Allocation of effective maintenance limit for railway track geometry

Hamid Khajehei, Alireza Ahmadi, Iman Soleimanmeigouni & Arne Nissen

To cite this article: Hamid Khajehei, Alireza Ahmadi, Iman Soleimanmeigouni & Arne Nissen (2019): Allocation of effective maintenance limit for railway track geometry, Structure and Infrastructure Engineering, DOI: 10.1080/15732479.2019.1629464

To link to this article: https://doi.org/10.1080/15732479.2019.1629464

© 2019 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group

Published online: 26 Jun 2019.

Submit your article to this journal

View Crossmark data
Allocation of effective maintenance limit for railway track geometry

Hamid Khajehei\textsuperscript{a}, Alireza Ahmadi\textsuperscript{a}, Iman Soleimanmeigouni\textsuperscript{a} and Arne Nissen\textsuperscript{b}

\textsuperscript{a}Division of Operation and Maintenance Engineering, Luleå University of Technology, Luleå, Sweden; \textsuperscript{b}Trafikverket, Luleå, Sweden

ABSTRACT
The objective of this study has been to develop an approach to the allocation of an effective maintenance limit for track geometry maintenance that leads to a minimisation of the total annual maintenance cost. A cost model was developed by considering the cost associated with inspection, preventive maintenance, normal corrective maintenance and emergency corrective maintenance. The standard deviation and extreme values of isolated defects of the longitudinal level were used as quality indicators for preventive and corrective maintenance activities. The Monte Carlo technique was used to simulate the track geometry behaviour under different maintenance limit scenarios and the effective limit was determined which minimises the total maintenance cost. The applicability of the model was tested in a case study on the Main Western Line in Sweden. Finally, a sensitivity analysis was carried out on the inspection intervals, the emergency corrective maintenance cost and the maintenance response time. The results show that there is an optimal region for selecting an effective limit. However, by considering the safety aspects in track geometry maintenance planning, it is suggested that the lower bound of the optimal region should be selected.

1. Introduction

The railway system is one of the most important assets for a country’s progress and is generally considered as the ‘lifeline’ of a nation. Today, it is a proven fact that the railway infrastructure is a key element for adding speed and efficiency to a country’s progress. The track is a fundamental part of the railway infrastructure and represents a significant part of the maintenance effort and cost. For example, in Sweden the annual maintenance cost for the track geometry alone is between 100 and 120 MSEK (Arasteh Khouy, 2013). The quality of the track is mainly represented by the track geometry parameters, that is, the cant, alignment, longitudinal level, twist and gauge. Several maintenance actions can be employed to restore the quality of the track geometry, that is, manual intervention, tamping and stone-blowing, among which tamping is the most applied maintenance action to remedy a degraded track geometry.

When the track quality deterioration reaches an unacceptable level, this can lead to derailment and serious consequences of great significance. The consequences can include, for example, a high cost of operation, damage to the railway asset, economic loss, environmental pollution and the possible loss of human lives. Hence, track geometry inspection is employed to measure the quality of the track geometry. When it is observed that the track geometry level exceeds a predetermined maintenance limit, maintenance actions will be implemented to restore the track geometry to an acceptable level.

Obviously, the allocation of an inappropriate maintenance limit may result in an ineffective tamping regime, which will ultimately negatively affect the overall quality of the track, the train punctuality and serviceability, the train safety, the ride quality, the passenger comfort and the total related maintenance costs. Performing over-tamping imposes higher maintenance costs and it should also be noted that while a tamping action improves the quality of the track geometry, the tines of the tamping machine break the ballast particles under the sleeper and reduce the life cycle of the ballast (Andrews, 2013). In addition, performing fewer tamping actions than required increases the time that the track spends in a bad condition, which may lead to a higher risk of train derailment. Summing up, the allocation of an effective maintenance limit for the performance of tamping is of crucial importance.

In recent years, several research studies have been conducted on the allocation of an optimal track geometry maintenance limit. Andrade and Teixeira (2016) studied the effect of different maintenance limits by considering the longitudinal level and the alignment as track quality indicators, as proposed by EN 13848-5 (2008). They developed an optimisation model with two objective functions, to identify the optimum limit that minimises both the total maintenance cost and delay. In another research study, Arasteh Khouy, Larsson-Kräik, Nissen, and Kumar (2016) proposed a cost model for the determination of cost-effective maintenance limits. They considered the costs related to inspection, corrective tamping, capacity loss and the risk of accidents due to poor quality of the track geometry. The standard deviation of the longitudinal level and the isolated...
defect of twist were considered as track quality indicators in their work. The authors assumed that when the standard deviation of the longitudinal level reaches a certain limit, trains reduce their speed and the cost due to the capacity loss should be considered in the cost model. They concluded that a specific 'cost-effective maintenance limit' needs to be determined for different track quality classes.

The effect of different maintenance thresholds on the quality of the track geometry was investigated by Prescott and Andrews (2013). By considering the standard deviation of the longitudinal level as a track quality index, a Markov model was developed to predict the track geometry degradation. Three different maintenance thresholds were defined which lead to four track geometry conditions, that is, track in good condition, maintenance requested, speed restriction and line closure. The results of the model developed by Prescott and Andrews (2013) show that increasing the maintenance threshold will increase the probability of the track condition being in the speed restriction and line closure states. Andrews, Prescott, and De Rozières (2014) analysed the effect of the maintenance limit and the maintenance response time on the overall quality of the track geometry, using the Petri net method to model the track geometry degradation. Their study concluded that setting lower limits significantly reduced the time that the track spent in a poor condition. They found that an increase in the mean response time would decrease the total number of maintenance actions and would have no effect on speed reduction or line closure.

In another research study, Zhao, Chan, Stirling, and Madelin (2006) developed an LCC model for joint optimisation of ballast tamping and renewal, considering the ballast service life. Their model includes the cost associated with tamping and renewal, and a penalty cost due to poor track quality. These authors compared the effect of the following three policies: (1) tamping and renewal with an optimal maintenance limit, (2) tamping and renewal based on an optimal constant frequency of planned tamping and (3) tamping and renewal based on an optimal non-constant frequency of planned tamping. Based on a comparison of the results of the three policies, the authors stated that the third policy would be the most economic. Quiroga, Schnieder, and Antoni (2012) developed a simulation technique to estimate the track geometry evolution in the long term and compared constant maintenance and dynamic maintenance thresholds. They concluded that the constant maintenance threshold required fewer maintenance activities than the dynamic maintenance threshold. Meier-Hirmer, Riboulet, Sourget, and Roussignol (2009) studied optimal track geometry maintenance limits considering two maintenance response times, that is, a response time shorter than the inspection period and a response time longer than the inspection period. They used a gamma process to model the track geometry degradation. The study concluded that lower...
maintenance limits should be set when the response time is greater than the inspection interval.

In order to achieve an applicable and effective maintenance limit, the track should be modelled at the line level by considering the variation among the track sections, which enables effective maintenance decisions for a set of track sections. In addition, the occurrence of isolated defects is of crucial importance, since it is a source of the generation of corrective maintenance activities. Isolated defects are the extreme geometry irregularities over the defined limits and occurs in a small portion of the track section (see EN 13848-1 (2003), Alemaizkoor, Ruppert, & Meidani, 2018; Cárdenas-Gallo, Sarmiento, Morales, Bolivar, & Akhavan-Tabatabaei (2017) and Sharma, Cui, He, Mohammadi, & Li, 2018 for more details). Furthermore, the maintenance response time can be affected by the resource availability, logistics issues, managerial decisions, etc. Hence, in order to achieve a more effective maintenance limit, the maintenance delay time (i.e. the maintenance response time) should be considered to reflect the risk associated with different quality states.

The aim of the study presented herein has been to develop an optimisation approach to determination of the effective maintenance limit that minimises the total annual maintenance cost while considering safety limits. Linear regression and ordinal logistic regression have been used for prediction of the track geometry evolution and the occurrence of isolated defects. Due to the existence of uncertainty and variation in the input parameters, the Monte Carlo technique has been used to estimate the expected number of preventive and corrective tamping actions corresponding to specific limits. A cost model has been developed to compare the cost-effectiveness of different limit scenarios, enabling the selection of the most effective decision. In the model, the costs associated with inspection, preventive tamping due to normal degradation, and corrective tamping due to isolated defects are considered. In order to verify the applicability of the model, a case study has been performed with data collected from the Main Western Line in Sweden. The MATLAB program has been used to enable the variation of the parameters and estimation of the number of corrective and preventive tamping through developed Monte Carlo simulation. Moreover, a sensitivity analysis has been performed on the inspection intervals, the emergency corrective maintenance cost and the maintenance response time to assess the varied effect of these parameters on the mean number of maintenance actions.

This study contributes in the development of a framework toward the determination of the optimal track geometry maintenance limit. Furthermore, it proposes an integrating approach taking into account the track geometry degradation and restoration, the occurrence of isolated defect and maintenance process. The proposed approach will lead to a more effective maintenance decision making. The rest of the paper is organised as follows. The track geometry degradation parameters, maintenance limits, and maintenance actions are presented in Section 2. Section 3 deals with the analytical models and the proposed framework, as well as the associated Monte Carlo simulation. The case study is presented in Section 4 and Section 5 reveals the conclusions.

2. Track geometry degradation parameters, maintenance limits and maintenance actions

The track geometry describes the position that each rail, or the track centre line, occupies in space (American Railway Engineering and Maintenance-of-Way Association, 2006). The defects and irregularities in the track geometry are mostly used to characterise the quality of the track and to plan track maintenance activities. Track geometry measures can be divided into five classes: (1) longitudinal level, (2) alignment, (3) gauge, (4) cant and (5) twist. Longitudinal level is the track geometry of the track centre line projected onto the longitudinal vertical plane. Alignment is the track geometry of the track centre line projected onto the longitudinal horizontal plane. Gauge is the distance between the inner sides of the rail heads. Cant (cross-level) is the difference in height of the adjacent running tables computed from the angle between the running surface and a horizontal reference plane. Twist is the algebraic difference between two cross-levels taken at a defined distance apart, usually expressed as the gradient between the two points of measurement (EN 13848-1, 2003; American Railway Engineering and Maintenance-of-Way Association, 2006).

Figure 1 presents the explained track geometry parameters. The track geometry irregularities can be classified into short-wavelength and long-wavelength irregularities. Given their nature, long-wavelength track irregularities normally have a negative effect on the comfort of passengers. However, short-wavelength irregularities generate more vibration on the axles and wheels (Soleimanneigouni, Ahmadi, & Kumar, 2018b). Accordingly, the European standard EN 13848-5 (2008) has determined the following three maintenance limits for different defects, based on different permissible speeds.

1. Immediate action limit (IAL): The IAL ‘refers to the value which, if exceeded, requires taking measures to reduce the risk of derailment to an acceptable level. This can be done either by closing the line, reducing speed or by correction of track geometry’.
2. Intervention limit (IL): The IL ‘refers to the value which, if exceeded, requires corrective maintenance in order that the immediate action limit shall not be reached before the next inspection’.
3. Alert limit (AL): The AL ‘refers to the value which, if exceeded, requires that the track geometry condition is analysed and considered in the regularly planned maintenance operations’.

The IAL takes into account the track-vehicle interaction, as well as the risk of unexpected events, and is normative. The AL and IL are linked with the type of maintenance policy being implemented and are informative. This means that infrastructure managers may set various ILS and ALs based
on their maintenance policy to achieve the desired safety, ride quality and lower life cycle cost.

Generally, in practice the standard deviation of the geometry measurements is used to control the need for PM activities, and isolated defects are used for CM actions. Figure 2 shows various maintenance action zones corresponding to limits associated with the standard deviation of the geometry measurements and the extreme values of isolated defects. From this figure the following observations can be made:

- When the standard deviation of the geometry measurements is less than the AL, no maintenance action will be performed, and when the standard deviation of the geometry measurements exceeds the AL, the track section(s) is monitored and considered for PM actions.

- When the indicator of an isolated defect (e.g. the mean to peak value of the longitudinal level irregularities) is between the IL and IAL, CM is carried out on the track geometry without any operational action (i.e. speed reduction or line closure). Because this action is not based on any prior plan, its execution is more expensive than PM.

- When the indicator of an isolated defect (e.g. the mean to peak value of the longitudinal level irregularities) exceeds the IAL, CM along with operational actions (speed reduction or line closure) is carried out on the track geometry.

According to the International Union of Railways, it is usually the short-wavelength of the longitudinal level measurement that drives the need for track geometry

Figure 1. Track geometry parameters.
maintenance activities (Union Internationale Des Chemins de Fer, 2008). This includes the measurement of single isolated track geometry defects, as well as the overall standard deviation of a short section of the track (usually a 200 m track section). Furthermore, in this study, the standard deviation of the longitudinal level and the extreme values of isolated defects of the longitudinal level were used to assess the need for preventive and corrective maintenance activities, respectively. In addition, the AL was used to control the quality of the standard deviation of the longitudinal level, and the IL and IAL were used to control the occurrence of isolated defects.

3. Proposed analytical model

Figure 3 provides a schematic description of the proposed analytical model. As can be seen, track geometry is inspected at discrete time intervals (τ) to determine its condition. At each inspection interval, the standard deviation of the longitudinal level (DLL) is monitored and if it exceeds the AL (DLL ≥ AL), the track will be considered for PM tamping in the first maintenance window (T_tamp). This means that even if the DLL, between two maintenance cycles, is higher than the AL, PM would not be performed on the track until the predefined PM time. In addition, when the peak value of the longitudinal level (IsoLL) exceeds the IL and IAL, normal and emergency CM actions will be performed, respectively.

In the proposed model, if the estimated probability of the occurrence of isolated defects exceeds the ψ or ψ' values, emergency or normal CM will be carried out on that track section, respectively. Hence, at each inspection time, if the probability of the occurrence of isolated defects is less than ψ' and ψ, the track is left as it is and we plan for the next inspection. Actions 1 and 2 in Figure 4 show the mentioned situations. When it is observed that P_ILS ≥ ψ', a normal CM action is carried out on that track section with a response time (RT) (see Figure 3). Moreover, if it is observed that P_IALS ≥ ψ, an emergency CM action is carried out on that track section immediately.

Obviously, the two limits for the probability of the occurrence of isolated defects (ψ' and ψ) should be varied in order to determine the optimal value. However, since the focus of the present research has been on allocating an effective maintenance limit, determining the optimal limit for the probability of the occurrence of isolated defects has been left intentionally for future research.

When the response time is considered for normal CM actions, the track geometry degradation will increase with time and the following two situations may occur: (1) the track condition may remain in the normal CM zone or (2) the track condition may go to the next state, which is the emergency CM zone. This situation can only be monitored when the applied response time is greater than the inspection interval. This phenomenon can occur in practice in the case of unavailability of machines and logistics.

In the present study, it has been assumed that the applied response time is less than the inspection interval. The situations explained above and the corresponding maintenance actions are summarised below.

1. If P_ILS < ψ' and P_IALS < ψ for track section s and at inspection interval τ_i, then the track section is left as it is. Action 1 in Figure 4 shows the state graphically.
2. If D_ILS(t) ≥ AL for track section s, but t < T_tamp, then no action is carried out on the track section, but the track section is considered for PM tamping in the first maintenance window. Action 2 in Figure 4 shows the state graphically.
3. If P_IALS ≥ ψ' for track section s and at inspection interval τ_i, then a normal CM maintenance action is performed on track section s after the response time. Action 3 in Figure 4 shows the state graphically.
4. If P_IALS ≥ ψ for track section s and at inspection interval τ_i, then an emergency CM action with speed reduction or line closure is carried out on track section s.
immediately after detection. Action 4 in Figure 4 shows the state graphically.

5. If \( D_{LLS} \geq AL \) at \( t = T_{tamp} \), then a PM action is performed on that track section. Action 5 in Figure 4 shows the state graphically.

Setting different ALs will change the number of maintenance activities as well as the quality of the track geometry. In order to achieve an effective maintenance limit, a framework has been constructed (see Figure 5) which consists of the following six main steps:

1. Modelling the track geometry degradation.
2. Estimation of the number of maintenance actions based on the initial AL.
3. Cost analysis according to the developed cost model.
4. Recording the cost of the current AL scenario.
5. Repeating steps 1 to 4 with a new AL.
6. Comparing all the recorded scenarios and selecting the scenario with the minimum cost.

Steps 1 to 3 in the framework are necessary steps and are discussed in detail in the following sections.

![Figure 4](image.jpg)  
**Figure 4.** Track geometry maintenance limits and possible maintenance actions.

![Figure 5](image.jpg)  
**Figure 5.** A framework for determining the effective track geometry maintenance limit.
3.1. Track geometry degradation model

The degradation of the track geometry varies along the track line, due to many structural and environmental factors that exert a different influence on the railway track (Soleimanmeigouni et al., 2018b). In order to cope with this variability, usually the track quality indicators are calculated for sections with specific length (usually 200 m) to plan maintenance activities (Soleimanmeigouni et al., 2018b). In the present study, the railway track has been considered as a multi-component system comprising $S = \{1, 2, \ldots, s\}$ track sections, each with a length of 200 m. All the track sections have been considered as independent and as having their own degradation behaviour. Modelling the degradation based on the standard deviation of the longitudinal level and modelling the probability of the occurrence of isolated defects are explained in the following subsections.

3.1.1. Modelling the track geometry degradation based on the standard deviation of the longitudinal level

The linear function is one of the commonplace tools widely used in the literature to model the track geometry degradation between two maintenance actions, as explained, for example, by Andrade and Teixeira (2011), Caetano and Teixeira (2016), Esveld (2001), Guler, Jovanovic, and Evren (2011) and Zhao et al., 2006). Many research studies have been published which have used this method, for example, those conducted by Andrade and Teixeira (2011, 2012, 2013), Andrews (2013), Caetano and Teixeira (2013, 2015, 2016), Lee, Choi, Kim, & Hwang (2018) and Wen, Li, and Salling (2016). In the present study, a linear model was used to model the track geometry degradation and Figure 6 shows the degradation parameters in this model. In the proposed degradation model, the degradation parameters ($D_{LLs}$ and $b_s$) are considered as random variables. The degradation for each track section, $D_{LLs}(t)$, between two consecutive maintenance actions is determined using:

$$D_{LLs}(t) = D_{LLs}^0 + b_s(t - t_n) + e_s$$  \hspace{1cm} (1)

where:

- $D_{LLs}^0$ is the initial degradation value after tamping for track section $s$;
- $D_{LLs}(t)$ is the degradation value for track section $s$ in time $t$, $t \geq 0$;
- $b_s$ is the degradation rate in a maintenance cycle for track section $s$;
- $e_s$ is the Gaussian random error term with a mean of zero and a constant variance, $e_s \sim N(0, \sigma^2_e)$; the error term is the deviation between the measured value and the predicted value (as shown in Figure 6);
- $t$ is time in days;
- $t_n$ is the time at the latest tamping intervention (it resets the local time after tamping to zero).

3.1.2. Modelling the probability of the occurrence of isolated defects

In order to consider the CM actions in our model, we need to estimate the probability of the occurrence of isolated defects. Therefore, we apply ordinal logistic regression (Harrell, 2015) to estimate the probability that the indicator of an isolated defect of the longitudinal level will exceed the IL and IAL by considering the standard deviation of the longitudinal level as the predictor. Ordinal logistic regression is a family of regression methods that can be used to model the relationship between a set of predictors and an ordinal response. In our case, we define $Y$ as the response variable and it takes different values as follows:

$$Y = \begin{cases} 
1, & \text{if there is no isolated defect} \\
2, & \text{if the indicator of an isolated defect exceeds the IL (level A defect)} \\
3, & \text{if the indicator of an isolated defect exceeds the IAL (level B defect)}
\end{cases}$$

By considering the standard deviation of the longitudinal level as the predictor, the three different event probabilities can be obtained as follows:

$$P(Y \leq 1 | D_{LLs}) = \frac{e^{C_0 + \beta \cdot D_{LLs}}}{1 + e^{C_0 + \beta \cdot D_{LLs}}}$$ \hspace{1cm} (2)

$$P(Y \leq 2 | D_{LLs}) = \frac{e^{C_1 + \beta \cdot D_{LLs}}}{1 + e^{C_1 + \beta \cdot D_{LLs}}}$$ \hspace{1cm} (3)

$$P_1 = P(Y = 1 | D_{LLs}) = \frac{e^{C_0 + \beta \cdot D_{LLs}}}{1 + e^{C_0 + \beta \cdot D_{LLs}}}$$ \hspace{1cm} (4)

$$P_2 = P(Y = 2 | D_{LLs}) = P(Y \leq 2 | D_{LLs}) - P(Y \leq 1 | D_{LLs}) \nonumber$$

$$= \frac{e^{C_1 + \beta \cdot D_{LLs}}}{1 + e^{C_1 + \beta \cdot D_{LLs}}} - \frac{e^{C_0 + \beta \cdot D_{LLs}}}{1 + e^{C_0 + \beta \cdot D_{LLs}}}$$ \hspace{1cm} (5)
The condition of the track geometry can be identified only at inspection times.

The model was developed according to the following characteristics and assumptions:

- The condition of the track geometry can be identified only at inspection times.
- The degradation rate for each 200 m track section is varied. However, it will remain constant by performing tamping over time.
- In this study, it has been assumed that the accumulated tonnage is constant along the track. Therefore, it would be possible to model the track geometry degradation based on time instead of the load (MGT).

### 3.3. Cost model

The choice of AL can greatly affect not only the track performance in the long run, but also the economic aspects of the maintenance. Therefore, we consider the AL for track geometry maintenance as a decision variable to be allocated effectively so that it will minimise the total cost of track maintenance per year in a given time horizon. For this purpose, a cost model has been developed by considering the costs associated with inspection, preventive maintenance, normal corrective maintenance and emergency corrective maintenance that leads to speed reduction or line closure. The proposed cost model is as follows:

\[
C(t)^{Tot} = \frac{E(C(t)^{Tot})}{T} = N_t C_t + E(N_{PM}) C_{PM} + E(N_{NCM,n}) C_{CM,n} + E(N_{NCM,e}) C_{CM,e}
\]

where:

- \(C^{Tot}\) is the expected total cost per year,
- \(N_t\) is the number of inspections in a given time horizon,
- \(E(N_{PM})\) is the expected number of preventive maintenance actions,
- \(E(N_{NCM,n})\) is the expected number of normal corrective maintenance actions,
- \(E(N_{NCM,e})\) is the expected number of emergency corrective maintenance actions requiring speed reduction or line closure,
- \(C_t\) is the cost of inspection,
- \(C_{PM}\) is the cost of preventive maintenance,
- \(C_{CM,n}\) is the cost of normal corrective maintenance,
- \(C_{CM,e}\) is the cost of emergency corrective maintenance,
- \(T\) is the given time horizon.

In order to estimate the components of the cost model, a simulation technique is used. Section 3.4 explains the simulation process.

### 3.4. Monte Carlo simulation to estimate the number of maintenance activities

Due to the existence of uncertainty in the degradation process and the maintenance effects, Monte Carlo simulation is used to estimate the mean number of PM actions \(N_{PM}\), the mean number of normal corrective maintenance actions \(N_{NCM,n}\) and the mean number of emergency corrective maintenance actions \(N_{NCM,e}\) with speed reduction or line closure. Figure 7 shows the simulation process. At the beginning, the values of the AL, \(N_{PM}\), \(N_{NCM,n}\), \(N_{NCM,e}\), \(T_{tamp}\) and \(T_{imp}\) are set. Then, the random coefficients of the
degradation model (consisting of $D_{LL,s}$, $b_s$ and the error term $\varepsilon_s$) are given and afterwards the degradation value at each simulation time $t$ is determined.

The degradation value ($D_{LL,s}$) during the simulation is unknown, unless the degradation condition has been identified at inspection intervals. Therefore, at each inspection time $(\mod(t, T_{insp}))$, the probability of the occurrence of isolated defects is computed for normal corrective maintenance and emergency corrective maintenance. If it is observed that the probability of the occurrence of emergency corrective maintenance ($P_{IM}$) is greater than $\phi'$, then a CM action is carried out on the track section after a response time. Regarding the PM actions, whenever the simulation time is equal to the pre-set tamping horizon, PM is carried out on those track sections whose degradation value is greater than the AL.

4. Case study

4.1. Data collection and data pre-processing

In order to verify the application of the proposed model, a case study was carried out using a data set collected from
line section 414 between Järna and Katrineholm Central Station. This line is a part of the Main Western Line in Sweden (Västra Stambanan). The measurement data were collected from Optram from 24 October 2007 to 21 April 2015. Optram is the system that has been used since 2007 by Banverket (the former Swedish Rail Administration) and Trafikverket (the Swedish Transport Administration) for studying the measurements performed on the track and overhead lines. This system visualises and graphically represents the track geometry measurements. Optram provides functionality for analysis and displays data trends. The maximum speed of trains on the Main Western Line is around 200 km/h and the line consists of UIC 60 and SJ 50 rails, M1 ballast material, Pandrol e-clip fasteners and concrete sleepers. Line 414 is 82 km long and is divided into 411 consecutive track sections, each with a length of 200 m. The railway track is measured by measurement cars two to four times per year. Totally, 30 inspections were carried out on most of the track sections.

The data were cleaned and pre-processed. In the first stage, the data relating to the standard deviation for the short wavelength (3–25 m) of the longitudinal level (DLL) were extracted for all the track sections. Based on the registered tamping times in the maintenance history, the exact times when tamping was conducted on a section or sections of track were determined. In addition, the degradation growth for all the track sections was visualised. It was observed that in some track sections the quality of the track geometry improved although there was not any registered tamping time in the maintenance history. Therefore, as a result of consultation with railway experts at Trafikverket, two criteria were used to minimise the errors in the degradation prediction model. The first criterion was that track sections with a degradation before tamping of DLL.Before < 0.8 of IL were to be considered as track sections in good condition, and if there was a reduction in the degradation value of more than 16% (>16%) at DLL = 1 mm and a reduction of more than 22% at DLL = 2 mm, using Equation (10), this was also to be considered as an indication of tamping activity:

\[
\frac{D_{LL\text{After}}}{D_{LL\text{Before}}} < 0.85
\]  
\[
\frac{D_{LL\text{After}}}{D_{LL\text{Before}}} < 0.9 - \frac{0.16}{D_{LL\text{Before}}}
\] (10)

4.2. Parameter estimation

4.2.1. Standard deviation of the longitudinal level

The degradation model presented in Section 3.1.1 was used to model the track geometry degradation. As mentioned in Section 3.1.1, the distribution of the random coefficients of the degradation model (DLL and b) needs to be identified. Figure 8 shows the scatter plots and histograms for the track geometry degradation rate and the degradation level values after tamping for all the track sections. As can be seen from the scatter plots, the track sections have different degradation parameters and it is shown that the behaviour of the track sections varies over the track.

In addition, the histogram of DLL and b shows that a lognormal distribution could be a good candidate for both degradation parameters. We applied the Anderson-Darling (AD) goodness-of-fit test to determine the best-fitting distribution for both degradation parameters and the likelihood method to estimate the parameters of the distribution. Table 1 presents the results of the AD test for both DLL and b. The results indicate that both these degradation parameters have a p value greater than the significance level (0.05) for a lognormal distribution. Therefore, it can be inferred that both DLL and b from the selected line follow a lognormal distribution with the parameters presented in Table 1.

The second criterion was that track sections with a degradation before tamping of DLL.Before > 0.8 of IL were to be considered as track sections in poor condition, and if there was a reduction in the degradation value of more than 16% (>16%) at DLL = 1 mm and a reduction of more than 22% at DLL = 2 mm, using Equation (10), this was also to be considered as an indication of tamping activity:

\[
\frac{D_{LL\text{After}}}{D_{LL\text{Before}}} < 0.85
\]  
\[
\frac{D_{LL\text{After}}}{D_{LL\text{Before}}} < 0.9 - \frac{0.16}{D_{LL\text{Before}}}
\] (10)

Figure 8. Scatter plots and histograms for (a) the degradation rate and (b) the degradation values after tamping.
The probability density function for the selected distribution is:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left\{ -\frac{(\ln x - \mu)^2}{2\sigma^2} \right\}$$  \hspace{1cm} (11)

where $\mu$ is the scale parameter and $\sigma$ is the shape parameter of the distribution.

In addition, the normality assumption for the error term in the degradation model (equation 1) was tested using the AD test. In this test, the null hypothesis was that the residuals of the linear model between two maintenance cycles were normally distributed. The AD test was conducted for the residuals of all the linear models between two maintenance cycles and for all the track sections. Figure 9 presents the results of the AD test based on the histogram of the $p$-values. As can be seen, the null hypothesis cannot be rejected for approximately 88% of the tests because their $p$-values are larger than the significance level (0.05). Based on the results of the test, it is reasonable to state that the residuals extracted from the linear model are normally distributed. The mean and the variance of the error term in the degradation model were determined using the Minitab software. The values of the error term can be seen in Table 1.

### 4.2.2. Isolated defects

In order to predict the probability of the occurrence of level A defects and level B defects in line 414, Equations (5) and (6) (presented in Section 3.1.2) were used, considering the standard deviation of the longitudinal level as the main predictor. The data relating to registered level A and level B defects in the database for line 414 were used to estimate the model parameters. Table 2 presents the results of fitting ordinal logistic regression on the dataset.

As can be seen in Table 2, the $p$-value for the standard deviation of the longitudinal level is less than the significance level (0.05) and shows that this factor is statistically significant. Therefore, the changes in the standard deviation of the longitudinal level are associated with the changes in the probabilities of the three outcomes of the model. Since the coefficient for the standard deviation of the longitudinal level is negative, one can conclude that an increase in $D_{LLs}$ will increase the probability of the occurrence of level A and level B defects. The McFadden’s $R$ square of the model is 0.41, which shows a reasonable goodness of fit for the proposed model. McFadden’s $R$ square (McFadden, 1973) is a method for calculating the $R$ square for ordinal logistic regression and for measuring how well the model fits the data. It takes a value between 0 and 1, with 0 indicating that the model is incapable of prediction and 1 indicating a perfect model for prediction (Allison, 2014).

### 4.2.3. Recovery model

The recovery values for partial and complete tamping in line 414 were extracted and used to construct the recovery model presented in Equation (7). After estimating the parameters of the recovery model in Equation (7), the recovery model, with the tamping type (partial or complete tamping) being considered, was formulated as follows:

$$R_{LL} = -0.269 + 0.51 \cdot (D_{LLs}) + 0.207 \cdot x_l - 0.043 \cdot x_r \cdot (D_{LLs}) + \epsilon_{rLL}$$  \hspace{1cm} (11)

Furthermore, the normality assumption for the error term in the recovery model was tested using the AD test. In the test, the null hypothesis stated that the residuals of the recovery model were normally distributed. The results of the test showed a $p$ value of 0.067, which is larger than the significance value (0.05) and the AD value of 0.699. Based on the results, there is not enough evidence to reject the null hypothesis. The mean and the variance of the error term were determined in the Minitab software and $\epsilon_{rLL}$ is estimated as follows:

$$\epsilon_{rLL} \sim N(0, 0.15)$$

### 4.3. Effective maintenance limit (AL)

This section concerns the determination of an effective AL that minimises the total maintenance cost per year. In total, we assessed the effect of 15 different AL scenarios. The scenarios for the AL started with the allocation of

---

**Table 1. The results of the AD test for the coefficients of the degradation model extracted from the data set for line 414.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AD value</th>
<th>$p$ value</th>
<th>Shape</th>
<th>Scale</th>
<th>Mean</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degradation rate ($b$)</td>
<td>0.376</td>
<td>0.411</td>
<td>-2.379</td>
<td>0.756</td>
<td>0.125</td>
<td>0.115</td>
</tr>
<tr>
<td>Degradation values after tamping ($D'_{LLs}$)</td>
<td>0.273</td>
<td>0.665</td>
<td>-0.352</td>
<td>0.3816</td>
<td>0.756</td>
<td>0.306</td>
</tr>
<tr>
<td>Error term ($c$)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.041</td>
<td>0.000</td>
</tr>
</tbody>
</table>

---

**Table 2. The estimated parameters for the ordinal logistic regression model.**

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>$p$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_0$</td>
<td>9.1875</td>
</tr>
<tr>
<td>$C_1$</td>
<td>13.39</td>
</tr>
<tr>
<td>$\beta$</td>
<td>-4.7712</td>
</tr>
</tbody>
</table>

---

[Image 9. Histogram of the $p$ value for the normality of the error term in the degradation model.]
$AL = 1.2 \text{mm}$, after which the AL was increased by increments of $0.05 \text{mm}$ up to the last scenario, where $AL = 1.9 \text{mm}$. The time horizon was set to 15 years. Over time, the track is inspected every four months. At the inspection time, whenever the $PIL$ and $PIAL$ exceed a certain value, corrective maintenance is carried out on the track section. In this case study, based on expert opinion, we assumed that whenever the probability of the occurrence of isolated defects, $PIL_s$, was greater than 70% ($PIL/C21 \geq 0.70$) for track section $s$ and at the inspection interval $\tau$, a normal corrective maintenance action would be scheduled with a response time. The response time for the performance of normal corrective maintenance was assumed to follow a normal distribution with a mean of $m = 5 \text{weeks}$ and a standard deviation of $\sigma = 1 \text{week}$. In addition, it was assumed that once the $PIAL/C21 \geq 0.05$ (5%), an emergency corrective maintenance action would be performed immediately with a speed reduction or line closure. In order to perform PM, the tamping horizon was set to 12 months. Therefore, at the point of time for tamping, preventive maintenance would be carried out on the track sections with $DLL_s \geq AL$.

MATLAB program has been used to run the Monte Carlo simulation presented in Section 3.4 to estimate the expected number of both preventive and corrective tamping. The results were used in Equation (8) to estimate the total maintenance cost for each scenario. For each simulation, 80,000 runs were performed to make sure that the simulation would be converged. Figure 10 shows a sample plot of a simulation for $AL$ equal to $1.9 \text{mm}$. As can be seen in this figure, after around 40,000 simulation runs, the results converge to an acceptable value. The cost model presented in Section 3.3 was used to determine the total maintenance cost (per year) of each scenario. The cost of inspection, preventive maintenance (tamping), normal corrective maintenance and emergency corrective maintenance are set as follow:

<table>
<thead>
<tr>
<th>Cost parameters</th>
<th>Cost (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspection (per 200 m track section)</td>
<td>240</td>
</tr>
<tr>
<td>Preventive tamping (per 200 m track section)</td>
<td>5000</td>
</tr>
<tr>
<td>Normal corrective tamping (per 200 m track section)</td>
<td>11,000</td>
</tr>
<tr>
<td>Emergency corrective tamping (per 200 m track section)</td>
<td>40,000</td>
</tr>
</tbody>
</table>

Table 3 shows the mean number of normal corrective maintenance actions, the mean number of emergency corrective maintenance actions and the mean number of PM actions for line 414 (411 track sections) in the given time horizon (15 years). As can be seen in this table, the mean number of PM actions decreases with an increase in the maintenance limit in each scenario. However, the mean number of normal and emergency corrective maintenance actions is approximately constant from scenario 1 ($AL = 1.2 \text{mm}$) to scenario 7 ($AL = 1.5 \text{mm}$) and increases exponentially after that. Therefore, scenario 7 can be considered as a turning point from the point of view of the mean number of maintenance actions.

Figure 11 presents the total cost of maintenance per year for all the scenarios for the whole line. As can be seen in this figure, allocating either a low or a high maintenance limit will not necessarily result in a low maintenance cost, because this affects the mean number of corrective and preventive maintenance actions. This figure clearly shows that a range of AL scenarios could be selected as effective maintenance limits from a cost point of view. The two vertical dashed lines in this figure show the mentioned range of effective scenarios (scenarios with $AL = 1.5 \text{mm}$, $AL = 1.55 \text{mm}$ and $AL = 1.6 \text{mm}$). However, as can be observed in Table 3, the mean number of normal and emergency corrective maintenance actions increases exponentially after allocating $AL = 1.5 \text{mm}$. Hence, it is suggested that the limit should be set at the lower bound of the effective region (i.e. $1.5 \text{mm} \leq AL \leq 1.6 \text{mm}$) as this would reduce the risk of probability occurrence of isolated defects.
4.4. Sensitivity analysis performed on the emergency corrective maintenance cost

The cost of emergency corrective maintenance is highly dependent on the type of traffic (passenger or freight trains) and the traffic congestion. Generally speaking, performing emergency corrective maintenance on lines with high traffic congestion incurs more cost for infrastructure managers as more scheduled trains need to be cancelled or rerouted. On the other hand, performing corrective maintenance on tracks with less traffic congestion may not greatly affect the train serviceability. In the present study, a sensitivity analysis was performed to assess the effect of various emergency corrective maintenance costs \(C_{CM_e}\) on the optimal track geometry maintenance limit. For this purpose, all the input

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Maintenance limit (AL)</th>
<th>Mean number of normal CM actions</th>
<th>Mean number of emergency CM actions</th>
<th>Mean number of PM actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>47.005</td>
<td>64.883</td>
<td>2048.14</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
<td>47.679</td>
<td>66.140</td>
<td>1996.052</td>
</tr>
<tr>
<td>3</td>
<td>1.3</td>
<td>48.457</td>
<td>66.374</td>
<td>1845.871</td>
</tr>
<tr>
<td>4</td>
<td>1.35</td>
<td>49.355</td>
<td>67.994</td>
<td>1739.603</td>
</tr>
<tr>
<td>5</td>
<td>1.4</td>
<td>50.031</td>
<td>71.103</td>
<td>1653.88</td>
</tr>
<tr>
<td>6</td>
<td>1.45</td>
<td>50.638</td>
<td>73.585</td>
<td>1580.811</td>
</tr>
<tr>
<td>7</td>
<td>1.5</td>
<td>51.976</td>
<td>78.575</td>
<td>1489.608</td>
</tr>
<tr>
<td>8</td>
<td>1.55</td>
<td>57.131</td>
<td>88.838</td>
<td>1426.723</td>
</tr>
<tr>
<td>9</td>
<td>1.6</td>
<td>63.354</td>
<td>103.321</td>
<td>1358.053</td>
</tr>
<tr>
<td>10</td>
<td>1.65</td>
<td>73.859</td>
<td>127.537</td>
<td>1297.404</td>
</tr>
<tr>
<td>11</td>
<td>1.7</td>
<td>87.087</td>
<td>157.608</td>
<td>1228.142</td>
</tr>
<tr>
<td>12</td>
<td>1.75</td>
<td>104.180</td>
<td>200.907</td>
<td>1166.977</td>
</tr>
<tr>
<td>13</td>
<td>1.8</td>
<td>126.736</td>
<td>249.987</td>
<td>1093.242</td>
</tr>
<tr>
<td>14</td>
<td>1.85</td>
<td>149.335</td>
<td>316.195</td>
<td>1017.883</td>
</tr>
<tr>
<td>15</td>
<td>1.9</td>
<td>173.421</td>
<td>392.071</td>
<td>928.229</td>
</tr>
</tbody>
</table>

Figure 11. The effect of allocating different maintenance limit scenarios on the mean total maintenance cost per year (SEK).

Figure 12. Optimal track geometry maintenance limit regions for various emergency CM costs.

4.4. Sensitivity analysis performed on the emergency corrective maintenance cost

The cost of emergency corrective maintenance is highly dependent on the type of traffic (passenger or freight trains) and the traffic congestion. Generally speaking, performing emergency corrective maintenance on lines with high traffic congestion incurs more cost for infrastructure managers as more scheduled trains need to be cancelled or rerouted. On the other hand, performing corrective maintenance on tracks with less traffic congestion may not greatly affect the train serviceability. In the present study, a sensitivity analysis was performed to assess the effect of various emergency corrective maintenance costs \(C_{CM_e}\) on the optimal track geometry maintenance limit. For this purpose, all the input
parameters except $C_{CM}$ (i.e. the inspection interval, maintenance response time and maintenance costs) were the same as those given in Section 4.3 for all the AL scenarios.

Figure 12 displays the effect of different values of $C_{CM}$ on the total annual maintenance cost for various track geometry maintenance limits. The results clearly indicate that different values of $C_{CM}$ give different optimal limits. As can be seen in this figure, lower maintenance limits should be assigned for tracks with a high cost for emergency corrective maintenance actions (e.g. main tracks with high traffic congestion). In addition, from the results it was observed that there is an optimal region for maintenance limits corresponding to each $C_{CM}$. Based on this figure, it can be concluded that infrastructure managers should set lower maintenance limits for tracks with higher $C_{CM}$.

### 4.5. Sensitivity analysis performed on the inspection interval

Periodic inspections of the track are conducted to monitor the quality of the track geometry over time. In the present case study, although the inspection interval was constant, a sensitivity analysis was performed to assess the impact of different inspection periodicity on the mean number of maintenance actions and the total maintenance cost. The effects of five different inspection intervals were investigated. As mentioned in Section 4.3, a range of limits could be selected as effective ALs. In the sensitivity analysis performed on the inspection interval, the effective AL was set to 1.5 mm and the rest of the specifications were kept constant during all the analysis. For the analysis it was assumed that performing inspections would not affect the serviceability of trains, even inspections executed with a high frequency (i.e. every month).

Table 4 gives the mean number of maintenance actions in a given time horizon for different inspection intervals. The results indicate that the mean number of PM actions is not sensitive to the frequency of inspections. The main reason is that PM is carried out on track sections at predetermined tamping times. In addition, the results show that the mean number of normal and emergency CM actions increases when the frequency of inspections decreases. This is explained by the fact that by decreasing the frequency of inspections, the probability of the occurrence of isolated defects will increase.

### 4.6. Sensitivity analysis performed on the maintenance response time

In order to assess the effect of maintenance response time on the range of effective ALs, an additional sensitivity analysis was performed on various response times. In this analysis, with the AL set to 1.5 mm and the rest of the parameters kept constant, we estimated the mean number of maintenance actions in the given time horizon for different response times. We set the range of response times to 0–15 weeks and considered a standard deviation of one week for the whole analysis. Table 5 presents the effect of the different response times on the mean number of maintenance actions for a time horizon of 15 years. As can be seen in this table, the variation of the normal and the emergency corrective maintenance actions for response times from 0–3 weeks is negligible, but after three weeks, the number of CM actions increases exponentially.

In addition, the number of PM actions is not sensitive to different response times. The main reason is that preventive tamping is carried out on the track at predetermined tamping times. Hence, in order to reduce the number of CM tamping actions, it is highly recommended that one should keep the maintenance response time to less than three weeks. One’s ability to decrease the response time depends on the available resources, logistic issues, budget limitations, managerial decisions, etc. A reduction of the response time for maintenance could be achieved by increasing the amount of resources, or even by performing a proper resource allocation.

### 5. Conclusions

The study presented in this paper has attempted to identify the optimum maintenance limit for the planning of railway track geometry maintenance. The objective has been to set the AL so that the total cost of maintenance per year would be minimised. The standard deviation of the longitudinal level and the extreme values of isolated defects of the longitudinal level were considered as quality indicators to assess the need for preventive and corrective maintenance activities, respectively. A framework has been introduced to achieve the effective track geometry maintenance limit. The proposed framework includes a prediction model for the track geometry condition and a cost model. Linear regression is used to model the track geometry degradation and restoration. In addition, ordinal logistic regression is applied...
to estimate the probability of the occurrence of isolated defects by considering the standard deviation of the longitudinal level as the main predictor.

The proposed framework was implemented using a case study with a data set collected from the Main Western Line in Sweden. Based on the results obtained, it has been determined that the proposed framework can be used to find a range of cost-effective maintenance limits. In consideration of safety aspects in the planning of railway track geometry maintenance, it is recommended that one should select the lower bound limit within a region of effective ALs. A set of sensitivity analyses were carried out to identify how the uncertainty in the output of the proposed model could be apportioned to different sources of uncertainty in its inputs. It was observed that tracks with a higher cost of emergency corrective maintenance require the allocation of a lower maintenance limit.

Sensitivity analysis performed on the inspection interval showed that the frequency of inspections can greatly affect the mean number of emergency corrective maintenance actions. Based on the results obtained, it was observed that the response time for maintenance activities can affect the mean number of corrective maintenance actions (both normal and emergency corrective maintenance actions). A lower response time will reduce the mean number of corrective maintenance actions.

Notes
1. The time between a maintenance request and a maintenance action.
2. version R2017a, in a personal computer with a Windows 10, Intel(R) Core i7 @ CPU 2.8GHz, 16GB RAM.

Acknowledgments
The authors would like to thank Swedish Transport Administration (Trafikverket), Luleå Railway Research Center (JVT) and Bana Våg För Framtiden (BVFF) for their technical and financial support provided during this project. Specific thanks is extended to the SIMTRACK project partners for their continuous technical and professional support and sharing their expertise. We also wish to thank Dr Mohammad Haddadzade for his informative comments to improve the quality of the paper. The authors also like to thank the anonymous reviewers for their productive comments that helped in improving the quality of the paper.

Disclosure statement
No potential conflict of interest was reported by the authors.

References


