Railway track geometry inspection optimization

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Maintenance Engineering, master's level (120 credits)
2018

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ACKNOWLEDGEMENTS

The research presented in this master thesis has been carried out at the division of Operation and Maintenance Engineering at Luleå University of Technology (LTU), Sweden.

First, I would like to express my utmost gratitude to my supervisor Prof. Alireza Ahmadi and my co-supervisor Iman Soleimanmeigouni for the continuous support during my Masters Degree thesis research, for their motivation, patience, immense knowledge and enthusiasm. Their guidance helped me in the process of my study and writing my thesis.

I would like also to thank Dr. Johan Odelius, Dr. Adithya Thaduri and Dr. Stephen Mayowa Famurewa for their insightful guidance, encouragement, and help with simulations.

I would like to thank the JVTC and Trafikverket for all of the support they provided to perform this research. I am particularly grateful to Dr. Arne Nissen for his support.

I would like to appreciate my fellow classmates: Keegan Mbiyana, Andreas Papadimitriou, Isaac Nkurunziza and Aly Hassabelnaby for the stimulating discussions and the fun we had the last 2 years of our Masters degree studies.

I am also grateful to the Swedish Institute scholarship for giving me the opportunity to see my dream come true in achieving my academic plans. Last but not least, my sincere appreciation to my parents for their continued support.

Michael Simba Muinde
June 2018
Luleå, Sweden

ABSTRACT

Railway transportation plays a vital role in modern societies. Due to increasing demands for transportation of passengers and goods, higher speed trains with heavier axle loads are introduced to the railway system, and it is expected to continue in the future. Therefore, track geometry bears huge static and dynamic forces that accelerate degradation process. As a result, railway track should be inspected regularly to detect geometry faults and to plan for maintenance actions in advance. Track geometry inspection has a profound impact on railway track availability and maintenance cost. Although there have been improvements in safety performance and maintenance planning of railway tracks, still infrastructure managers expect a more effective maintenance planning and scheduling regime. This thesis proposes a simulation-based model for optimization of track geometry inspection intervals. To simulate the track geometry evolution a linear model is used to model track geometry degradation in a maintenance cycle. It is assumed that the parameters of degradation model are random variables following lognormal distribution. Using the proposed model, the track geometry behaviour is simulated under different inspection intervals. Later, different inspection intervals are compared with respect to the cost function and the optimal range of inspection intervals is obtained.

Keywords: *Maintenance Cost, track Inspection, Optimization, inspection intervals, inspection optimization, Track Degradation, Track Geometry*.

ACRONYMS & SYMBOLS

RAMS	Reliability, Availability, Maintainability, and Safety
LCC	Life cycle costing
SDL	Standard deviation of the longitudinal level
STRIX & IMV200	Track SDL measurement cars
BS EN	British Standard European Norm
SS EN	Swedish Standard European Norm
SD	Standard deviation
CM	Corrective maintenance
PM	Preventive maintenance
LN	log normally distributed
N	normally distributed (for equations)
AL	Alert limit(mm/m)
IAL	Immediate action limit(m)
IL	Intervention limit(mm/m)
D1	Wavelength range *D1*: $3\ m < \lambda \leq 25\ m$
D2	Wavelength range *D2*: $25\ m < \lambda \leq 70\ m$
D3	Wavelength range *D3*: $70\ m < \lambda \leq 150$ m for longitudinal level
	Wavelength range *D3*: $70\ m < \lambda \leq 200$ m for alignment
UIC	International Union of Railways
E(C)	Total expected cost,
L1	Comfort limit (1.6mm)
L2	Safety limit (2.0mm)
C_{L1}	Penalty cost over L1,
$E(N_t)$	Expected number of tamping,
C_{L2}	Penalty cost for exceeding L2,
$E(\mathrm{T}_{\mathrm{oveL1}})$	Expected time over L1
$E(T_{overL2})$	Expected times over L2,
C_i	Cost of inspection,
N_i,	Number of inspections and
C_t	Cost of tamping.

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1. Introduction and background

Railway transport is one of the most important factors for a country's progress and is considered as the “lifeline” of a nation. Today, it is proven that transport infrastructure is a key element for adding speed and efficiency to a country's progress. This requires that the railway system to have highest level of safety, availability, and comfort ride at lowest possible cost.

A reliable and robust railway track geometry is one of the most important feature of a dependable railway track systems. Track geometry degrades with age and usage; and loses its functionality over time. This necessitates development and implementation of an applicable and cost-effective maintenance program, to control the degradation of the track, restore the damaged track to an operational state, and to identify the optimum intervention activities.

It is worth noting that, irregular track geometry can cause increased track loading that can lead to a high risk of derailment, and reduced component useful life. In addition, track vibration and cyclic loading creating ballast settlement can increase the complications related to track geometry degradation. With the current technological advancement coupled with budget limitations and competition in the market, railway operators tend to employ efficient operations and maintenance techniques and plans.

To provide a reliable maintenance plan, an accurate inspection program is needed. In this way, track geometry condition can be evaluated, and the failures and risks can be mitigated. An optimal inspection plan creates room for timely detection track geometry defects and for planning maintenance activities.

Track maintenance can be carried out in different ways, e.g. manual intervention, stone blowing and tamping. Among which, tamping is the most commonplace technique for maintenance of track geometry. Tamping procedure is done by repacking ballast below the sleepers restoring the track geometry to its desired position (Andrews, Prescott, & De-Rozières, 2014). Although tamping is used in railway track geometry maintenance, a keen look into the historical data indicates that it does not always restore track to its original geometry. Thus, it generally improves the quality of track to somewhere between “as good as new” and “as bad as old”. Tamping yields a visually obvious effect, generating sudden drop in degradation of track geometry (Saussine, et al., 2009). Technical and human resources required for performing tamping interventions are a major cost factor in railway systems (Quiroga & Schnieder, 2011). Furthermore, due to high logistical cost constraints, most track geometry maintenance activities need to be planned, up to one year in advance.

It should be noted that, unnecessary early tamping actions can reduce the lifetime of the existing track. On the other hand, late tamping actions may increase the risk of derailment and reduce the comfort ride. These facts make it clear that the maintenance analysis of railway track geometry is highly important.

Therefore, there is a need to have an effective inspection plan to detect track geometry defects in proper time to rectify them before exceeding safety limits. In addition, the inspection plan should be cost effective. This can be done by comparing the total maintenance cost and overall condition of track geometry under different inspection scenarios. To plan railway track geometry maintenance activities, a simulation model would be of great advantage to simulate the track geometry behavior. Such simulation requires a mathematical model that will show how track geometry will behave under a specific maintenance plan.

1.1. Problem statement

Currently, there is an increase in demand in using railway as a mode of transport. To respond to this demand, trains with higher speed and heavier axle loads are introduced to railway system. This in turn results to increased degradation and increased maintenance costs. Infrastructure managers have high demands to ensure safe, comfortable and reliable railway transportation services. To meet these demands there is a need to improve track infrastructure condition and proper maintenance planning is required. In addition, there is a plan by the European region to create a single competitive and efficient railway transport system, which needs to be competitive and sustainable. According to the European Commission, (2011) white paper, efficient and effective transport is fundamental towards economic and societal growth.

According to SIKA, (2017) Sweden’s infrastructure development plan on transportation and communication, there is a targeted 17% reduction in fuel consumption on road transportation by 2020. According to the forecast, there is an expected increase of 21 billion tonne-kilometers by 2020, which in turn will result in a 16% load increase in railway transport. Combining these recurrent situations, this can lead to an increased track geometry degradation. Therefore, an ideal simulation model to predict track geometry behaviour is required for an effective maintenance strategy to achieve the minimum inspection and maintenance cost.

In order to meet the required safety and comfort, high track quality is required. If track quality is poor, it may directly or indirectly lead to such issues like speed reduction, derailment, high maintenance costs as well as increased degradation rates. To avoid these issues, inspection optimization is essential, which can result to identify geometry defects in proper times, an increased asset life, and decreased maintenance costs.

Normally, for infrastructure managers to perform inspection and tamping they outsource the required service to different contractors per line. This leaves the contractors with the task to design and plan maintenance work. Depending on the class of the line, inspections can vary from one to six times per year. For contractors to perform inspection, they rely on the condition of the track. If the inspection interval is wrongly selected, there is a probability that track quality degrades beyond the required intervention limits. When required intervention limits are exceeded, there is a high chance of immediate or urgent tamping which may result to high maintenance costs. This can be avoided by optimizing inspection interval.

To optimize inspection intervals, simulation of track geometry is needed. Simulation can be referred to as a process or method of imitating a real-world process or system operation. In general, simulation can be used in a number of contexts such as testing, training, safety engineering, and simulating performance optimization (Albright, Winston, & Zappe, 2010). Compared to other methods like spreadsheets, which are static and only able to provide single quantitative results at a time, simulations can replicate one's dynamic business reality. For instance, when running future anticipated orders can be hard when using spreadsheets. On the other hand, simulations can provide one with multiple metrics that can help them understand and look into the future (Albright, Winston, & Zappe, 2010). Based on the advantages of simulation, this study uses Monte-Carlo simulation to simulate track geometry evolution to specify an optimal inspection interval for maintenance planning. Based on the required levels of alertness in railway track maintenance, this research uses degradation and maintenance history data from line 414 (a part of Main Western Line in Sweden) to estimate model parameters and to simulate track geometry evolution.

1.2. Research goal and objectives

The main purpose of this research is to optimize railway track geometry inspection interval with respect to cost considering safety limits. In order to achieve the goal of this study, the following objectives have been defined:

- To develop a simulation model for track geometry evolution over time,
- Develop a cost-based safety constraint inspection optimization model

1.3. Research questions

The following research questions are designed to fulfill the intended objectives of the research as well as acting as the pillars around which the research is focusing on:

1. How to develop an integrated track geometry degradation model by considering different degradation behaviours along track line?
2. How to use track geometry data to identify the cost-effective inspection interval, considering safety and maintenance limits, using simulation-based optimization?

1.4. Scope and limitations

This research covers different aspects of railway track geometry degradation and the process of railway track geometry maintenance. Model proposed for this study is for ballasted track. In this research study, standard deviation of longitudinal level is used as track quality index for degradation modeling. Therefore, other track geometry parameters, i.e. alignment, cant, twist, and gauge are left out of the scope of this study. It is assumed that traffic parameters including speed and axle load will not change. In addition, the effects of environmental condition and maintenance history on track geometry degradation are not considered in this study.

The remaining part of the thesis is as follows. Chapter 2 investigates theoretical framework concerning railway track geometry measurement, irregularities and indicators. Chapter 3 involves the literature review on track geometry degradation models as well as track geometry inspection. Chapter 4 presents the information on data used in this thesis research, and data sorting and analysis. Chapter 5 explains the proposed track geometry degradation model and procedure used to estimate the parameters of the model. Chapter 6 explains the proposed inspection optimization model using Monte-Carlo simulation. Finally, chapter 7 provides conclusions and main findings and chapter 8 gives suggestions for future research.

2. Theoretical framework

2.1. Track geometry measurement

In the process of railway infrastructure maintenance, it is crucial to measure and keep the track geometry in acceptable level (Ižvolta & Šmalob, 2015). To provide a regular and smooth support for rail and to minimize the derailment risk, track geometry must be measured to determine the levels of deviation. Higgins & Liu (2018), mentioned that when measured deviation is above a given limit, traveling speeds must be reduced and comfort ride will be affected. Thus, track geometry can be considered as a measure of both safety and travel quality. To provide proper maintenance planning, maintenance managers measure geometrical characteristics of the railway track (Ben-Daya, Kumar, & Murthy, 2016). The main track geometry defects include alignment, longitudinal level, gauge, cant, and twist (Weston, et al., 2015).

Alignment

Deviation y_p in y-direction of consecutive positions of point P (*see figure 2.1*) on any rail, expressed as an excursion from the mean horizontal position (reference line) covering the wavelength ranges stipulated below and calculated from successive measurements (EN13848-1, 2008).

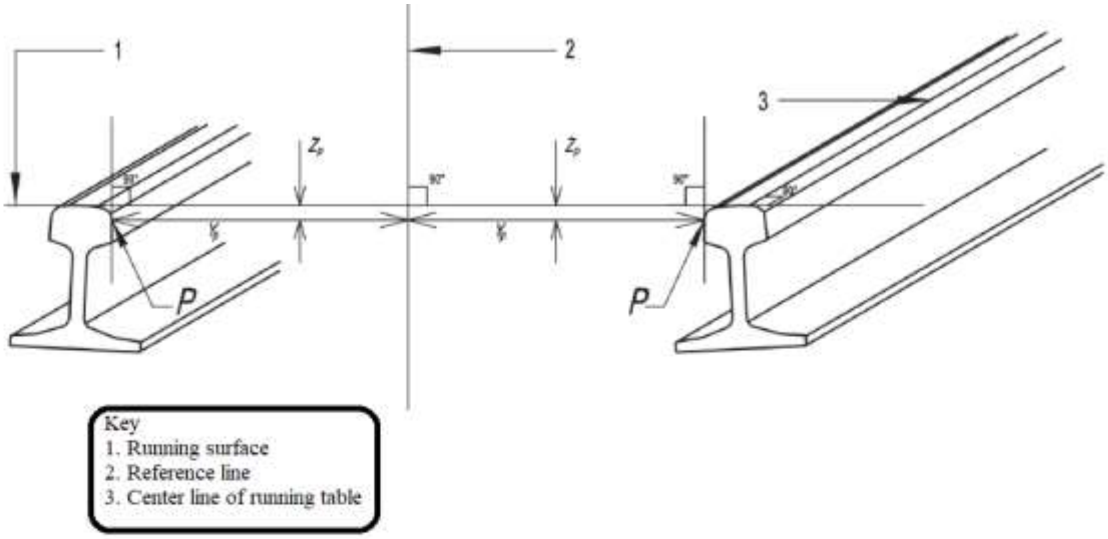

Figure 2.1: Alignment (EN13848-1, 2008)

Longitudinal level

Deviation z_p, in z-direction (see figure 2.2) of consecutive running table levels on any rail, 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). Standard deviation of the longitudinal level is the main indicator of the track quality (Setiawan & Rosyidi, 2016).

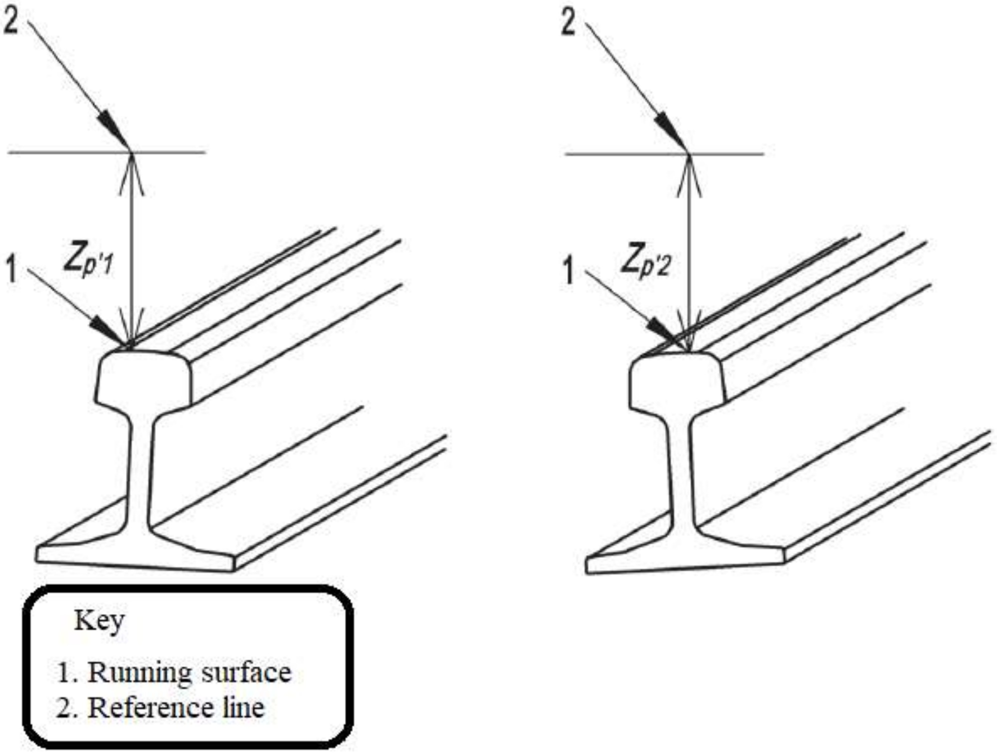

Figure 2.2: Longitudinal level (EN13848-1, 2008)

Track gauge

Track gauge, *G*, is the smallest distance between lines perpendicular to the running surface intersecting each rail head profile at point P in a range from 0 to Z_p below the running surface. Z_p is always 14 mm. For different countries, track gauge is different. However, the most common track gauge in 60% of the railways is 1,435 mm (EN13848-1, 2008).

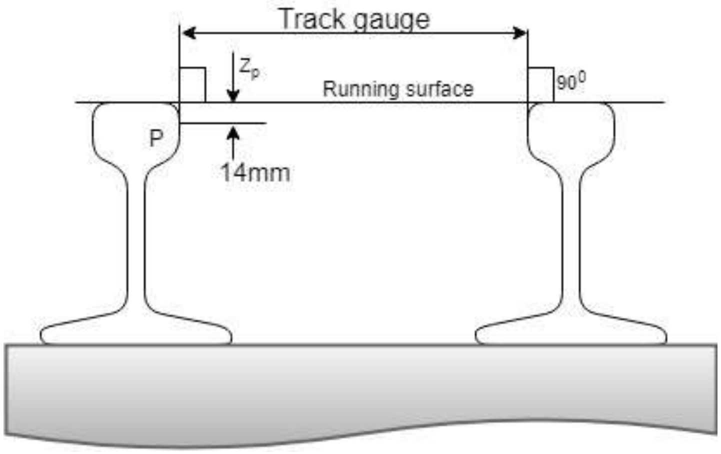

Figure 2.3: Track gauge (EN13848-1, 2008)

Track gradient

The relative elevation that occurs along two rails is referred to track gradient (see figure 2.4). Normally expressed as horizontal distance traveled in terms of the difference in inclination for a given track distance (EN13848-1, 2008).

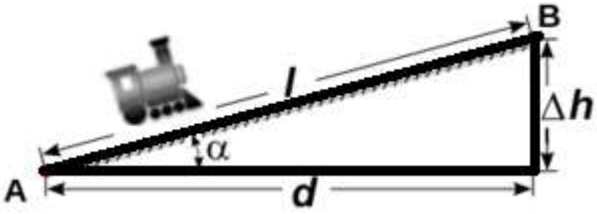

Figure 2.4: Track gradient (EN-13848-1)

Where:

d = horizontal distance

l = slope length

Δh = rise

α= Inclination angle

Track cant (cross-level)

The difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane. It is expressed as the height of the vertical leg of the right-angled triangle having a hypotenuse that relates to the nominal track gauge plus the width of the rail head rounded to the nearest 10 mm (EN13848-1, 2008).

Maximum cant is usually regulated to control the unloading of the high rail wheels at low speeds.

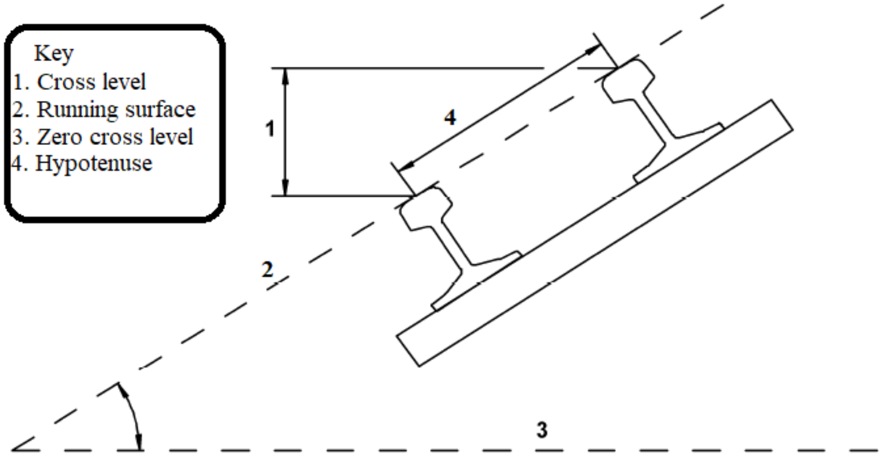

Figure 2.5: Cant (BS-EN-13848-1)

Twist

The algebraic difference between two cross levels taken at a defined distance apart, usually expressed as a gradient between the two points of measurement. It should be noted that, twist may be expressed as a ratio (% or mm/m). When the twist is higher than the expected value, this is considered as a fault on the railway track (EN13848-1, 2008).

2.2. Track irregularities

Track irregularities can be considered as deviations from normal projected track geometry and they exceed tolerance levels (see figure 2.6). A normal track geometry is one in which the horizontal and vertical alignment is as per the original operating design which meets normal operation (BS-EN-13848-6, 2012).

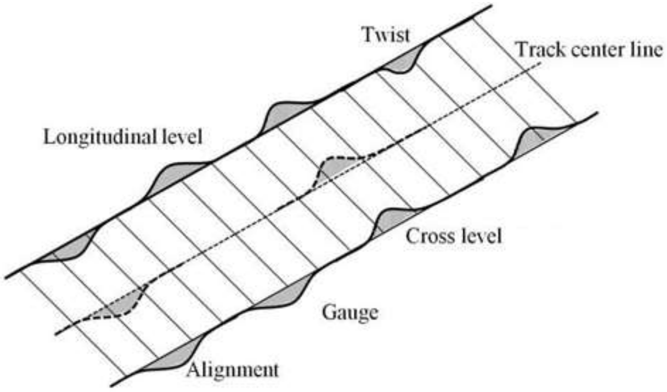

Figure 2.6: Track irregularities

Normally, for a new track, there are minimal track irregularities. However, as the track operations start, there can be sudden and large deviations caused by repacking and breakage of ballast to level and settle the sleepers. Such cases do not always occur since it can be costly if the deviations are extensive. Therefore, proper initial design parameters must be studied before installation of a new rail track.

Depending on the extent under which the track irregularity is, track irregularities can be classified in various groups. According to Swedish standard SS-EN-13848-5:2017, an isolated defect is a single segment that exceeds given limits like IL, or AL, IAL with at least a single 0.25 m sampling distance. In the standard minimum requirements are given for track geometry for the safe operation of trains based on isolated defects. Isolated defects are shortest irregularities and can induce dynamic forces on the moving vehicles leading to passenger discomfort. If it is not controlled and corrected in time, they can lead to extreme track wear that can lead to fatigue on the fasteners, sleepers, and rail, which is risky and can cause derailments.

According to Yu, Li, & Wang (2016), short wavelength irregularity can either originate from the rail manufacturing or installation of the sleepers or alignment of sleepers. Normally, short wavelength irregularity produces short wavelength periodical disturbance that will be hardly noticed and cause the problem to low-speed trains. This is normally indicated by small amplitude and short wavelength. In most cases when there is sleeper deviation emerging from laying process, there are short-wave irregularities that are associated with the deviation.

Long-wavelength irregularities, on the other hand, are considered to have wavelength above 25m (Grassie, 2012). This kind of irregularities have an effect on high-speed trains and creating a swaying movement that is uncomfortable for the passengers. In most cases, it is not easy to detect long-wavelength irregularities with accelerometers used in measuring equipment. Since this does not pose any major safety effect and discomfort of the passengers, no maintenance action is done (Ben-Daya, Kumar, & Murthy, 2016).

Geometric faults on the track geometry that occur in short lengths can lead to extreme dynamic effects between the rail and wheel accelerating their degradation. Isolated defects and short-wavelengths are rectified by the tamping process (Ben-Daya, Kumar, & Murthy, 2016).

2.3. Track geometry maintenance activities

To restore track geometry, there are two main maintenance actions that can be performed, stone blowing procedure and tamping procedure (Famurewa, et. al, 2015) .

Stone blowing procedure

Stone blowing process was motivated by the observation that after tamping ballast tends to go back to the condition that was there before tamping. The current maintenance strategy used in the UK, stone blowing is done on sections of the track that needs frequent tamping since this causes less ballast damage (Bowman, 2015). It is considered that stone blowing is associated to low lift with correction of short wavelength geometry faults and tampers are associated with high lift for removal of long wavelength faults. Therefore, stone blowing is not as effective as tamping but rather a complement.

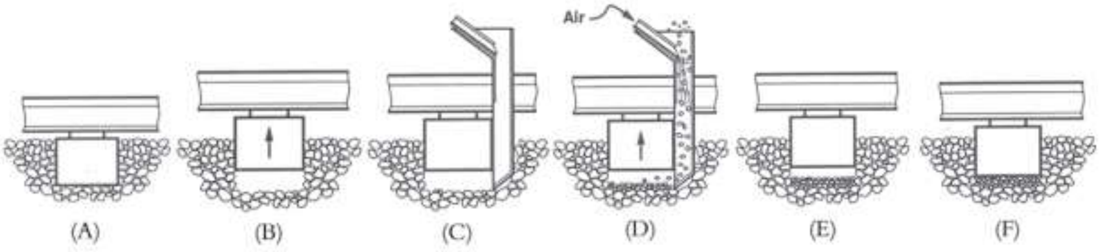

Figure 2.7: Stone blowing process (Saussine, et al., 2009)

Figure 2.7 shows different stages of stone blowing and they are highlighted as follows:

A) Prior to adjustment ballast settles around the sleeper.

B) To create a space below the sleeper, a machine is used to lift the sleeper and tubes for stone blowing are inserted near the sleeper with ballast (stage B and C).

C) Compressed air used to blow a measured quantity of ballast in the space bellow the sleeper.

D) Once ballast blowing is completed, the stone blowing tubes are removed.
E) Lastly, once the stone blowing is completed, sleeper is lowered, and the ballast compacted by traffic.

Tamping procedure

Track geometry degradation occurs as a result of long wavelength faults caused by vibrations resulting from repeated traffic on the track. Tamping is the maintenance action performed to rectify these faults (Arastehkhouy, et. al, 2016). Other faults like short wavelength are corrected by rail gridding or weld straitening.

Despite being one of the most essential track maintenance activities, tamping remains to be costly to execute. Tamping rearranges and compacts ballast to rectify both lateral and vertical track geometry deviations. According to Martey & Attoh-Okine, (2018), tamping can be effective when performed over D1 wavelengths (3 - 25m) in the smoothing mode and in design mode, 25m upwards (D2 and D3). Evaluating track geometry there are three wavelengths stipulated in EN 13848:

- D1 (2-25m)
- D2 (25-70m)
- D3 (70-150m)

Tamping can be preventive or corrective, depending on the deviation levels and limits considered. Also, tamping can be classified as either partial or complete tamping procedure. To do complete tamping, tamping is executed along the entire length of the track section while partial tamping is carried out on segments of the track section. Effect of tamping on the track varies depending on the type of tamping procedure carried out on the track. As a result, this kind of interventions can give varying recovery values for the track after tamping.

After tamping action, track geometry irregularity measurements decrease significantly (Arastehkhouy, et. al, 2014). In addition, tamping significantly influences the capacity on the railway network in terms of track quality demand, track possession, heavy equipment utilization and scheduling constraints.

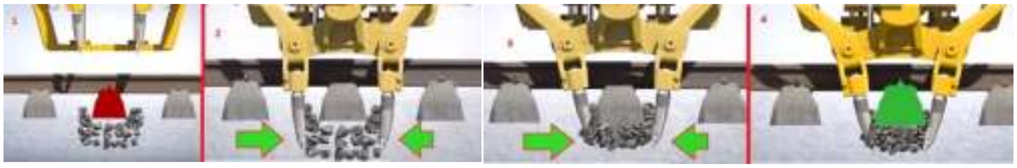

Figure 2.8: Tamping procedure

From figure 2.8 above, tamping procedure is described as follows:

Step 1 tamping machine lifting rollers raise the sleeper to the desired level of the reference rail creating a space bellow the sleeper.

Step 2 Tamping tines are inserted on the sides of the sleeper

Step 3 and 4 ballast is squeezed bellow the sleeper using vibration of the tamping tines retaining the sleeper in the desired position.

Step 5 tamping tines are removed then the sleeper lowered, and the tamper moves to the next sleeper.

Parameters that are significant in determining the quality of tamping include amplitude, pressure used for tamping, frequency, squeezing time (0.8-1.2s) and speed of the tamping unit. To achieve quality tamping, it is important that the tamping tines have a free space of approximately 15mm between the sleeper base and the tamping tine plate (Arastehkhouy, et. al, 2014)

2.4. Track geometry indicators

In the recent years, different techniques have been developed to evaluate track conditions. This has been done for purposes of qualitative or quantitative assessment with an aim of providing a comfortable travel for passengers and serviceability. These techniques mostly use data from inspections carried out using automated systems. Standard deviation of geometry parameters such as alignment and longitudinal level act as the primary basis for these indices. Their application is based on the fact that they have shown a good indication of the track geometric conditions. Using the mentioned indicators, it would be possible to determine when and where the track geometry need to be modified. (Sadeghi & Askarinejad, 2011). When it comes to measuring structural defects, these approaches tend to be limited. It is, therefore, important to use the evaluation of track structure in parallel with the current approaches used in the evaluation of track geometry, to get a strategy that is more precise. Over time, different countries have developed indices to analyze track conditions see table 2.1.

Table 2.1: Current practice track geometry index (Sadeghi & Askarinejad, 2011).

no	Index	Developer	Formula
1	Q index	Swedish National Railway	$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H_{\lim}}} + 2\times\frac{\sigma_S}{\sigma_{S_{\lim}}}\right]/3$
2	Track roughness index	USA railway	$R^2 = \sum_{i=1}^{n} d_i^2/N$
3	Standard deviation	ORE	SD
4	Geometric index (TGI)	Indian railway	$TGI = \frac{2UI + TI + 6AI + GI}{10}, \begin{cases} UI \\ TI \\ AI \\ GI \end{cases} = 100 \times e^{-\frac{SD_m - SD_n}{SD_u - SD_n}}$
5	Five parameter track defectiveness	Australia railway	$W_5 = 1 - (1 - w_e)(1 - w_g)(1 - w_w)(1 - w_y)(1 - w_z)$
6	J index	Polish railway	$J = \frac{S_Z + S_Y + S_W + 0.5S_e}{3.5}$
7	Track quality index (TQI)	USA railway	$TQI = \left[\frac{L_s}{L_0} - 1\right] \times 10^6$

Where:

w_z – calculated average vertical irregularities
w_y – calculated average horizontal irregularities
w_e -track gauge defectiveness
w_g- cant defectiveness
w_w – twist defectiveness
SD_m- measure parameter standard deviation
SD_n - new track standard deviation
SD_u - track urgent maintenance standard deviations
σ_H - average standard deviations of right and left level
σ_S - average standard deviations of alignment and cant
$\sigma_{H_{\lim}}$ - allowable value of s_H based on track categories
$\sigma_{H_{\lim}}$ - allowable value of s_S as per track categories
s_e - Vertical irregularities standard deviation
s_y – horizontal irregularities standard deviation
S_w – twist standard deviation
S_z - gauge standard deviation
n – total number of measurements in length
d_i – mid chord measurement for profile (longitudinal level) and alignment, and deviation for cross level and gauge
L_s- space curve traced length
L_0- track segment (theoretical length)
SD -the standard deviation for every 1000 m section of the data collected

Q index used by the Swedish national railway to evaluate track geometry condition based on statistical analysis. Standard deviation of longitudinal level, the sum of standard deviation of the cant error and the lateral position error, and the comfort limits for these standard deviations are used to develop Q index. According to Ebersöhn and Conrad (2003), a summation of the squares of the deviations is divided by the number of points measured to calculate this index. European Railway Research Center based in France recommends the use of direct standard deviation (SD) approach and is used by some European, Middle East and Asian countries. As contained in the ORE (1981) report, the SD of the geometry parameters is calculated for sections of 1000 m including profile, cross level, alignment, and gauge using mid-chord offsets of 18.9 m. Table 2.2 shows how different SD values can be used in railway track rating.

Table 2.2: Track condition (Sadeghi & Askarinejad, 2010)

Condition of Track	SD value
Poor	4<SD
Average	2<SD<4
Good	1<SD<2
Very good	SD<1

Geometric index (TGI) is a standard deviation based index developed by Indian railway. TGI considers index for different geometry parameters, analyzing condition of the track by comparing "best maintained track" to track that needs urgent maintenance. According to Mundrey (2003) index for individual parameters such as gauge can be calculated as follows:

$$GI = 100 \times e^{-(SD_m - SD_N)/(SD_u - SD_N)} \tag{1}$$

Where: SD_M =measured parameter SD; SD_N =new laid track SD value; and SD_U =track that needs maintenance SD value. For the newly laid track and track needing maintenance SD values are as indicated in table 2.3 (Mundrey, 2003).

Table 2.3: SD values (Mundrey, 2003)

		Newly laid track	**SD for Track needing maintenance (mm)**	
Parameters	Chord length (m)	SD values(mm)	Speed>105kph	Speed<105kph
Twist	3.6	1.75	3.8	4.2
Alignment	7.2	1.5	3	3
Gauge	_	1	3.6	3.6
Unevenness	9.6	2.6	6.2	7.2

For calculation of the data obtained from geometry measurement cars, the Australian railway uses five parameters track defectiveness (Madejski & Grabozyk, 2000). The ratio of the sum of the subsections exceeding acceptable deviation to the section total length for each evaluated section is the value of defectiveness for each parameter. For each measured track parameter, track defectiveness is calculated as follows:

$$W = \frac{\sum L_i}{L} \qquad (2)$$

Where: $L_i =$ subsection length exceeding acceptable limits, and L is the length of the track section. Treating each geometry parameter independently and assuming that each parameter has a negligible effect on each other the five-parameter index is as indicated in table 2.3.

Sadeghi & Askarinejad, (2011) proposed a method of evaluating track based on observations made from structural defects of the track.. In their study, they proposed to use profile, twist, alignment, cant, and gauge in one track geometry index (TGI) based on allowable limits. To design the TGI they used justifiable coefficients to combine the parameters. This proposed index can be used in different locations for slab or ballasted tracks. The proposed index is a ratio of deficiency of parameters to allowable limit of parameters shown in equation 3, which is used to indicate the condition of track section geometry parameters.

$$T_i = \frac{\sum_n \Delta x_i}{\tilde{x}} \qquad (3)$$

Where,
n- track section recordings
x-track geometry parameters

Then the five indices were combined to form integrated track geometry index (ITGI), which is an improvement on the TGI and represented in equation 4 below:

$$ITGI = \frac{\sum_{i=1}^{5} T_i W_i}{\sum_{i=1}^{5} W_i} \qquad (4)$$

Where W is model coefficient found by calculating geometry parameters.

3. Literature review

A review of track geometry literature is performed in this section. In order to model track geometry behavior, there is a need to model track geometry degradation and tamping effectiveness (restoration). In this section, different models that have been used in the literature to forecast track geometry behavior are reviewed. In addition, the proposed models for track geometry inspection optimization are discussed in this section.

3.1. Track geometry degradation

Geometric deviations, characterized by displacements in the range of millimeters, can significantly decrease the safety and reliability of the railway track infrastructure. A risk assessment by Qing, et al., (2014) showed that in 2009 the second cause of freight railroad derailments in the USA was a result of the failure of track geometry (the first one being broken rails). Additionally, with track-related costs accounting for over half of maintenance budgets, infrastructure managers need to understand how tracks function and degrade (Sadeghi & Askarinejad, 2010). According to Kaminka, Fox, & Bouquet, 2016 degradation is the ‘change of a component’s original appearance as a result of external influences. Normally, track degradation is slow. However, this cannot be ignored since it can result in high-cost consequences emerging from failures caused by degradation (Qing, et al., 2014). Proper decisions can be made on inspection optimization by residual life estimation for both components and track, life cycle cost calculation and reliability analysis.

In a study by Elkhoury, et al., (2018) it is considered that an effective maintenance strategy needs a model to predict track geometry degradation. In their study, they highlighted some causes of degradation as being caused by axle load, traffic load, type of traffic, rail size, elevation, profile, track alignment, lubrication of the rail, the curvature of the track, speed, age of the rail, and rail-wheel interaction. Figure 3.1 shows two approaches for modeling track geometry degradation.

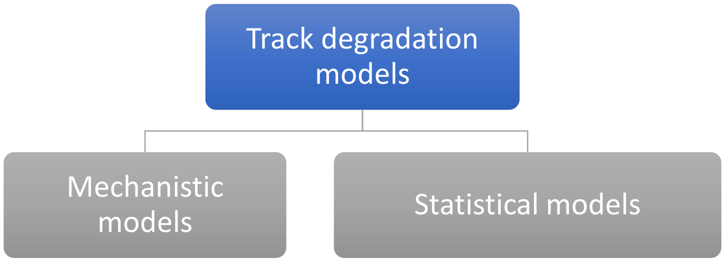

Figure 3.1:Degradation models (Elkhoury, et al., 2018)

3.1.1. Mechanistic models

Mechanistic models combine theory and testing to institute mechanical properties of the railroad vehicles and track structure. Generally, to assess track degradation, it entails calculation of forces and stresses of the degradation variations. Mechanical models rely on physical priori information. Simply, it can be regarded as an approach that uses track mechanical properties that cause degradation. One advantage of this model is that it is easy to differentiate between the track responses and traffic parameters. However, one disadvantage of the mechanistic models is that, it is not able to cope with the uncertainty associated with track geometry degradation. The varying behavior of the maintenance, operational and environmental conditions affect the efficiency of these models. In addition, when one of the influencing factors is not available the results can be unrealistic. Another issue is related to quantifying track and vehicle properties. An integrated track degradation model (*ITDM*) is presented by Zhang, Murray, & Ferreira, (2000), which is a comprehensive track degradation model. In their proposal, they considered an integrated mechanistic model to include an interactive operation of the track components. Therefore, this model is able to predict overall track behavior for three sub-models (rail, ballast and the sleeper). In this model, it is assumed that changes in dynamic forces are the main factor affecting track degradation. In another work, Ping, et al., (2016) made a conclusion that ballast depth and stiffness of the subgrade are highly affects the roughness of track. They used system level model aimed at both component interaction and degradation. Thus, they considered these degradation models as being comprehensive in representing track behavior as well as track condition.

Stjepan & Ahac, (2017) studied track degradation mechanisms by considering sleeper spacing, rail shape, substructure, ballast settlement and dynamic forces. In their study, they argued that ballast settlement plays an important role in track degradation. Therefore, they suggested developing a model that puts into consideration the axle load, ballast type, sleeper size and type, and subgrade condition. Among these factors, axle load was found to have the most crucial effect on the ballast settlement having the fifth root of axle loads. Furthermore, they showed that tamping action does not affect rail track internal properties.

To predict track geometry degradation, the mechanistic approach has been used in different studies among them two are presented here as follows:

- Japanese based model; and
- Austria based model.

On the Japanese based model, companies established a relationship between ballast settlement and cyclic loading. In this model, for heavy haul narrow gauge line and high standard, track degradation (y) is determined using the relationship in equation 5:

$$y = \Upsilon(1 - e^{-\alpha x}) + \beta x \tag{5}$$

Where, x is the repeated number of loadings on the track, β is a coefficient proportional to the sleeper pressure and peak acceleration that ballast experienced and, α is vertical acceleration initial slip, and γ is a constant value which rely on the initial packing of ballast (Elkhoury, et al., 2018).

Based on the Austria model, the mechanistic approach is used to study track settlement considering the track degradation emerging from vehicle acceleration (Elkhoury, et al., 2018). The index consists of track deviations for both vertical and horizontal with no superelevation and speed. The exponential structure of the model is shown in equation 6 representing track quality (Q):

$$Q = a_0 \times e^{-bt} \tag{6}$$

Where, a_0 is the initial track quality, b is the rate of degradation constant and t is the time the measurement is taken (Elkhoury, et al., 2018).

Based on this model, the exponential model in equation 6 indicates that more roughness on the track will lead to more dynamic forces on the rail. The induced dynamic forces lead to track geometry degradation.

Mechanistic models show the interaction between materials. In general, these sorts of models are highly challenging and time consuming because the interaction of many parameters should be considered in the model.

3.1.2. Statistical models

Ideally, statistical models give a full representation of data generation. According to Elkhoury, et, al, (2018), a statistical model can be termed as a mathematical model with a set of statistical assumptions that comes from a big population of the sample or similar data. What differentiates the statistical models from other mathematical and non-statistical models is the inherent probability distributions.

As highlighted by Soleimanmeigouni, Ahmadi, & Kumar, (2018), one of the major characteristics that differentiate statistical models from mechanistic models is how the track geometry exhibits an uncertain behavior. These uncertainties are important in making maintenance decisions. Therefore, to achieve effective and accurate degradation modeling, concepts from statistical modeling, probability theory, and stochastic processes are considered effective. For doing so, it is important to have sufficient data from track degradation.

In the recent years, there have been a number of monitoring devices that have been developed with improvements to take measurements on track geometry degradation. Jovanović, Božović, & Tomičić, (2014), presented a set of condition monitoring technologies that is currently in use across the globe in the maintenance of railway infrastructure. In their work, they described a way of track surface inspection. According to them, they considered laser measurement system as more effective than contact measurement systems. According to their observation, with continued improvement in technology, there will be more understanding of track condition. This has been the case where huge amounts of historical data are provided which reflects track geometry condition. Additionally, with rapid change in computational techniques, data analysis and computation are faster and effective. This has led to more researchers in model track geometry degradation using statistical methods.

To construct a statistical model a set of inputs and output variables are required. Sufficient data is required for this kind of modeling. The ability to cope with a large number of variables that have an effect on track geometry degradation, statistical models are preferred for degradation modeling. This kind of models use large data about the track performance (outputs) and the influencing factors (inputs). Soleimanmeigouni, Ahmadi, & Kumar, (2018), mentioned that statistical methods such as stochastic processes, linear model, and exponential model can be used to model track geometry degradation. One of the advantages of statistical modeling is that it uses real data to construction track degradation model. Therefore, it gives an accurate prediction of track degradation. However, there is a disadvantage of having poor mechanical background about the interaction between the track components and the influencing factors and this can lead to results that are unrealistic.

According to Jovanović, et. al, (2014), to develop a good model, it is important to have sufficient data from condition measurement, work history, superstructure, and infrastructure inventory.

As noted by Soleimanmeigouni, et al., (2018), a wide range of statistical models has been applied to model track geometry degradation. To make this realistic, statistical model uses the track geometry degradation-based observations as well as influencing factors such as traffic, track components, and maintenance history. Hence, they use predictions based on real-life behavior to simulate track degradation behavior.

Sadeghi & Askarinejad, (2010) developed a track geometry deterioration model to analyze track characteristics, renewal, and maintenance policies, as well as environmental conditions on the measured track parameters. Based on the obtained results, they point out that natural events, like falling rocks and flooding increase deterioration rate, while other factors such as snow had no effect on track deterioration. Another factor found from the model that can expedite the track geometry deterioration is curvature. From the results, it was also noted that geometry deterioration can be affected by type of rail regarding jointed rail or welded rail and the type of sleeper used on the rail assembly. Additionally, the study show that deterioration increases with line speed increase.

Stochastic models are considered as statistical models that use historical data and records to make models. Although these models do not deliver based on the underlying physics insights, they use probability to achieve the desired predictions (Andrews, Prescott, & De-Rozières, 2014).

To predict track geometry degradation, several statistical models have developed. Gamma process, Inverse Gaussian process, and Wiener process are some of the statistical methods that have been used in degradation modelling. It has been noted that most of the researchers have used Gamma process among the mentioned methods to model track geometry degradation (Soleimanmeigouni, Ahmadi, & Kumar, 2018). In a review by Tan, et al., (2017), they gave a suggestion of stochastic models from rail tracks in Melbourne, Australia. Therefore, they found that it is necessary to use different ways to identify failure progress.

Following a heuristic based method, Quiroga & Schnieder, (2011) proposed a stochastic degradation model that used Monte-Carlo simulation to simulate and schedule tamping intervention. Their model was based on data collected for 20 years from the French railways SNCF.

In their model data for the first three months after tamping intervention was ignored based on the assumption that the track after tamping faces a bedding-in behaviour. Therefore, their model used data sets with at least 1-year period as this was perceived as a good way to improve precision on the model. In their model, they used two assumptions:

- The first assumption is that the initial degradation values after the nth maintenance (tamping) action (a_n) follow log normal distribution with a mean and variance:

$$a_n \sim LN\left(\mu_a(n), \sigma_a^2(n)\right) \tag{7}$$

Where, μ_a is the mean value, and σ^2 is the variance.

- The second assumption is that evolution of degradation values from one tamping to the next is exponentially distributed.

$$a_n e^{b_n(t-t_n)} + \varepsilon(t) \tag{8}$$

Where t is the time, t_n is the time for the last tamping activity, b_n is the rate of degradation and is log normally distributed stochastic variable with mean and standard deviation $b_n \sim LN\ (\mu_b\ (n), \sigma_b\ (n))$, with an error $\varepsilon(t)$, which is normally distributed variable with zero mean $\varepsilon(t) \sim N(0, \sigma_\varepsilon^2)$.

Andrews, Prescott, & De-Rozières, (2014) developed a Petri net stochastic model to analyze track degradation, maintenance, renewal, and inspection. Using this model, one can study asset management process efficiency and predict track geometry deterioration. In their model, they considered how the rate of track degradation is affected by maintenance.

Using Portuguese railway northern line, Vale & Ribeiro, (2012) developed a stochastic model for geometrical track degradation. From their model, the probabilistic and statistical analysis was performed for different speed group of vehicles, which was shown with longitudinal level for both rails. From their model, it was discovered that there exists an asymmetric distribution of the degradation rate with heavy tailedness shown as:

$$\gamma = \frac{\mu_3}{\sigma^3} \tag{9}$$

Where γ is the random variable skewness x, μ is the mean of the third moment, and σ is va ariable standard deviation.

Lyngby et al. (2008) optimized the intervals of track geometry inspection by taking advantages of Markov methodology. Twist was used as an indicator to show the level of track geometry degradation. 50 states were defined in the Markov model, where each state indicate 1 mm change in twist in the track section. One challenge with a model based on Markov is that there is a constant rate transition between states.

3.2. Tamping effectiveness and recovery

Once track geometry degradation exceeds a predetermined maintenance threshold, a maintenance action is performed to track in order to return the track quality to a better condition. Therefore, the safety of the trains, pathing through the track can be guaranteed. Tamping is currently the main maintenance procedure commonly used internationally to restore tracks to the desired geometrical position (Janaka & Kimitoshi, 2016). Generally, tamping has two major effects on the track geometry including change in the degradation rate and track geometry jump reduction Soleimanmeigouni, et. al, (2018).

The recovery in track geometry condition may be dependent on several factors including track quality prior to tamping, the frequency of previous tamping operations (maintenance history), subsurface (ballast) conditions, tamping procedure, the age of track components, operational speeds, and human factors (Martey & Attoh-Okine, 2018). The dominant factor that influences tamping efficiency or tamping recovery is the track condition just before tamping.

Tamping recovery is dependent on previous tamping procedures since tamping has a damaging effect on the ballast (the tamping machine arms crush the ballast particles). This leads to the resultant quality in the current tamping being lower than the resultant quality of the preceding tamping. Tamping effectiveness also reduces with increase in the number of tamping interventions due to the ballast deterioration with traffic loads as well as the ballast damage due to successive tamping procedures. Tamping efficiency decreases with increase in ballast service life leading to a reduction in the durability of track quality and increased frequency of tamping to maintain track condition at acceptable standards.

There are two main approaches for modeling restoration (or recovery) after tamping, namely deterministic or probabilistic approaches (Martey & Attoh-Okine, 2018). The proper approach to model taming recovery should be based on the degree of uncertainty in the recovery values after tamping. In deterministic techniques, tamping recovery is directly evaluated in relation to the influencing factors such as track quality prior to tamping, the operational speeds, and maintenance history. Majority of studies have evaluated tamping recovery using deterministic techniques such as linear regression models and have assumed that tamping effectiveness is mainly dependent on the quality of track geometry prior to tamping. According to Soleimanmeigouni, Ahmadi, & Kumar (2018), linear regression models are highly popular due to their simplicity and have been employed in the development of track geometry maintenance models and optimization scheduling models.

Zhang, Murray, & Ferreira, (2000) employed linear tamping restoration model as well as a linear track deterioration model, which were subsequently used in the development of a mathematical maintenance model (formulated as integer (mixed 0-1 linear) programming), which optimizes tamping operations in ballasted track as preventive maintenance.

Mercier, Meier-Hirmer, & Roussignol, (2012) developed a maintenance strategy model comprising three sub-models namely an intervention efficiency model, a gamma process track deterioration model, and a maintenance cost model. This model was used to establish the long-term costs of various maintenance strategies and optimize these costs based on various parameters such as intervention threshold or inspection interval. In this study, they employed linear regression to characterize the intervention benefit, which was assumed to be dependent on the deterioration prior to intervention. Famurewa, et al., (2015) used an empirical regression model for recovery after tamping intervention based on previous (longitudinal level) data on examined routes. The empirical recovery model was combined with an exponential track degradation model to optimize the tamping intervention schedule through the minimization of the total intervention cost particularly the track possession cost.

Oyama & Miwa, (2006) investigated tamping recovery based on both the track condition before tamping and the frequency/number of previously performed tamping procedures. This restoration model was subsequently employed in a mixed integer linear programming (*MILP*) model formulated for the scheduling optimization of preventive condition-based tamping through the minimization of net present costs considering several factors. Teixeira & Caetano, (2013) evaluated the effect of the age of track sections (segments) operations on tamping recovery by comparing renewed sections (ages of approximately 10 years) and non-renewed sections (approximately 20 years). Despite the variation in the deterioration rates of track geometry due to loss of tamping effectiveness, the average number of maintenance tamping procedures was found to be greater in older track sections. Soleimanmeigouni, et. al, (2018) proposed a two-level piecewise linear model to characterize the recovery and deterioration of track geometry with possible spatial dependencies within deterioration parameters captured using autoregressive moving average models. Multivariate linear regression was employed to tie various explanatory variables with response variables such as recovery values and changes in the deterioration rates after tamping. Tamping recovery was dependent on both track condition before tamping and tamping type (partial or complete) with the interaction effect between the two covariates also considered.

Linear regression models are highly popular due to their simplicity. However, in many cases, there exists a high degree of uncertainty in recovery values even in instances where track quality is identical prior to tamping, which cannot be accounted for using deterministic techniques. For this reason, probabilistic techniques have increasingly been employed to consider this variation by assuming the recovery after tamping as a random variable with a given probability distribution. A unique distribution for the recovery values after tamping is selected given a group of influencing variables with the parameters (or measures) of the distribution assumed to be a function of the inputs.

3.3. Track geometry inspection

The quality of track geometry frequently changes and being aware of its state is of vital for infrastructure maintenance managers to make the best decision for maintenance (Jovanović, Božović, & Tomičić-Torlaković, 2014). Inspection does not improve the condition of the system (Kurniati, Yeh, & Linc, 2015), but it is the only way to identify the condition of the track. In railway track geometry, many practical issues prevent infrastructure managers to continuously inspect track geometry in time. In one hand, inspecting track geometry frequently, in small periods, severely affect the availability of track and raise some economic issues. On the other hand, there are a limited number of inspection cars and they are not available anytime to inspect the track geometry frequently. These are the main reasons that indicate the importance of finding an optimal inspection interval. In recent years a number of researchers tried to determine an optimal inspection interval with different objective functions. For example, Arasteh khouy et al. (2014) optimized the track geometry inspection intervals with the aim of minimizing total ballast maintenance cost. They considered the cost of inspection, corrective tamping, preventive tamping, and risk of accident in their model. They evaluated the condition of track using two fault limits of B-fault and C-fault which are correspond to every 25cm track sections (isolated defects). Also, they used the probability occurrence of twist in 3m and 6m, fault greater than 15 mm and 25 mm respectively, to consider the risk of derailment. In the proposed model, they assumed that track consists of identical track sections and tamping effectiveness is prefect. Also, in the proposed inspection model, the authors assumed that execution of inspection does not have effect on the track availability. Three inspection scenarios including inspection in every 2 months, 3 months, and 4 months were evaluated and the optimal inspection interval was determined by comparing the cost of all three inspection scenarios. The result of their work showed that expanding inspection frequency from 2 months to 4 months decrease track maintenance cost. A similar approach can be found in Soleimanmeigouni et al. (2016). The Wiener process, exponential distribution, and probabilistic approach were used to model track geometry degradation, shock event times, and recovery after tamping respectively. Standard deviation of longitudinal level was considered as dominant factor to evaluate track condition. After modelling the long-term behavior of track geometry on a 200 m track section, they assessed four scenarios including inspection with intervals of 6, 12, 24, 48 weeks to find the optimal inspection interval that lead to lowest possible cost. The costs associated to corrective tamping, inspection, and penalty was included in their cost model. The proposed model was applied on a track section with a time horizon of 7.5 years. The results of the model can be more applicable and practical by applying the model on a track line. Moreover, in this study, only corrective maintenance was considered as maintenance strategy. The model can run by applying the PM strategy. The authors can also extend their study by optimizing track geometry inspection with different objective functions. Lyngby et al. (2008) also conducted a research to optimize the intervals of track geometry inspection with the same objective. Markov methodology was used to model track geometry degradation and twist was considered as track quality indicator. In the proposed model, the CM and PM are perfect as execution of maintenance restores the track to initial state. Optimal inspection interval that leads to minimization of total maintenance cost was determined by considering the costs of derailment, inspection, and tamping. Model can become more complex by considering imperfect maintenance. Also, the same method can be used by applying different track measurement indicators such as standard deviation of longitudinal level, alignment, and gauge. Meier-Hirmer, et. al, (2009) tried to determine a trade-off between inspection interval and maintenance threshold that lead to minimum track maintenance cost. The cost related to inspection and interventions were considered in their model. The evolution of track geometry degradation and tamping effectiveness were modelled using gamma process and linear regression, respectively. Longitudinal level was selected as quality indicator of track geometry. The 24 years inspection data from Paris and Lyon track line is used to assess the model. The 20 years of the data related to track before opening the Mediterranean line with inspection every three months and the rest of 4 years data related to track after opening the line with inspection everyone and a half month. A numerical method was used to determine the mean cost respect to decision variables. By applying the model to the available data, the authors carried out an optimal inspection interval and maintenance threshold and compared to current inspection intervals and maintenance threshold. The proposed model can become more practical by considering machine availability as constraint and risk assessment respect to train derailment.

4. Preliminary analysis of track geometry data.

In this section, the information about the track line which is used for the case study is provided. In addition, issues about processing and filtering of geometry data are discussed here. The tamping practice for the studied line is also presented. Finally, a preliminary analysis on the effect of tamping on track geometry condition is presented.

4.1. Information on the line and measurement cars

Data collected for the research comes from line 414, which runs from Järna to Katrineholm (see figure 4.1) central station and the track was divided into 200-meter sections. Dividing the area under study in equal non-overlapping sections is done to ensure that the acquired data is proper to provide quantitative measurements.

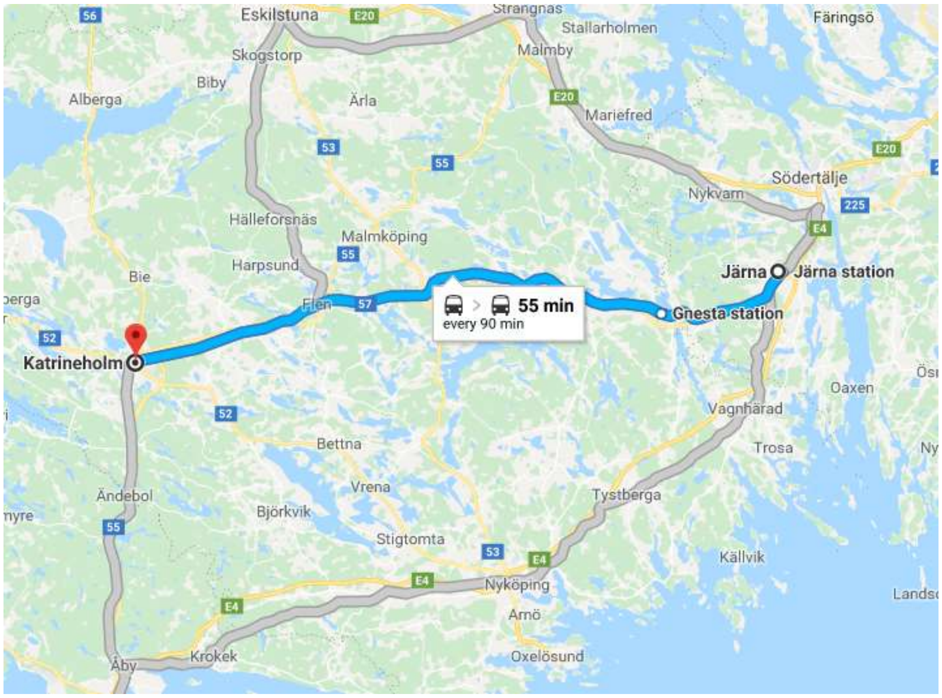

Figure 4.1: Line location

Measurements used in this research are based on the data collected between 2010 and 2015 where the two measurement cars STRIX and IMV200 are used due to their consistency in data recording. Depending on the track class, inspections are carried out between 1 to 6 times per year for different track lines. Scope considered in data collected for this study follows the following guidelines by Trafikverket, (2018):

- Track mode measured *1-6* times in a year;
- Rail profile measured up to *2* times in a year;
- Raves and waves measure (corrugation) up to *1* time per year, and
- Ballast profile measured up to ¼ − 1 time in a year.

STRIX car uses optical instruments and an accelerometer to record longitudinal deviations and wheel to measure alignment to a reference point. *STRIX* trolley was used to measure what was measured by the high-speed trolley. *IMV200* has the capacity to take measurements on track at *200km/h*. This makes it easy for the traffic managers to directly trace mode errors. Although *IMV200* can measure up to 200 km/h, in practice it measures at approximately 160 km/h due to lack of high-speed locomotives (Trafikverket, 2018).

Below each measuring car, there are cameras and lasers for measuring track skew, width, side and height position, rail profile, rail wear and rail raising (Trafikverket, 2018). In addition, at any measurement point, the carriage has a GPS that registers the position. In case there is track error that is detected the carriage sends an alarm, which is used by the operators to speed up for immediate action to solve the error. Depending on the seriousness of the error the proper action is taken to ensure that there is no delay in traffic or risk of derailment (Arastehkhouy, et. al, 2014).

According to Trafikverket (2018), between 2009 and 2011 there was an increase in the number of recorded errors. However, with interventions and action taken in 2013, the errors were controlled and reduced, which resulted in few measurement errors.

It is important to note that the measuring cars do not capture all the measurement errors on the track such as fortifications, which usually need manual inspection by the maintenance personnel. Trafikverket’s contractors are assigned the duty to carry out these inspections.

4.2. Missing data

When there are some activities that involve traffic or ongoing maintenance along the track under inspection, these calls for the need to stop inspection cars. Car stopping comes with speed reduction, which is less than 40 km/h and if track geometry is measured at this speed they are rejected since they are not within the acceptable range of speed. Due to these stoppages of the measurement car and speeds below 40 km/h during the recording the data, there are some measurements missing in this final data presented for analysis within any given section (Ben-Daya, Kumar, & Murthy, 2016). Based on this theory, missing data can be attributed to both traffic and random stoppages that may have been due to ongoing maintenance activities on the line.

4.3. Processing and analyzing geometry data

To convert data to useful information, several methods were used in the process of data transformation for the purposes of decision support. Methods used helped in developing knowledge about the data to create objective phenomena in which data is deemed valid, understandable and useful. To establish the baseline for maintenance decision making, degradation data must be analyzed to establish the relationship between the design requirements and usage with time. To achieve this, two stages were used in the process of data processing:

- Data cleaning and checking,
- Alignment and preliminary data analysis

4.3.1. Data cleaning and checking.

This research is based on secondary data collection; thus, data scrutiny was required. This was for the purposes of confirmation of suitability of the available data on basis of reliability, adequacy and if the source data meets the demands of the problem. Considerations made when cleaning the data included measurement cars record short, medium and long wavelength signals. Since tamping procedure deals with only isolated defects and short-wave irregularities, medium and long-wavelength data had been filtered from the data during data pre-processing. Therefore, the data was sorted to work with only the standard deviation values of the longitudinal levels recorded for 200m sections.

4.3.2. Data alignment and preliminary analysis

Due to different reasons, e.g. a change on the starting point of the measurement car, there could be a position shifting error in the recorded data. In this case, it can be corrected by scaling and position shifting in that section.

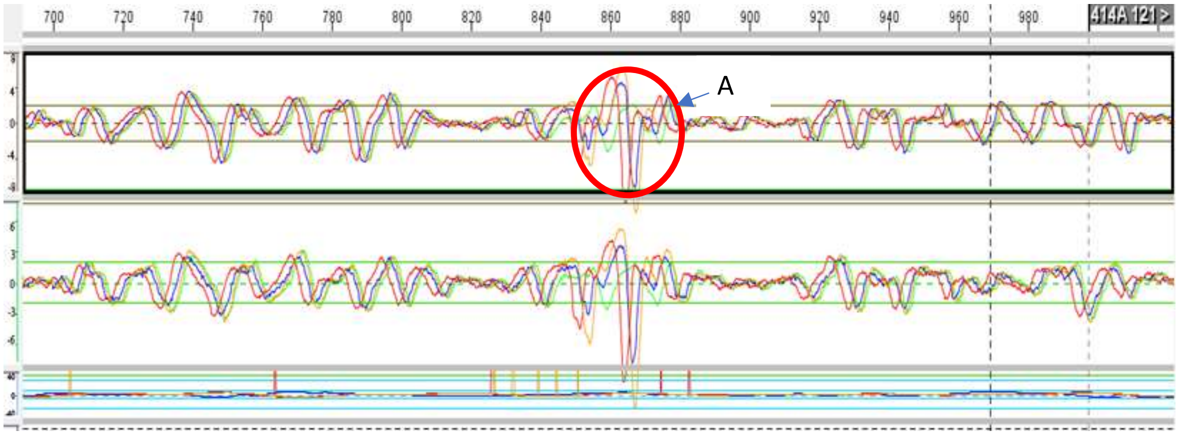

Figure 4.2: Positioning error

Figure 4.2 above is a plot of measurements taken, which shows accuracy of the measuring machine where the plot shows positioning error of the machine shown by section A on figure 4.2. Such positioning error can be adjusted with a shifting value e_i to produce a smoothing alignment $y_i = x_i + e_i$, where y_i is the desired line and x_i is the track irregularity to be corrected. From the plot it is clear that measured data at each section has been done correctly every time there is data collection within that line. This provides validity in ensuring that data used in this research is reliable and good for purposes of simulation of the track geometry degradation.

4.4. Tamping practices on line 414

Since tamping machines have been equipped to perform tamping procedure and level the lining, it helps in rectifying the horizontal and vertical defects simultaneously. A stable sleeper bed is provided by the tamping tines as they penetrate the ballast and compacting it under the sleeper using a squeezing motion. Tamping machines can be classified based on speed, which mainly depends on the number of sleepers that can be tamped, or they can be classified depending on intermittent and continuous action tamping machines. Intermittent based tamping machines can perform tamping on a group of sleepers and then stop to conduct tamping on the next group of sleepers. Continuous based tamping machines have tamping trolley hooked under the machine which enables the trolley to move forward and backward as the tamping machine moves at a constant speed. Some other tamping machines are specifically designed for crossings and switches. Lightweight machines and tractors can be used for tamping in cases of point failures. For line 414, for straight lines the machine used are single and double sleeper tampers.

Soon after tamping intervention, there are some ballast particles that are not stable or consolidated as desired. Therefore, stabilization can be done through two ways. The first option is to let ballast settle as the traffic continues; and the second option is to use a track stabilizing machine to settle ballast bed. Stabilization in line 414 is done mainly using stabilizing machine. However, depending on the planning time and availability of the machine sometimes track stabilization can be done using traffic load. To achieve this when traffic load is used, traffic speed is lowered until track is stabilized.

Looking at tamping intervals in Line 414, there is no specific tamping interval. Corrective maintenance is performed based on the condition of the track as observed from Optram system. Within the five years collected data, it was observed that some track sections have been tamped more than three times, while some other track sections have had a good track quality and had no tamping activity. In addition, tamping for different consecutive sections is carried out at different times.

4.5. Effect of tamping on track geometry

When tamping is carried out based on the alert limit it is associated with riding comfort and preventive maintenance practices. On other instances, tamping can be executed at intervention limit, which is associated with corrective maintenance practices.

Most of the sections in line 414 have one tamping action during the inspection period from 2010 to 2015. This poses a challenge as data might not be sufficient to make conclusions based on the effect of tamping history on tamping effectiveness on the line. Among 411 track sections, 68 of them have been tamped twice and there are only five track sections that three times tamping has been carried out on them.

Using expert-based opinion, 15% change in degradation level between two consecutive measurements are considered as tamping. This assumption was used to identify sections that had been tamped but are not registered in the maintenance history:

$$PTL = \frac{SDH_i}{SDH_{i-1}} < 0.85 \tag{12}$$

Where, PTL (Parameter of Tamping Level) is ratio representing change in degradation level, SDH_i and SDH_{i-1} are the current and previous standard deviations.

Once the tamping positions were identified, data was sorted based on standard deviation of longitudinal level before tamping and the restored standard deviation of longitudinal value after tamping. After the tamping actions had been identified, degradation in each maintenance cycle for each section was tabulated as per figure 4.3.

After filtering and alignment of the degradation data from 2010 to 2015, the changes of standard deviation of longitudinal levels were obtained. To understand how the degradation process is recovered with tamping actions, table 3.1 gives changes in standard deviation of longitudinal level for two track sections.

Table 4.1: Sample section tamping data

Dates	**Longitudinal level**		**Dates**	**Longitudinal level**	
	Segment 1	Segment 2		Segment 1	Segment 2
2010/05/08	1.367052	1.709735	2012/11/21	1.482956	0.893294
2010/06/20	1.376018	1.653214	2013/03/07	1.50118	0.947624
2010/08/22	1.577079		2013/04/10		
2011/03/19	1.898316	1.28526	2013/07/05	2.2564	1.084645
2011/07/14	2.103717	1.724447	2013/11/21	2.257957	1.125057
2011/09/11	2.130664	1.698326	2014/03/12	2.65192	1.204261
2011/11/25	2.507979	1.828086	2014/05/04	1.363531	0.913077
2012/03/08	2.458894	1.846358	2014/08/10	1.416686	0.91566
2012/07/01	3.104347	0.901574	2014/10/19	1.552819	0.948936
2012/09/02	3.166103	0.919987	2015/03/16	1.833274	0.960853

As it can be seen from the figure 4.3, the standard deviation is increasing with time in approximately 2.5 to 3 years where tamping is carried out and the standard deviation is reduced. However, after performing tamping on track section, degradation on the track occurs with time and later after approximately two years there is another tamping on the section. Using the same formulation, the remaining sections were analyzed and the majority of sections showed similar characteristics and similar behavior were exhibited on the track.

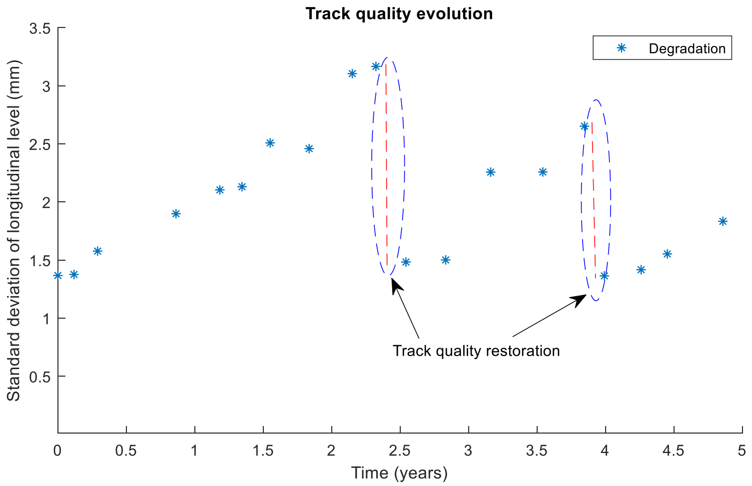

Figure 4.3: Track quality evolution.

Looking at the standard deviation of longitudinal level presented in figure 4.3 tamping action was carried out at levels 3.2 and then 2.6 mm for the first and the second tamping respectively, which according the UIC required standards is beyond the IL threshold, hence corrective tamping was paramount. According to the riding limits given by the Swedish standards, degradation on the analysed sample section had exceeded the intervention limit, which calls for corrective maintenance. Using this model, it is clear that a maintenance strategy is required for studying degradation behaviour and determining when inspection should be done to avoid delayed maintenance.

To understand the effect of tamping on the longitudinal levels, scatter plots in figure 4.4 show the reduction of the longitudinal levels due to tamping. In figure 4.4, standard deviation of longitudinal level after tamping are plotted against standard deviation of longitudinal level before tamping for line 414. From the tamping scatter plot, majority of the segments show that tamping improved the condition of the track and indicating a positive linear relationship between the levels before and after tamping. However, some outliers show no effect of the tamping and hence disregarded.

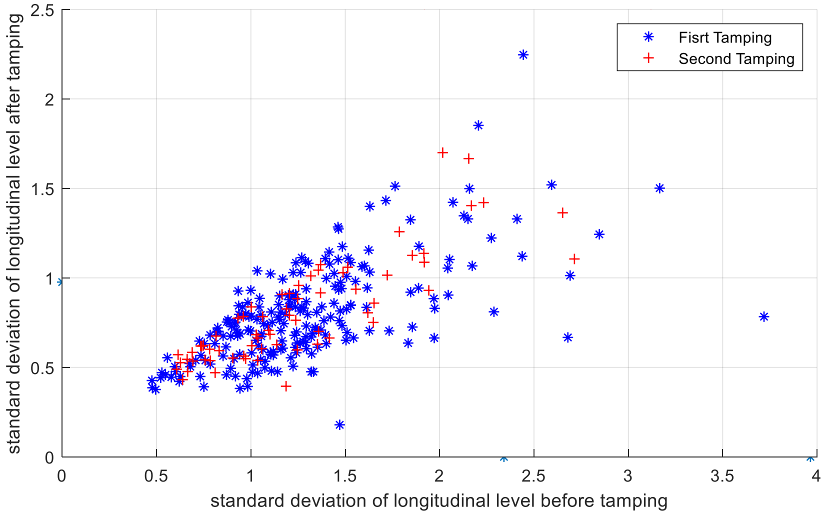

Figure 4.4: Effect of tamping

It should be noted that according to the required limit level after tamping intervention, the standard deviation of longitudinal values after tamping are required to be below 1.6 mm (SS-EN-13848-5:2017, 2017).

To present the effect of tamping on standard deviation of longitudinal level, figure 4.5 shows the effect of tamping on longitudinal level in different sections.

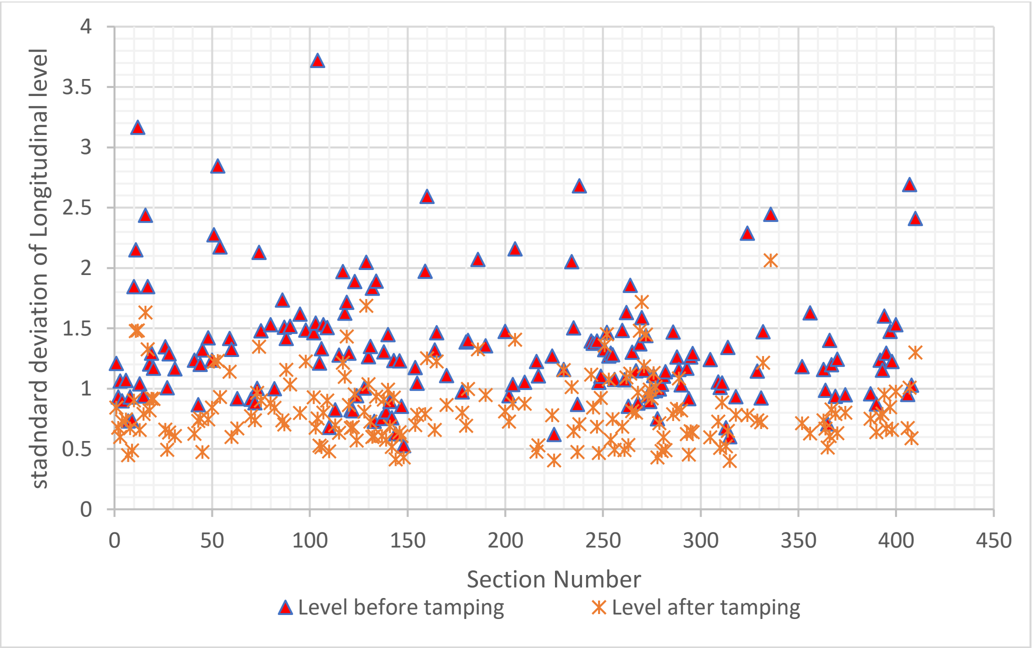

Figure 4.5: Comparing longitudinal standard deviation (SDL) before and after tamping

The degradation of track depends on the traffic, type of substructure and different construction materials. A histogram plot of the standard deviation of longitudinal level after tamping is shown in figure 4.6. Figure 4.7 shows the histogram of degradation rates for different track sections. It is clear from the plot that degradation level after tamping and degradation rates have a high variability for different sections.

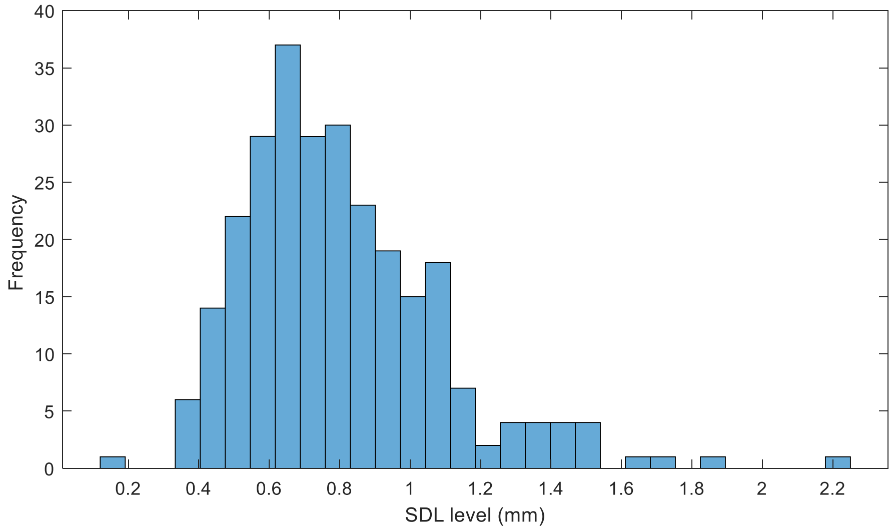

Figure 4.6: Histogram of standard deviation of longitudinal level after tamping.

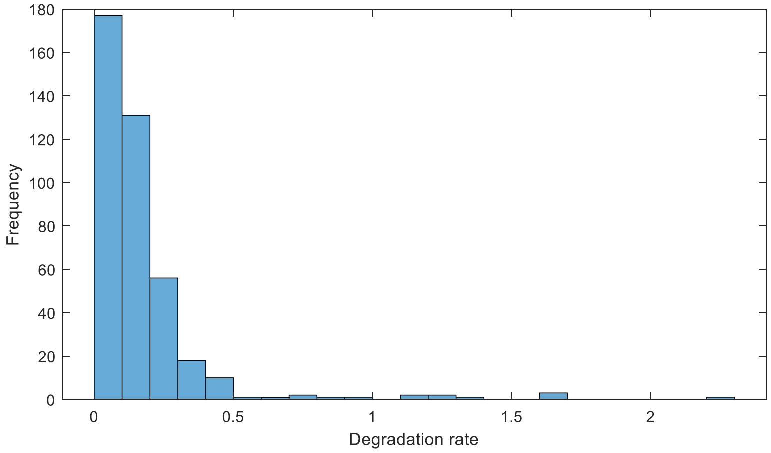

Figure 4.7: Histogram of degradation rates

5. Modeling track geometry degradation

5.1. Track geometry degradation and parameter estimation

To model track geometry degradation, a linear model was selected by considering the literature on track geometry degradation modelling. For any track section, degradation in a maintenance cycle can be modelled with time (in years) with an assumption that traffic would be constant along the track. At any time t, the degradation is modelled using linear regression as follow:

$$Y_t = a_n + b_n t + \varepsilon \tag{13}$$

Where a_n standerd deviation of longitudinal level after n number of tamping, b_n degratation rate after n number of tampings and ε, gaussian error term used in the model to consider the uncertainties from track geometry evolution. However, it should be noted that to consider n tampings, more data is needed so that there will be more accurate model for decision making. In this study, number of tamping interventions are not considered in the model.

Depending on tamping effectiveness, values a and b can vary in each section. These values are considered as variables in the model which need to be estimated using data set.

For the proposed degradation model, two assumptions were used. The first assumption is that linear function was used to describe the degradation evolution between consecutive tamping activities. The second assumption is that, the degradation value after tamping intervention a and degradation rate b are considered as stochastic variables which are log-normally distributed with some specific mean and standard deviation. However, this assumption can only rely on tamping intervention effects from the studied railway line.

$$a \sim LN(\mu_a, {\sigma^2}_a) \tag{14}$$

$$b \sim LN(\mu_b, \sigma_b^2) \tag{15}$$

$$\varepsilon \sim N(0, \sigma_\varepsilon^2) \tag{16}$$

To make this model applicable, it is important to have $\mu_a, \sigma_a,$ and μ_b, σ_b, which have been determined in parameter estimation using track geometry historical data. These values are estimated using data which have been obtained from 2010 to 2015 from Trafikverket Optram system database.

Based on the histogram plots in figures 4.6 and 4.7, the degradation level after tamping and degradation rate are assumed to follow lognormal distribution. Meaning the rate of degradation and the standard deviation of longitudinal level after tamping are lognormally distributed. Looking at figure 4.6 and 4.7, it can be noted that standard deviation of longitudinal level after tamping and degradation rates at some sections are very high and more inspection is recommended for those sections, and corrective actions must be taken.

Therefore, to test log normality of these parameters, Anderson Darling (AD) test was performed for the standard deviation of longitudinal level levels after tamping and degradation rate. Using the standard deviation of longitudinal level after tamping a and degradation rate $b,$ AD and p-values were generated for lognormal, gamma, Weibull, and exponential distributions. From the tests, the best fitted distribution was selected by considering the value with the smallest AD-value and p-value greater than significance level. This means that p-value selected must be greater than the critical value α. To perform AD test, the hypothesises are set as follow:

$H_0(Null\ hypothesis)$: follows the specified distribution

$H_1(Alternative)$: does not follow the specified distribution

Significance level: $\alpha = 0.05$

Table 5.1: AD goodness of fit test of a and b

	a		b	
Distribution	**AD**	**P**	**AD**	**P**
Lognormal	0.62	0.101	0.65	0.090
Exponential	13.88	<0.003	11.75	<0.003
Weibull	1.68	<0.010	8.61	<0.010
Gamma	0.93	0.021	5.99	<0.005

From the tested values, it was found that $\alpha < P - value$, hence null hypothesis accepted for lognormal distribution.

Estimation of the model parameters was done using maximum likelihood estimators (MLE). Normally MLE was used in parameter estimation due to its capability to estimate parameters without considering the prior distributions but only considers estimates from the statistical model and observations.

Using Minitab, the estimation for degradation level after tamping and the degradation rate were calculated and recorded in table 5.2 below:

Table 5.2: ML Estimates of Distribution Parameters a and b

		a			***b***	
Distribution	Location	Shape	Scale	Location	Shape	Scale
Lognormal*	-0.27		0.33	-2.16		0.84
Exponential			0.81			0.17
Weibull		2.90	0.90		1.11	0.18
Gamma		8.95	0.09		1.45	0.12

** Scale: Adjusted ML estimate*

6. Proposed inspection optimization model.

Based on the Swedish and European standards, railway track geometry degradation should not exceed the required riding and safety limits. In this research two limits were considered including limit level 1, for comfort limit (L1=1.6mm) and limit level 2 for safety limit (L2=2.0mm). Comfort limit considered in this research, is the level at which degradation will be detected at an early date and tamping will be planned and executed in relation to riding comfort performance. This will ensure proper resource allocation, planning and execute maintenance in time. On the other hand, safety limits are used to find the sections which need corrective maintenance actions. In such cases, it becomes unsafe to use the track and operations on the track can be interrupted. Such sudden stoppages can result to high maintenance costs, derailment and other related costs.

To identify the degradation level, an inspection interval must be specified. Inspection interval is the period taken to collect track geometry degradation data using inspection cars. The main reason of track inspection is that, degradation levels can be detected in advance and preventive maintenance planned in time using a predictive model. Another reason for considering inspection interval within reasonable duration is that, there are a limited number of inspection machines that can be available on demand. Therefore, it is important to have optimal period of inspection that minimize cost of inspection considering the penalty cost in case of exceeding comfort ride and safety limits, cost of tamping and inspection cost.

6.1. Monte Carlo simulation

Monte Carlo simulation uses random sampling with repetition to generate data that will be simulated using a mathematical model. Since the purpose of doing a simulation is to duplicate and predict reality, it is an evaluation tool that has been proved to be effective in analyzing system performance for different designs (Usman & Shaaban, 2012). Generally, Monte-Carlo simulation reproduces random variables using its numerical procedures so that the variables can camouflage the properties of the specified distribution. From assumed or known probabilistic laws Monte Carlo simulation helps the system to generate parameter sets that relate to the system of interest.

To perform Monte-Carlo simulation, 30000 simulations were carried out on a test period of 15 years. Flow chart in figure 6.1, consists of steps required in the simulation process. The flow chart is a brief description of the simulation process which involves initializing the parameters a, b and

ε, the measurement noise, then at each simulation process involves calculating degradation level until a tamping condition is achieved. Simulation is repeated until the end time is attained. However, this model has to follow a number of requirements, that include track geometry degradation growth, which follows an linear regreassion. Secondly, the values of a and degradation growth rate (b) follow lognormal dostribution with estimated parameters.

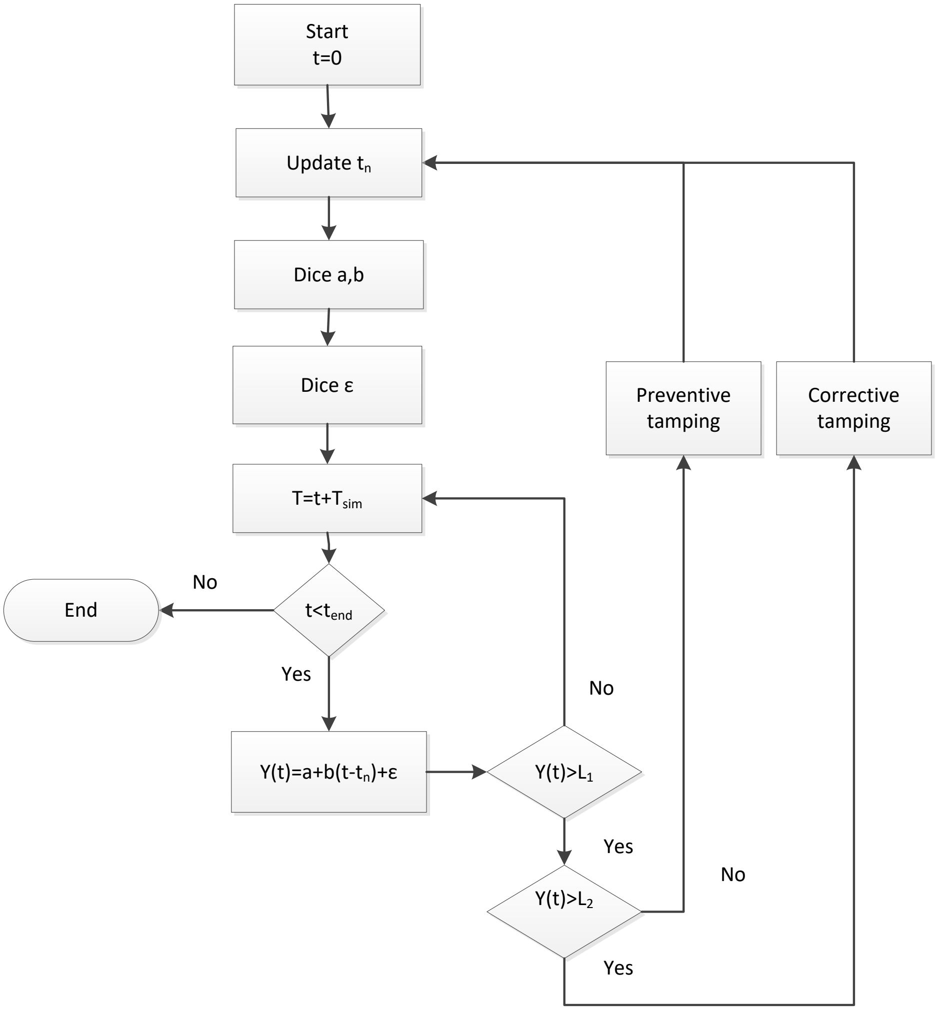

Figure 6.1: Monte-Carlo simulation frame work

From the flow chart it is given than, t time taken for a simulation, t_n last tamping time, n tamping interventions accumulated, T_{sim} simulation step, t_{end} is the ending time of simulation, and a and b are standard deviation of longitudinal level after tamping and degradation rate respectively.

A number of input parameters required for this simulation including start and end time of the desired simulation, the simulation steps and threshold of degradation at which maintenance intervention should take place. These parameters are set according to the desired objectives of the simulation. This way we are able to understand how the evolution of track geometry can be simulated.

Having set parameters based on the simulation flow chart, simulated behaviour was expected to follow a certain trend shown in figure 6.2. From figure 6.2, the number of tampings, $a_{i1}, a_{i2}, \dots, a_{in}$ is the estimated standard deviation of longitudinal level after tamping interventions and b is the degradation rate. A renewal is expected in case there is an addition or replacement of ballast on the track.

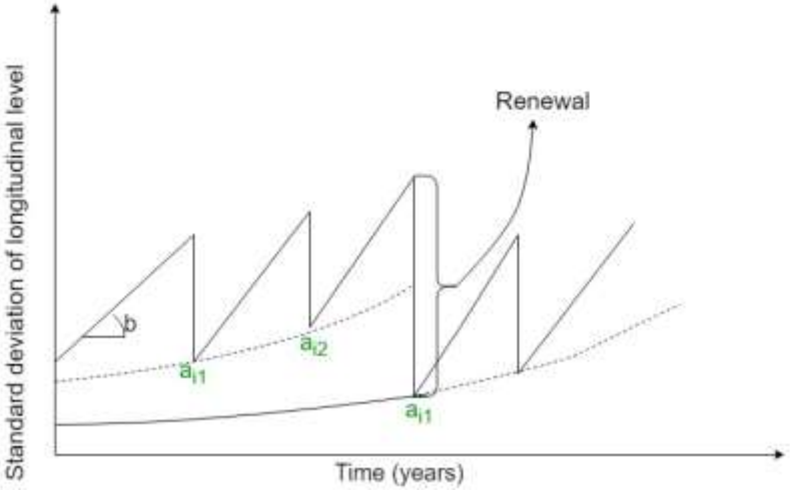

Figure 6.2: Track geometry evolution with several tampings

Based on the expected track quality behavior shown in figure 6.2. According to Swedish standard (SS-EN-13848-5:2017, 2017), standard deviation of longitudinal level should be within certain limits. Figure 6.3 shows a sample behavior of track geometry degradation and restoration generated by proposed Monte Carlo simulation model.

Degradation behavior for the section of line 414 was simulated and showed similar characteristics as shown in figure 6.3.

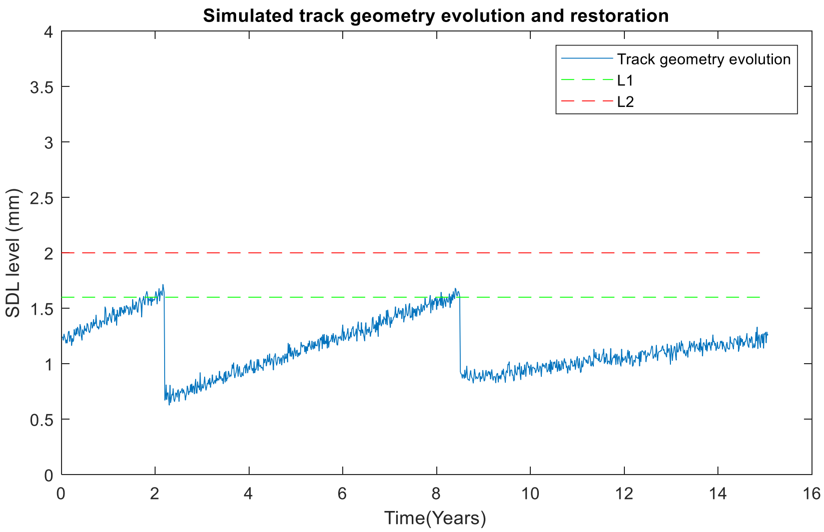

Figure 6.3: Simulated track geometry evolution.

A plot of the expected number of tamping is given to show the effect of length of inspection interval on number of tamping actions. This was done for different inspection intervals 30, 60,90,120,180 and 360 days respectively. Convergence of the number of tamping was plotted in figure 6.4 below.

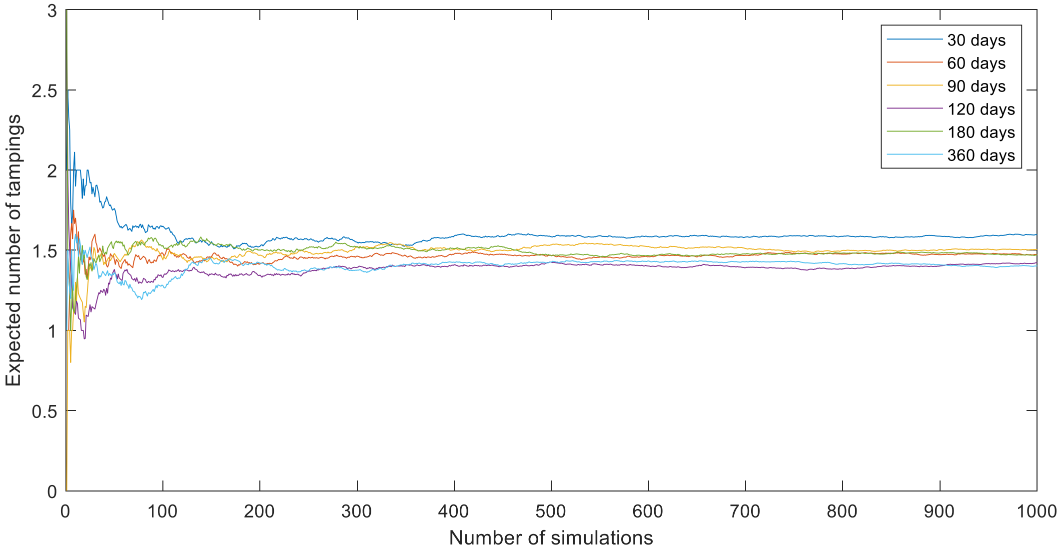

Figure 6.4: Convergence for expected number of tamping.

From the expected number of tamping shown in figure 6.4, it is observed that varying inspection intervals will not make a significant change in expected number of tamping.

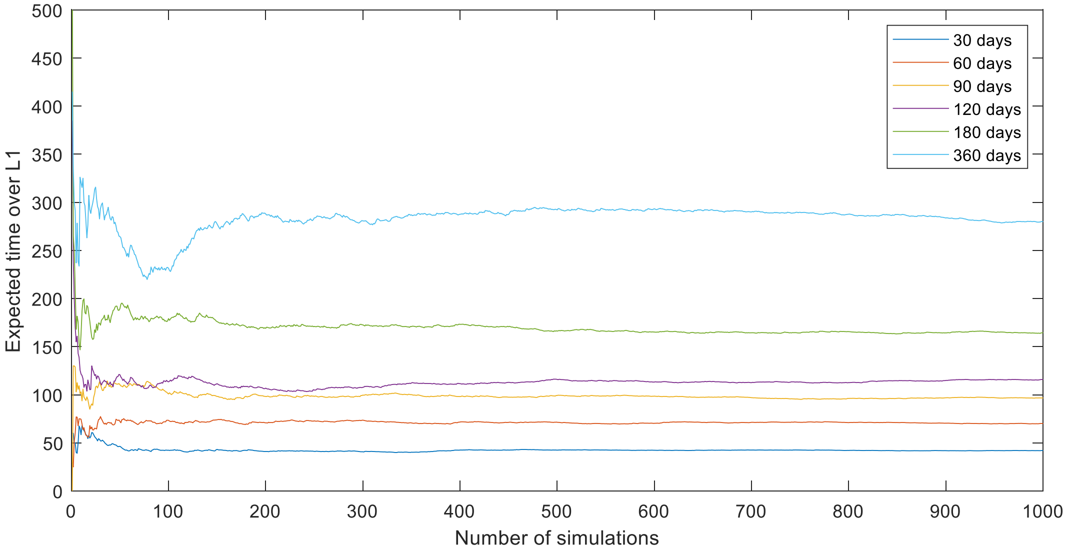

Figure 6.5: Expected time over L1

Figure 6.5 is an illustration of the expected time over L1 with respect to different inspection intervals. Considering different inspection intervals, expected time over L1 for inspection interval of 360 days is maximum among the studied scenarios. It could be concluded that with large inspection intervals defects will be detected late. As a result, this can lead to other related costs like high penalties that may arise from the exceeding comfort ride limit. On the other hand, for inspection within every 30days can have high inspection cost arising from the number of inspections that must be carried out.

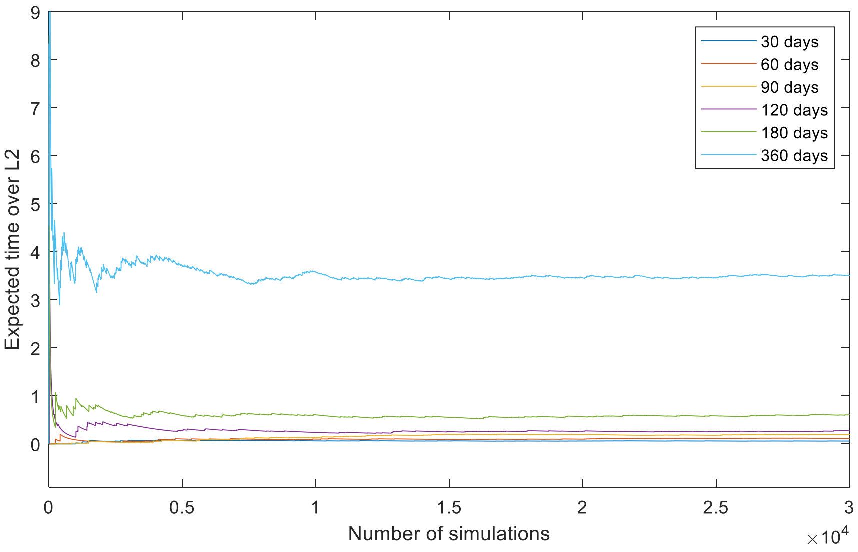

Figure 6.6: Convergence expected time over L2

Figure 6.6 is an illustration of expected time over L2 where 360 days inspection interval showed to have longer expected time over L2. If inspection period is long, there is an increase in expected time over L2. For longer inspection intervals, there is a higher probability of corrective maintenance attributed to late detection of fault in the line.

Expected times over L1 and L2 are indicated in figure 6.7. Consequences of exceeding these limits have been illustrated using the cost function in figure 6.8 and 6.9.

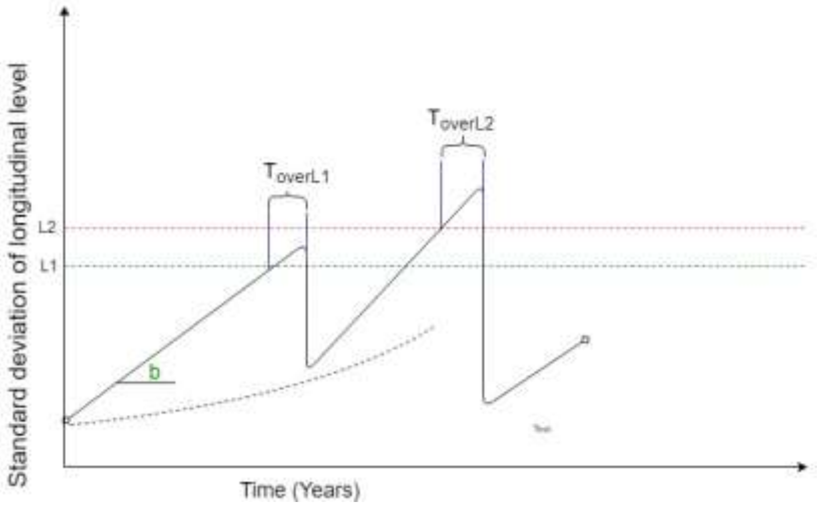

Figure 6.7: Expected time over L1 and L2

6.2. Optimal periodic inspection scenario with respect to cost

Using the degradation model, we are able to simulate track geometry behaviour under a specific inspection interval. A cost function is used to compare inspection strategies and to select the one with the lowest possible cost. Once degradation exceeds maintenance limit L2, a large penalty is charged. In addition to the need to meet the desirable optimal inspection cost, inspection period needs to ensure track availability. Most importantly, a reliable inspection period is desirable so that the risk of derailment be minimized.

Different scenarios are compared in this section to find an optimal interval for inspection. As explained in the previous sections, six scenarios considered were from 30 to 360 days. For standard deviation of longitudinal level, it was assumed that L1 and L2 be 1.6 and 2.0 mm respectively. Having considered degradation limits, a cost function was defined to find the best inspection scenario. The cost function used inspection cost, tamping cost and penalty cost for exceeding L1 and L2.

$$E(C) = C_t E(N_t) + C_{L1} E(T_{overL1}) + C_{L2} E(T_{overL2}) + C_i N_i \qquad (16)$$

Where: E(C) is the total expected cost, $\mathrm{C_{L1}}$ is the penalty cost over L1, $E(N_t)$ is the expected number of tamping, C_{L2} is the penalty cost for exceeding L2, $E(\mathrm{T_{oveL1}})$ and $E(T_{overL2})$ are expected times over L1 and L2, C_i is the cost of inspection, N_i, is the number of inspections and C_t is the cost of tamping. Table 6.1 show the cost considered in this study.

Table 6.1: Table of the costs

Maintenance activity	Cost (SEK)
C_i	240
C_t	10000
L1 Penalty (C_{L1})	200
L2 Penalty (C_{L2})	15000

The expected costs for different inspection intervals recorded in table 5.2. The results of the simulation show that inspection with 90 days period gives the lowest possible cost. Carrying out inspection in 30 days can lead to accumulation of many inspections. On the other hand, carrying out inspection in 360 days has the effect of delayed inspection and this can lead to detecting faults late, thereby contributing to urgent tamping coupled with high tamping cost.

Table 6.2: Total inspection cost for different scenarios

		Inspection Scenario (days)					
		30	60	90	120	180	360
Expected cost	Over L1	7954	13843	19081	23684	32536	55260
	Over L2	895	1695	2883	4108	9073	52668
	Tamping	15615	15058	15036	14545	14341	13960
	Inspection	43920	22080	14640	11040	7440	3600
	Total cost	68384	52676	51640	53377	63390	125488
Expected time over	TL1	39.77	69.22	95.41	118.42	161.77	276.30
	TL2	0.060	0.11	0.19	0.27	0.58	3.51

It was noted that expected penalty cost due to exceeding limit L1 and L2 increases with decrease in number of inspections per year, which is the result of increased penalty due to time over L1 and

L2 limits. In addition, the cost of tamping remains almost constant since no drastic changes are expected for tamping action due to change in inspection intervals.

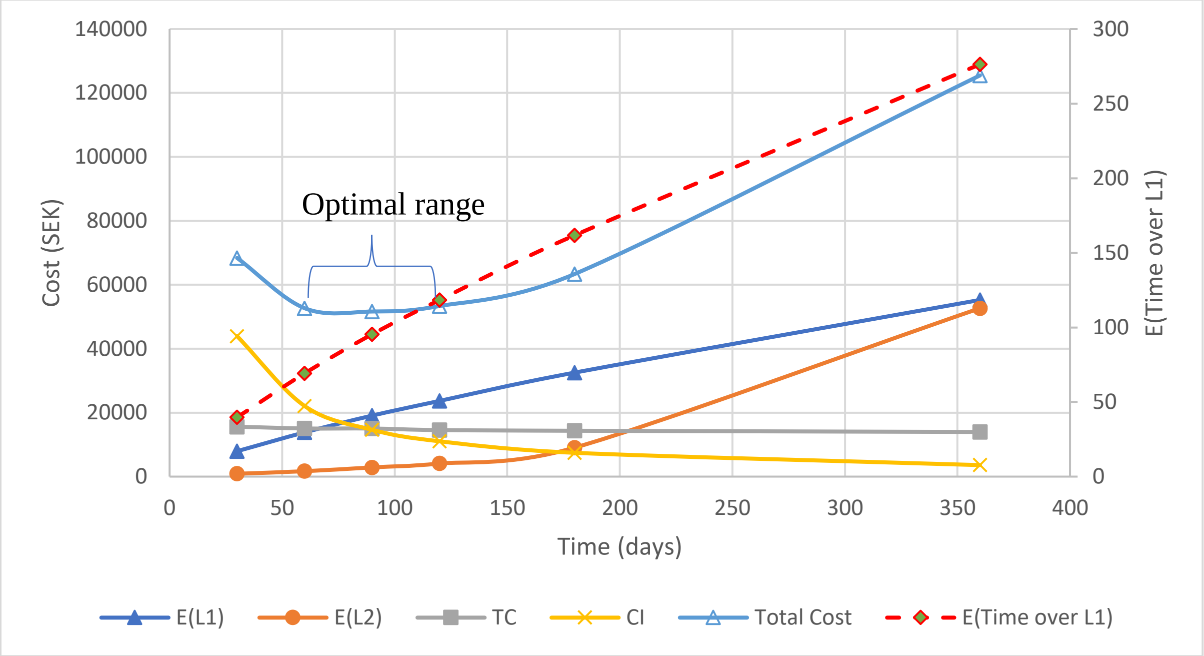

Figure 6.8: Optimization of inspection intervals over L1

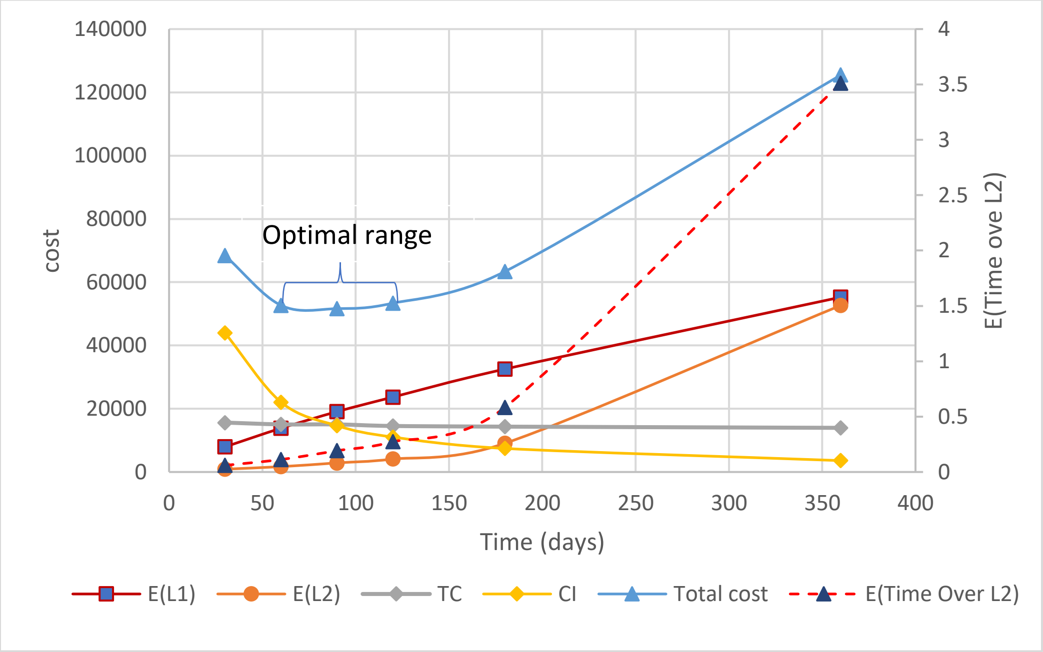

Figure 6.9: Optimization of inspection interval for expected time over L2

From the figures 6.8 and 6.9, $E(L1)$ and $E(L2)$ are expected cost over $L1$ and $L2$, TC is tamping cost, CI is the inspection cost, $E(time\ over\ L1)$ is the expected time over $L1$ limit, and $E(time\ over\ L2)$ is the expected time over $L2$ limit. Comparing the expected total cost from table 6.2, it was noted that the lowest expected total cost is for inspection interval of 90 days. However, since the difference between costs for the range between 60 to 120 days is relatively small, it can be seen from figures 6.8 and 6.9 a range of optimal points can be selected for inspection interval. To select an optimal inspection interval between 60 to 120 days, a number of factors should be considered. First issue to consider is the availability of the inspection car and the second one is the expected time over comfort and safety performance limits. If the inspection car is available, the optimal inspection interval is every 60 days, else if there is a scarcity of the inspection cars, then a bigger inspection interval should be selected within the optimal inspection range. The reason is that, as noted earlier, if the inspection is done less frequently the geometry defects might be detected later, and this would affect performance and safety limits (Times over L1 and L2 limits). Other factors that can be considered to choose the inspection interval from the optimal range include, availability of man power, financial resources, traffic and weather conditions.

7. Conclusion

Track geometry degradation is modelled using linear regression while the parameters of the model considered as random variables. Using historical data, model parameters were estimated. It was found that the initial degradation value after tamping and degradation rate are following lognormal distribution. It was also observed from the tale of the distributions, that some track sections have very high degradation rates and should be considered for more inspections and corrective tamping. Thereafter, simulation of track geometry degradation has been performed to compare different inspection intervals. Then a cost function was developed to estimate the related total cost of each inspection interval and to find out the inspection interval with minimum cost. This was done by simulating track geometry degradation using Monte Carlo method. The results of simulation showed that with longer inspection interval the expected time over L1 and L2 limits will increase linearly and exponentially, respectively. It was therefore, concluded that exceeding L2 limit levels cause high penalty costs that relate to late detection of defects and maintenance managers should consider inspection intervals that will help in mitigating the late detection of defects. Taking into account the components of the cost function, inspection cost reduces with increasing the length of inspection intervals. It is observed that varying inspection intervals will not make a significant change in expected number of tamping. In addition, with different inspection intervals considered for different scenarios 30, 60,90,120,180 and 360 days respectively, it was concluded that the optimal inspection interval is in a range from 60-120 days. However, it should be noted that to carry out inspection within this range would depend on some factors such as availability of inspection vehicle, manpower, weather conditions, availability of resources, and the expected times over comfort ride and safety limits.

This research shows the importance of optimization of inspection intervals to evaluate and predict track geometry condition to plan maintenance activities with minimum cost. It must be noted that the degradation behaviour of track will affect the optimal range of inspection intervals. However, the same approach could be used by collecting data from other lines to estimate the parameters of degradation model and to optimize inspection intervals.

8. Scope for future works

A number of suggestions that are given for future research include:

- Development of a maintenance plan model that will allocate available free slots of the track for maintenance with respect to RAMS parameters.
- Develop of Markov based degradation simulation model with optimization on periodic inspections with respect to RAMS parameters and asset LCC.
- Develop a model that can be used to conduct a cost analysis to balance preventive and corrective maintenance to improve asset remaining useful life.

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