). Others have evaluated the effects of the switch angle and frog angle on the wear rate. For instance, Elkins et al. (1989) concluded that the wear at the switch should be reduced by decreasing the switch entry angle.

In addition, several attempts have been made to optimise track geometry maintenance in terms of planning and cost efficiency. Markow (1985) applied a demand-responsive approach to the life cycle costing method, creating a model to estimate the total costs for different maintenance alternatives. Chrismer and Selig (1993) combined a mechanistic method of timing ballast maintenance with an economic model to identify the life cycle cost of different maintenance methods. Higgins (1998) proposed a model to determine the best allocation of maintenance activities and crews to minimise maintenance costs while keeping the track condition at an acceptable level. By using track geometry historical data, Miwa et al. (2000) developed a degradation model and a restoration model and applied these models within a mathematical programming model to determine an optimal maintenance schedule for a multiple tie tamper. Jovanovic and Esveld (2001) presented ECOTRACK, an objective condition-based decision support system developed by ERRI's D 187 Committee and 24 European railways between 1991 and 1998. The aim of this system is to provide solutions to the problems of restoring track at the required quality level with minimum cost and resolving a trade-off between maintenance and renewal. Zhao et al. (2006) developed a life cycle model to optimise 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. 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. Larsson-Kråik (2012) used cost benefit risk analysis to evaluate future maintenance and reinvestment activities which lead to risk reduction of avalanches and wet slush flow. Finally, Famurewa et al. (2013) proposed a methodology to optimise tamping scheduling by minimising the total maintenance cost.

In the optimisation of track geometry inspection, more attention has been paid to optimising 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. Silvast et al. (2013) studied the integrated track geometry data and ground penetrating radar (GPR) data analysis in locating problem section and identifying the root causes of faults.

On the other hand, limited research has considered the optimisation of track geometry inspection intervals. An exception is Lyngby et al. (2008) who studied the optimisation of track geometry inspection intervals on the Norwegian railway network and showed that by optimising inspection intervals about 20000 NOK (Norwegian Krone) per year could be saved on a specific track.

1.2 Problem definition

Following the European Commission, the Trafikverket (Swedish Transport Administration) vision to 2020 looks to increase capacity and market share of passenger and goods traffic and decrease maintenance costs and emission of pollutants (White Paper, 2001).

Accordingly, in 2000, the Swedish mining company LKAB increased the axle load on the iron ore line (Malmbanan) from 25 to 30 tonnes and the maximum speed of a loaded train from 50 to 60 km/h. In addition, the total traffic volume in terms of million gross hauled tonne-kilometres for passenger and freight traffic increased by 5% from 2006 to 2010. This combination of circumstances can result in faster degradation of railway assets and higher maintenance costs. Therefore, a cost-effective maintenance strategy should be designed, linking maintenance objectives to organisational objectives.

Given limited maintenance budgets and short track access time for maintenance, it is essential to have an effective and efficient maintenance strategy which alters maintenance actions from corrective to preventive. Through shifting the focus of the maintenance strategy from meeting safety limits to obtaining cost-effective maintenance thresholds by applying maintenance decision support tools such as RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life Cycle Cost), high quality track standards can be maintained while assuring safety standards. Note that Trafikverket's LCC analysis is performed for new investment and renewal projects, not for all track maintenance actions (Patra, 2007).

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

If the proper track geometry maintenance is not selected, the track quality may deteriorate beyond the intervention limit (IL), which results in higher frequency of tamping and, consequently, greater maintenance costs. And since tamping can cause ballast degradation, higher frequency leads to a higher degradation rate and shorter life length of the asset. In other words, it is essential to select a cost-effective maintenance strategy based on reliability and LCC analysis.

1.3 Research purpose and objectives

The purpose of the study is to propose a decision support tool to optimise track geometry maintenance by identifying cost-effective maintenance limits. The objectives are:

- To analyse track geometry degradation and its influencing parameters;
- To evaluate the effectiveness of the present track geometry maintenance strategy of Trafikverket;
- To increase knowledge about geometrical degradation process in turnouts.
- To develop a cost models to specify a cost-effective inspection interval and maintenance limits.

1.4 Research questions

To fulfil the objectives of the study, the following 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. What is the geometrical degradation process in turnouts?
4. How can geometry condition data be used to specify a cost-effective inspection interval?
5. How can a cost-effective maintenance limit be specified for the current maintenance strategy?

1.5 Scope and limitations

Track quality degradation can be analysed based on different track geometry parameters. Since the longitudinal level of the track is the main parameter driving the need for tamping, the evaluation of track geometry deterioration in this study is based on the longitudinal level degradation. The main safety faults causing derailment are twist 3 m, twist 6 m and track gauge (see Chapter 2 for definitions). As tamping is not used to restore track gauge faults, the study collected only data of twist 3 m and 6 m to analyse the distribution of safety faults. In addition, although track geometry faults occur due to deterioration in substructure (e.g. ballast), it has not analysed ballast degradation.

BASIC CONCEPTS AND DEFINITIONS

Basic concepts of railway track geometry such as track quality and track geometry parameters are described in this section. The maintenance activities to restore track quality are also explained. Finally, the section describes the application of maintenance decision support tools such as RAMS and LCC, in railway systems.

2.1 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).

2.2 Track geometry parameters

Track geometry is a key aspect of safety and ride quality. The main geometry parameters used to assess track quality are longitudinal 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 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.

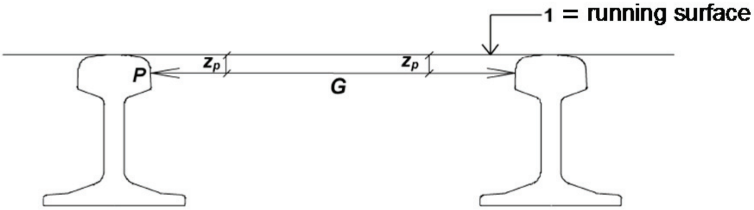


Figure 2.1 Definition of track gauge (EN 13848-1)

Alignment

In 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).

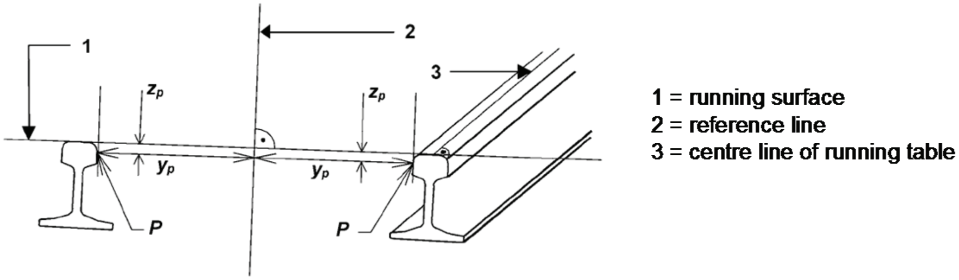


Figure 2.2 Alignment (EN 13848-1)

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).

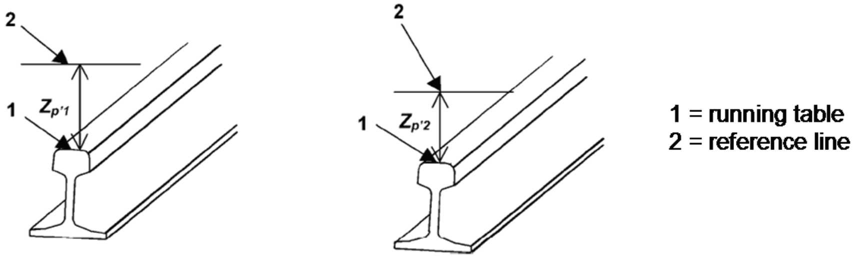


Figure 2.3 Longitudinal level (EN 13848-1)

Cant (cross level)

Cant is defined as "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 a nominal gauge of 1435 mm is 1500 mm long (EN 13848-1).

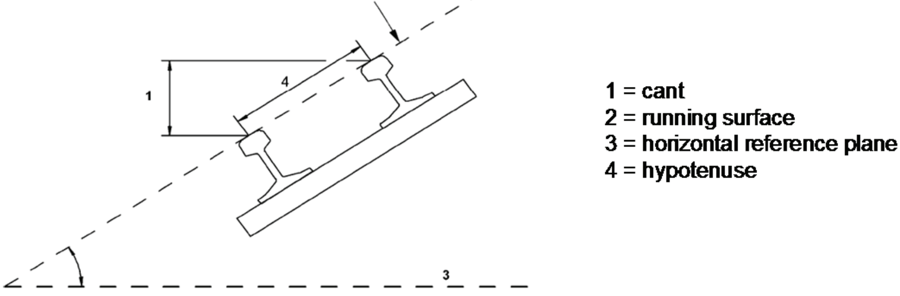


Figure 2.4 Cant (EN 13848-1)

Twist

Twist is defined as “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).

2.3 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 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 analysed and included in the regularly planned maintenance operations.

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

2.4 Track geometry maintenance

Two different maintenance actions can be performed to restore track quality: tamping and stone-blowing.

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.

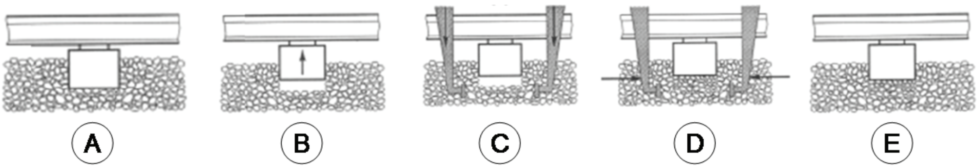


Figure 2.5 Sequence of Tamping (Selig and Waters, 1994)

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 standard deviation of the track faults is decreased by tamping. This improvement is followed by exponential growth of the geometry faults 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; higher lifts 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. For optimum compaction, there should be a 15 mm free space between the top of the tamping tine plate and the sleeper base (Lichtberger, 2005).

Stone-blowing

The motivation for the development of the stone-blowing process was the observation that ballast memory results in the track's tendency to move back to the condition prior to tamping (Esveld, 2001). According to the current maintenance strategy in the UK, stone-blowing is applied on track sections which require more frequent tamping as it causes less damage to the ballast (Aursudkij, 2007).

Stone-blowers are suitable for the low lift associated with removal of the short wavelength geometry faults while tampers are appropriate for relatively high lift associated with the removal of long wavelength faults (Selig and Waters, 1994). Therefore, stone-blowing should be considered a complement to tamping, not a substitute (Esveld, 2001).

The different stages of stone-blowing are as follows (Selig and Waters, 1994):

(A) The ballast rests in the sleeper prior to adjustment.
(B) The sleeper is raised by the machine to create a void under the sleeper.
(C) The stone-blowing tubes are inserted in the ballast alongside the sleeper.
(D) A measured quantity of stone is blown by compressed air into the empty space under the sleeper.

(E) The stone-blowing tubes are withdrawn from the ballast
(F) The machine lowers the sleeper onto the surface of the blown stone where it will be compacted by subsequent traffic.

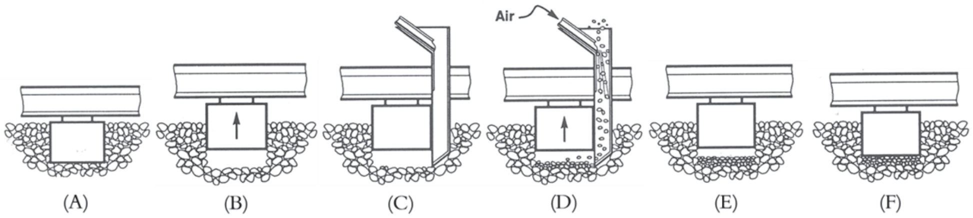


Figure 2.6 The stone-blowing process (Selig and Waters, 1994)

2.5 RAMS requirements for railway systems

In railways, RAMS is vital to a system's long-term operation and is obtained by applying established engineering concepts, methods and techniques throughout the lifecycle of the system (EN 50126, 1999). By meeting the needs of RAMS, a railway can meet its goal of reaching 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 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 the railway is illustrated in Figure 2.7.

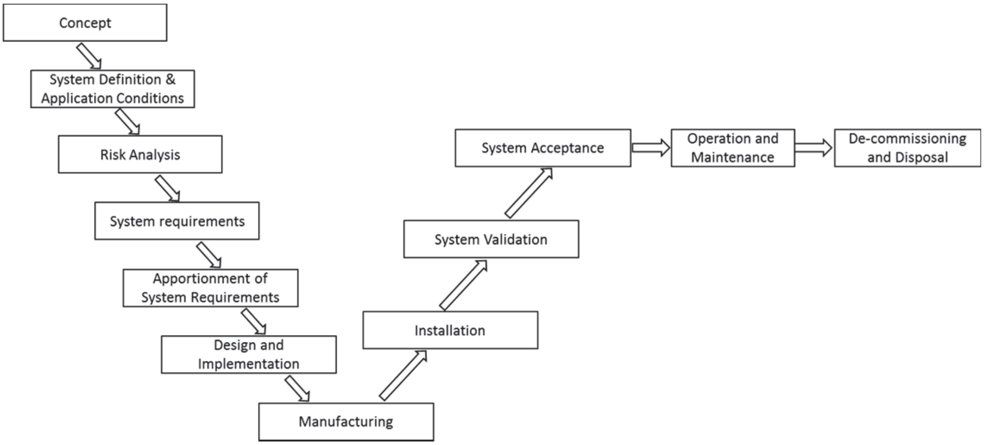


Figure 2.7 The "V" Representation of Railway Lifecycle (EN 50126, 1999)

The left side of this "V" representation of a railway lifecycle is generally called development; it 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 a 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 2.8).

Some of the failures in track system can be categorized as hidden failures. Hidden failures are not identified until either a demand is made or inspection is performed. Ahmadi and Kumar (2011) developed a cost rate function (CRF) to identify inspection and restoration intervals of hidden failures subject to aging.

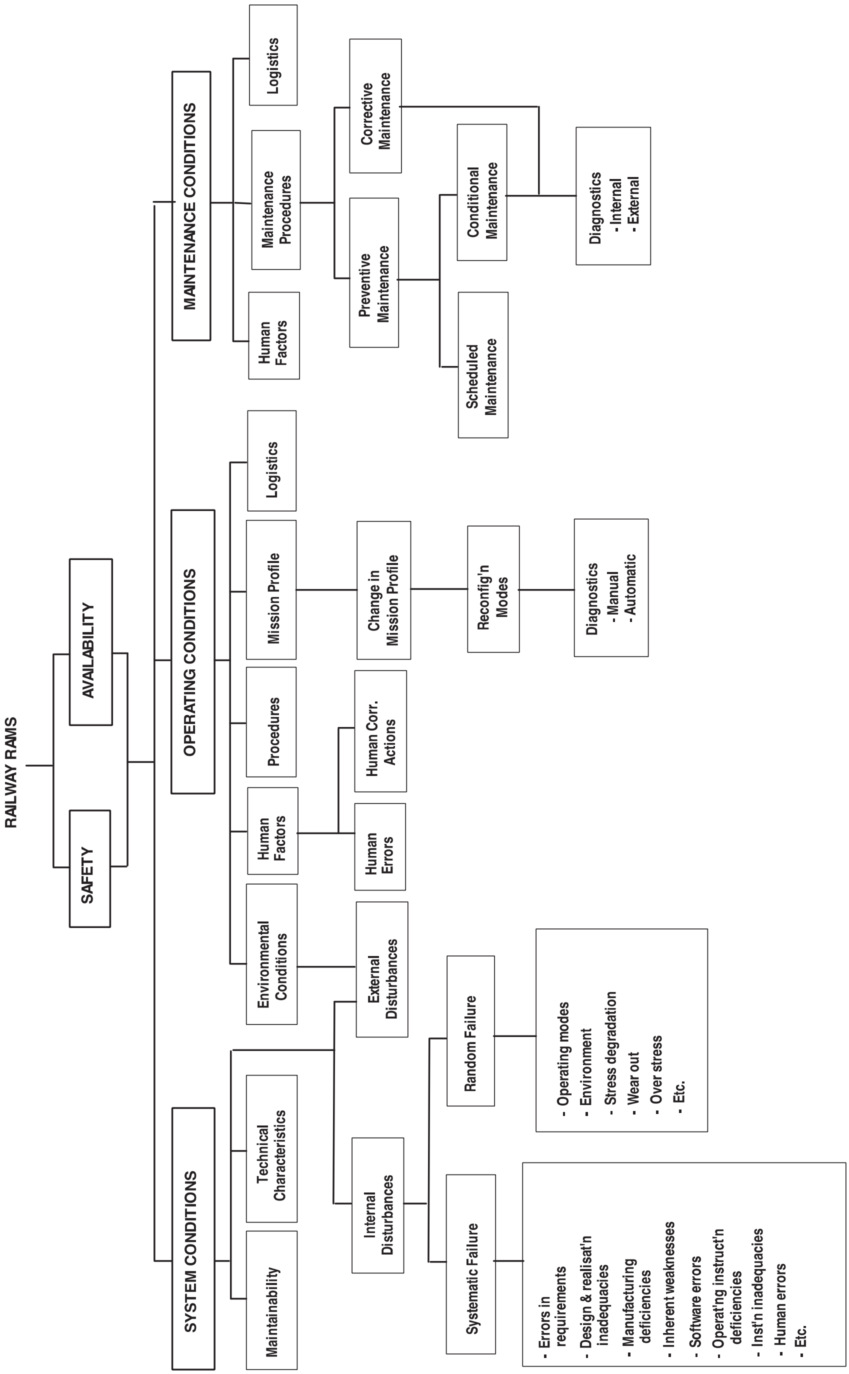


Figure 2.8 *Factors Influencing Railway RAMS (EN 50126, 1999)*

2.6 LCC in railway systems

Since investment in railway infrastructure is costly, and the infrastructure has a long lifespan, an optimal maintenance strategy should be developed through 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 (INNOTRACK, 2008).

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

1. Collect data for all cost elements 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 or availability or any limitation that may affect the applicability of the scenarios considered;
6. Summarise 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 plan.

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

1. Tangible versus intangible costs: In tangible costs, the exact costs are known, including the costs of construction and maintenance (labour, materials and machines). For intangible costs, the precise costs are unknown. These 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 operating period of a railway.

Some research has applied LCC to the railway industry. A guideline for LCC and RAMS analysis proposed by the INNOTRACK project is applicable to some European countries. The guideline explains principles, applications and advantages of LCC analysis. INNOTRACK (2010) has established a harmonised LCC method at the European level, which can specify cost drivers, evaluate the track components/modules and make cross-country comparisons.

IMPROVERAIL (2003) was 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)

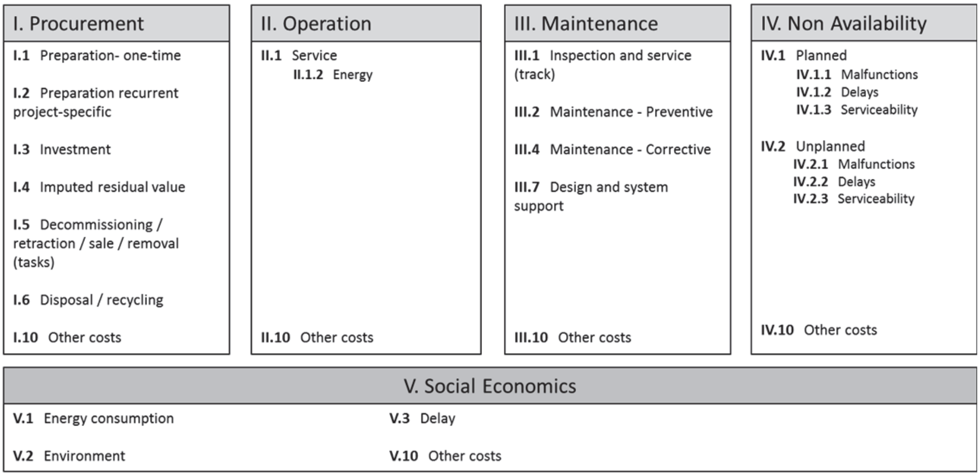


Figure 2.9 LCC cost matrix for railway infrastructure analysis (INNOTRACK, 2010)

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 the 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 are all those, not under the 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 disputable 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. Patra et al. (2008) presented a methodology for estimation of uncertainty linked with railway track life cycle cost based on a combination of Monte Carlo simulation and Design of Experiment (DoE).

Sensitivity analysis and Monte Carlo simulation are two methods of dealing with uncertainties in LCC analysis (Flanagan and Norman, 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.

TRACK GEOMETRY MAINTENANCE AT TRAFIKVERKET - A CASE STUDY

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

3.1 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 (Banverket, 2008).

Track geometry inspection is performed to control track irregularities and displacement from the designed geometry. In track geometry monitoring, the longitudinal level, alignment, track gauge, rail elevation, twist (over 3 m or 6 m) and curvature are inspected (BVF 807.2, 2005).

Inspection trains STRIX/IMV100 continuously monitor the geometry of every 25 cm of the track. STRIX uses a contactless measurement system, based on an inertial measurement system and an optical system. All measuring cars must meet the standards specified in EN 13848-2. The measurement procedures for longitudinal level, cant, track gauge and alignment are explained in the following sections.

Longitudinal level measurement

The vertical position of the right and left rails is measured by a position sensor (HL) and an accelerometer (HA) (Figure 3.1). The accelerometer measures the vertical acceleration of the wagon. This acceleration measurement 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 (equation [1]) (Gripner, 2006).

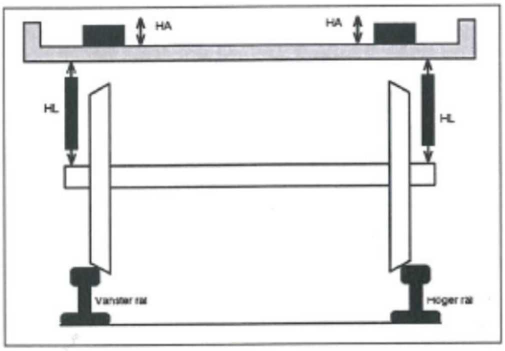


Figure 3.1 Vertical position measurement (Gripner, 2006)

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

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

Cant measurement

Track cant is used to overcome centrifugal force in curves. Cant measurement is performed by a gyro which measures the angle between ground and wagon. Two vertical position sensors (HLh and HLv) are used to measure the angle between the wagon and the wheel axle (see Figure 3.2). 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.

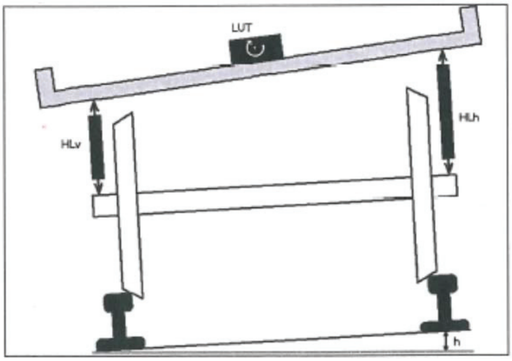


Figure 3.2 Cant measurement (Gripner, 2006)

Twist is defined as the variation of cant over 3 m or 6 m of track. STRIX measures the values of cant, allowing the subsequent calculation of twist.

Alignment and track gauge measurement

The track gauge is measured by two laser devices, one for each of the right and left rails (see Figure 3.3). 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 an accelerometer, as shown in Figure 3.3.

The inspection data are recorded in the BESSY database; critical failures, which can cause derailment, are reported immediately to the operation control centre. BESSY is one of Trafikverket's asset databases; these databases are described in Section 4.2.

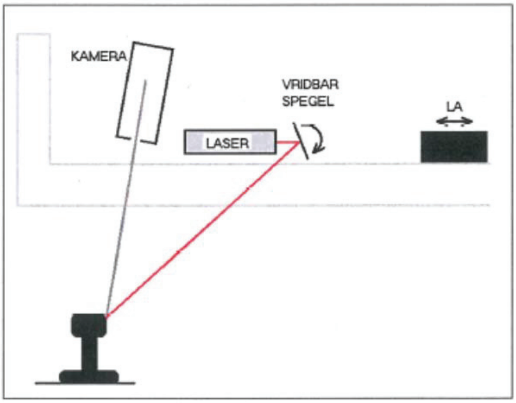


Figure 3.3 Measurement of track gauge and alignment (Gripner, 2006)

3.2 Tamping strategy

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 deviations σ_H and σ_S, and the comfort limits that define the acceptable standard deviation of the longitudinal level for 200 m track sections. σ_S is the sum of standard deviations of the cant error (C) and the lateral position error of the high rail (S_{High}) (see Figure 3.4 and equation [2]). σ_H is the standard deviation of the average longitudinal level for the left and right rails.

$$\sigma_S = \sigma_C + \sigma_{S_{High}} \qquad [2]$$

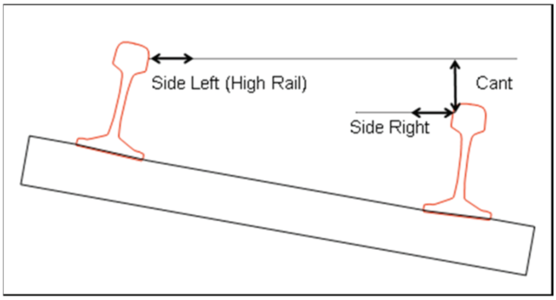


Figure 3.4 Calculation of σ_S

The Q-value indicates the quality of the track geometry and is calculated by the following formula (BVF 587.02, 1997):

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

where $\sigma_{S\,lim}$ is the comfort limit for the σ_S value, defined for different track classes and $\sigma_{H\,lim}$ is the comfort limit for the σ_H value, defined for different track classes.

The other index, the K-value, is the ratio of the total length of the track with deviations below comfort limits ($\sum l$) 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 equation [4]:

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

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

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 (BVF 587.02, 1997). C-faults identify the limits for the execution of corrective maintenance (intervention limits) whereas B-faults identify the limits for the execution of preventive maintenance (alert limits). However, interviews with the line contractor revealed that, in reality, B-limits are not always used by the contractor as a criterion for preventive maintenance execution.

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 the necessary work. They are responsible for both regular measurements of track geometry and tamping.

Tamping is executed as either preventive maintenance or corrective maintenance. Execution of tamping as a result of a C-fault is considered corrective maintenance; tamping based on 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, tamping should be performed.

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 receive a bonus, whereas if it is below the contractual limit, they must pay a penalty.

The main phases of Trafikverket's maintenance strategy are shown in Figure 3.5. The figure shows how the maintenance decision criteria are used to specify the need for preventive or corrective tamping.

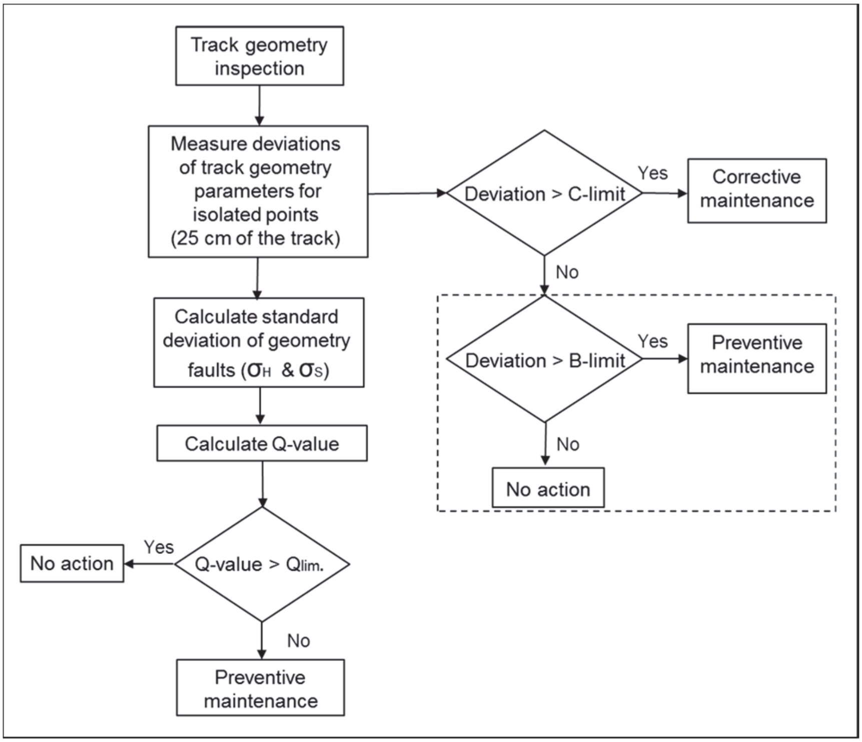


Figure 3.5 The steps of Trafikverket's maintenance strategy

RESEARCH METHODOLOGY

The term "research" has been defined in different ways. Kumar (2008) calls it a systematic and scientific activity undertaken to establish a fact, a theory, a principle or an application. Most agree that it is a stepwise process of finding answers to questions (Neuman, 2003). Different research approaches require different steps, the most common of which are shown in Figure 4.1.

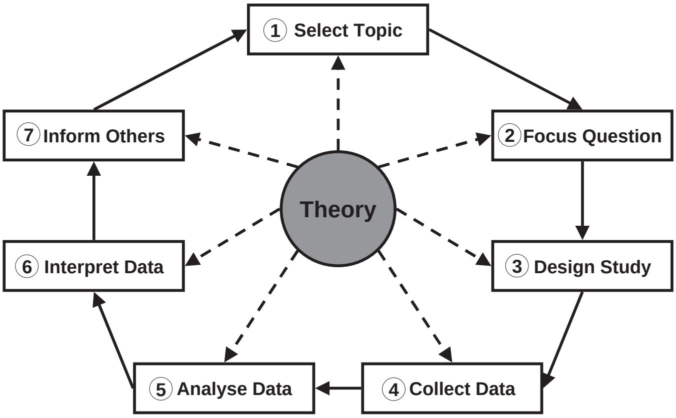


Figure 4.1 Steps in research process (Neuman, 2003)

Selecting an appropriate and clear methodology is a necessary requirement of good research. Research methodology, as defined by Kazdin (1992), 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 organised 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 4.1.

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

Table 4.1 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

4.1 Research approach

Research style can be categorised as quantitative or qualitative. The main features of each are shown in Table 4.2.

Table 4.2 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.

The present study uses both quantitative and qualitative analysis. The research problem has a direct application in the railway industry and it is solved using both inductive and deductive approaches: a deductive method is applied to the analysis of geometrical degradation in turnouts; an inductive approach is used to assess track geometry degradation patterns and to develop a cost rate function to specify the optimal inspection interval and the cost-effective maintenance limit.

4.2 Data collection

Data can be defined as the empirical evidence or information that scientists carefully collect according to rules or procedures to support or reject theories (Neuman, 2003). Data can be categorised 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 for both qualitative and quantitative data on well-known online databases and peer reviewed international journals, including IEEE Xplore, Emerald, Elsevier Science Direct, Journal of Rail and Rapid Transit, 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 databases: BIS (asset register system), BESSY (inspection report system), 0felia (failure report system) and Optram (track geometry measurement database). The details of these databases are given below.

BIS

BIS is an asset register database which contains information on infrastructure and facilities, agreements, the history of tamping (such as location of tamped section, length of tamping, date, etc.), grinding and curves.

BESSY

BESSY is an inspection report system which contains information on inspections and the types of actions performed after inspection comments (Nissen, 2009).

0felia

The data on corrective maintenance actions are registered in Ofelia. It contains report information from the track maintenance contractors on fault symptoms, reasons for faults, the actions performed, the time of fault occurrences and repair, the time required for repair, etc. (Nissen, 2009).

Optram

Optram is a maintenance decision support system implemented in 2009 that can graphically show the results of track geometry measurements. Only measurement data after 2007 are available in this database. The system also provides functionality for analysis and displays data trends (Banportalen, 2013).

These quantitative data were related to two sections of the iron ore railway line, Malmbanan. Cost-related data were collected by consulting Trafikverket's experts and examining scientific papers.

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

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.

4.3 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 trends and dependency characteristics of data can be checked by an IID test. Ascher and Feingold (1984) have proposed the steps which should be taken before choosing the best fitting distribution model (see Figure 4.2).

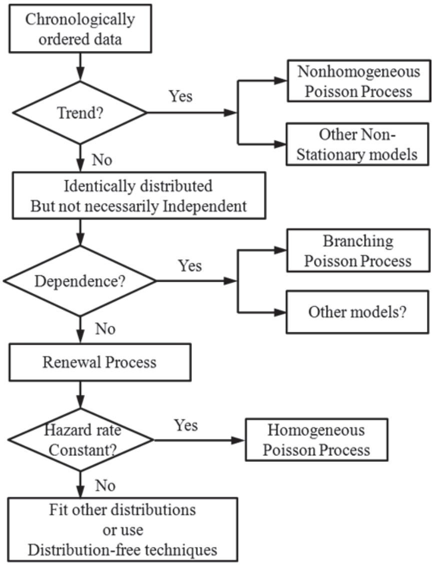


Figure 4.2 The steps of failure data analysis before selecting the best fitting model (Ascher and Feingold, 1984)

A railway system is a system which undergoes repair and can be restored by a method other than replacement. 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. However, the third state is more common in track geometry maintenance. As tamping is not entirely effective, the state of the system after maintenance will be better than old but worse than new.

Methods used in paper I

In the first paper, statistical analysis was performed to assess the trend of different geometry faults over time to find the distribution of C-faults in different seasons and to indicate the critical sections in terms of C-fault occurrence. To ensure comparable data for the selected track, it considered segments of 1000 m from both quality classes K2 and K3 and left out stations and other parts of the track after or before stations with lengths shorter than 1000 m.

Methods used in paper II

The collected data were reviewed and discussed with experts to assess their quality. The European railway standard EN 13848-5 was considered in order to compare and evaluate current maintenance limits in Sweden with the suggested intervention limits (IL) in the European standard. 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 used to define an IL based on the maximum allowable speed on the track (see Figure 4.3). This defined limit was applied as a benchmark to evaluate tamping execution at different tamping intervals. The tamping intervention graph, developed by Austrian Railways and presented in UIC code (2008), was used to evaluate the maintenance efficiency.

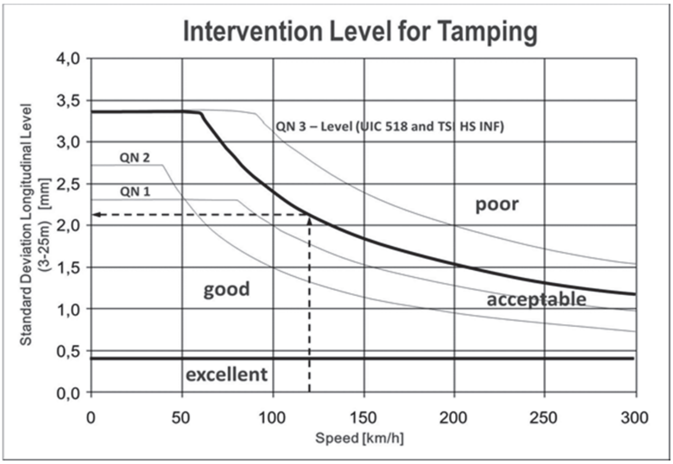


Figure 4.3 Lines of constant riding comfort at different speeds [UIC, 2008]

Methods used in paper III

In the third article, two different approaches were proposed to analyse the geometrical deterioration of turnouts. In the first approach, two parameters were defined in geometrical degradation analysis: the absolute residual area (AR_a) and the maximum settlement (S_{max}.). The AR_a was defined as the absolute value of the area obtained from the differences in the longitudinal level values of two adjusted measurements at the crossing point (see Figure 4.4). The maximum settlement (S_{max}) was defined as the difference between the value of the longitudinal level at the crossing point and the value obtained from the intersection of the vertical line passing through the crossing point, with the straight line connecting the positive peaks before and after the crossing point (see Figure 4.5).

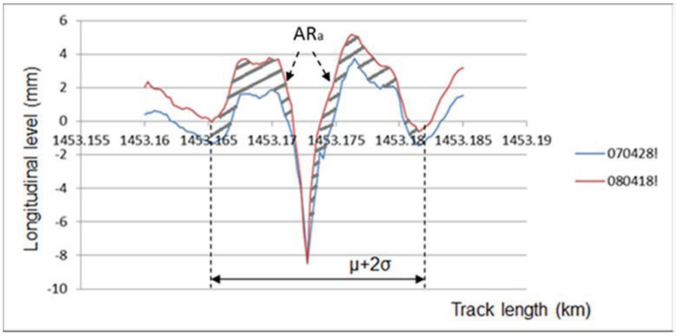


Figure 4.4 Illustration of the absolute residual area (AR_a) between two measurements

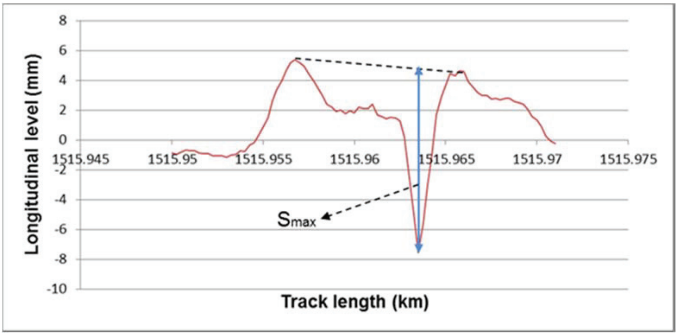


Figure 4.5 Illustration of the maximum settlement (S_{max})

In the second approach, various geometry parameters were defined to estimate the degradation in each measurement separately. This approach was inspired by surface roughness measurements, a useful and reliable method for at least 60 years. The defined parameters in this approach were the following (Figure 4.6):

- A: the distance between the peaks after and before crossing valley;
- C: the slope of the measurement line 1 metre before the crossing point;
- D: the slope of the measurement line 1 metre after the crossing point;
- E: the longitudinal level value at the first peak before the crossing point;
- E': the difference of the longitudinal level values between the first peak before the crossing and the valley before it;

- F: the longitudinal level value at the second peak after the crossing point;
- F': the difference of the longitudinal level values between the second peak after the crossing and the valley after it;
- G: the difference of the longitudinal level values between the first peak before the crossing and the crossing valley;
- H: the difference of the longitudinal level values between the second peak after the crossing and the crossing valley.

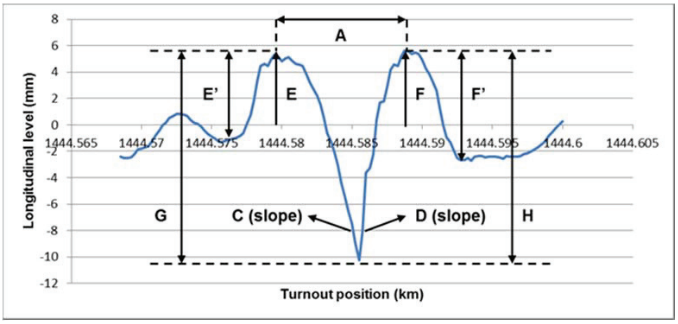


Figure 4.6 Defined geometry parameters in the second approach

Methods used in paper IV

In the fourth paper a Cost Rate Function (CRF) was developed to find the most cost-effective inspection interval with a view of minimising the total ballast maintenance cost per unit of traffic load. The proposed model considers inspection time and the maintenance-planning horizon time after inspection and takes into account the costs associated with inspection, tamping and risk of accidents due to poor track quality.

The trend and dependency characteristics of the collected geometry fault data were examined using the Laplace trend test and the serial correlation test. The following assumptions were made prior to the analysis of the probability distribution of faults:

- The track consists of identical track segments.
- The maintenance effectiveness is perfect. This means that the status of the segment will be restored to "as good as new" condition after maintenance.

Under these assumptions and after ensuring the collected data were IID, the probability distributions of faults were estimated. The Weibull ++7 software was used to find the probability distribution function with the appropriate fit to the data. To obtain applicable results from the analysis, only main distributions such as Weibull, normal/lognormal, exponential, etc. were considered; other theoretical distributions were not.

The probability distribution analysis was based on the number of detected segments with geometry faults over the time interval between two consecutive inspections. No difference was considered between the occurrence of a single point fault and multiple point faults on the same segment in the same time interval because maintenance should be carried out on the segment regardless of the number of detected geometry faults.

Since the exact times of fault occurrences were not known, the fault time data were considered interval-censored, whereby the object of interest is not constantly monitored. Thus, the inspection times in terms of MGT were used as interval ranges for fault times. The segments without any fault occurrences over the studied time period were also considered right-censored data.

The linear regression technique was used to rank probability distributions, with goodness of fit illustrated by the correlation coefficient parameter (ρ).

Methods used in paper V

In the fifth article, a cost model was proposed to specify the cost-effective maintenance limits for track geometry maintenance. The proposed model considers the degradation rates of different track sections and takes into account the costs associated with inspection, tamping, delay time penalties and risk of accidents due to poor track quality.

Since the effect of frost heaves on track geometry can introduce error into degradation trend analysis, only measurement data from June to October were considered.

As the inspection car (STRIX / IMV 100) has an error of 10-15 m (in some cases even higher) in specifying the longitudinal location of the track, the first step in data treatment is to adjust the sampled measurement data. Since the accuracy of the available programmes in data adjustment was unacceptable, the measurement data were adjusted manually.

Next, the standard deviation of the longitudinal level for each 200 m track section was calculated in every measurement. By applying the exponential regression trend line over the time series of the standard deviations, the degradation rate of each section could be estimated.

Since the occurrence of a twist 3 m fault greater than 15 mm or a twist 6 m fault greater than 25 mm is critical to derailment risk, the data reporting the occurrence of these failures between 2004 and 2010 were collected from the inspection reporting system to find the probability distribution of their occurrence. Results are presented in the previous study (Paper IV). The probability function is used to determine the probability of safety fault occurrences at specified time intervals.

The model considers two types of faults: standard deviations of the longitudinal level and isolated safety faults (twist 3 m and 6 m). If the standard deviation of the longitudinal level for a 200 m track section goes over the specified IL and/or detection of safety faults, corrective tamping is performed at a fixed time interval after the inspection.

To cover all tamping efficiencies, the model was run for two scenarios: the optimum scenario and the worst scenario. The optimum scenario used the achieved efficiency on the high efficient maintenance bound, while the worst scenario considered the low efficient maintenance bound.

4.4 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 conceptualises an idea in a conceptualised 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.

SUMMARY OF APPENDED PAPERS

This section summarises the five appended papers. Each paper corresponds to one of the research questions and reports the outcome of the case studies.

Paper I analyses the degradation rate of geometry parameters over time. 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. 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 3 m, increases over time. In addition, the evaluation reveals that in some segments, tamping does not remove the root cause of failures since the failures recur repeatedly.

Paper II describes Trafikverket's (Swedish Transport Administration) tamping strategy and evaluates its effectiveness in measuring, reporting and improving track quality. It also evaluates the performance of the maintenance contractor and discusses the importance of the functional requirements stated in the outsourcing contracts. The maintenance performance assessment shows that the decision-making process for the execution of tamping does not use all defined limits for geometry parameters. It also finds that 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. Finally, it indicate that the nature 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 the maintenance strategy.

Paper III analyses the geometrical degradation of turnouts due to dynamic forces generated from train traffic using two different approaches. In the first approach, the recorded measurements are adjusted at crossing points; then the relative geometrical degradation of turnouts is evaluated by using two defined parameters, the absolute residual area (AR_a) and the maximum settlement (S_{max}), In the second approach, various geometry parameters are defined to estimate the degradation in each measurement separately. The growth rate of the longitudinal level degradation as a function of million gross tonnes (MGT) / time is evaluated. The proposed methods are based on characterisation of the individual track measurements. The results indicate that a limit for crossing position settlement can be defined. Before reaching this limit, the vertical degradation rate at the crossing point (deepening) is higher than the degradation rate in the vicinity of the crossing (widening). However, after reaching the settlement limit, the crossing can no longer settle, and the geometry faults transfer to the next waves in the crossing neighbourhood.

Paper IV discusses optimisation of the track geometry inspection interval with a view to minimising the total ballast maintenance costs per unit traffic load. The proposed model considers inspection time and the maintenance-planning horizon time after inspection and takes into account the costs associated with inspection, tamping and risk of accidents 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 geometry faults. The analysis shows that in the current maintenance strategy, the probability of fault occurrences in short time intervals is quite low since the majority of track segments have slow degradation rates. Therefore, the inspection interval can be expanded from two to four months.

Paper V proposes a cost model to specify the cost-effective maintenance limits for track geometry maintenance. The proposed model considers the degradation rates of different track sections and takes into account the costs associated with inspection, tamping, delay time penalties and risk of accidents 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 estimate the geometrical degradation rate of each section. The methodology is based on reliability and cost analysis and facilitates the maintenance decision-making process to identify cost-effective maintenance thresholds. The results show that the capacity loss penalties due to the speed reduction in higher IL can significantly increase the total maintenance cost. It also finds that by improving the maintenance efficiency, the total maintenance cost can considerably be reduced.

RESULTS AND DISCUSSION

The degradation of track geometry is a complex phenomenon occurring under the influence of dynamic loads and is normally calculated as a function of traffic in mm/MGT, or time in mm/year (Esveld, 2001). Some factors which can affect the track geometry degradation are shown in the Ishikawa diagram in Figure 6.1. These factors are classified as design, construction, operation, and maintenance.

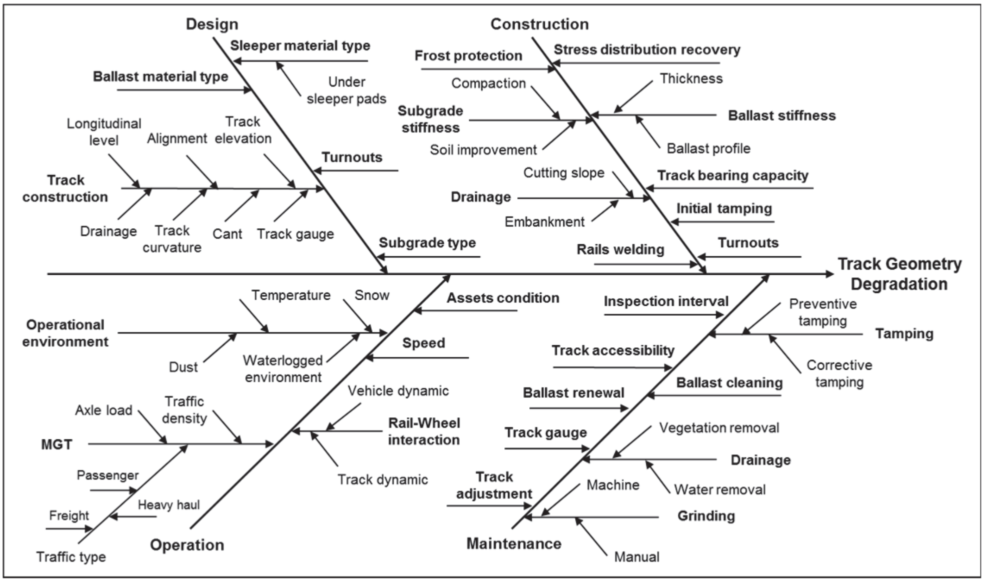


Figure 6.1 Ishikawa diagram (cause and effect diagram) of the factors influencing track geometry degradation.

For a track section with similar traffic, the rate of degradation varies depending on construction and differences in substructure. Figure 6.2 shows the variability of longitudinal level degradation rate in different 200 m 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 sections having low degradation rates that can be controlled by preventive tamping at infrequent intervals. However, the tail of the distribution consists of sections with 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 study.

Optimising 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.

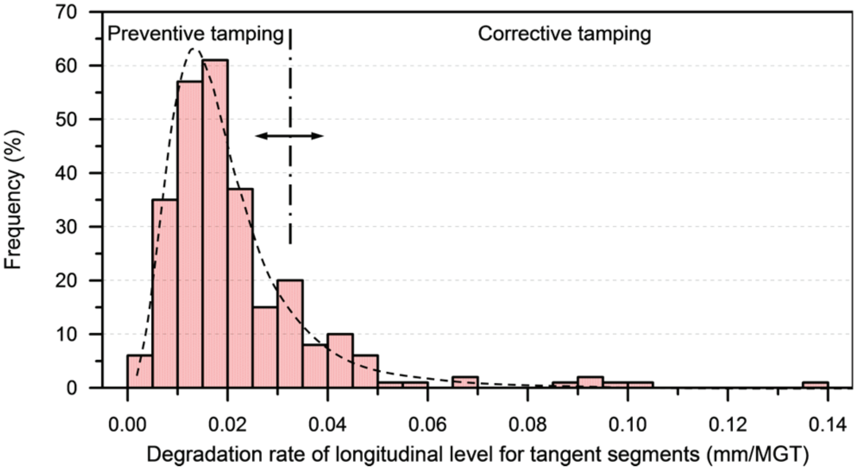


Figure 6.2 Histogram of longitudinal level degradation rates in tangent segments between 2007 and 2009.

Given this, Paper I analyses the degradation rate of longitudinal level and twist 3 m 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 6.3 shows the cumulative trends of C-failures for the longitudinal level and twist 3 m. 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 3 m increases over time, possibly indicating an aging effect. The rates of C-failure for cant, alignment and twist 6 m show an aging trend similar to that shown by twist 3 m. The curve trend indicates an aging effect, but the exact reason for this behaviour is not clear. 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.

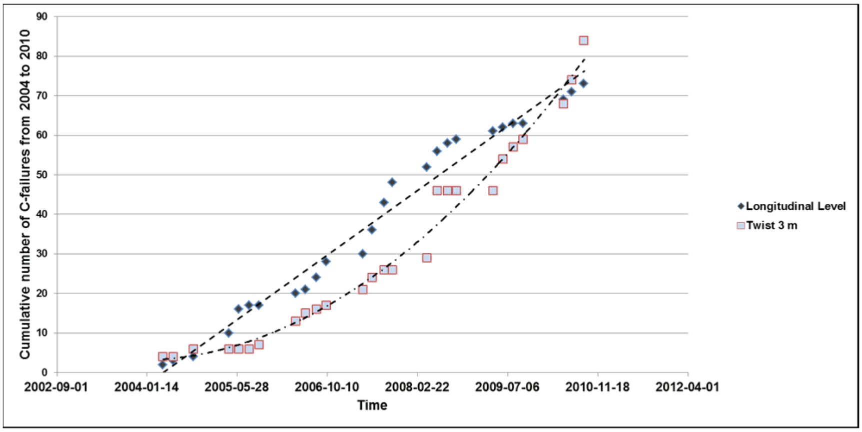


Figure 6.3 Cumulative trends of number of C-failures from 2004 to 2010

Moreover, 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 m or 6 m). This can be related to the dissimilar criticality of each parameter fault in terms of derailment risk. If the size of twist 3 m 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 6 m faults and track gauge faults are 25 mm and 1470 mm respectively.

To optimise 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 6.4. The figure shows the distribution of identified C-failures for two geometry parameters: longitudinal level and twist 3 m. For the other geometry parameters, including cant, alignment and twist 6 m, the trend is similar to that shown by twist 3 m.

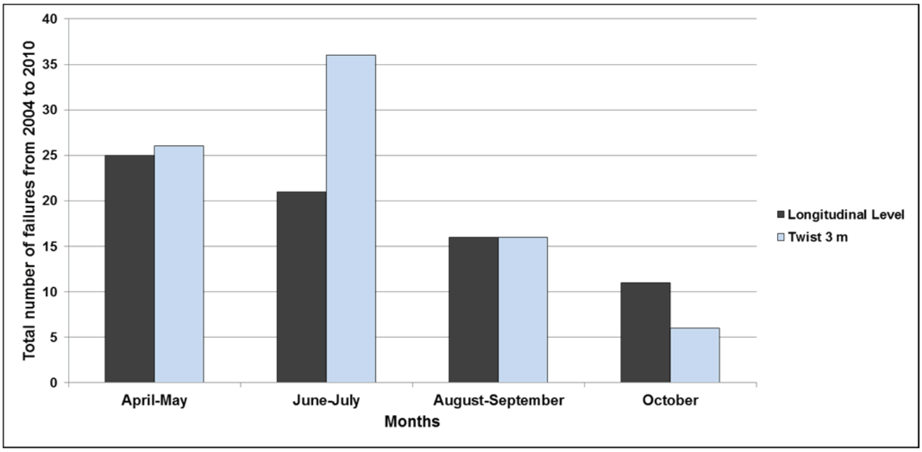


Figure 6.4 Number of detected C-failures on each inspection

To interpret the variation of failure occurrences in different seasons, factors such as climate and temperature, drainage and maintenance strategy should be considered. Figure 6.5 shows the minimum, maximum and average temperature observed in Gällivare for each month between 2004 and 2010. 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, a trend identified by the increased quantity of detected twist 3 m 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. Drainage reduces track stability and twist usually occurs in track segments with soft subsoil (Lichtberger, 2005); this explains the increase in detected twist faults during June and July. The increased twist failure rate in April/May to June/July is due to frost boils, while the effect of poor drainage is noticeable in June/July.

To evaluate the entire section and identify subsections with a high probability of failure, it is necessary to evaluate the distribution of longitudinal level failure occurrence in different track segments (see Figure 6.6). Factors such as substructure characteristics, geometrical locations and maintenance history can possibly influence the rate of failure occurrence in different parts of the track.

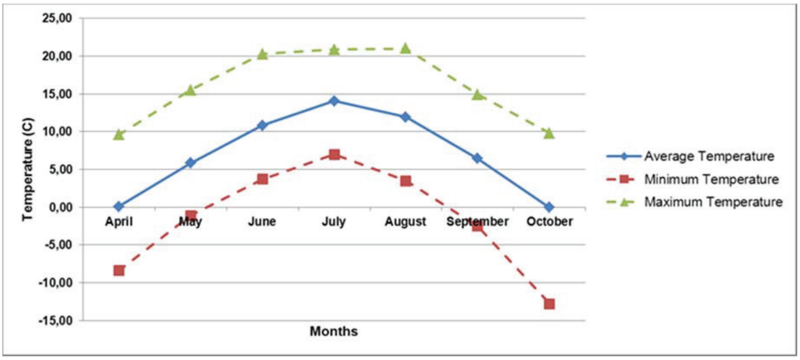


Figure 6.5 Recorded temperatures in Gällivare between 2004 and 2010

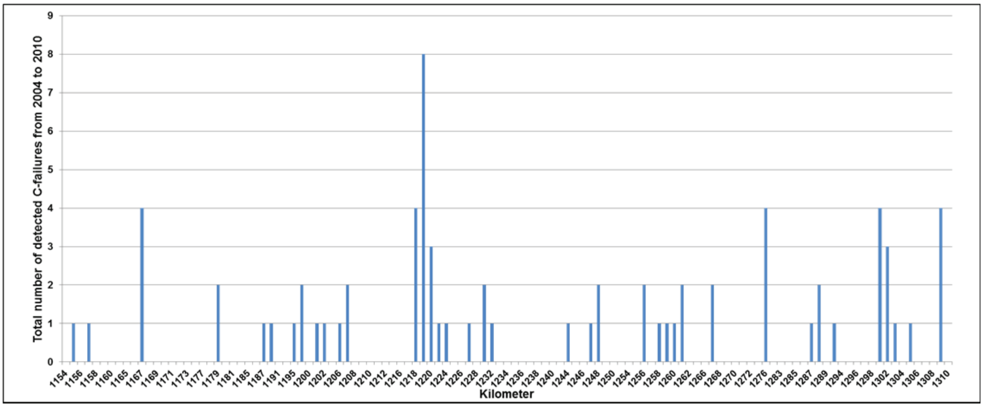


Figure 6.6 Total numbers of longitudinal level C-failures from 2004 to 2010

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 6.7 shows the distribution of the occurrence of longitudinal level faults over kilometre 1218. In this case, four main failures 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 is not effective to remove the root cause of failures since the failures repeatedly recur. For instance, visiting the track reveals a culvert located at kilometre 1218 (indicated by a red circle in Figure 6.8). This culvert, which has an effect on the track stiffness, can be a root cause of the high failure rate on this segment of the track. Figure 6.9 shows a clear bump on the track over the culvert.

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 costs for years afterwards to compensate for the track substructure shortcomings. This can prevented if LCC analysis is used to select a cost effective maintenance action.

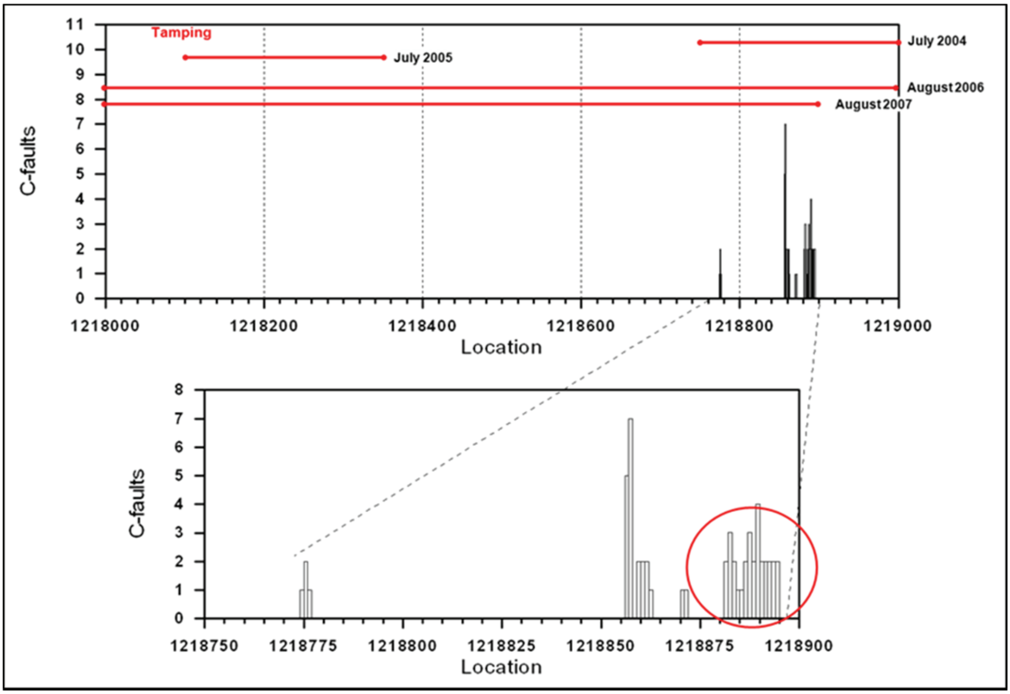


Figure 6.7 Locations of longitudinal level faults over kilometre 1218

Figure 6.8 A culvert under the track

Figure 6.9 The effect of a culvert on the track geometry

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

Paper II 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.

To provide an overview of the tamping frequency, a histogram of the standard deviations of the longitudinal level before tamping is plotted in Figure 6.10. The dashed line represents the IL limit defined by UIC for poor ride 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 IL (2.1 mm) which is classified as a poor track condition in the UIC document. However, a substantial amount of tamping is done at a much higher value than is expected from a ride comfort point of view.

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 ride comfort. On other occasions, tamping is performed at levels exceeding the ride comfort limit; on still other occasions, tamping has not been executed until almost double the level of the ride comfort limit for the 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.

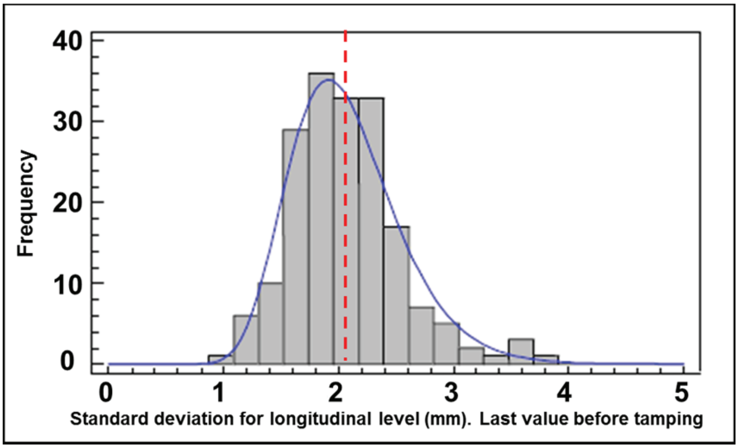


Figure 6.10 Probability density function of tamping execution at different level intervals

Performing maintenance after the IL has been reached can result in lower maintenance efficiency. This means that the initial quality of the track cannot be obtained by normal tamping and more than one tamping operation will be needed to achieve the initial geometry quality. However, performing maintenance more frequently will cause a higher deterioration rate (UIC, 2008). Hence, to reduce maintenance cost and increase efficiency, tamping should be performed before the track quality passes the IL.

An evaluation of tamping efficiency (Figure 6.11) that compares the longitudinal level before and after tamping execution reveals that the tamping efficiency in the majority of the segments falls into the categories of either good or bad. There are two possible reasons for low tamping efficiency. Possibly, only parts of the segment are tamped, not the entire section, but to confirm this, more comprehensive information about maintenance history is required. Alternatively, these particular segments could have bad substructure conditions. It should also be noted that the assessment of tamping efficiency is based on results reported by Austrian Railways which, in turn, are based on different substructure conditions and a dissimilar maintenance strategy.

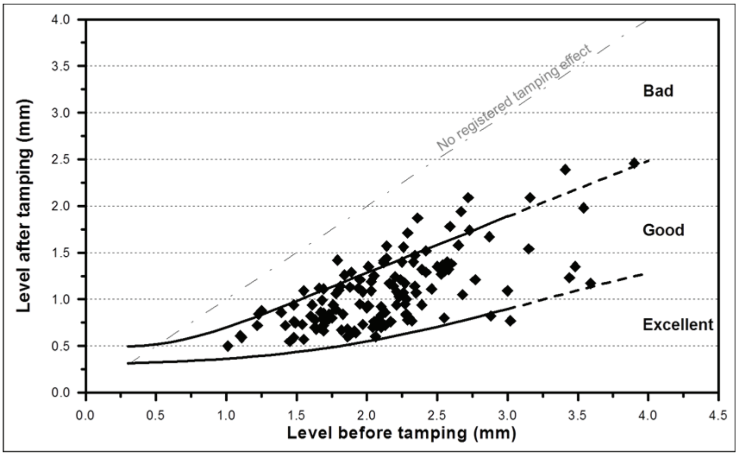


Figure 6.11 Efficiency of tamping

To explore the reasons for the high variability in tamping efficiency, the effects of a number of factors are assessed. The speed and axle load are the same for all track segments. To assess the effect of ballast age on tamping efficiency, all sections are divided into groups based on the ballast age. When the tamping efficiency of each group is evaluated by plotting its data in the tamping intervention graph, no clear effect of ballast age is observed. A comparison of tamping efficiency between the ballast ages of 1987 and 1992 in class 2 appears in Figure 6.12.

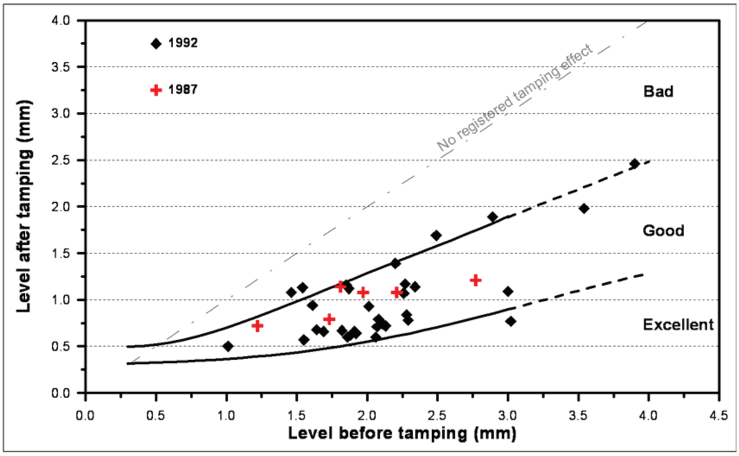
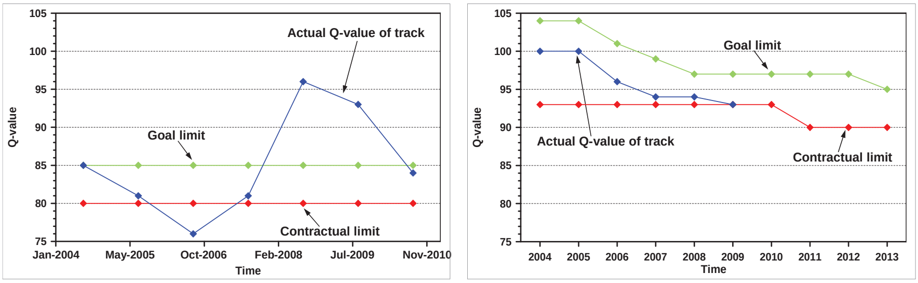


Figure 6.12 Comparison of ballast age in tamping efficiency

Figure 6.13 evaluates the contractor performance from 2004 to 2010 on a case study line (Figure 6.13(a)) and a reference line in central Sweden (Figure 6.13(b)). It should be noted that the contractor is the same for both lines, but the contracts are different.



a) Contractor's performance on the case study line.

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

Figure 6.13 Evaluation of the contractor's performance

The comparison of a contractor's performance on two different lines 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, various 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.

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-values and C-faults.

These findings answer research question two on the effectiveness of Trafikverket's current track geometry maintenance strategy.

Paper III analyses the geometrical degradation of turnouts due to dynamic forces by using two different approaches. In the first approach, two parameters of AR_a and S_{max} are defined. Figure 6.14 shows the variation of the calculated AR_a over time for the turnouts Bfs 2, Sbk 1 and Soa 2. The trend of this parameter before performing maintenance is illustrated by the dashed circles.

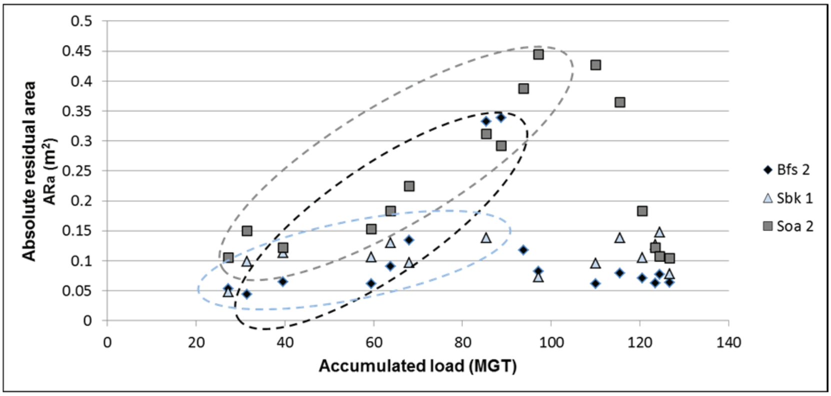


Figure 6.14 Trend of AR_a over time for the turnouts Bfs 2, Sbk 1 and Soa 2

Assuming the longitudinal level of the reference points between the measurement events is constant, a number of results can be obtained from the first approach. As can be seen, the AR_as for the turnouts Bfs 2 and Soa 2 have increased with an increasing accumulated MGT to 0.35 and 0.45 m^2, respectively. Failure reports found in the corrective maintenance report system (0felia) give information on the need to perform corrective maintenance on both turnouts around these points in time (corresponding to 90 and 110 MGT). After performing maintenance, the rate of geometry degradation stayed low and constant for the remaining period of this study. At the same time, the degradation rate for the S&C Sbk 1 is lower than that for Bfs 2 and Soa 2. Nevertheless, corrective maintenance was carried out on Sbk 1 during the same period as the maintenance on Bfs 2, lowering the value from 0.14 to 0.07 m^2. The same pattern is observed for the AR_as for the turnouts Rsn 1, Rsn 2 and Bln 2. The AR_as were lowered by maintenance performed after 90 MGT.

The trends of the S_{max} with an increasing accumulated load in the turnouts Rsn 1, Rsn 2 and Bln 2 are depicted in Figure 6.15. The S_{max} at the crossing position indicates when maintenance is needed. The AR_a seems to be more sensitive to changes than the S_{max}.

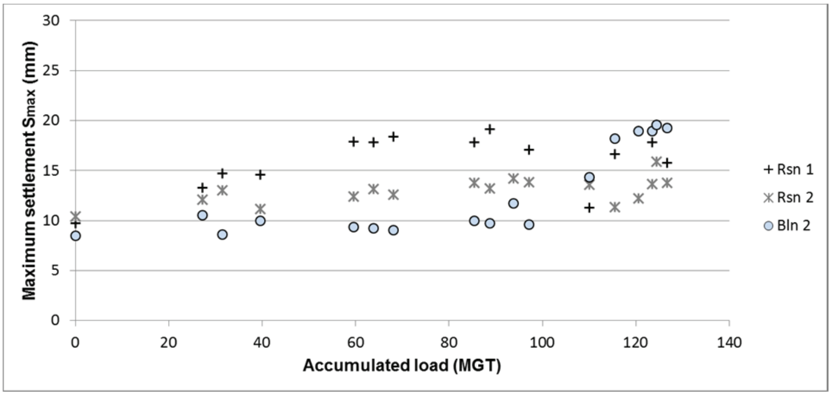
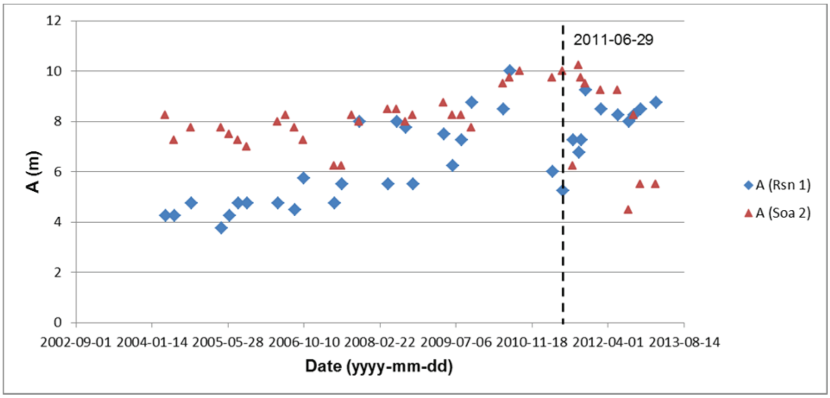


Figure 6.15 Trend of S_{max} for turnouts Rsn 1, Rsn 2 and Bln 2

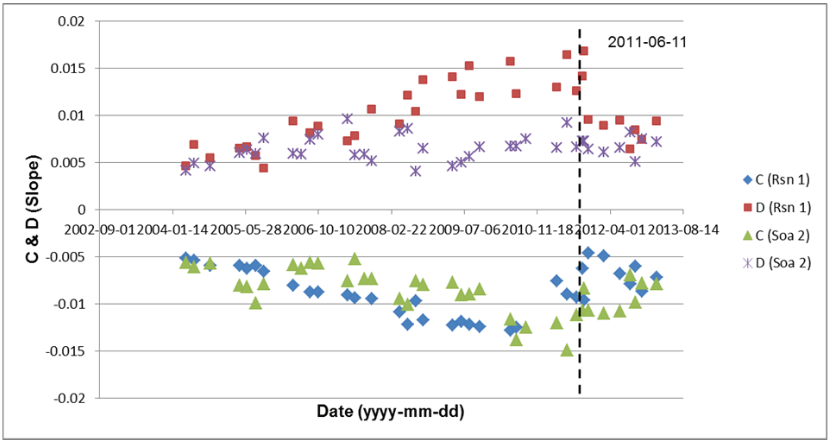
The analysis of the S_{max} & AR_a can be used to estimate the critical residual area in which the maintenance should be performed. However, the shortcoming of this approach is that the longitudinal level of the reference point is considered constant, leading to results that estimate the relative geometrical degradation rate instead of the actual one.

To overcome this shortcoming, various geometry parameters are defined in the second approach to estimate the degradation in each measurement separately.

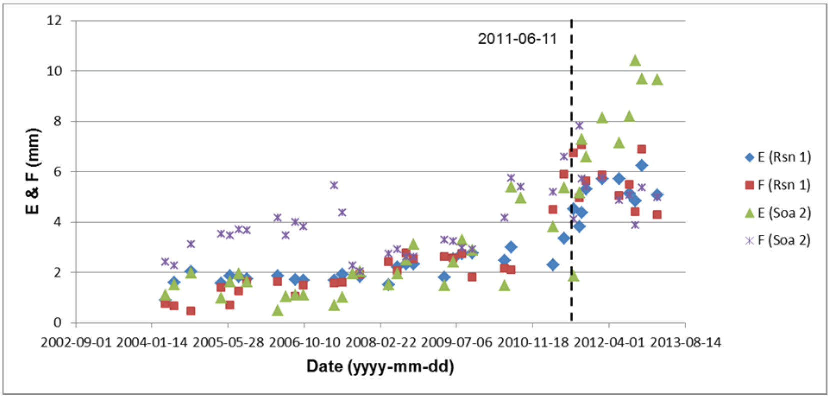
The trends of the defined geometry parameters are shown in Figure 6.16. As can be seen in the figure (part (a)), parameter A in both turnouts has an increasing trend until 2011-06-29. As maintenance was carried out on Rsn 1 after 2010-06-29, the value of A for Rsn1 drops. However, after the maintenance execution, the magnitude of A again increases, reaching 9.5 m by 2011-06-29. At this point, the growing trend ends and the magnitude remains constant. Similarly, the C & D show an increasing trend in both turnouts until 2011-06-11; after this, they demonstrate a reducing trend until they ultimately become stable. This pattern shows that the crossing has continuously settled until it reaches a limit. After reaching this limit, the crossing cannot settle anymore, and the geometry fault widens. As expected, the trend for E & F is similar to that for E' & F'; the degradation grows slightly until 2011-06-11, and after this time, a sharp increase can be seen. To interpret these trends, it is necessary to consider the trends of G and H simultaneously. The G and H grow exponentially until 2011-06-11; at this point, they become constant. This indicates that the geometry fault wave at the crossing has reached its limit (about 25 mm) and the fault has transferred to the next wave in the crossing neighbourhood. This transfer can be perceived by the sharp increase in E/F & E'/ F' trends.


2011-06-29
A (m)
0
2
4
6
8
10
12
2002-09-01
2004-01-14
2005-05-28
2006-10-10
2008-02-22
2009-07-06
2010-11-18
2012-04-01
2013-08-14
Date (yyyy-mm-dd)
A (Rsn 1)
A (Soa 2)

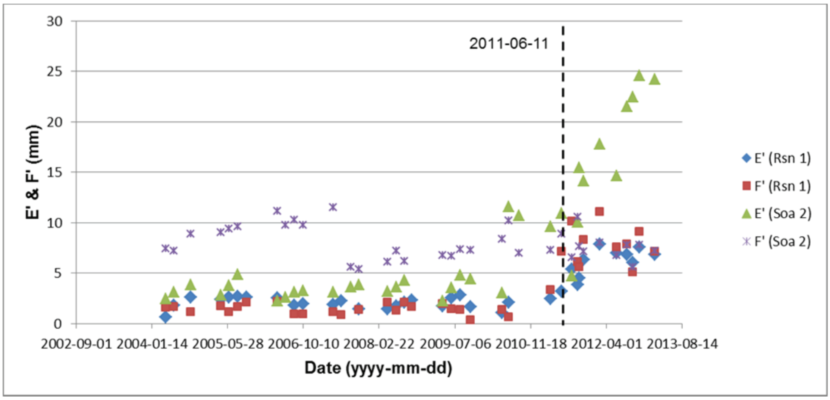
(a)


2011-06-11
C & D (Slope)
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
2002-09-01
2004-01-14
2005-05-28
2006-10-10
2008-02-22
2009-07-06
2010-11-18
2012-04-01
2013-08-14
Date (yyyy-mm-dd)
C (Rsn 1)
D (Rsn 1)
C (Soa 2)
D (Soa 2)

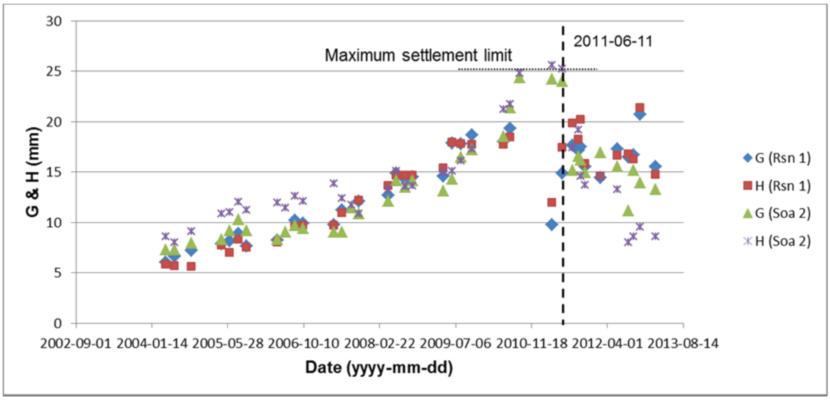
(b)


2011-06-11
E & F (mm)
0
2
4
6
8
10
12
2002-09-01
2004-01-14
2005-05-28
2006-10-10
2008-02-22
2009-07-06
2010-11-18
2012-04-01
2013-08-14
Date (yyyy-mm-dd)
E (Rsn 1)
F (Rsn 1)
E (Soa 2)
F (Soa 2)

(c)



(d)



(e)

Figure 6.16 Trends of the defined Geometry parameters in selected turnouts (a) Parameter A, (b) Parameters C & D, (c) Parameters E & F, (d) Parameters E' & F' and (e) Parameters G & H

Not surprisingly, the results show that the studied turnouts exhibit different geometrical degradation rates. A number of factors such as the traffic, the subgrade quality, the age of the asset and the maintenance strategy selected can have an effect on the rate of degradation. Another important factor is the location and environment in which the turnout has been placed. The qualities of the subgrade and the weather affect the track stiffness; different track stiffness results in dissimilar stress distribution behaviour and, consequently, different degradation rates. The geometry degradation analysis indicates that turnouts should be treated as individuals with different degradation rates and different maintenance frequencies.

The results also indicate that the maintenance has been carried out at different geometry levels for different turnouts. Due to the limited maintenance resources available, it is important to analyse the degradation rate of the asset and to utilise maintenance decision support tools such as RAMS and LCC to define a cost-effective maintenance threshold. This, in turn, will indicate the optimal time for performing maintenance to reduce the cost and increase the availability.

The analysis of geometry parameters (defined in the second approach) provides more accurate and reliable information on the deepening and widening growth rate due to the accumulated loads along the life cycle course of turnouts. It also indicates the limits for maximum track settlement in the crossing section.

These findings answer research question three regarding geometrical degradation in turnouts.

Paper IV discusses optimisation of the track geometry inspection interval and aims to minimise 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 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).

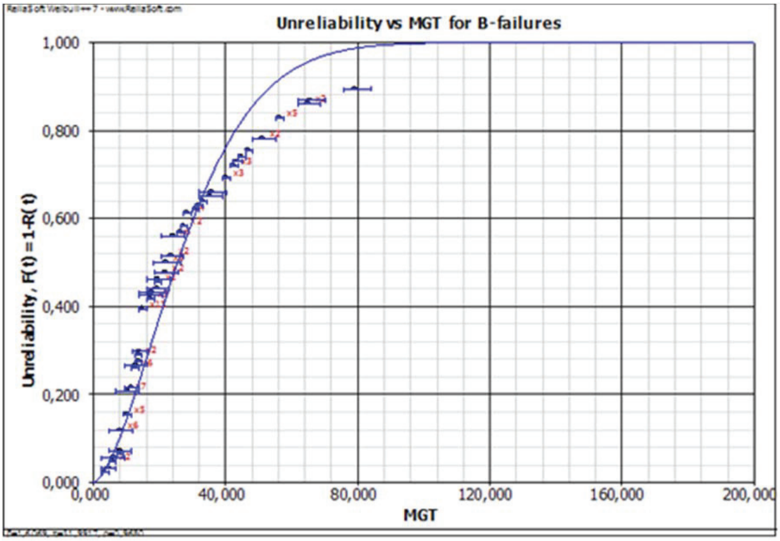
Time-to-failure data collected from BIS and Optram databases are inputted to calculate the probability of the distribution of failures. Since the exact times of the occurrence of the fault are not known, the fault time data are considered as interval-censored data, whereby the object of interest is not constantly monitored. Thus, the inspection times in terms of MGT are used as interval ranges for fault times. The segments without any fault occurrences over the studied time period are also considered right-censored data.

The probability distribution analysis, performed using Weibull++7 software, shows that for B-faults, the lognormal distribution is the best fitted distribution at ρ=0.9889. The Weibull distribution provides the best fit for C-faults and safety faults data sets. Since the Weibull distribution is a flexible distribution which can be used to model many types of failure rate behaviour (Rausand and Høyland, 2004) and because the difference between ρ values obtained from the Weibull distribution and the lognormal distribution is very small, the Weibull distribution is also used to estimate the probability of B-faults (see figure 6.17). The parameter values of the Weibull distribution and the value of the correlation coefficient (ρ) of each distribution for B-faults, C-faults and twist (3 m and 6 m) are shown in Table 6.1.

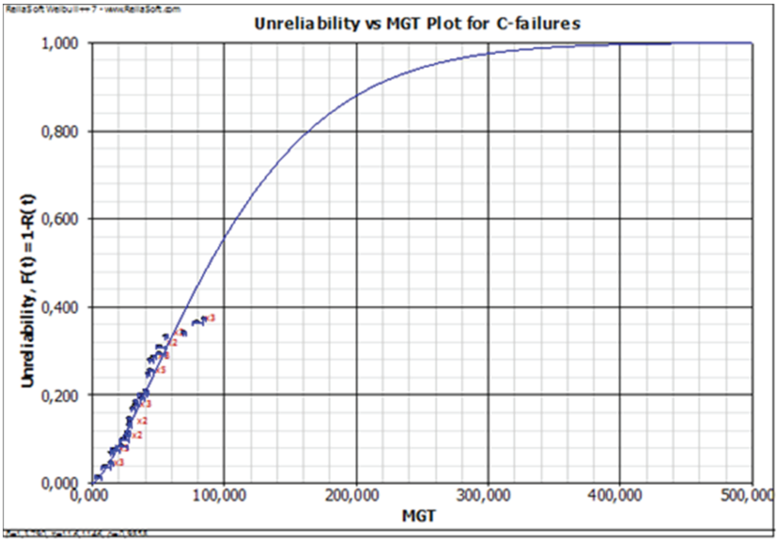
Table 6.1 The characteristics of pdf of B-failures, C-failures and twist (3 m and 6 m)

Type of failures	Type of distribution	Values of distribution parameters		ρ
		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 (3 m & 6 m)	Weibull 2parameters	1.857	329.771	0.971

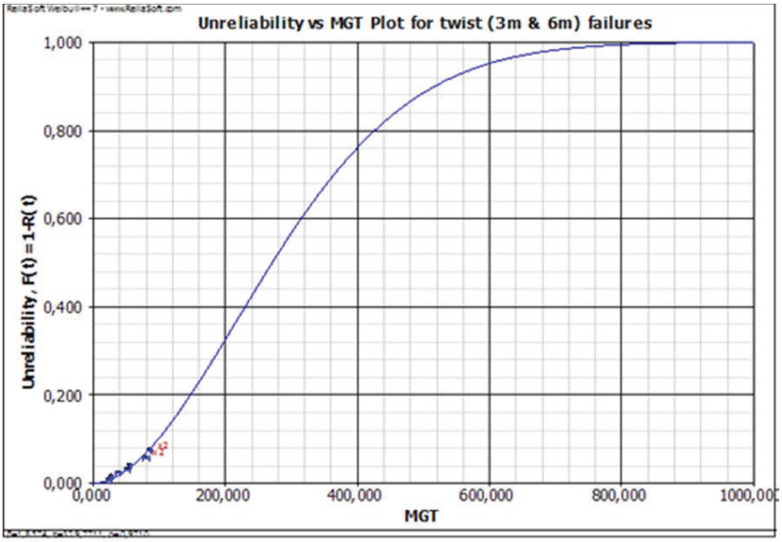
The results show that by expanding the inspection interval from every 2 months to every 4 months, the total maintenance cost per MGT will decrease. The slow degradation rate in the majority of track segments results in the very low probability of the occurrence of C-faults and safety faults (twist in this study) within short time intervals. The probability distribution of the occurrence of both types of faults is a two-parameter Weibull function. The Weibull scale parameters (η) of C-faults and twist are 116.114 and 329.771 MGT respectively. η is also known as the characteristic life; this means that 63.2% of the faults occur by the characteristic life point, regardless of the value of shape parameter (β) (Dodson, 2006). This means that 63.2% of C-faults and twist faults occur at around 116 and 329 MGT load cycles, respectively.



(a)



(b)



(c)

Figure 6.17 Cumulative distribution functions of geometry faults versus MGT (a) B-faults, (b) C-faults and (c) twist (3 m & 6 m) failures.

The obtained results are based on certain assumptions. One assumption is that all track segments are identical regardless of geometric characteristics, location (curve or tangent), substructure characteristics and construction time and maintenance history. However, as shown in Figure 6.1, the degradation rates of the tangent segments vary significantly. To reduce the risk and ensure the safety level, 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. Another assumption is that the effectiveness of the maintenance is perfect. However, as shown in figure 6.11, the tamping efficiency can be dissimilar in different track sections. Note that "track memory" which results in sudden settling of the ballast in a short interval after tamping is not considered in this model. The probability distributions of faults used in the analysis are obtained based on the current maintenance strategy, but any change in maintenance strategy may result in different probability distributions. Further study is required to analyse the effect of variations in probability distribution on the optimal inspection interval.

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

In Paper V, a cost model is proposed to specify the cost-effective maintenance limits for track geometry maintenance. The proposed model considers the degradation rates of different track sections and takes into account the costs associated with inspection, tamping, delay time penalties and risk of accidents due to poor track quality.

To cover all observed tamping efficiencies, the model is run for two scenarios; the optimum and the worst scenario. The optimum scenario uses the high efficient maintenance bound, while the worst scenario considers the low efficient maintenance bound (see Figure 6.18).

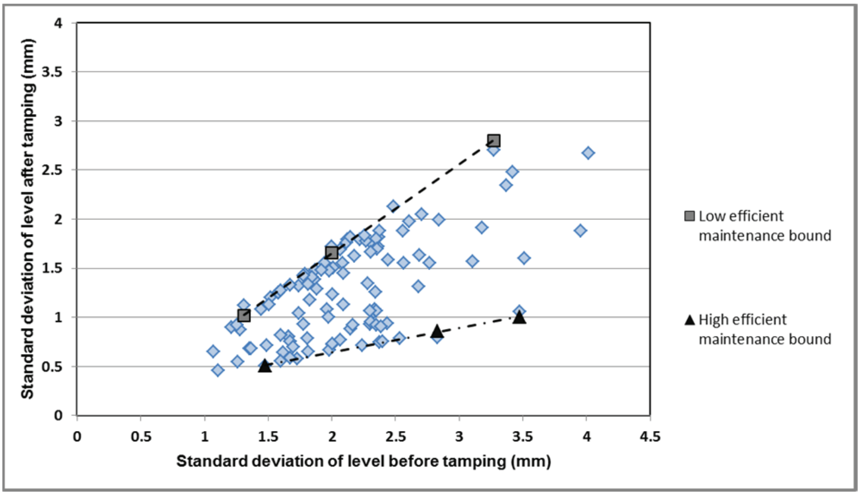


Figure 6.18 Observed tamping efficiency within studied time interval

The simulation is performed for the time interval from 2013-04 to 2017-10. The total maintenance cost per MGT for each IL is shown in Figure 6.19. Depending on the maintenance efficiency, the actual maintenance cost for each scenario can vary between the high and low efficient maintenance boundaries (grey dashed area in Figure 6.19). As can be seen, the seventh scenario (IL = 2 mm) is the most cost-effective alternative.

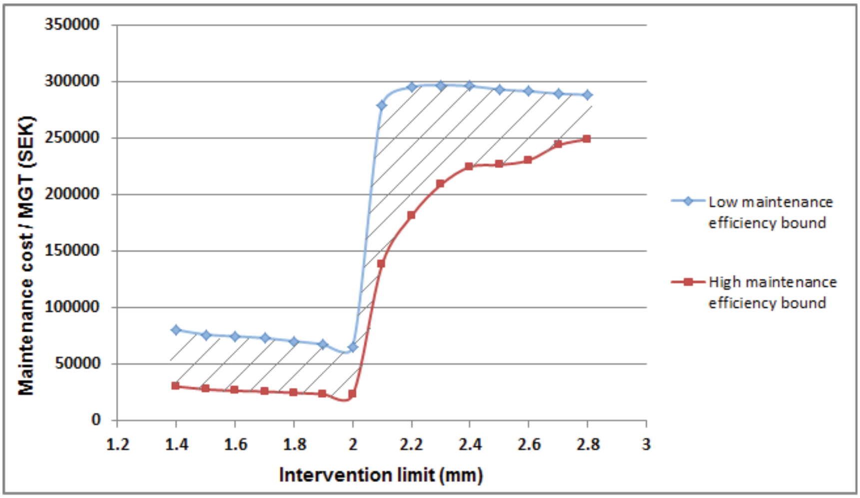
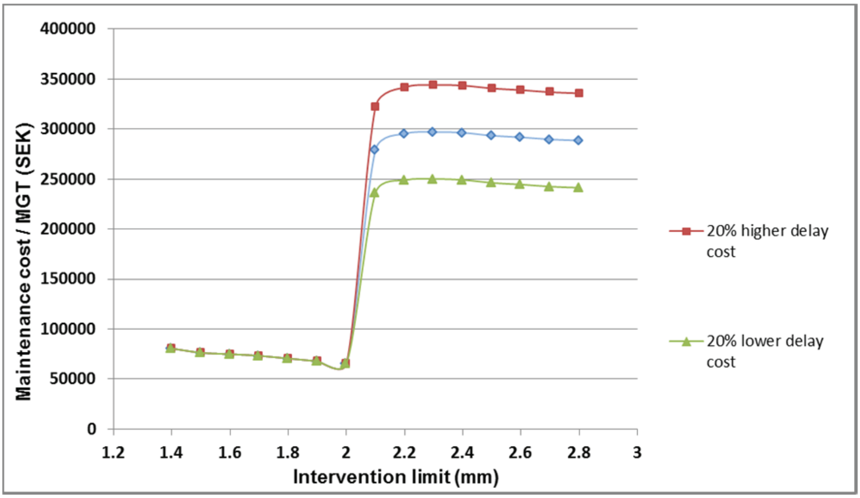
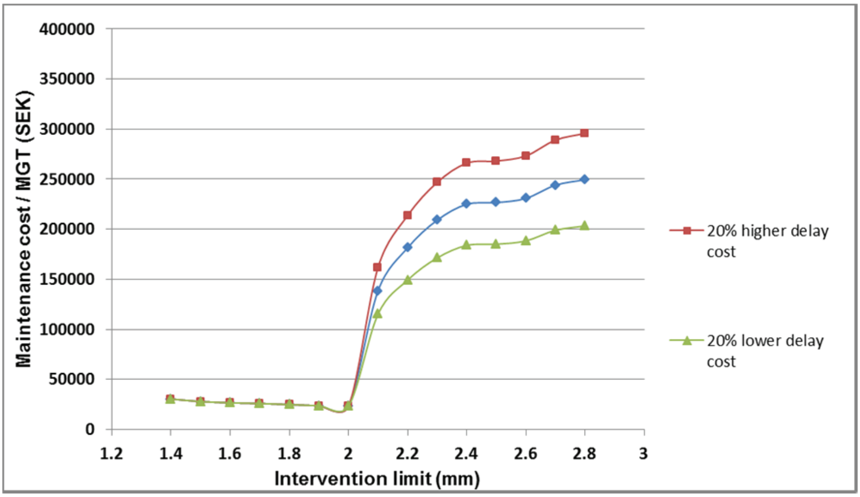


Figure 6.19 Comparison of maintenance cost per MGT for different intervention limits

The main reason for a sharp increase in maintenance cost by selecting the IL equal to or greater than 2.1 mm is the capacity loss cost due to speed reduction of passenger trains within a one-month planning horizon time interval. In different seasons and different regions, the demand rate for passenger trains can differ. This will result in variations of delay time penalties. To investigate how much the delay cost affects the total maintenance cost, the model is run with 20% higher and 20% lower delay costs than the value selected earlier (i.e. 450 SEK). The results are shown in Figure 6.20 (a) & (b).



(a)



(b)

Figure 6.20 Variation of delay cost in total maintenance cost (a) low efficient maintenance (b) High efficient maintenance

The results show that the most cost-effective IL for the standard deviation of the longitudinal level on the studied line is 2 mm. When higher IL are selected, the maintenance frequency (and total maintenance cost) is reduced, but when it reaches 2.1 mm, the passenger trains must reduce their speed to preserve safety and comfort. This does not affect the speed of iron ore trains, as the maximum speeds of loaded and unloaded iron ore trains are 60 and 70 km/h respectively. However, the additional capacity loss cost due to the speed reduction of passenger trains will result in a sharp rise in the total maintenance cost. It should be noted that the traffic disruption from the speed reduction of passenger trains has an effect on the schedule of iron ore trains. Any delay over 2 hours will result in cancellation of one iron ore train which costs 5,000,000 SEK.

The cost-effective IL should be specified for different track quality classes. The results of this study fit the quality class 2 of the studied line. In the south of Sweden, due to greater demand, the lines have better quality classes, allowing the trains to run at higher speeds. Therefore, lower intervention limits must be selected for tamping.

Also, as mentioned earlier, the delay time penalties depend on the demand rate. In the regions with a greater demand for passenger trains, the capacity loss cost increases. For instance, the delay time penalty in the south of Sweden is around 1200 SEK per minute; i.e. about 3 times higher than in the north. Therefore, keeping the track quality in acceptable condition to prevent any speed reduction is much more important in the south.

Although selecting IL=2 mm will result in the lowest maintenance cost, the amount of savings generated by deferring maintenance from 1.4 mm to 2 mm is not considerable. Allowing the track to deviate to higher levels can affect the energy consumption, ride comfort, and degradation rate of other components, and lead to faster settlement after tamping due to "track memory" etc. Therefore, in the long run and by considering the whole railway system, it may be more beneficial to select a lower IL than 2 mm.

The results also illustrate the impact of maintenance efficiency on the total maintenance cost. Efficient maintenance can help to reduce the total maintenance cost significantly.

The obtained results are based on certain assumptions. The degradation rate of track segments is assumed to be constant over time. However, due to the deterioration of track components such as ballast, the geometry degradation rate can increase over time. Higher degradation rates lead to more frequent maintenance which affects the total maintenance cost. In addition, the study uses a model consisting of direct and quantitative cost parameters; indirect cost parameters, such as the effect of lower track quality on the degradation rate of other components, are not considered. But low quality track may affect the degradation rates of other parts, such as wheel-sets, thereby increasing the total maintenance costs. By including the indirect and qualitative cost factors, a more reliable cost-effective intervention limit for tamping can be obtained.

These findings answer research question five on specifying cost-effective maintenance limits.

CONCLUSIONS AND FURTHER RESEARCH

The research in this doctoral thesis has focused on developing approaches to convert condition-monitoring data into useful information for the maintenance decision making process for a railway infrastructure. The proposed approaches cover estimating track geometry degradation, assessing maintenance efficiency, specifying cost-effective inspection intervals and determining cost-effective maintenance limits. The following conclusions are drawn from this study.

- Tamping execution is not effective in some segments 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.
- 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.
- It introduces two new approaches to analyse the geometrical degradation of turnouts due to dynamic forces generated from train traffic. In the first approach, the recorded measurements are adjusted at crossing point and then the relative geometrical degradation of turnouts is evaluated by using two defined parameters, the absolute residual area (AR_a) and the maximum settlement (S_{max}). In the second approach, various geometry parameters are defined to estimate the degradation in each measurement separately.
- A limit for crossing position settlement can be defined. It can be used as a criterion for maintenance decision making.
- Before reaching this limit, the vertical degradation rate at the crossing point (deepening) is higher than the degradation rate in the vicinity of the crossing (widening). However, after reaching the settlement limit, the crossing can no longer settle and the geometry faults transfer to the next waves in the crossing neighbourhood.
- In the current maintenance strategy, the probability of fault occurrence in short time intervals is quite low since the majority of track segments have slow degradation rates.
- Degradation rates and the efficiency of tamping on different tangent segments of the track vary considerably.
- To reduce risk and ensure the safety level, track sections with high degradation rates should be monitored and restored more frequently; this requires shorter inspection intervals.
- The capacity loss penalties due to the speed reduction at higher intervention limits can increase the total maintenance cost significantly.

- By improving the maintenance efficiency, the total maintenance cost can be reduced considerably.
- The cost-effective intervention limits should be specified for different track quality classes.

Research Contributions

The research contributions can be summarised as follows:

- Identification of critical track segments and time of year (months) in terms of track geometry fault occurrences (Paper I)
- Evaluation of the effect of climate on failure occurrence (Paper I)
- Development of an approach to assess the efficiency of the track geometry maintenance strategy (Paper II)
- Development of approaches to analyse the geometrical degradation process in turnouts (Paper III)
- Analysis of probability distribution of geometrical fault occurrences over time (MGT) (Paper IV)
- Development of a cost model to identify a cost-effective inspection interval (Paper IV)
- Development of a cost model to determine cost-effective maintenance limits for tamping (Paper V).

Future Research

The following areas are recommended for further research:

- The development of a Markov model for track geometry degradation to facilitate optimal maintenance planning;
- The development of a comprehensive cost model for specifying cost-effective maintenance limits which considers all geometry parameters, including track aging and indirect cost factors such as the effect of poor track quality on degradation rates of other components;
- The development of a geometrical degradation model for turnouts which correlates all the parameters defined in this study.
- The implementation of approaches, which developed to analyse geometrical degradation of turnouts, on other track sections where the track stiffness varies, such as tunnels, bridges, culverts.

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APPENDED PAPERS

PAPER I

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

Arasteh khouy, I., Juntti, U., Nissen, A. and Schunnesson, H. (2012). Evaluation of track geometry degradation in Swedish heavy haul railroad - A Case Study. *Published in International Journal of COMADEM*, 15(1), 11-16.

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

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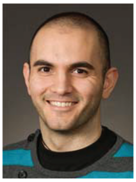

Mr. Iman Arasteh khouy obtained his M.Sc. in Maintenance Management and Engineering in 2008 from Luleå University of Technology (LTU) and Sharif University of Technology. He is currently a doctoral student at LTU in the area of operation and maintenance of railway infrastructure.

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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].

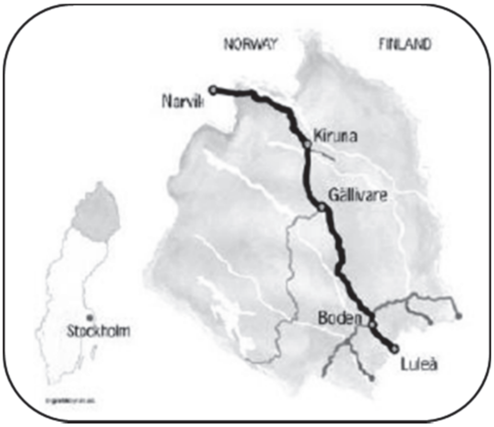

Figure 1: Iron ore line from Luleå to Narvik [11]

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:

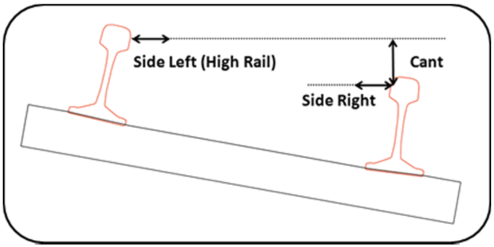

Figure 2: Calculation of σ_S

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

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

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

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).

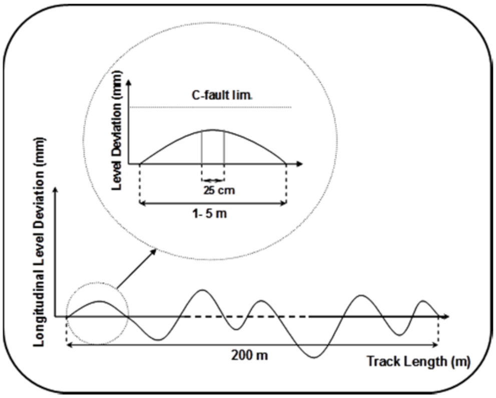

Figure 3: Illustration of C-fault limits

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

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

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 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 3 m. For the other geometry parameters, including cant, alignment and twist 6 m, the trend is similar to the trend shown by twist 3 m.

To interpret the variance of failure occurrence in different months, some factors such as climate and temperature, drainage and maintenance strategy should be considered. Figure 5 shows the minimum, maximum and average temperature which has been observed in Gällivare on each month between 2004 and 2010. 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 3 m 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 boils and poor drainage are two other possible reasons for the high rate of failure between April and July. Frost boil is a track displacement cause by the melting of ice within the upper surface of subgrade or within the ballast section. Since poor drainage reduce track stability and by considering that twist usually occurs in track segments with soft subsoil [16], the growth of detected twist faults during June and July can be explained.

The effect of frost boils on failure occurrence rate can be observed from April/May to June/July by raise of twist failure rates. The effect of poor drainage is visible in June/July by considering the highest number of detected failures.

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 3 m. 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 3 m increases over time, possibly indicating an aging effect. The rates of C-failure for cant, alignment and twist 6 m show an aging trend similar to that shown by twist 3 m. The curve trend can indicate an aging effect, but the other reasons for this behaviour cannot be excluded. 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.

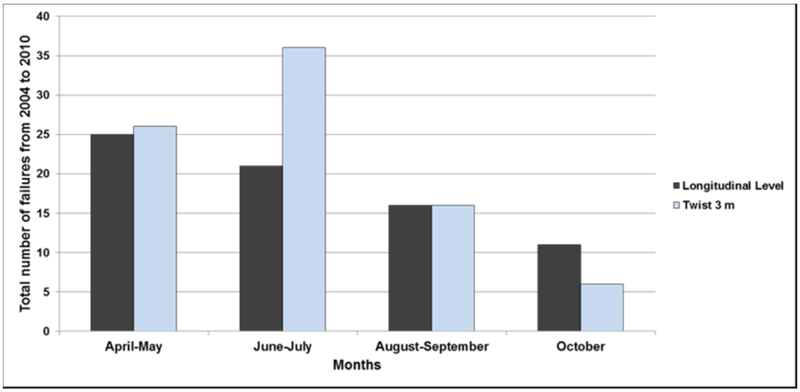

Figure 4: Number of detected C-failures on each inspection

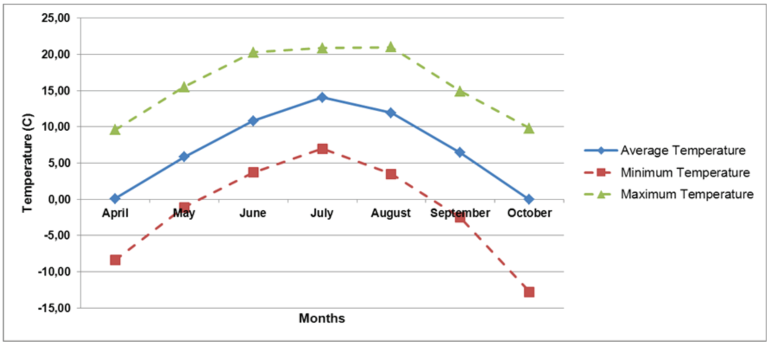

Figure 5: Temperature has been observed in Gällivare between 2004 and 2010

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 m or 6 m). This can be related to the dissimilar criticality of each parameter fault in terms of risk of derailment. If the size of twist 3 m 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 6 m faults and track gauge faults are 25 mm and 1470 mm respectively.

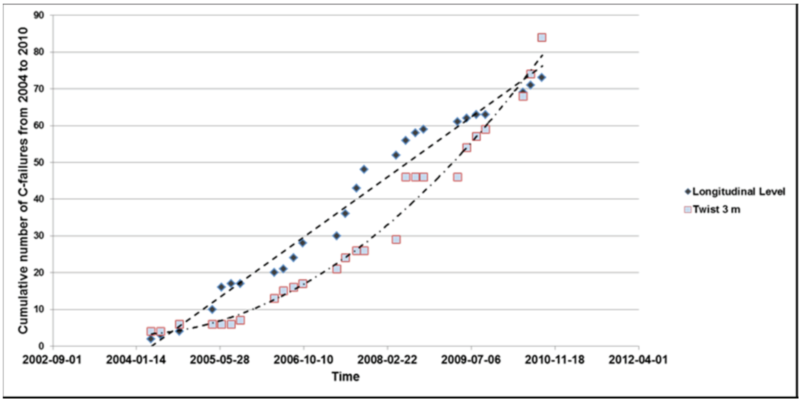

Figure 6: Cumulative number of C-failures from 2004 to 2010

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 1218 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. For instance, visiting the track showed that on the part of the kilometre 1218 that is emphasized with red circle in the figure 8, there is a culvert (Figure 9). This culvert, which has an effect on the track stiffness, can be a root cause of high failure rate on this segment of the track. Figure 10 shows a clear bump on the track over the culvert.

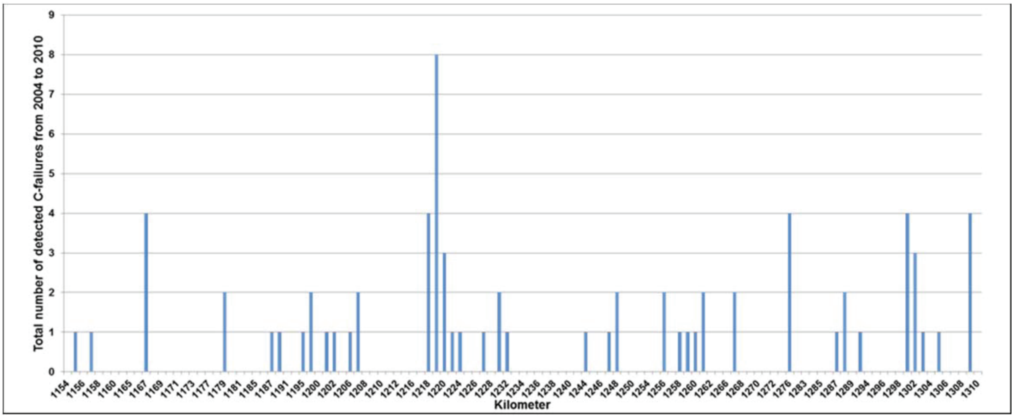

Figure 7: Total number of longitudinal level C-failures from 2004 to 2010

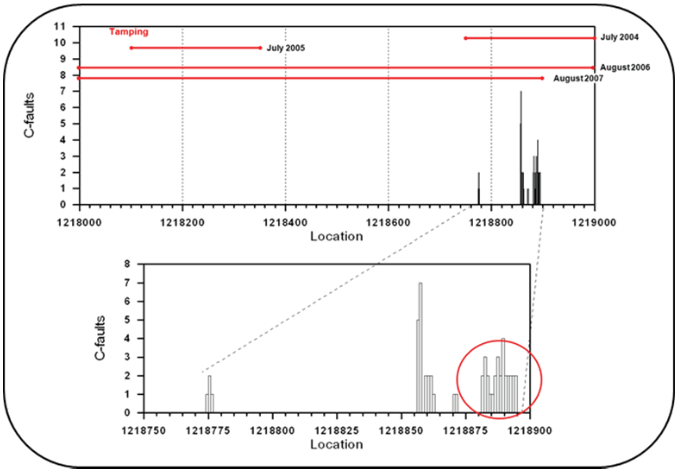

Figure 8: Locations of longitudinal level faults over kilometre 1218

Figure 9: A culvert under the track

Figure 10: The effect of culvert on the track geometry

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

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 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.

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PAPER II

Evaluation of track geometry maintenance for a heavy haul railroad in Sweden - A Case Study

Arasteh khouy, I., Schunnesson, H., Juntti, U., Nissen, A. and Larsson-Kråik, P-O. (2013). Evaluation of track geometry maintenance for heavy haul railroad in Sweden - A Case Study. *Published in Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.*

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Evaluation of track geometry maintenance for a heavy haul railroad in Sweden: A case study

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Abstract

The measurement and improvement of track quality are key issues in determining both the restoration time and cost of railway maintenance. Applying the 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 evaluate track geometry maintenance 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 evaluates the performance of the maintenance contractor and discusses the importance of the functional requirements stated in the outsourcing contracts.

Keywords

Maintenance, railway track geometry, tamping

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Introduction

Today's railway industry handles an increasing number of trains that travel at higher speeds and have higher axle loads; this combination of circumstances can result in faster degradation of railway assets and higher maintenance costs. To ensure track safety and maintain high quality standards, an optimized and cost-effective track maintenance strategy is required that is 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). The parameter that usually drives the need for tamping is the short wavelength longitudinal level.[1] In Sweden, the annual cost of tamping is about 100–120 MSEK (approximately 11–13.5M€), and the total amount of tamped track is around 1700 km, about 14% of the total track length.[2]

Empirical models of track geometry degradation to create a better understanding of the degradation have been reported in the literature.[3–5] Several studies have been performed on ballast degradation due to cyclic loads[6–8] and the effects of variables such as speed and axle load on track deterioration have also been investigated.[9–11] However, it has been claimed that current standards and assessment methods may not be adequate for track maintenance, since they do not consider dynamic responses at the wheel–rail interface.[12,13]

In this paper, the Swedish Transport Administration's (Trafikverket) strategy for tamping is described, its efficiency evaluated and the quality and accuracy of data discussed. However, this study does not analyse the ballast degradation and its effect on track geometry degradation; it only considers the longitudinal level due to its significant effect on track quality. To this end, track geometry data from a section of the iron ore line (Malmbanan) between Boden and Gällivare in northern Sweden are considered. It has been found that time utilization in tamping is not very effective[2] with only about 25% of the available time being used for maintenance execution. The main reason for this low efficiency is the limited amount of

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access time to the track. Thus, there is a need to optimize the track geometry maintenance strategy. In particular, an estimation of track degradation and its consequences is required to optimize track maintenance.[14] With this knowledge, the right time for inspection, maintenance and renewal can be estimated.

Background information about the case study

The iron ore line runs from Narvik to Riksgränsen (Ofotenban) in Norway and from Riksgränsen to Boden in Sweden (Malmbanan). The Swedish mining company LKAB transports iron ore 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 the Malmbanan line from 25 to 30 t and the maximum speed of the loaded train from 50 to 60 km/h. This change is expected to result in higher track geometry degradation levels. In addition to iron ore transportation, the line is used by passenger trains and other freight trains. The train speeds vary from 50 to 60 km/h for loaded iron ore trains, 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 $+25^\circ$C in summer.[15]

Track quality monitoring and maintenance

To monitor track quality, Trafikverket regularly (every 1 to 2 months between April and October) uses an inspection car to measure the deviation of the track using both 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 cm intervals.

Based on these 25 cm 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 equation 1) are calculated for 200 m sections. The standard deviation of the average monitored vertical error for the left and right rail, σ_H, is also calculated for 200 m sections

$$\sigma_S = \sigma_C + \sigma_{SHigh} \tag{1}$$

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 m track sections (see Table 1). The Q-value indicates the quality of the track geometry and is calculated by the following formula

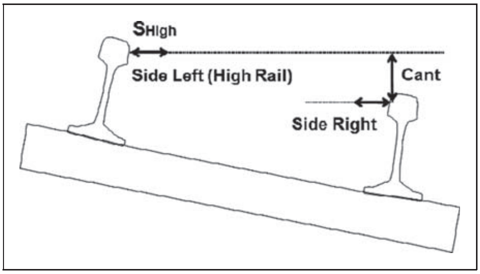

Figure 1. Calculation of σ_S.

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{Hlim}} + 2\frac{\sigma_S}{\sigma_{Slim}}\right]\Big/3 \tag{2}$$

where σ_{Slim} is the comfort limit for the σ_S value, defined for different track classes (see Table 1) and σ_{Hlim} is the comfort limit for the σ_H value, defined for different track classes (see Table 1).

The other index, the K-value, is the ratio between ($\sum l$), 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 (3)

$$K = \frac{\sum l}{L} \times 100\% \tag{3}$$

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 identify the limits for the execution of corrective maintenance (Intervention limits) (see Figure 2) whereas B-faults identify the limits for the execution of preventive maintenance (Alert limits).[16] However, in interviews carried out with the line contractor revealed that, in reality, B-limits are not always used by the contractor as a criterion for preventive maintenance execution. Although these limits are defined for a point failure (25 cm), the fault normally occurs over a length of at least 1 to 5 m due to rail stiffness.

The track of the iron ore line consists of alternating sections with quality classes K2 and K3.[16] Each of these quality classes has a different allowable speed, dissimilar fault thresholds and comfort limits for local trains (see Table 1).

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 the

Table 1. Comparison of the allowable limits between K2 and K3.

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

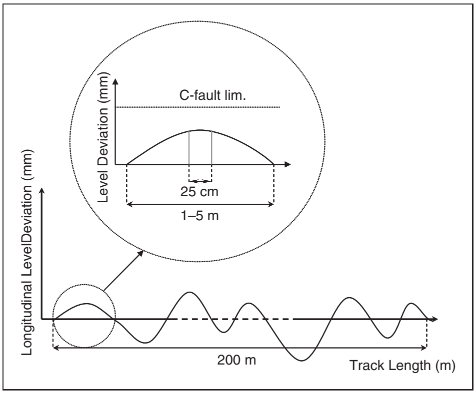

Figure 2. Illustration of C-fault limits.

necessary 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 as a result of a C-fault is considered corrective maintenance; tamping based on 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 (intervention 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 receive a bonus, wheras if it is below the contractual limit, they must pay a penalty.

The main phases of Trafikverket's maintenance strategy are shown in Figure 3. The figure shows how the maintenance decision criteria are used to specify the need for preventive or corrective tamping execution.

Data collection and data treatment

The main steps of the approach, applied in this study (Figure 4), were as follows.

1. Data collection: Inspection and maintenance data were collected for a certain time period.
2. Data processing: The extracted data were processed through consultations with experts. This step was carried out to assess the data quality and to account for missing data.
3. Apply UIC ride comfort limits graph[1]: This graph was used to define an intervention limit based on the maximum allowable speed on the track. This defined limit was applied as a benchmark to evaluate tamping execution at different tamping intervals.
4. Apply UIC tamping intervention graph[1]: The tamping intervention graph, developed by Austrian Railways, was used to evaluate the maintenance efficiency.

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

As the first step, the tamping and inspection data for the selected track for the period 2007–2009 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

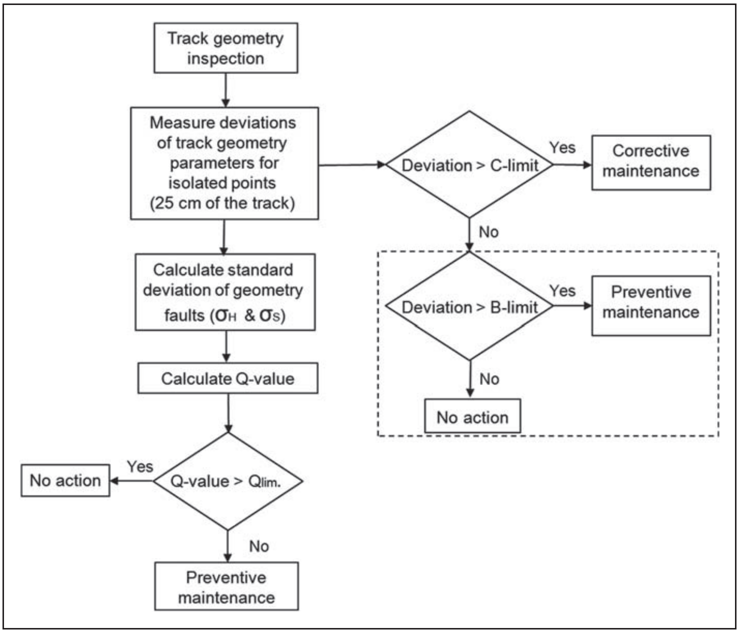

Figure 3. The steps of Trafikverket's maintenance strategy.

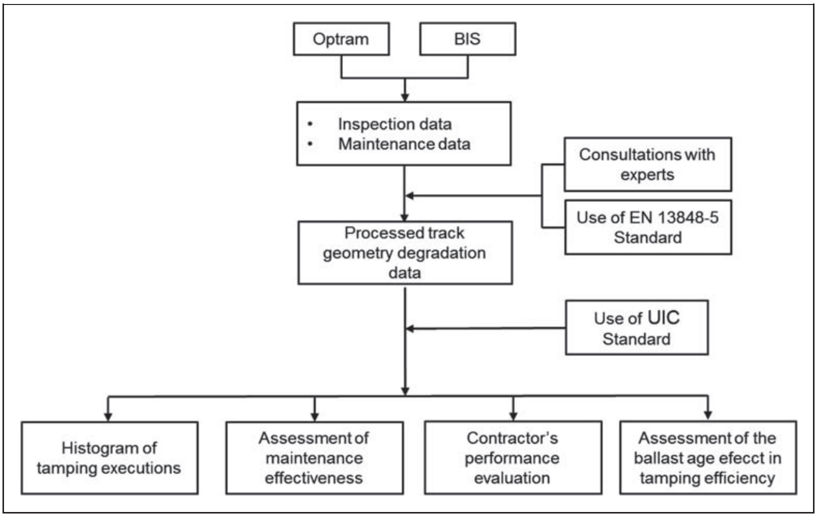

Figure 4. The approach used in this study.

of tamped section, length of tamping, date, etc.) and grinding and curves.[17] Optram is a system implemented in 2009 by Trafikverket to visualize and show graphically the results of time series for track geometry measurements. The system provides functionality for analysis and displays data trends.[18] To gain access to all information on tamping, it is essential to consider both systems.[2]

In BIS, tamping information can be inaccurate, since corrective tamping is not always reported to the system by the contractors because it is not a requirement.[2] Optram, which is based on inspection

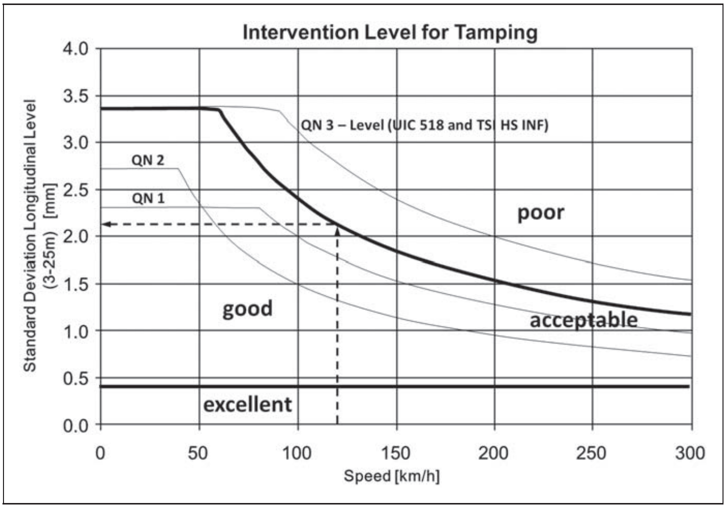

Figure 5. Lines of constant riding comfort at different speeds.[1]

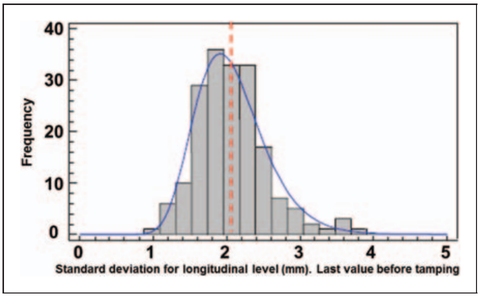

Figure 6. Histogram of tamping execution at different level intervals.

data, is more reliable; however, data in this system is only available from 2007.

The collected data has been reviewed and discussed with experts to assess its quality. The European railway standard EN 13848-5 was also considered to compare and evaluate current maintenance limits in Sweden with the suggested intervention limits in the European standard.[19] The comparison revealed that the recommended intervention limits in the standards have higher values than the maintenance limits in Sweden.

A tamping intervention graph was used To evaluate the performed tamping efficiency.[1] Here, the tamping efficiency is classified as bad, good or excellent based on how much the track quality has been improved after the tamping operation. In the original graph, the maximum value before tamping is 3 mm, and since some of the data in this case study have values larger than 3 mm, the graph was extended using trend regression analysis (this will be clearly demonstrated in Figure 7).

When the longitudinal level value goes beyond the intervention limit (IL), corrective maintenance should be performed. The IL can be defined either for isolated defects or for a 200 m track segment. Trafikverket only defines an IL for isolated defects. When the studied data belong to 200 m track segments, the UIC ride comfort limits graph (‘Lines of constant riding comfort at different speeds’) was used to specify the IL for the longitudinal level of 200 m track segments (Figure 5). When the maximum allowable speed of quality class K2 (120 km/h) is considered, the IL is equal to 2.1 mm. By considering the maximum speed, the IL value becomes more conservative. In this way, all possible failures in the allowable speed range are considered.

Furthermore, the effect of ballast age on tamping efficiency and the performance of the maintenance contractor were evaluated. To assess the contractors’ performances the qualities of track geometry from 2004 to 2010 on a case study line and a reference line in central Sweden were collected.

Results

To provide an overview of the tamping frequency, a histogram of the standard deviations of the longitudinal level before tamping is plotted in Figure 6. The dashed line represent the IL limit defined by UIC for a poor ride comfort at 120 km/h, the maximum allowable speed in the track quality class K2. As shown in the figure, the majority of tamping was executed around the defined intervention limit (2.1 mm) which is classified as a poor track condition in the UIC document. However, a substantial amount of tamping

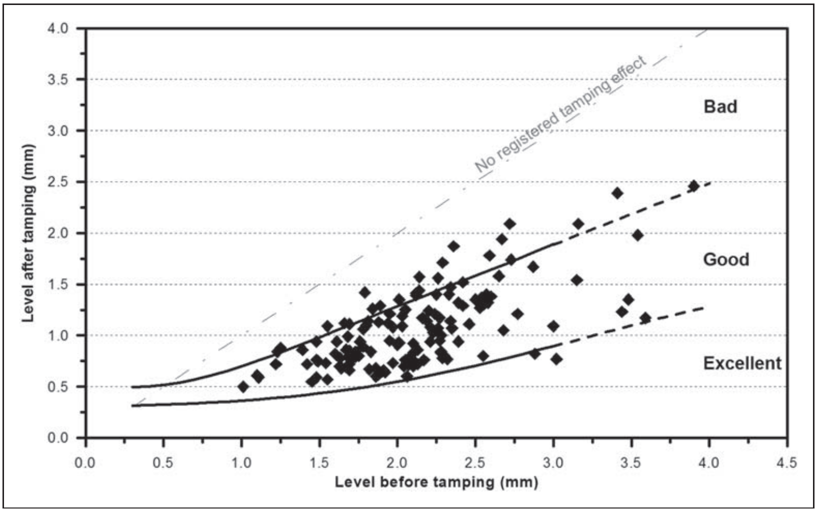

Figure 7. Efficiency of tamping.

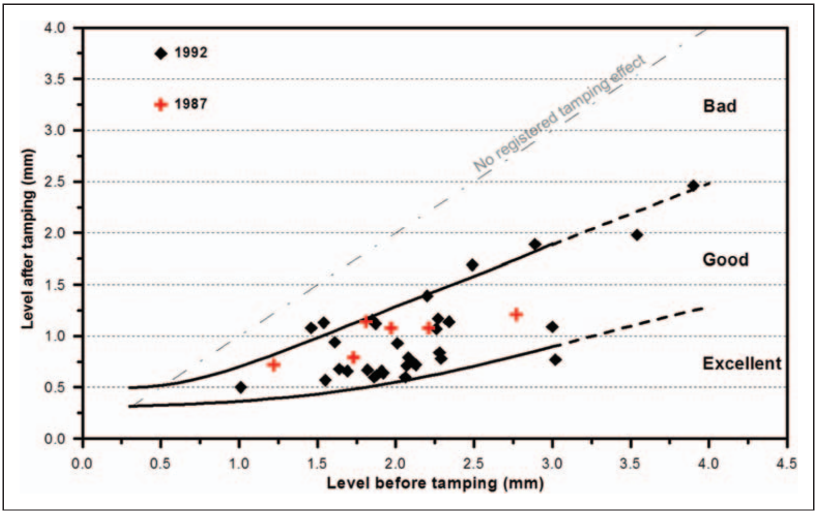

Figure 8. Comparison of ballast age in tamping efficiency.

is done at a much higher value than is expected from a ride comfort point of view.

To evaluate tamping efficiency and to understand the reduction of longitudinal level deviations caused by maintenance, all tamping points were plotted in a UIC 'Tamping Intervention' graph, see Figure 7. 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.

To explore the reasons for the high variability in tamping efficiency, the effects of a number of factors were assessed. The speed and axle load are the same for all track segments. To assess the effect of ballast age on tamping efficiency, all sections were divided into groups based on the ballast age. Then the tamping efficiency of each group was evaluated by plotting its data in the tamping intervention graph, no clear effect of ballast age could be observed. A comparison of tamping efficiency between the ballast ages of 1987 and 1992 in class 2 appears in Figure 8.

Figure 9 evaluates the contractor performance from 2004 to 2010 on a case study line (Figure 9(a)) and a reference line in central Sweden (Figure 9(b)).

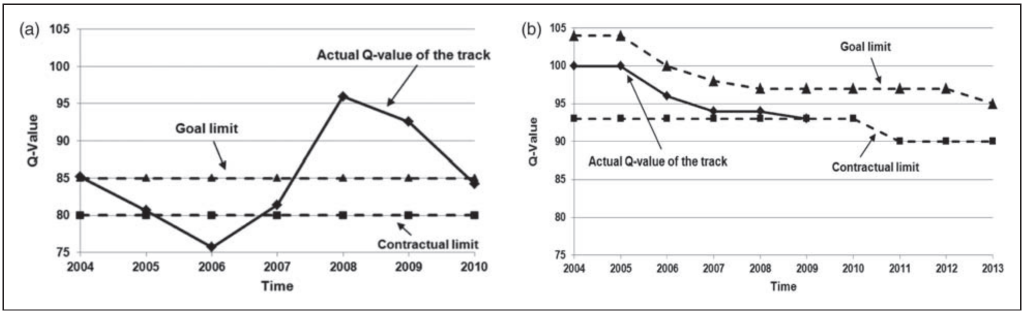

Figure 9. Evaluation of the contractor's performance (a) on the case study line and (b) on a reference line in central Sweden.

It should be noted that the contractor is the same for both lines, but the contracts are different.

Discussion

The case study was designed to analyse the efficiency of track geometry maintenance by 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, graphical inspection data and expert judgment was used.

The standard deviation for the longitudinal level at which tamping is executed varies extensively during the period examined (see Figure 6). Tamping is sometimes executed at a very low level and is, therefore, not motivated by ride comfort. On other occasions, tamping has been performed at levels exceeding the ride comfort limit; on still other occasions, tamping has not been executed until almost double the level of the ride comfort limit for the 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.

Performing maintenance after the IL has been reached can result in lower maintenance efficiency. This means that the initial quality of the track cannot be obtained by normal tamping execution and instead, more than one tamping operation will be needed to achieve the initial geometry quality. However, on the other hand, performing maintenance more frequently will cause a higher deterioration rate.[1] Hence, to reduce maintenance cost and increase its efficiency, tamping should be performed before the track quality passes the IL.

The evaluation of tamping efficiency (Figure 7) reveals that the efficiency is quite low in some segments. Possibly, only parts of the segment are tamped, not the entire section, but to confirm this, more comprehensive information about maintenance history is required. Alternatively, these particular segments could have bad substructure conditions. It should also be noted that the assessment of tamping efficiency is based on results reported by Austrian Railways which, in turn, are based on different substructure conditions and a dissimilar maintenance strategy.

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 a contractor's performance on two different lines (see Figure 9) 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.

Conclusions

The following conclusions can be drawn from the reported study.

1. Available and accurate data on geometry conditions and performed maintenance actions are the main requirements for track degradation analysis. However, the data available for this study are inadequate for precise analysis.
2. The decision-making process for the execution of tamping does not use all defined limits for geometry parameters.
3. Evaluation of the standard deviation for the longitudinal level at which tamping is executed

indicates that the execution of tamping is not optimally planned.

4. 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.
5. 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.

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PAPER III

Geometrical degradation of railway turnouts - A Case Study from a Swedish heavy haul railroad

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Geometrical degradation of railway turnouts - A Case Study from a Swedish heavy haul railroad

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Abstract

Turnouts are critical components of railway track systems in terms of safety, operation and maintenance. Each year, a considerable part of the maintenance budget is spent on their inspection, maintenance and renewal. Applying a cost-effective maintenance strategy helps to achieve the best performance at the lowest possible cost. In Sweden, the geometry of turnouts is inspected at pre-defined time intervals by the STRIX / IMV 100 track measurement car. This study uses time series for the measured longitudinal level of turnouts on the Iron Ore Line (Malmbanan) in northern Sweden. Two different approaches are applied to analyse the geometrical degradation of turnouts due to dynamic forces generated from train traffic. In the first approach, the recorded measurements are adjusted at crossing point and then the relative geometrical degradation of turnouts is evaluated by using two defined parameters, the absolute residual area (AR_a) and the maximum settlement (S_{max}), In the second approach, various geometry parameters are defined to estimate the degradation in each measurement separately. The growth rate of the longitudinal level degradation as a function of million gross tonnes (MGT) / time is evaluated. The proposed methods are based on characterisation of the individual track measurements. The results facilitate correct decision making in the maintenance process through understanding the degradation rate and defining the optimal maintenance thresholds for the planning process. In the long run, this can lead to a cost-effective maintenance strategy with optimized inspection and maintenance intervals.

Index Terms: Turnouts, Track geometry degradation, Maintenance decision, Maintenance thresholds.

1. Introduction

Today's railway industry handles an increasing number of trains that travel at higher speeds and have higher axle loads; this combination of circumstances results in faster degradation of railway assets and higher maintenance costs. However, high quality track standards can be maintained by shifting the focus of the maintenance strategy from meeting safety limits to obtaining cost-effective maintenance thresholds through reliability and life cycle cost analyses.

Turnouts are one of the main subsystems of railway superstructure in terms of safety, operation punctuality and maintenance cost. A study of train delay statistics for the period 2001-2003 in the Swedish railway system shows that the share of S&C failures in the total number of infrastructure-related delays is about 14% [1]. In 2009, the maintenance cost of turnouts in Sweden was around 8% of the total maintenance cost [2].

Both static and dynamic loads cause the turnouts to deteriorate due to [3]:

- geometrical degradation
- tear, wear and plastic deformation of components

Several studies have modelled the track geometry degradation process [4,5,6]. Some researchers have also proposed models to optimise track geometry maintenance by increasing the track availability and reducing the maintenance cost [7,8]. However, most studies have been conducted for plain tracks, i.e. straights and curves. Particularly in the case of turnouts, only a few attempts have been made to model degradation in addition to optimising maintenance. An exception is Zwanenburg who modelled the degradation process of turnouts for maintenance and renewal planning on the Swiss railway network [3]. The European project, INNOTRACK, has specified the key parameters for monitoring turnouts by using the FMECA (Failure Mode Effects and Criticality Analysis) method [9]. The INNOTRACK project has also studied the optimisation of turnouts by optimising the geometry and track stiffness [10].

Some researchers have examined the dynamic interaction between the train and the turnout to simulate the wear, rolling contact fatigue (RCF) and plastic deformation in turnout components [11,12]. Others have evaluated the effects of the switch angle and frog angle on the wear rate. For instance, Elkins et al. concluded that the wear at the switch should be reduced by decreasing the switch entry angle [13].

The present study uses time series for the measured longitudinal level of turnouts on the Iron Ore Line (Malmbanan) in northern Sweden to analyse the vertical geometry degradation rate due to dynamic loading forces generated by train traffic. It also evaluates the growth rate of the longitudinal level degradation as a function of million gross tonnes (MGT). Note that the deterioration of turnout components in terms of wear, RCF and plastic deformation has not been analysed.

2. Background to the studied line

The Iron Ore Line runs from Narvik to Riksgränsen (Ofotenban) in Norway and from Riksgränsen to Boden in Sweden (Malmbanan). 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 Fig. 1). In 2000, LKAB increased the axle load on the Iron Ore Line from 25 to 30 tonnes and the maximum speed of the loaded train from 50 to 60 km/h.

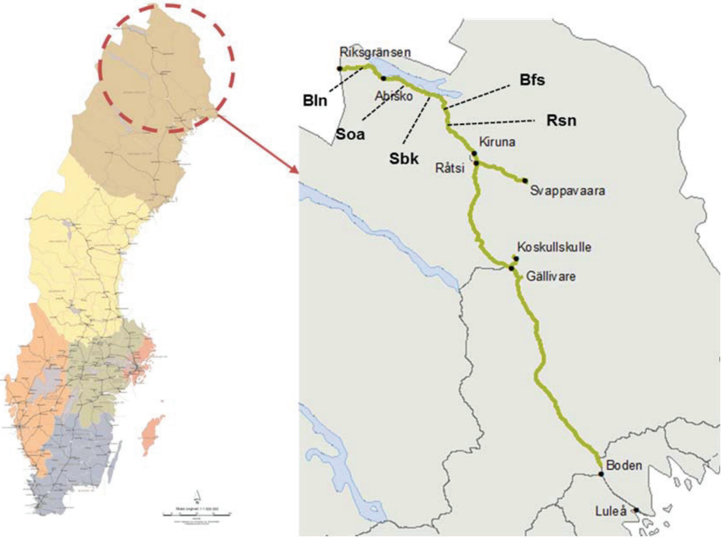


Figure 1: Iron Ore Line from Boden to Riksgränsen [14]

The turnouts selected for the study are from the main line in track section 111, between Kiruna and Riksgränsen (see Fig. 1). In addition to the iron ore trains, the line is used by two passenger trains per day. 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 of the line is about 28 MGT. The track consists of UIC 60 rails (UIC standing for International Union of Railways) and concrete sleepers. The ballast type is M1 (crushed granite) (SS-EN 13450), and the track gauge is 1435 mm. The region is subject to harsh climate conditions: large amounts of winter snowfall and extreme temperatures, ranging from -40˚C in the winter to +25˚C in the summer [15]. The specifications of the studied turnouts are shown in Table 1.

Table 1: The specifications of the studied turnouts

Turnout	Turnout type	Turnout direction	Installation year	Sleeper type	Ballast type
Rsn 2	EV-UIC60-760-1:15	Left	2001	Concrete	M1
Rsn 1	EV-UIC60-760-1:15	Right	2003	Concrete	M1
Bfs 2	EV-UIC60-760-1:15	Right	1999	Concrete	M1
Sbk 1	EV-UIC60-760-1:15	Right	2000	Concrete	M1
Soa 2	EV-UIC60-760-1:15	Right	2000	Concrete	M1
Bln 2	EV-UIC60-760-1:15	Right	2003	Concrete	M1

3. Data collection and data treatment

Six turnouts in section 111 of the Iron Ore Line, located between Kiruna and Riksgränsen, were selected for the case study. To ensure comparable data, only turnouts of type EV-UIC60-760-1:15 were considered and the other types of turnout were excluded.

Two different approaches were applied in this study to analyse the geometrical deterioration of turnouts. The data collection and data treatment for each of these approaches are described in the following sections.

3.1 First approach

The design and inspection information for the selected turnouts was extracted from two databases at Trafikverket, BIS (track asset information system) and Optram. BIS contains information on Trafikverket's infrastructure and facilities, e.g. the turnout type, turnout position, sleeper and ballast type, etc. Optram is a maintenance decision support system implemented since 2009 that can be used to graphically show the results of track geometry measurements. Only measurement data after 2007 are available in this database.

The main track geometry parameter considered in this study is the longitudinal level. Hence, the longitudinal level values of turnouts from 2007 to 2011 were collected from Optram. For this time interval, the data of 17 measurements were available. Table 2 shows the frequency of the measurements for each year.

Table 2: The frequency of available inspections for each year (date format: yyyy-mm-dd)

	2007	2008	2009	2010	2011
Measurement dates	2007-04-28	2008-04-18	2009-06-13	2010-05-16	2011-04-01
		2008-06-13	2009-08-08	2010-06-29	2011-06-11
		2008-09-27	2009-10-02	2010-09-03	2011-08-16
				2010-10-16	2011-09-23
					2011-10-06
					2011-11-04

Information on the history of the performed maintenance was collected from two other databases, Bessy and Ofelia. Bessy (Trafikverket's inspection report system) contains information on inspections and the types of actions performed after inspection remarks [16]. The data on corrective maintenance actions are registered in Ofelia (Trafikverket's failure report system), which contains report information from the track maintenance contractors concerning fault symptoms, reasons for faults, the actions performed, the times of fault occurrence and repair, the time required for repair, etc. [16].

Considering that the STRIX / IMV 100 inspection car has an error tolerance of 10-15 metres in specifying the longitudinal location of the track, the first step in data treatment was to adjust the sampled measurement data according to a well-defined reference point. This was accomplished by finding the crossing location for each measurement and adjusting all the measurements based on this reference point. Fig. 2 illustrates an example of specification of the crossing location for one measurement. In this example, the crossing reference point was located between kms 1435.16 and 1435.18.

Two parameters are considered in geometrical degradation analysis, namely, the *absolute residual area (AR_a)* and the *maximum settlement (S_{max})*. The AR_a is defined as the absolute value of the area obtained from the differences in the longitudinal level values between two adjusted measurements at the crossing point. Fig. 3 shows this parameter as the grey dashed area between two measurements performed on 2007-04-28 and 2008-04-18.

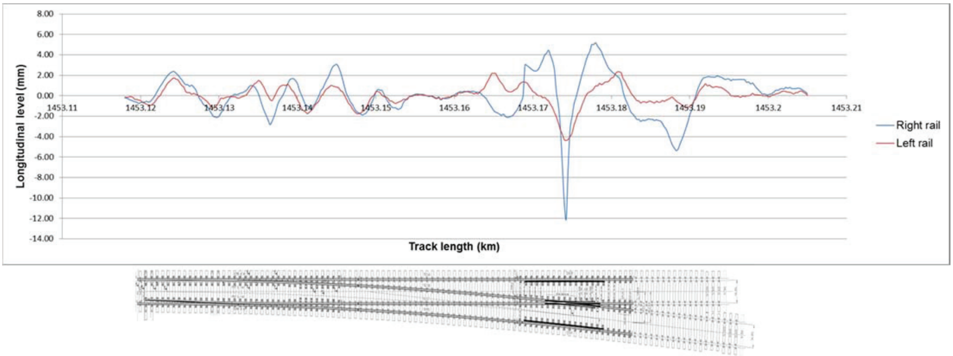


Figure 2: Specifying the crossing location for each measurement

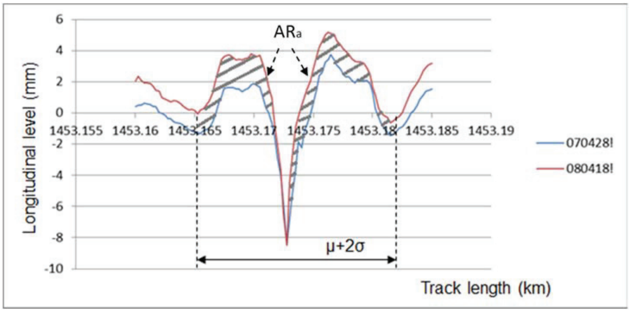


Figure 3: Illustration of the absolute residual area (AR_a) between two measurements

The trend of the AR_a indicates how much the track has settled due to the accumulated loading from traffic over a certain period. This parameter is calculated between the lower peaks immediately before and immediately after the crossing point (Fig. 3). To define this interval, the distance between the peaks for every inspection and turnout (in total 6 turnouts x 17 measurements, see Tables 1 and 2) is measured to obtain the mean (μ) and the standard deviation (σ). Then the distance of μ+2σ, which covers around 95% of the total measurement population, is used to calculate the AR_a. This means that the crossing point will be considered as the reference point and the AR_a is calculated at an interval of $[\frac{-(\mu+2\sigma)}{2}, \frac{(\mu+2\sigma)}{2}]$ for each individual S&C; see Figure 3.

The maximum settlement (S_{max}) is defined as the difference between the value of the longitudinal level at the crossing point and the value obtained from the intersection of the vertical line passing through the crossing point with the straight line connecting the positive peaks before and after the crossing point. This parameter is shown in Fig. 4 by the blue line.

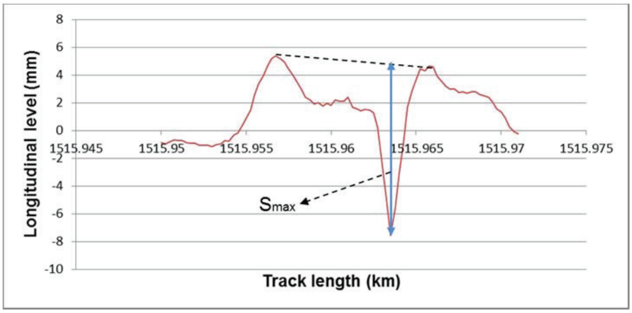


Figure 4: Illustration of the maximum settlement (S_{max})

In the trend analysis of both parameters, the first measurement (2007-04-28) is considered the starting and reference time point, and the rest of the consecutive measurements will be compared to this reference point.

However, the shortcoming with this approach is that the longitudinal level of the reference point is considered constant, leading to results that estimate the relative geometrical degradation rate instead of the actual one.

3.2 Second approach

To overcome the shortcoming in the first approach, various geometry parameters are defined to estimate the degradation in each measurement separately. This approach is inspired by surface roughness measurements, which have been a useful and reliable method for at least 60 years. The defined parameters in this approach are as follows (figure 5):

- A: The distance between the peaks after and before crossing valley
- C: The slope of the measurement line 1 metre before the crossing point
- D: The slope of the measurement line 1 metre after the crossing point
- E: The longitudinal level value at the first peak (before crossing point)
- E’: The difference of longitudinal level values between the first peak (before crossing) and the valley before it
- F: The longitudinal level value at the second peak (after crossing point)
- F’: The difference of longitudinal level values between the second peak (after crossing) and the valley after it
- G: The difference of longitudinal level values between the first peak (before crossing) and the crossing valley
- H: The difference of longitudinal level values between the second peak (after crossing) and the crossing valley

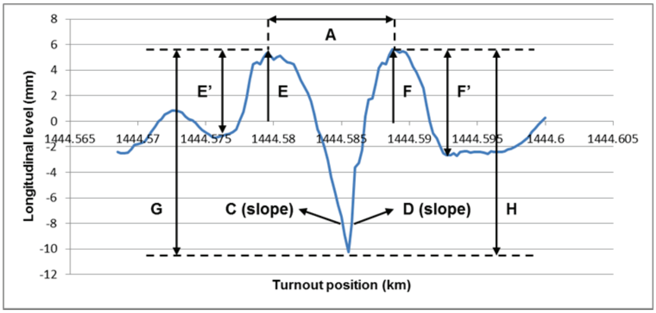


Figure 5: Defined geometry parameters in the second approach

The trends of these parameters as a function of time for the turnouts Rsn 1 & Soa 2 are estimated for the time interval from 2004 to 2013. The measurement data for the period between 2004 and 2007 was collected from the track recording database.

4. Results and discussion

The normal distribution analysis of the distance between the negative peaks before and after the crossing point indicates that the values of the mean (μ) and the standard deviation (σ) are 24.16 and 4.74 metres, respectively. By considering these values, the AR_a was calculated on the basis of a distance of 33.64 metres (μ+2σ) with reference to the centre of the crossing point. Fig. 6 shows the variation of the calculated AR_a over time for the turnouts Bfs 2, Sbk 1 and Soa 2. The trend of this parameter before performing maintenance is illustrated by the dashed circles.

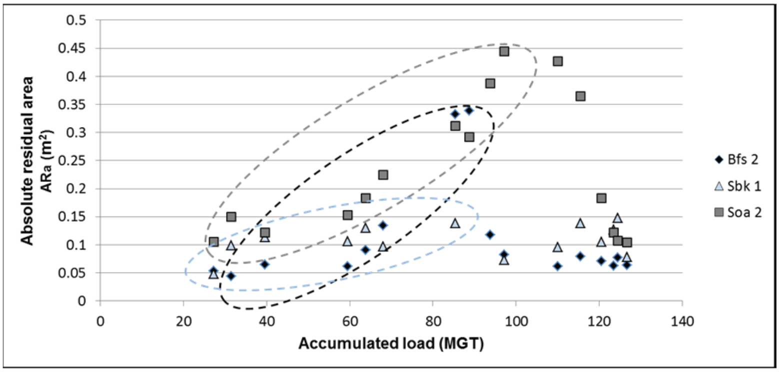


Figure 6: Trend of AR_a over time for the turnouts Bfs 2, Sbk 1 and Soa 2

Assuming the longitudinal level of the reference points between the measurement events is constant, a number of results can be obtained from the first approach. As can be seen in Fig. 6, the AR_as for the turnouts Bfs 2 and Soa 2 have increased with an increasing accumulated MGT to 0.35 and 0.45 m^2, respectively. Failure reports found in the corrective maintenance report system (Ofelia) gave information on the need to perform corrective maintenance on both turnouts around these points in time (corresponding to 90 and 110 MGT). After performing maintenance, the rate of geometry degradation stayed low and constant for the remaining period of this study. At the same time, the degradation rate for the S&C Sbk 1 was lower than that for Bfs 2 and Soa 2. Nevertheless, corrective maintenance was carried out on Sbk 1 during the same period as the maintenance on Bfs2, lowering the value from 0.14 to 0.07 m^2.

The same pattern has been observed for the AR_as for the turnouts Rsn 1, Rsn2 and Bln 2. The AR_as were lowered by maintenance performed after 90 MGT.

The trends of the S_{max} with an increasing accumulated load in the turnouts Rsn 1, Rsn 2 and Bln 2 are depicted in Fig. 7. The S_{max} at the crossing position indicates when maintenance is needed. The AR_a seems to be more sensitive to changes than the S_{max}.

The trends of the defined geometry parameters (in the second approach) are shown in Fig. 8. As can be seen in the figure (part (a)), the parameter A in both turnouts has an increasing trend until 2011-06-29. Since maintenance was carried out on Rsn 1 after 2010-06-29, the value of A for Rsn1 has dropped. However, after the maintenance execution, the magnitude of A again increased, reaching 9.5 metres by 2011-06-29. At this point, the growing trend ended and the magnitude remained constant. Similarly, the C & D show an increasing trend in both turnouts until 2011-06-11; after this, they demonstrate a reducing trend until they ultimately become stable. This pattern shows that the crossing has continuously settled down until it reaches a limit. After reaching this limit, the crossing cannot settle anymore, and the geometry fault widens. As expected, the trend for E & F is similar to that for E' & F'; the degradation grows slightly until 2011-06-11, and after this time a sharp increase can be seen. To interpret these trends, it is necessary to consider the trends of G and H at the same time. The G and H grow exponentially until 2011-06-11; afterwards, they become constant. This indicates that the geometry fault wave at the crossing has reached its limit (about 25 mm) and the fault has transferred to the next wave in the crossing neighbourhood. This transfer can be perceived by the sharp increase in E/F & E'/ F' Trends.

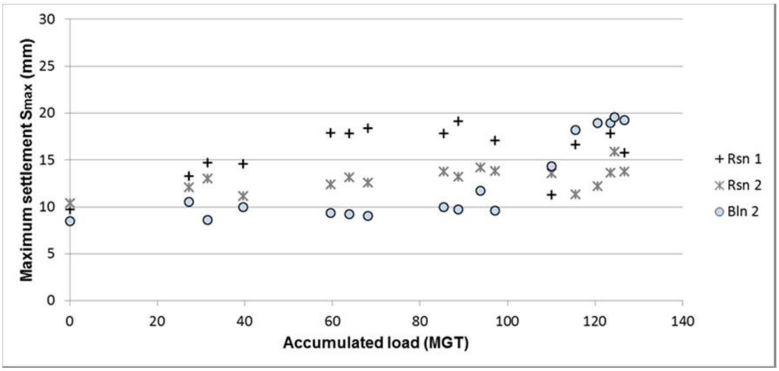
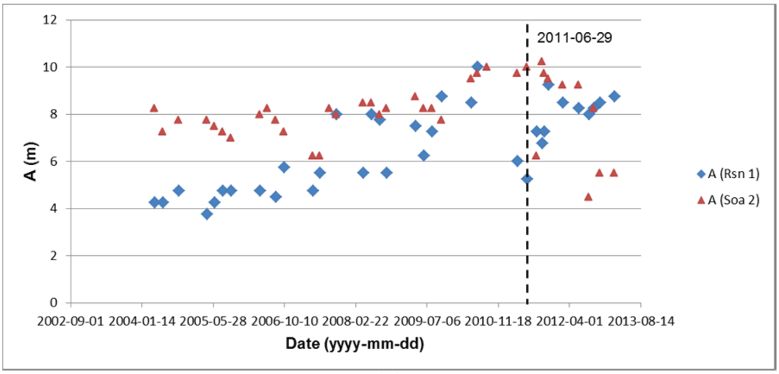
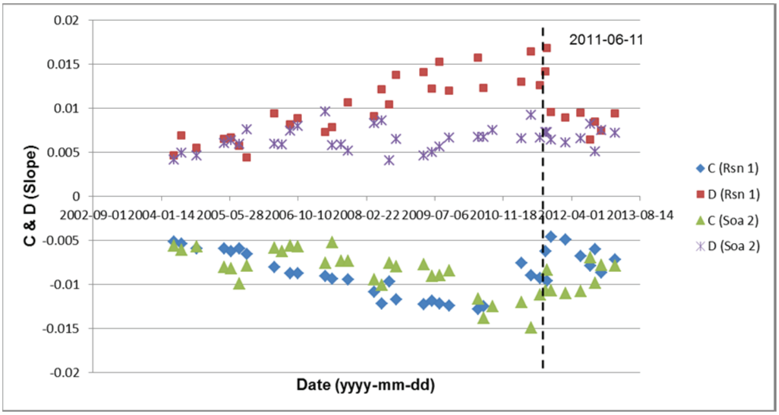


Figure 7: Trend of S_{max} for turnouts Rsn 1, Rsn 2 and Bln 2



(a)



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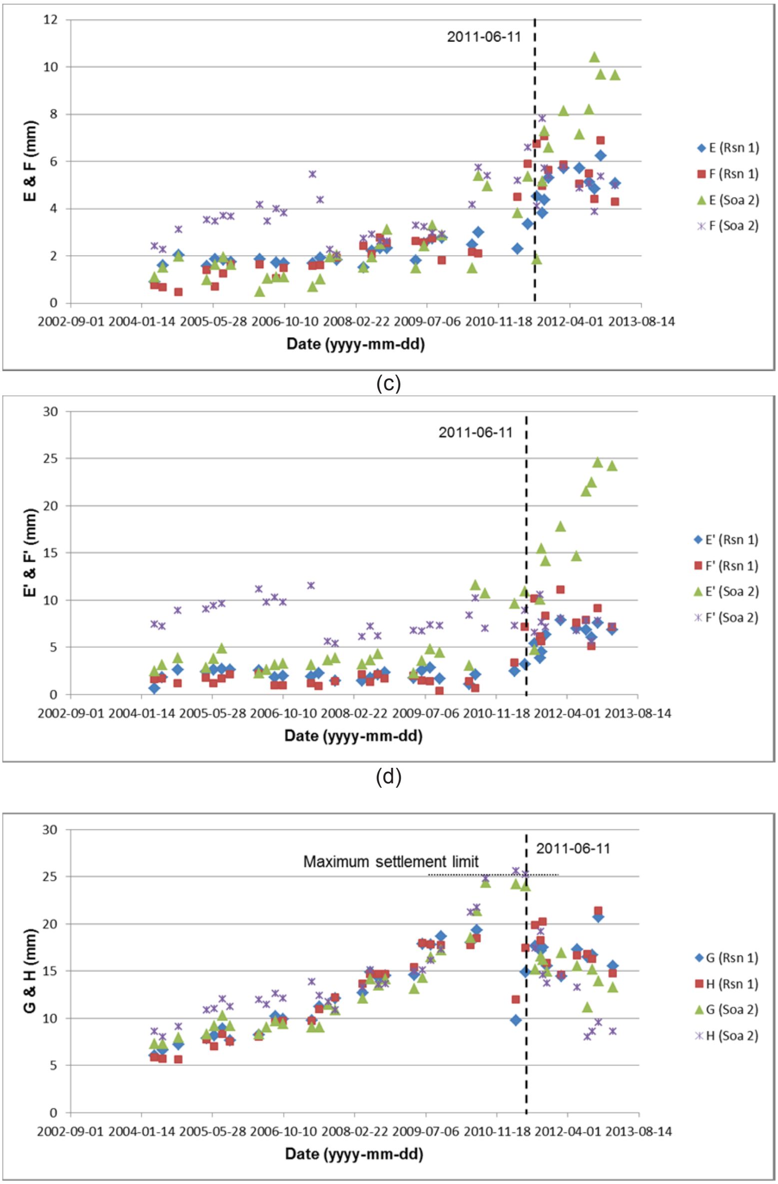

(c)

(d)

(e)

Figure 8: Trends of the defined Geometry parameters in selected turnouts (a) Parameter A, (b) Parameters C & D, (c) Parameters E & F, (d) Parameters E' & F' and (e) Parameters G & H

Not surprisingly, the results show that the studied turnouts exhibit different geometrical degradation rates. Different factors such as the traffic, the subgrade quality, the age of the asset and the maintenance strategy selected can have an effect on the rate of degradation. Another important factor is the location and environment in which the turnout has been placed. The qualities of the subgrade and the weather affect the track stiffness; different track stiffness results in dissimilar stress distribution behaviour and, consequently, different degradation rates. The geometry degradation analysis indicates that turnouts should be treated as individuals with different degradation rates and different maintenance frequencies.

The results also indicate that the maintenance has been carried out at different geometry levels for different turnouts. Due to the limited maintenance resources available, it is important to analyse the degradation rate of the asset and to utilise maintenance decision support tools such as RAMS (Reliability, Availability, Maintainability and Supportability) and LCC (Life Cycle Cost) to define a cost-effective maintenance threshold. This, in turn, will indicate the optimal time for performing maintenance to reduce the cost and increase the availability.

The analysis of the S_{max} & AR_a can be used to estimate the critical residual area in which the maintenance should be performed. On the other hand, the analysis of geometry parameters provides more accurate and reliable information on the deepening and widening growth rate due to the accumulated loads along the life cycle course of turnouts. It also indicates the limits for maximum track settlement in the crossing section. Trend analysis of G and H parameters indicates that the maximum settlement limit for the studied turnouts (Rsn 1 & Soa 2) is about 25 mm (see Figure 8(e)). Although, the age and the location of the turnouts are different, similar trends can be seen in both of them. After reaching this limit the values of G and H have become scattered. This shows that the geometry fault wave at the crossing has reached its limit and the fault has transferred to the next wave in the crossing neighbourhood. This transfer can be observed by the sharp increase in E/F & E'/ F' Trends. Applying this knowledge within a life cycle cost model facilitates the maintenance decision making process to specify cost-effective alert / intervention limits.

5. Conclusions

The study proposes two different approaches to analyse the geometrical degradation of turnouts at crossing sections. It concludes the following:

- The defined parameters in both approaches indicate that turnouts are to be treated as individuals with different degradation rates and different maintenance frequencies.
- The results of the second approach (i.e., the analysis of geometry parameters) indicate that a limit for crossing position settlement can be defined.
- Before reaching this limit, the vertical degradation rate at the crossing point (deepening) is higher than the degradation rate in the vicinity of the crossing (widening). However, after reaching the settlement limit, the crossing can no longer settle and the geometry faults transfer to the next waves in the crossing neighbourhood.

Funding

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PAPER IV

Optimisation of track geometry inspection interval

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Optimisation of track geometry inspection interval

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Abstract

The measurement and improvement of track quality are key issues in determining the time at which railway maintenance must be performed and its cost. Efficient track maintenance ensures optimum allocation of limited maintenance resources which 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 levels. This paper discusses optimisation of the track geometry inspection interval with a view to minimising 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 accidents 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 geometry faults.

Keywords

Track geometry degradation, maintenance, inspection interval, optimisation, tamping

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Introduction

Today's railway industry handles an increasing number of trains that travel at higher speeds and have higher axle loads; this combination of circumstances can result in faster degradation of railway assets and higher maintenance costs. However, by shifting the focus of the maintenance strategy from meeting safety limits to obtaining cost-effective maintenance thresholds by using 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. Currently, 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 length of tamped track is approximately 1700 km, about 14% of the total track length.[2]

A number of railway research institutes and individual researchers have attempted to analyse the deterioration of track geometry. The research institutes include the Office for Research and Experiments of the International Union of Railways (UIC), European Rail Research Institute in the Netherlands, Transportation Technology Centre Inc. in the USA and Graz University of Technology in Austria. As for individual researchers, Sato[3] has proposed a degradation model that considers the superstructural aspect in which the degradation depends on tonnage, speed, type of rail connection (jointed or continuously welded) and quality of the subgrade. Bing and Gross[4] presented a model that could be used to predict how the track quality, measured in terms of track quality indices, changes as a function of causal parameters, such as traffic, track type and maintenance.

Vale et al.[5] developed a model for scheduling tamping on ballasted tracks by considering the track degradation, the track layout, the dependency of track

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quality improvement on the quality of the track at the time of maintenance, and the track quality limits that depend on train speed. Zhao et al.[1] developed a life cycle model to optimise ballast tamping and renewal by incorporating a track deterioration model and a tamping model. Their model uses 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. Finally, Higgins[6] proposed a model to determine the best allocation of maintenance activities and crews to minimise maintenance costs while keeping the track condition at an acceptable level.

In the optimisation of track geometry inspection, significant attention has been paid to optimising the inspection procedure by correlating irregularities in the track's geometry with dynamic responses at the wheel/rail interface.[7,8] With the notable exception of Podofillini et al.[9] little attention has been focused on considering the optimisation of track geometry inspection intervals. To determine an optimal inspection strategy, Podofillini et al.[9] used a genetic algorithm to develop a model to calculate the risks and costs associated with such a strategy. Specifying a cost-effective inspection interval can help railways perform maintenance on infrastructure before irregularities in a track geometry reach intervention limits, thus reducing maintenance expenditures.

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

Background information about the studied line

The Swedish mining company LKAB uses the railway line from Narvik to Luleå, "the iron ore line", to transport iron ore pellets from its mine in Kiruna to Narvik and from its mine in Vitåfors, near Malmberget, to Luleå (see Figure 1).[10] In 2000, LKAB increased the axle load on the Malmbanan line from 25 to 30 t and the maximum speed of a loaded train from 50 to 60 km/h. This change is expected to result in higher track geometry degradation levels. In addition to iron ore transportation, the line is used by passenger trains and other freight trains. The train speeds vary from 50 to 60 km/h for loaded iron ore trains, 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 (see Figure 1), the annual passing tonnage is about 13.8 MGT (million gross tonnes).

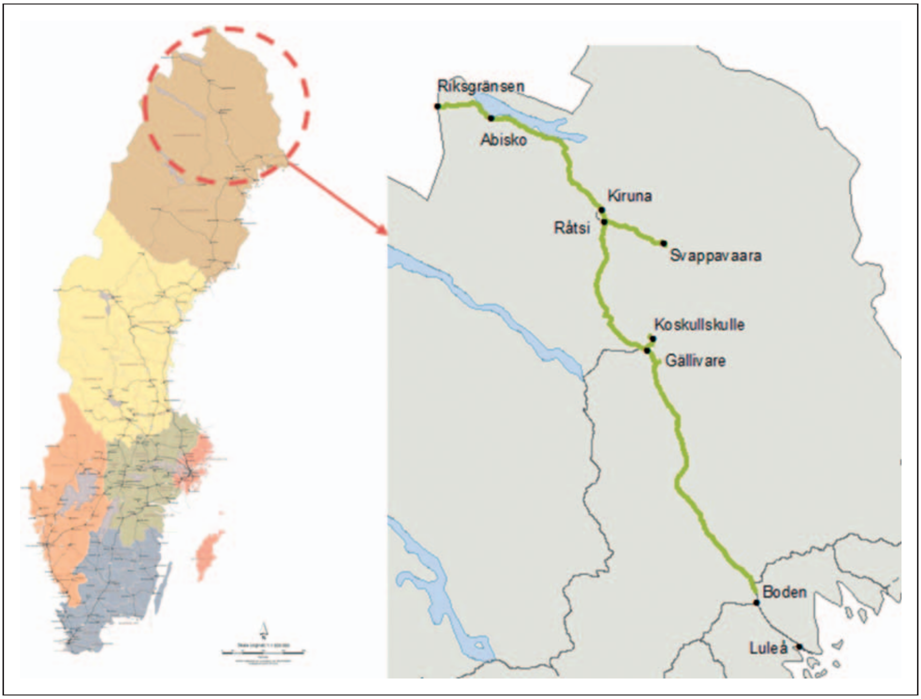

Figure 1. Iron ore line from Luleå to Narvik.

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: winter snowfall and extreme temperatures, ranging from −40 °C in winter to +25 °C in summer.[11]

Track quality monitoring and maintenance

To monitor track quality, the infrastructure owner (Trafikverket) regularly (every 1 to 2 months from April to October) uses an inspection car (STRIX) to measure the deviation of the track using both 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-cm intervals.

Based on these 25-cm interval measurements, standard deviations σ_S and σ_H for 200-m track sections are calculated. σ_S is the sum of standard deviations of the cant error (C) and the lateral position error of the high rail (S_{High}) (see Figure 2 and equation (1)).[12] σ_H is the standard deviation of the average longitudinal level for the left and right rails

$$\sigma_S = \sigma_C + \sigma_{S_{High}} \tag{1}$$

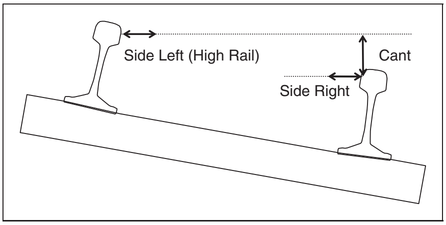

Figure 2. Calculation of σ_S.

These standard deviations (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 between 1 and 25 m.

Several condition indices are used to describe the condition of the track geometry; the most important are the Q-value and the K-value. The Q-value indicates the quality of track geometry and is calculated based on σ_H, σ_S and the comfort limits that define the acceptable standard deviation for 200-m track sections (see Table 1).[13] The formula for calculating the Q-value is

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

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

The other index, the K-value, is the ratio of the total length of the track with deviations below comfort limits ($\sum l$) 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

$$K = \frac{\sum l}{L} \times 100\% \tag{3}$$

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 identify the limits for the execution of corrective maintenance (Intervention limits) (see Figure 3),[12] whereas B-faults identify the limits for the execution of preventive maintenance (Alert limits).[13] These limits are defined for 'point failures' (25 cm), but since a failure often is caused by a movement in the substructure, it affects at least 1 m of the track.

The selected track consists of two quality classes, K2 and K3, each with a different allowable speed and

Table 1. Comparison of the allowable limits between K2 and K3.

		Comfort limits		B-fault limits	C-fault limits
Quality class	Maximum allowable speed for local trains (km/h)	$\sigma_{H\ limit}$ The comfort limit for standard deviation of longitudinal level (mm)	$\sigma_{S\ limit}$ The comfort limit for sum of standard deviations of the cant error and the lateral position error of the high rail (mm)	Alert limit for 25-cm interval (1–25 m wavelength) (mm)	Intervention limit for 25-cm interval (1–25 m wavelength) (mm)
K2	105–120	1.5	1.9	7	12
K3	75–100	1.9	2.4	10	16

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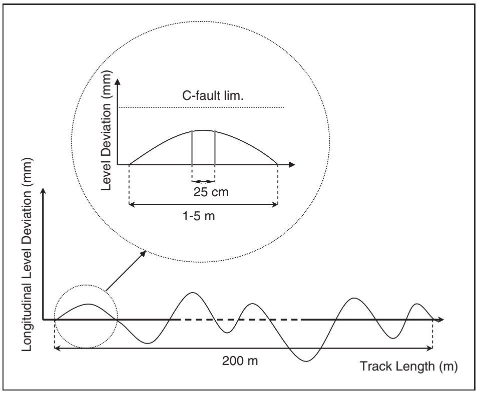

Figure 3. Illustration of C-fault limits.

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 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.

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 a 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 (Intervention limits), tamping is required.

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 track sections before or after stations with a length shorter than 1000 m were excluded.

The geometry fault data for the selected track section were extracted from the inspection reporting system, STRIX. In this case, inspection 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-faults detected in that segment. The second level contains more detailed information about C-faults such as type, location, size and length of fault. These critical faults, which can cause derailment, are reported immediately to the operation control centre so that the track can be restored.

The study used two of Trafikverket's databases: Ban Information System (BIS) (Trafikverket asset register) and Optram (Optimised track management system). 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.), grinding and curves.[14] Optram is a maintenance decision support system implemented in 2009 that can be used to graphically show the results of track geometry measurements. Only measurement data after 2007 are available in this database. The system also provides functionality for analysis and displays data trends.[10] To gain access to all available information on tamping, it is essential to consider both systems.[2]

A railway track is a repairable system; hence, reliability analysis techniques for repairable systems should be used in failure data analysis. The first step of analysis is to check whether or not the data are independently and identically distributed (IID). The trend and dependency characteristics of data can be examined using the Laplace trend test and the serial correlation test. If the data are IID, the renewal process can be used; if not, the nonhomogeneous Poisson process or branching Poisson process are appropriate.[15]

The following assumptions were made prior to the analysis of the probability distribution of faults.

1. The track consists of identical track segments.
2. The maintenance effectiveness is perfect. This means that the status of the segment will be restored to 'as good as new' condition after maintenance.

Under these assumptions and after ensuring the collected data were IID, the probability distributions of faults were estimated. The Weibull++7 software was used to find the probability distribution function with the appropriate fit to the data. To obtain applicable results from the analysis, only main distributions such as Weibull, normal/lognormal, exponential, etc. were considered; other theoretical distributions were not considered.

The probability distribution analysis was based on the number of detected segments with geometry faults over the time interval between two consecutive inspections. No difference was considered between the occurrence of a single point fault and multiple point faults on the same segment in the same time interval because maintenance should be carried out on the segment regardless of the number of detected geometry faults.

Since the exact times of the occurrence of the fault were not known, the fault time data were considered as interval-censored data, in which the object of interest is not constantly monitored. Thus, the inspection times in terms of MGT were used as interval ranges for fault times. The segments without any fault occurrence over the studied time period were also considered as right-censored data.

The linear regression technique was used to rank different probability distributions. The goodness of fit was illustrated by the correlation coefficient parameter (ρ). This parameter shows how well the linear regression model fits the data set: $\rho = 1$ indicates a perfect fit, whereas $\rho = 0$ shows that the data have no pattern or correlation in relation to the regression line model.[16]

Degradation of track geometry

The degradation of track geometry is a complex phenomenon occurring under the influence of dynamic loads and is normally calculated as a function of traffic in mm/MGT, or time in mm/year.[17] Some factors which can affect the track geometry degradation are shown in the Ishikawa diagram in Figure 4. These factors are classified as design, construction, operation, and maintenance.

For a track section with similar traffic, the rate of degradation varies depending on construction and differences in substructure. Figure 5 shows the variability of longitudinal level degradation rate in different 200-m 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 sections having low degradation rates that can be controlled by preventive tamping at infrequent intervals. However, the tail of the distribution consists of sections with 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.

Next, the data on B-faults and C-faults of the longitudinal level between 2004 and 2010 were collected to estimate the probability of fault occurrence over time. The probability density functions (PDFs) of B-faults and C-faults were used to indicate the probability of preventive tamping and corrective tamping being required at a specified time.

Since the occurrence of twist 3-m fault greater than 15 mm and a twist 6-m fault greater than 25 mm are critical in terms of derailment risk, the data of occurrence of these faults between 2004 and 2010 were used to find the PDF of their occurrences. This probability function was then used to determine the probability of safety fault occurences at specified intervals.

The probability distribution analysis, performed using Weibull++7 software, showed that for

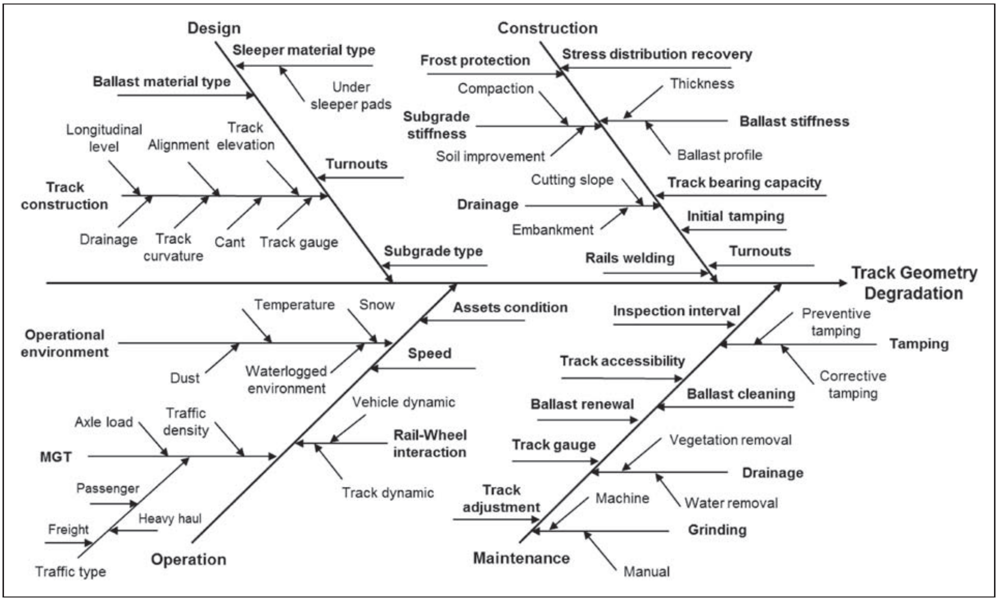

Figure 4. Ishikawa diagram (cause and effect diagram) of the factors influencing track geometry degradation.

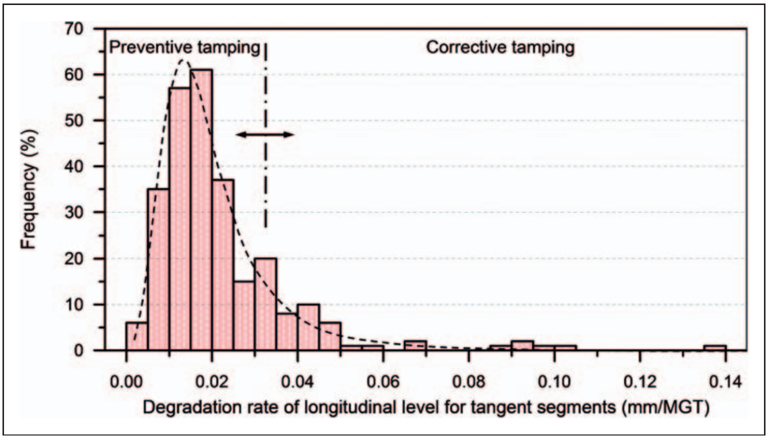

Figure 5. Histogram of longitudinal level degradation rates in tangent segments between 2007 and 2009.

Table 2. The characteristics of the PDF of B-faults, C-faults and twist (3 and 6 m).

Type of fault	Total number of detected segments with geometry fault over the studied time	Type of probability distribution function	Values of distribution parameters		ρ
			Shape (β)	Scale (η)	
B-fault	107	Two-parameter Weibull	1.606	31.99	0.968
C-fault	48	Two-parameter Weibull	1.379	116.114	0.986
Twist (3 and 6 m)	9	Two-parameter Weibull	1.857	329.771	0.971

B-faults, the lognormal distribution was the best fitted distribution at $\rho = 0.9889$. The Weibull distribution provided the best fit for C-faults and safety faults data sets. Since the Weibull distribution is a flexible distribution which can be used to model many types of failure rate behaviour[18] and because the difference between ρ values obtained from the Weibull distribution and the lognormal distribution is very small, the Weibull distribution was also used to estimate the probability of B-faults. The parameter values of the Weibull distribution and the value of the correlation coefficient (ρ) of each distribution for B-faults, C-faults and twist (3 and 6 m) are shown in Table 2.

The cumulative distribution functions (CDFs) of B-faults, C-faults and twist (3 and 6 m) are shown in Figure 6(a), (b) and (c), respectively.

Proposed inspection model

Figure 7 shows a schematic description of the track geometry maintenance events.

In this model 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 fault occurrence that can cause a derailment. T_P is the time for the preventive tamping execution.

The model assumes that based on the inspection data, corrective tamping is performed on a fixed ratio (A) of the total track length, while preventive tamping is executed at fixed time intervals (time-based maintenance). The ratio (A) is the ratio of the track length that should be tamped correctively after each inspection to the total track length. The time interval for preventive tamping execution is defined based on the infrastructure maintenance strategy. 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 minimise the total cost per unit of traffic load (MGT) for any length of track section. In other words, an inspection should be performed only when its cost is offset by a resulting reduction in expected future costs.

The following assumptions underpin the proposed model.

1. 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.

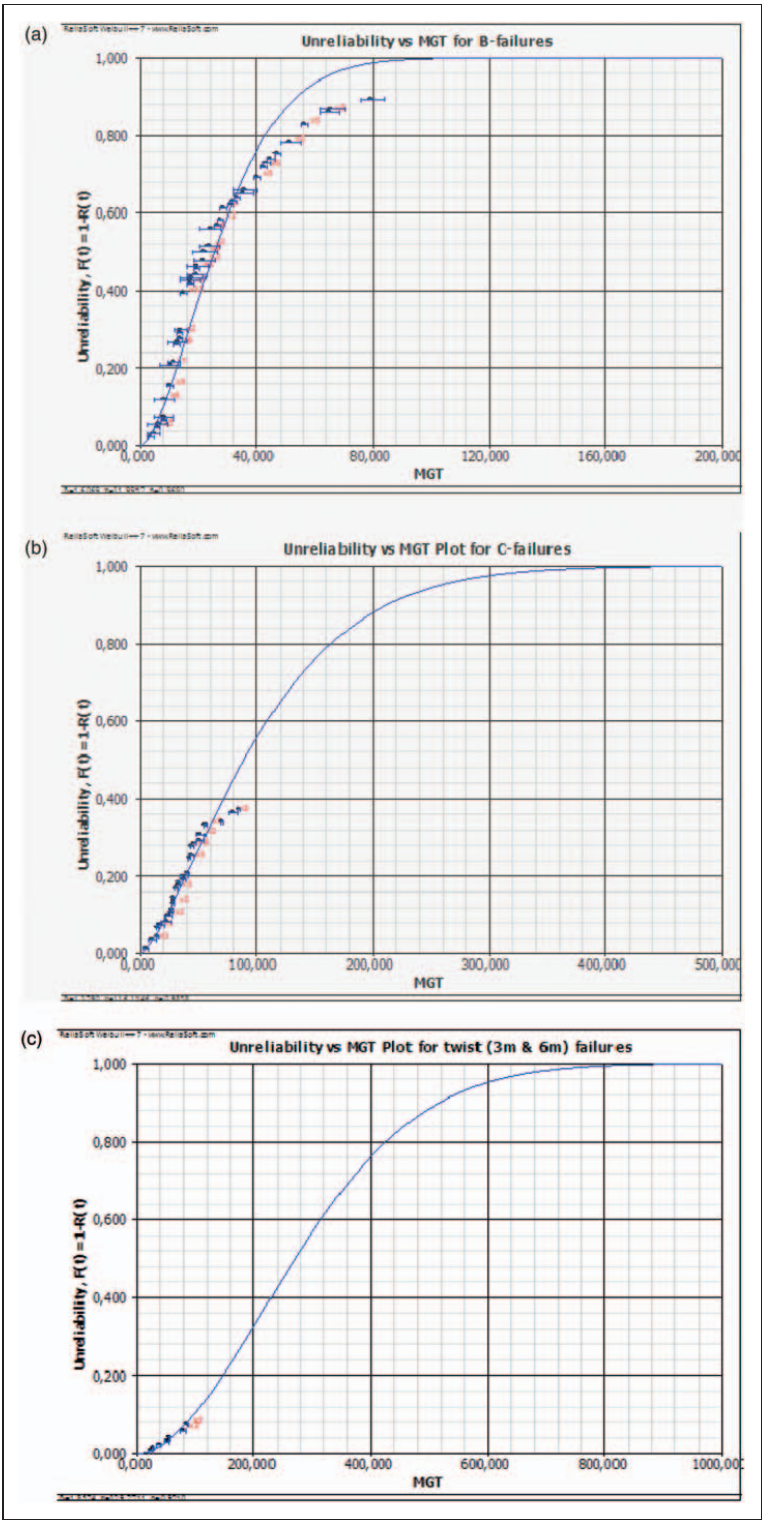

Figure 6. CDF of geometry faults versus MGT (a) B-faults, (b) C-faults and (c) twist (3 & 6 m) failures.

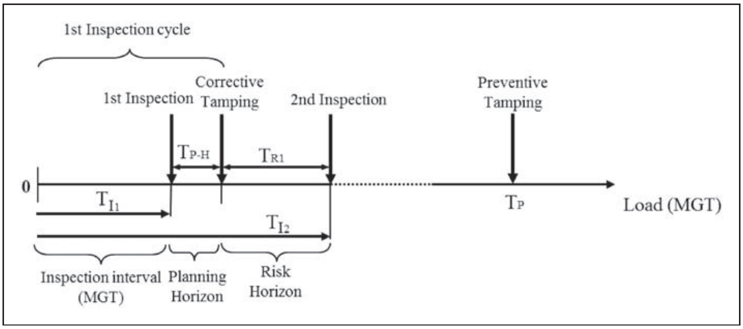

Figure 7. Schematic model of inspection cycles.

2. The whole track is considered as a system consisting of identical segments.
3. The maintenance effectiveness is perfect, which means that the condition of the track after maintenance will be restored to ‘as good as new’ condition.
4. The probability of fault occurrence at the planning horizon interval is considered to be zero.
5. The ratio (A) is constant and is independent of the frequency of tamping.
6. Any change in maintenance strategy has no effect on the probability of fault occurrence, and the probability of fault occurrence is the same for all inspection strategies.

Amongst all factors mentioned in Figure 4 (Ishikawa diagram), only the costs of the following main parameters for which the data were available are considered in the proposed cost model.

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 ($C_{\mathrm{C.T}}$), the probability of C-fault occurrence at the specified time interval ($P_{\mathrm{C}}(T_{\mathrm{I}})$) and the ratio ($A$). Since corrective tamping is performed on only part of the track, just that portion will be restored to ‘as good as new’ condition; the rest will be ‘as bad as old’. Therefore, the probability of fault detection during each inspection should be subtracted from the probability of fault in the previous inspection when a part of the track was restored to ‘as good as new’ condition by corrective tamping. Hence, $A \times C_{\mathrm{C.T}}\ [P_{\mathrm{C}}(T_{\mathrm{I}\,i}) - P_{\mathrm{C}}(T_{\mathrm{I}\,i-1})]$.
3. Preventive tamping cost: this is the cost of preventive tamping ($C_{\mathrm{P.T}}$) which is executed at a fixed time interval.
4. Risk of accident cost: this cost can be estimated by multiplying the cost of derailment ($C_{\mathrm{Acc.}}$) by the probability of safety fault occurrence that can cause derailment in the interval between maintenance execution and the next inspection ($P_{\mathrm{S.F}}(T_{\mathrm{R}})$). Hence, $C_{\mathrm{Acc.}}\ P_{\mathrm{S.F}}(T_{\mathrm{R}})$.

Since it is assumed that the entire track will be restored to ‘as good as new’ condition 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 kth series of inspection cycles can be expressed as

$$\text{Total Cost} = \frac{\begin{pmatrix} \sum_{i=1}^{k} C_1 + \sum_{i=1}^{k} A C_{C.T}\left[P_C(T_{I_i}) - P_C(T_{I_{i-1}})\right] \\ + \sum_{i=1}^{k} C_{ACC.} P_{S.F}\left(T_{R_i}\right) + C_{P.T} \end{pmatrix}}{T_P} \tag{4}$$

Application of the model on the studied line

As previously mentioned, the studied line is usually inspected every 2 months. However, according to regulations, this inspection interval can be expanded to every 4 months. By applying the proposed model, three inspection scenarios – every 2 months, every 3 months and every 4 months – are compared to find the alternative with the lowest total maintenance cost.

The costs of inspection, preventive tamping and corrective tamping per kilometre were collected from Trafikverket experts. The cost of accidents was adopted from the study of Podofillini et al.[9] on the optimisation of railway track inspection and maintenance procedures. The costs used in the model are listed in Table 3.

The study assumes that preventive tamping is performed every 2 years on the entire line and based on this assumption, we have analysed the total maintenance costs for the three considered scenarios. By analysing the corrective maintenance history, it is also assumed that, on average, 10% of the track ($A = 0.1$) needs to be restored by corrective tamping after each inspection. The corrective tamping is performed by the contractor within 1 to 2 weeks of each inspection. During winter (November to March) no inspection or maintenance actions take place. The first inspection every year is performed in April.

To illustrate the method of calculation, the schematic model of the third scenario (inspection every 4 months) is shown in Figure 8.

As it is assumed that the state of the entire track will be restored to ‘as good as new’ condition after preventive maintenance, the time (T) starts from zero again, as shown in Figure 8. In this study, the operational load (MGT) is considered as a surrogate of time.

The total maintenance cost per MGT for each scenario is shown in Figure 9. As can be seen, the third scenario (inspection every 4 months) is the optimal option in terms of lowest maintenance cost.

Discussion

The results show that by expanding the inspection interval from every 2 months to every 4 months, the total maintenance cost per MGT will decrease. The slow degradation rate in the majority of track segments results in the very low probability of the occurrence of C-faults and safety faults (twist in this study) within short time intervals. The probability distribution of the occurrence of both types of faults is a two-parameter Weibull function. The Weibull scale parameters (η) of C-faults and twist are 116.114 and 329.771 MGT respectively. η is also known as the characteristic life; this means that 63.2% of the faults occur by the characteristic life point, regardless of the value of shape parameter (β).[19] This means that 63.2% of C-faults and twist faults occur at around 116 and 329 MGT load cycles, respectively.

Table 3. The costs considered in the model.

Type	Cost (SEK: 1€ ≈ 9 SEK)
Inspection per kilometre	1200
Preventive tamping per kilometre	20,000
Corrective tamping per kilometre	50,000
Accident	15,000,000

The obtained results are based on certain assumptions. It was assumed that all track segments are identical regardless of geometric characteristics, location (curve or tangent), substructure characteristics and construction time and maintenance history. However, as shown in Figure 5, the degradation rates of the tangent segments vary significantly. To reduce the risk and ensure the safety level, 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 effectiveness of the maintenance was also assumed to be perfect. However, when the tamping intervention graph developed by the Austrian Railway[20] was used to evaluate the efficiency of tamping on 200-m tangent segments, results showed high

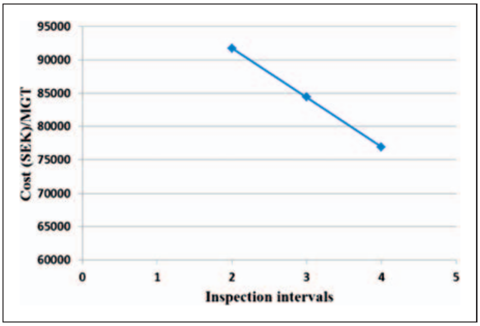

Figure 9. Comparison of maintenance cost per MGT for different inspection intervals.

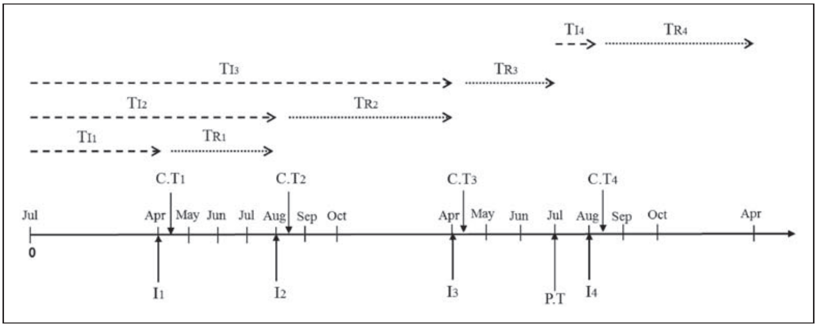

Figure 8. Schematic illustration of third scenario (inspection every 4 months).

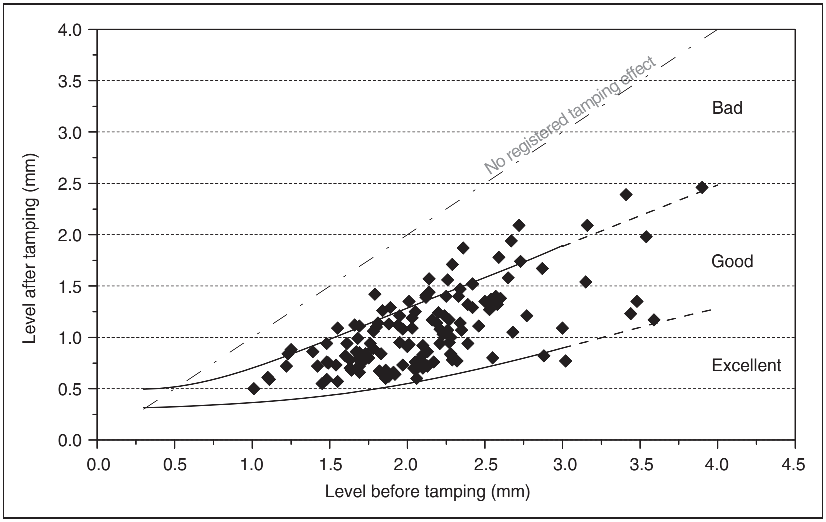

Figure 10. Efficiency of tamping on 200-m tangent segments.

variability of efficiency in different segments (see Figure 10).

Also, 'track memory' which results in sudden settling of the ballast in a short interval after tamping has not been considered in this model. As explained earlier, the probability distributions of faults used in the analysis were obtained based on the current maintenance strategy. Any change in maintenance strategy may result in different probability distributions. Further study is required to analyse the effect of variation in probability distribution on the optimal inspection interval.

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 considered; these include costs incurred by loss of comfort or by the effect of lower track quality on the degradation rate of other components. This means that expanding the inspection interval and reducing the maintenance frequency might result in lower comfort levels; 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, thereby increasing costs. By including the indirect and qualitative cost factors, a more reliable specification of the most cost-effective inspection interval can be obtained.

Conclusions

The following conclusions are drawn from this study.

1. In the current maintenance strategy, the probability of fault occurrence in short time intervals is quite low since the majority of track segments have slow degradation rates.
2. Degradation rates and the efficiency of tamping on different tangent segments of the track vary considerably.
3. To reduce risk and ensure the safety level, track sections with high degradation rates should be monitored and restored more frequently; this requires shorter inspection intervals.
4. 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.

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PAPER V

Cost-effective track geometry maintenance limits

Arasteh khouy, I., Larsson-Kråik, P-O., Nissen, A., and Kumar, U. (2013). Cost-effective track geometry maintenance limits. *Submitted for publication.*

Cost-effective track geometry maintenance limits

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Abstract

In the past, railway maintenance actions were usually planned based on the knowledge and experience of the infrastructure owner. The main goal was to provide a high level of safety, and there was little concern for economic and operational optimisation issues. Today, however, the deregulated competitive environment and budget limitations are forcing railway infrastructures to move from safety limits to cost-effective maintenance limits to optimise operation and maintenance procedures. By so doing, one widens the discussion to include both operational safety and cost-effectiveness for the whole railway transport system. In this study, a cost model is proposed to specify the cost-effective maintenance limits for track geometry maintenance. The proposed model considers the degradation rates of different track sections and takes into account the costs associated with inspection, tamping, delay time penalties and risk of accidents 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 estimate the geometrical degradation rate of each section. The methodology is based on reliability and cost analysis and facilitates the maintenance decision-making process to identify cost-effective maintenance thresholds.

Index Terms: Maintenance limits, Track geometry degradation, Tamping, Cost-effective intervention limits.

Introduction

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 can result in greater degradation of railway assets and higher maintenance costs. Formerly, maintenance procedures were usually 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. Today, however, the competitive environment and budget limitations are compelling railway infrastructures to optimise operation and maintenance procedures by moving from safety limits to maintenance limits. The goal is to make operation and maintenance cost-effective while still meeting high safety standards.

The quality of the track geometry is highly dependent on ballast and substructure conditions. Currently, 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 length of tamped track is approximately 1700 km, about 14% of the total track length [2].

A number of railway research institutes and individual researchers have attempted to analyse the deterioration of track geometry. The research institutes include the Office for Research and Experiments of the International Union of Railways (UIC), European Rail Research Institute in the Netherlands, Transportation Technology Center Inc. in the USA and Graz University of Technology in Austria. As for individual researchers, Sato [3] proposed a degradation model that considers the superstructural aspect in which the degradation depends on tonnage, speed, type of rail connection (jointed or continuously welded) and quality of the subgrade. Bing and Gross [4] presented a model that could be used to predict how the track quality, measured in terms of track quality indices, changes as a function of causal parameters, such as traffic, track type and maintenance.

In addition, several attempts have been made to optimise track geometry maintenance in terms of planning and cost efficiency. Markow developed a model that combined the demand-responsive approach with the life cycle costing method to estimate the total costs for various maintenance alternatives [5]. Chrismer and Selig combined a mechanistic method of timing ballast maintenance with an economic model to identify the life cycle cost of different maintenance methods [6]. Higgins proposed a model to determine the best allocation of maintenance activities and crews to minimise maintenance costs while keeping the track condition at an acceptable level [7]. By using track geometry historical data, Miwa et al. developed a degradation model and a restoration model. Then, they applied these models within a mathematical programming model to determine an optimal maintenance schedule for a multiple tie tamper [8]. Zhao et al. developed a life cycle model to optimise ballast tamping and renewal [1]. Their model incorporated the track deterioration model proposed by Riessberger [9] 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. Vale et al. 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 [10]. Finally, Famurewa et al. proposed a methodology to optimise tamping scheduling by minimising the total maintenance cost [11].

In this study, a cost model is proposed to specify the cost-effective maintenance limits for track geometry maintenance. The proposed model considers the degradation rates of different track sections and takes into account the costs associated with inspection, tamping, delay time penalties and risk of accidents 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 estimate the geometrical degradation rate of each section. The methodology is based on reliability and cost analysis, and the goal is to facilitate the maintenance decision-making ability to identify cost-effective maintenance thresholds.

Background information about the studied line

The Swedish mining company LKAB uses the railway line from Narvik to Luleå, ‘‘the iron ore line’’, to transport 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 the iron ore line from 25 to 30 t and the maximum speed of a loaded train from 50 to 60 km/h. This change is expected to result in higher track geometry degradation levels. In addition to iron ore transportation, the line is used by passenger trains and other freight trains. The train speeds vary from 50 to 60 km/h for loaded iron ore trains, 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 (see Figure 1), the annual passing tonnage is about 13.8 MGT (million gross tonnes). The track consists of UIC 60 rails (UIC stands for International Union of Railways) and concrete sleepers. The ballast type is M1 (crushed granite) (SS-EN 13450), 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 [12].

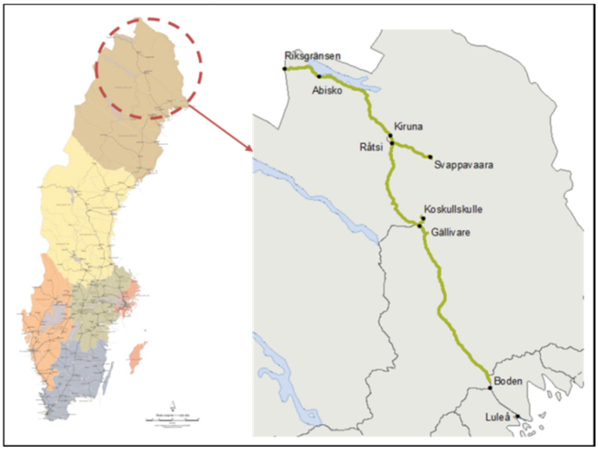


Figure 1: Iron ore line from Luleå to Narvik [13]

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 / IMV100) to measure the deviation of the track with an inertia measurement system and an optical system. An accelerometer measures the acceleration of the vehicle; from the recorded accelerations, the vertical and lateral deviation of the track is calculated for consecutive 25-cm intervals.

Based on these 25-cm interval measurements, standard deviations σ_S and σ_H for 200-m track sections are calculated. σ_S is the sum of standard deviations of the cant error (C) and the lateral position error of the high rail (S_{High}) (see Figure 2 and equation (1)). σ_H is the standard deviation of the average longitudinal level for the left and right rails.

$$\sigma_S = \sigma_C + \sigma_{S_{High}} \tag{1}$$

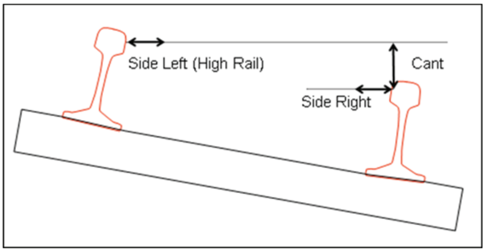


Figure 2: Calculation of σ_S [14]

These standard deviations (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 m.

Several condition indices are used to describe the condition of the track geometry; the most important are the Q-value and the K-value. The Q-value indicates the quality of track geometry and is calculated based on σ_H, σ_S and the comfort limits that define the acceptable standard deviation for 200-m track sections (see Table 1). The formula for calculating the Q-value is:

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

Where σ_{Slim} is the comfort limit for the σ_S value, defined for different track classes (see Table 1) and σ_{Hlim} is the comfort limit for the σ_H value, defined for different track classes (see Table 1).

Table 1: Comparison of the allowable limits between K2 and K3 [15]

Quality class	Maximum allowable speed for local trains (km/h)	Comfort limits		B-fault limits	C-fault limits
		$\sigma_{H\ limit}$ The comfort limit for standard deviation of longitudinal level (mm)	$\sigma_{S\ limit}$ The comfort limit for sum of standard deviations of the cant error and the lateral position error of the high rail (mm)	Alert limit for 25-cm interval (1-25 m wavelength) (mm)	Intervention limit for 25 cm interval (1-25m wavelength) (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

$$K = \frac{\sum l}{L} * 100\% \qquad (3)$$

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 identify the limits for the execution of corrective maintenance (Intervention limits) (see Figure 3), whereas B-faults identify the limits for the execution of preventive maintenance (Alert limits) [15]. These limits are defined for “isolated defects” (25 cm), but since a failure is often caused by a movement in the substructure, it affects at least 1 m of the track.

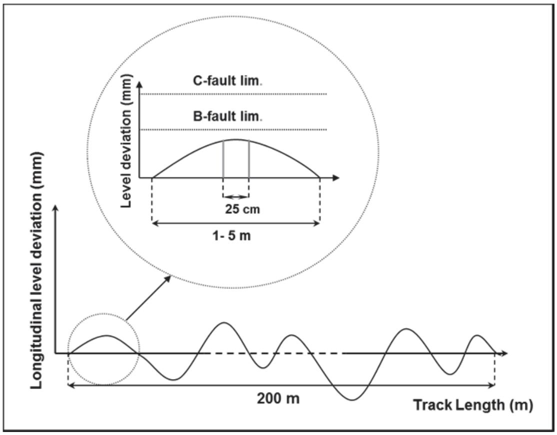


Figure 3: Illustration of C-fault limits [14]

The selected track consists of alternating sections with 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 measurement data and executing tamping based on the calculation of Q-values and detection of C-faults.

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.

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. On the other words, 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 (Intervention limits), tamping is required.

Data collection and data treatment

The study used two of Trafikverket’s (Swedish Transport Administration) databases: BIS (Trafikverket Asset Register) and Optram (Optimised Track Management System). 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 [16]. Optram is a maintenance decision support system implemented in 2009 to graphically show the results of track geometry measurements. Only measurement data after 2007 are available in this database. The system also provides functionality for analysis and displays data trends [13]. To gain access to all available information on tamping, it is essential to consider both systems [2].

The main track geometry parameters considered in this study are the longitudinal level and twist (3 m & 6 m). The longitudinal level values of the track from 2007 to 2012 were collected from Optram. Since the effect of frost heaves on track geometry can introduce error in degradation trend analysis, only measurement data from June to October were considered. For this time interval, the data of 14 measurements were available. Table 2 shows the frequency of the measurements for each year.

Table 2: The frequency of available inspections for each year (date format: yyyy-mm-dd)

	2007	**2008**	**2009**	**2010**	**2011**	**2012**
Measurement dates	2007-10-09	2008-06-12	2009-06-12	2010-06-28	2011-06-10	2012-06-07
		2008-08-08	2009-08-07	2010-09-02	2011-08-08	2012-09-20
		2008-09-26	2009-10-01		2011-09-22	

As the inspection car (STRIX / IMV 100) has an error of 10-15 m (in some cases even higher) in specifying the longitudinal location of the track, the first step in data treatment is to adjust the sampled measurement data. Since the accuracy of the available programmes in data adjustment was unacceptable, the measurement data were adjusted manually. As the manual data adjustment is time consuming, only a section of the track with a length of 14 km was selected for this purpose. To ensure comparable data, a section of the track with the same quality class and similar curvature on the main line was chosen. Stations and other track sections which are allowed to have lower quality were excluded.

Next, the standard deviation of the longitudinal level for each 200 m track section was calculated in every measurement. By applying the exponential regression trend line over the time series of the standard deviations, the degradation rate of each section can be estimated over time.

Since the occurrence of a twist 3 m fault greater than 15 mm or a twist 6 m fault greater than 25 mm is critical to derailment risk, the data reporting the occurrence of these failures between 2004 and 2010 were collected from the inspection reporting system to find the probability distribution of their occurrence. The result has been presented in the previous study [17]. The probability function is used to determine the probability of safety fault occurrences at specified time intervals.

Track geometry degradation and maintenance efficiency

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 time in mm/year [18]. Some factors which can affect the track geometry degradation are shown in the Ishikawa diagram in Figure 4. These factors are classified as Design, Construction, Operation and Maintenance.

For track sections with similar traffic, the degradation rates can vary depending on construction and differences in substructure. Figure 5 shows the variability of longitudinal level degradation rates, obtained from the exponential regression trend analysis for the time interval 2007-2012, in different 200 m segments of the studied track. The figure clearly shows the high variability of degradation rates for the track, with the majority of the sections having low degradation rates that can be controlled by preventive tamping at infrequent intervals. However, the tail of the distribution consists of sections with high degradation rates that need to be accurately monitored and restored with corrective tamping to reduce safety risks.

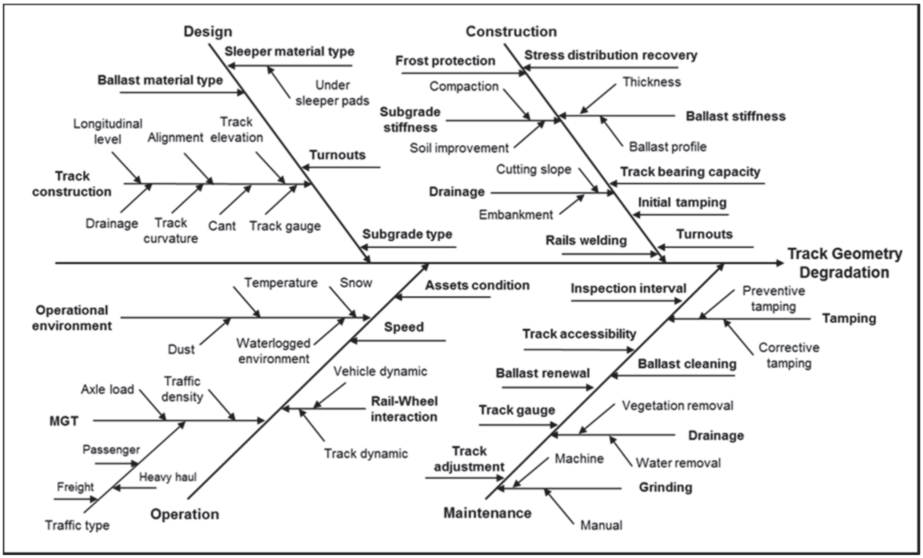


Figure 4: Ishikawa diagram (cause and effect diagram) of the factors influencing track geometry degradation [17]

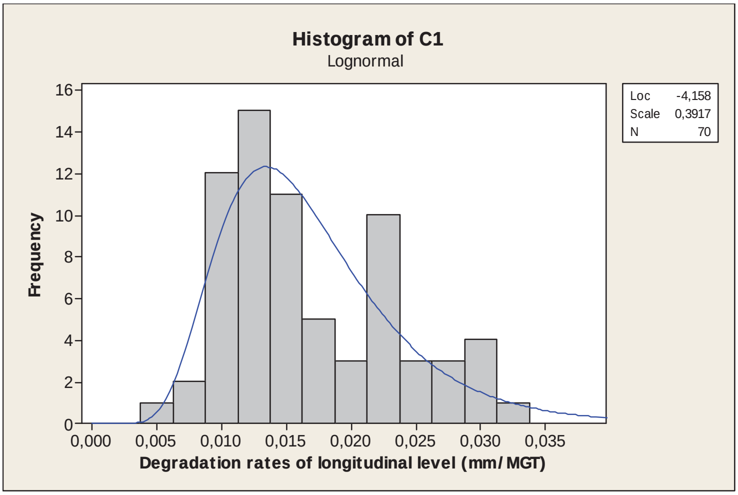


Figure 5: Histogram of longitudinal level degradation rates in different 200 m track sections between 2007 and 2012

According to the previous study [17], the Weibull distribution provides the best fit for the safety failures data set (see Figure 6). The parameter values of the Weibull distribution, shape (β) and scale (η), are1.857 and 329.771 MGT respectively.

Figure 7 shows the observed tamping efficiency on the selected track sections, between 2007 and 2012, by specifying how much the longitudinal level deviation of each segment has been reduced by tamping. It also indicates the maintenance actions performed at different intervention limits.

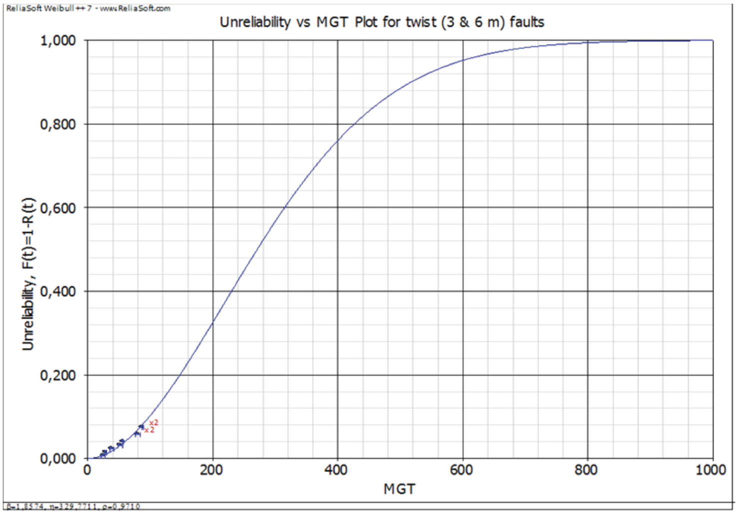


Figure 6: Cumulative distribution functions (cdf) of (twist 3 m & 6 m) faults versus MGT [17]

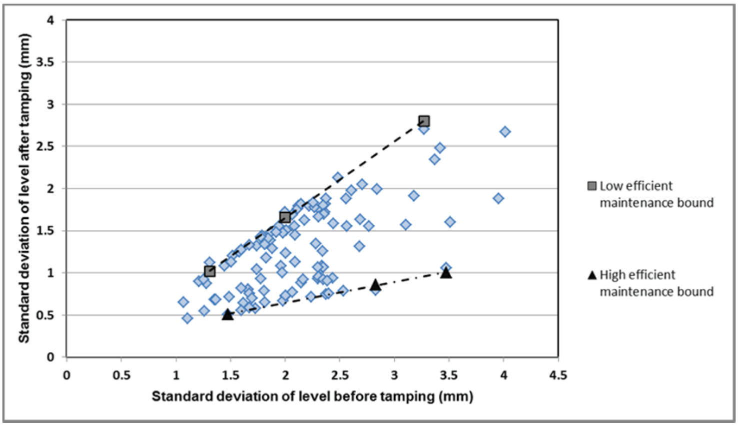


Figure 7: Observed tamping efficiency within studied time interval

Proposed Cost Rate Function (CRF)

Figure 8 shows a schematic description of the track geometry maintenance events.

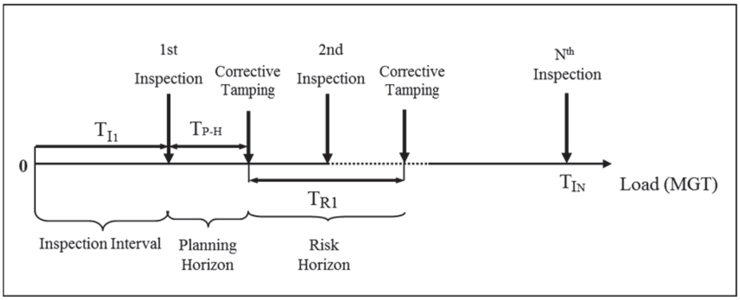


Figure 8: Schematic model of maintenance events

In this model, T_I is the operational interval between inspections, $T_{P\text{–}H}$ is the maintenance planning horizon time interval during which the track can be operated until deferred maintenance takes place, and T_R is the risk horizon time between two consecutive maintenance actions.

The aim of the model is to specify the cost-effective maintenance limit for track geometry maintenance which will minimise the total cost per unit of traffic load (MGT) for any length of track section. The model aims to evaluate how much different intervention limits affect the total maintenance cost.

The model considers two types of faults: standard deviations of the longitudinal level and isolated safety faults (twist 3 m and 6 m). If the standard deviation of the longitudinal level for a 200 m track section goes over the specified intervention limit and/or detection of safety faults, corrective tamping is performed at a fixed time interval after the inspection.

The following assumptions underpin the proposed model.

- 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 probability of safety fault occurrence is independent of longitudinal level intervention limits. This means that selecting different intervention limits for longitudinal level has no effect on the probability of safety fault occurrence.
- The model considers the geometrical degradation rate of each 200 m track section. However, it assumes that these degradation rates are constant over time.
- The maximum allowable train speed on the studied line is 120 km/h. The track quality is classified as poor when the standard deviation of the longitudinal level reaches 2.1 mm (see Figure 9). The study assumes that when the standard deviation of the longitudinal level reaches 2.1 mm or higher the passenger trains should reduce their speed from 120 to 70 km/h to preserve safety as well as comfort.

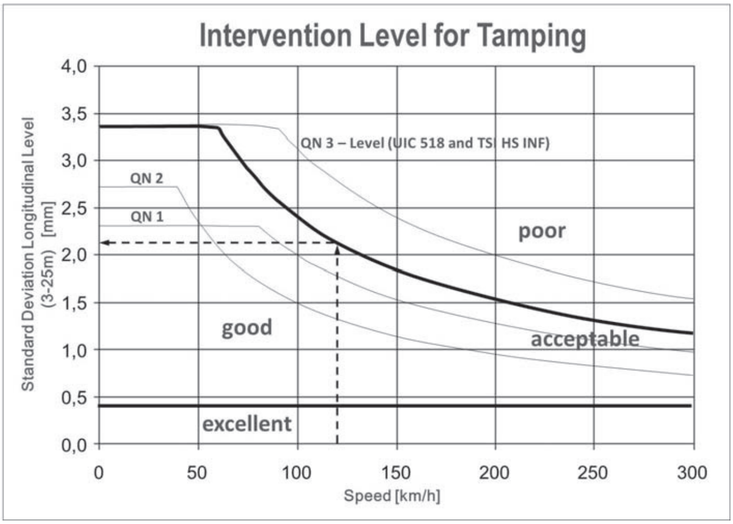


Figure 9: UIC ride comfort limits graph (“Lines of constant riding comfort at different speeds”) [19]

Amongst all factors mentioned in Figure 4 (Ishikawa diagram), only the costs of the following main parameters for which the data were available are considered in the proposed cost model.

- Inspection cost (C_I): This deterministic value is calculated by summing up the costs of all inspections within the study time.
- Corrective tamping cost ($C_{C.T}$): This represents the tamping cost for restoring the sections with deviations over the intervention limit during the study time.

- Risk of accident cost ($C_{ACC.}$): This cost can be estimated by multiplying the cost of derailment by the probability of safety fault occurrence in the interval of two consecutive maintenance events.
- Capacity lost cost ($C_{C.L}$): When the standard deviation of the longitudinal level goes over a limit, the train needs to reduce its speed to assure safety. Reduction of train speed will result in capacity loss of the line. This cost is assessed in the planning horizon time interval ($T_{P\text{-}H}$) during which the trains should run at lower speeds until deferred tamping is performed.

The cost model to assess the total maintenance cost per unit of traffic load (MGT) for k series of the inspection cycles can be expressed as

$$Total\ cost = \frac{\sum_{i=1}^{k} C_I + \sum_{i=1}^{k} N_i C_{C.T} + \sum_{i=1}^{k} P_{S.F}\left(T_{R_i}\right) C_{Acc.} + \sum_{i=1}^{k} C_{C.L_i}}{T} \tag{4}$$

In the model, T is the total accumulated operating time (MGT) and N is the total length of the track (km) which should be tamped after each inspection. To estimate the extent of N after each inspection, the degradation rate of each segment is used to simulate the value of the standard deviation of longitudinal level. Those segments which have deviations above the intervention limit should be tamped.

The next step is to estimate the tamping efficiency in each segment by simulating the value of the standard deviation of the longitudinal level after performing tamping. As shown in Figure 7, the evaluation of tamping efficiency on 200 m segments indicates a high variability in efficiency in different segments. The efficiency of tamping depends on several factors, such as the ballast quality, the track environment and the size of the deviation when the track is tamped. To cover all tamping efficiencies, the model was run for two scenarios: the optimum scenario and the worst scenario. The optimum scenario used the high efficient maintenance bound, while the worst scenario considered the low efficient maintenance bound (see Figure 7).

Application of the model on the studied line

As previously mentioned, 14 km of the line 118 with the same quality class and similar characteristics was selected for this study. All the measurement data were adjusted manually to estimate the degradation rates of each 200 m segment (see Figure 5). By applying the proposed model, we can compare the results of selecting 15 different intervention limits on total maintenance cost to find the most cost-effective alternative. These 15 different intervention limits for the standard deviation of the longitudinal level range from 1.4 to 2.8 mm with a sequence unit of 0.1 mm.

The costs of inspection and corrective tamping per kilometre and the delay cost per minute for passenger trains were collected from Trafikverket experts. The cost of accidents was adopted from the study of Podofillini et al. [20] on the optimisation of railway track inspection and maintenance procedures. The costs used in the model are listed in Table 3.

Table 3: The costs considered in the model

Type	Cost (SEK: 1 € ≈ 9 SEK)
Inspection per kilometre	1200
Corrective tamping per kilometre	50,000
Delay cost per minute for passenger trains	450
Accident	15,000,000

The study assumes that the line is used by 4 iron ore trains and 8 passenger trains per day. The track is inspected every 2 months from April to October (4 times per year). The first inspection every year is performed in April. The corrective tamping is planned and performed by the contractor within 1 month after each inspection. During winter (November to March) no inspection or maintenance actions take place. In this study, the operational load (MGT) is considered as a surrogate of time.

The simulation was performed for the time interval from 2013-04 to 2017-10. The total maintenance cost per MGT for each IL is shown in Figure 10. Depending on the maintenance efficiency, the actual maintenance cost for each scenario can vary between the high and low efficient maintenance boundaries (grey dashed area in Figure 10). As can be seen, the seventh scenario (IL = 2 mm) is the most cost-effective alternative.

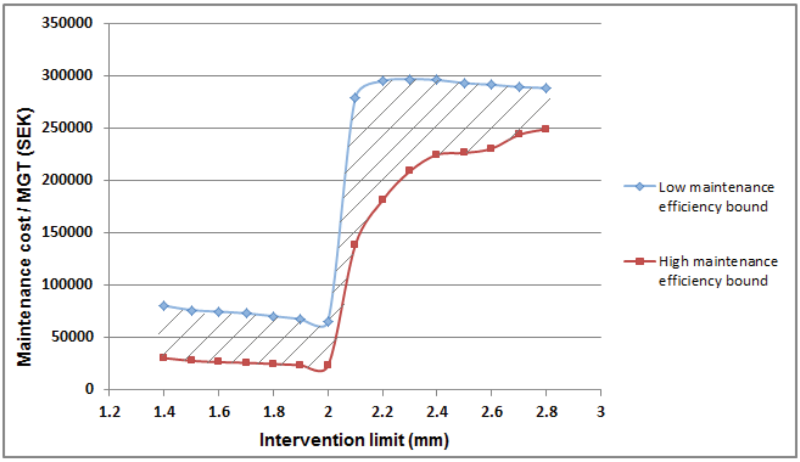
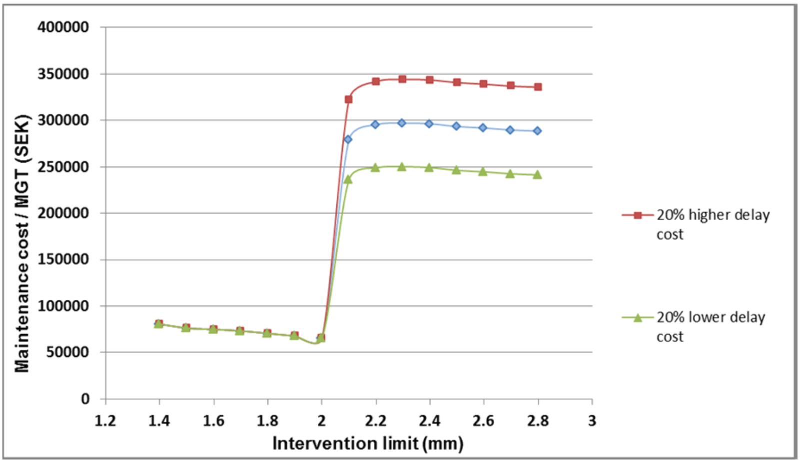
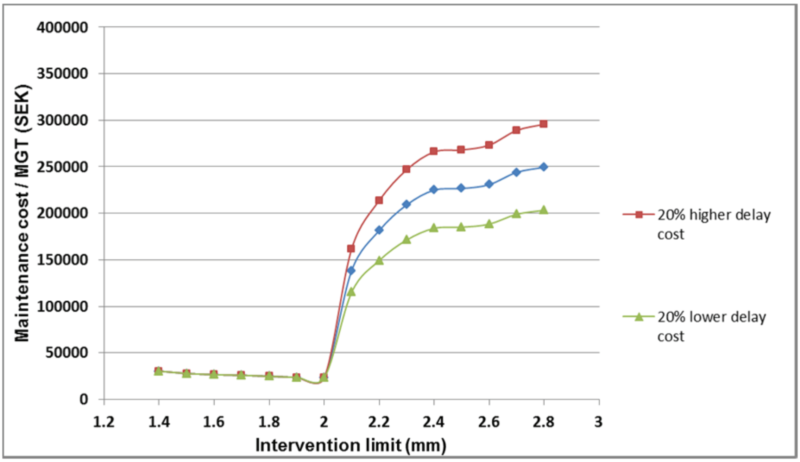


Figure 10: Comparison of maintenance cost per MGT for different intervention limits

The main reason for a sharp increase in maintenance cost by selecting the IL equal to or greater than 2.1 mm is the capacity loss cost due to speed reduction of passenger trains within a one-month planning horizon time interval. In different seasons and different regions, the demand rate for passenger trains can differ. This will result in variations of delay time penalties. To investigate how much the delay cost affects the total maintenance cost, the model was run with 20% higher and 20% lower delay costs than the value selected earlier (i.e. 450 SEK). The results are shown in Figure 11 (a) & (b).



(a)



(b)

Figure 11: Variation of delay cost in total maintenance cost (a) low efficient maintenance (b) High efficient maintenance

Discussion

The results show that the most cost-effective IL for the standard deviation of the longitudinal level on the studied line is 2 mm. When higher IL are selected, the maintenance frequency (and total maintenance cost) is reduced, but when it reaches 2.1 mm, the passenger trains must reduce their speed to preserve safety and comfort. This does not affect the speed of iron ore trains, as the maximum speeds of loaded and unloaded iron ore trains are 60 and 70 km/h respectively. However, the additional capacity loss cost due to the speed reduction of passenger trains will result in a sharp rise in the total maintenance cost. It should be noted that the traffic disruption from the speed reduction of passenger trains has an effect on the schedule of iron ore trains. Any delay over 2 hours will result in cancellation of one iron ore train which costs 5,000,000 SEK.

The cost-effective IL should be specified for different track quality classes. The results of this study fit the quality class 2 of the studied line. In the south of Sweden, due to greater demand, the lines have better quality classes, allowing the trains to run at higher speeds. Therefore, lower intervention limits must be selected for tamping.

Also, as mentioned earlier, the delay time penalties depend on the demand rate. In the regions with a greater demand for passenger trains, the capacity loss cost increases. For instance, the delay time penalty in the south of Sweden is around 1200 SEK per minute; i.e. about 3 times higher than in the north. Therefore, keeping the track quality in acceptable condition to prevent any speed reduction is much more important in the south.

Although selecting IL=2 mm will result in the lowest maintenance cost, the amount of savings generated by deferring maintenance from 1.4 mm to 2 mm is not considerable. Allowing the track to deviate to higher levels can affect the energy consumption, ride comfort, and degradation rate of other components, and lead to faster settlement after tamping due to “track memory” etc. Therefore, in the long run and by considering the whole railway system, it may be more beneficial to select a lower IL than 2 mm.

The results also illustrate the impact of maintenance efficiency on the total maintenance cost. Efficient maintenance can help to reduce the total maintenance cost significantly.

The obtained results are based on certain assumptions. The degradation rate of track segments was assumed to be constant over time. However, due to the deterioration of track components such as ballast, the geometry degradation rate can increase over time. Higher degradation rates lead to more frequent maintenance which affects the total maintenance cost. In addition, “track memory” which results in sudden settling of the ballast in a short interval after tamping has not been considered in this model.

The study uses a model consisting of direct and quantitative cost parameters; indirect cost parameters, such as the effect of lower track quality on the degradation rate of other components, have not been considered. But low quality track may affect the degradation rates of other parts, such as wheel-sets, thereby increasing the total maintenance costs. By including the indirect and qualitative cost factors, a more reliable cost-effective intervention limit for tamping can be obtained.

Conclusion

The following conclusions are drawn from this study.

1. The capacity loss penalties due to the speed reduction at higher intervention limits can increase the total maintenance cost significantly.
2. By improving the maintenance efficiency, the total maintenance cost can be reduced considerably.
3. The cost-effective intervention limits should be specified for different track quality classes.
4. Since the initial track quality cannot be re-obtained by normal tamping and because the extent of cost saving by increasing the intervention limit from 1.4 to 2.0 mm was not significant, performing tamping at lower intervention limits can increase the useful life length of the asset.

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