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Abstract

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

Keywords

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

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Introduction

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

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

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

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

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

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

This paper aims to minimise the total ballast maintenance costs per unit traffic load by identifying the optimal inspection interval for track geometry. It draws on track geometry data from the iron ore line (Malmbanan) in northern Sweden, used by both passenger and freight trains, to find the probability distribution of geometry faults.

Background information about the studied line

The Swedish mining company LKAB uses the railway line from Narvik to Luleå, "the iron ore line", to transport iron ore pellets from its mine in Kiruna to Narvik and from its mine in Vitåfors, near Malmberget, to Luleå (see Figure 1).[10] In 2000, LKAB increased the axle load on the Malmbanan line from 25 to 30 t and the maximum speed of a loaded train from 50 to 60 km/h. This change is expected to result in higher track geometry degradation levels. In addition to iron ore transportation, the line is used by passenger trains and other freight trains. The train speeds vary from 50 to 60 km/h for loaded iron ore trains, 60–70 km/h for unloaded ones and 80–135 km/h for passenger trains.

On the selected track section, section 118 between Boden and Gällivare (see Figure 1), the annual passing tonnage is about 13.8 MGT (million gross tonnes).

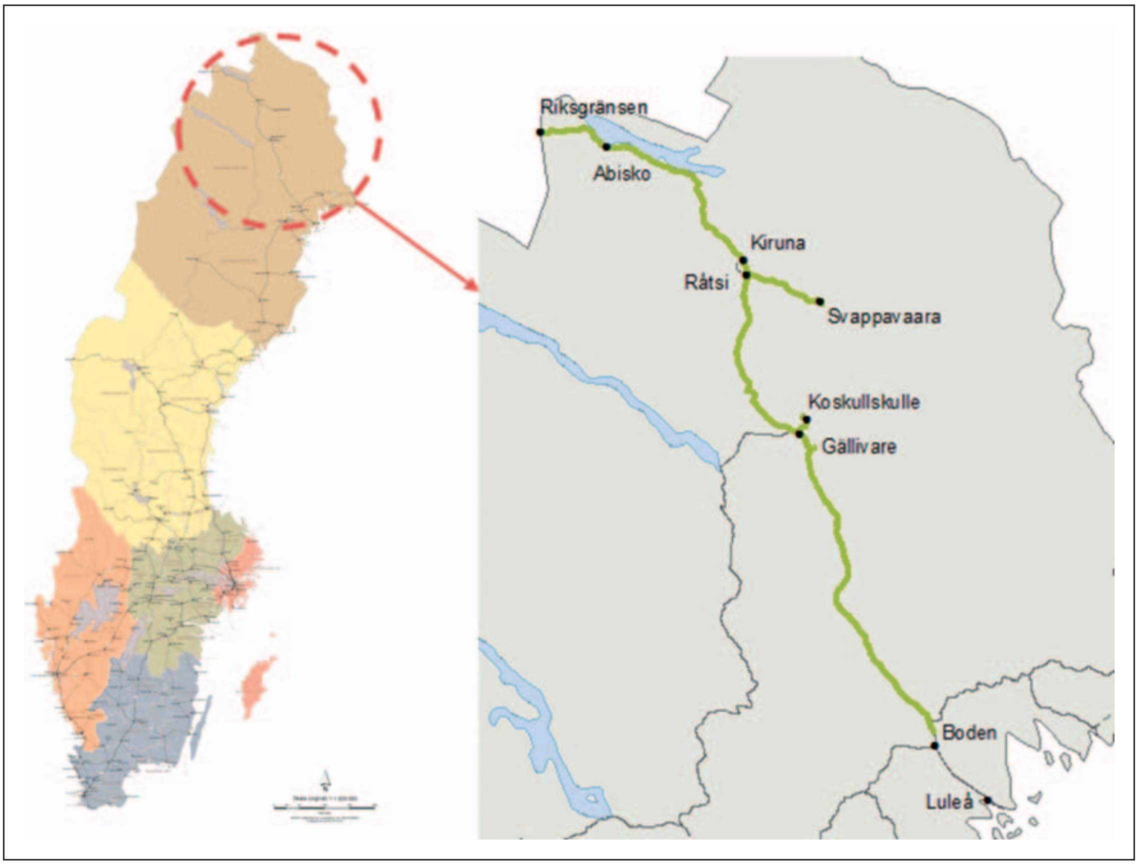

Figure 1. Iron ore line from Luleå to Narvik.

The track consists of UIC 60 rails and concrete sleepers. The ballast type is M1 (crushed granite), and the track gauge is 1435 mm. The region is subject to harsh climate conditions: winter snowfall and extreme temperatures, ranging from −40 °C in winter to +25 °C in summer.[11]

Track quality monitoring and maintenance

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

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

$$\sigma_S = \sigma_C + \sigma_{S_{High}} \quad (1)$$

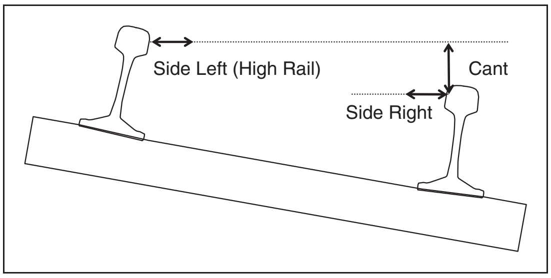

Figure 2. Calculation of σ_S.

These standard deviations (σ_S and σ_H) are calculated from short wavelength signals. Since the recorded signals from the measuring car combine long and short wavelengths, filtering is required. This can be done by selecting only signals in the range between 1 and 25 m.

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

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

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

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

$$K = \frac{\sum l}{L} \times 100\% \quad (3)$$

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

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

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

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

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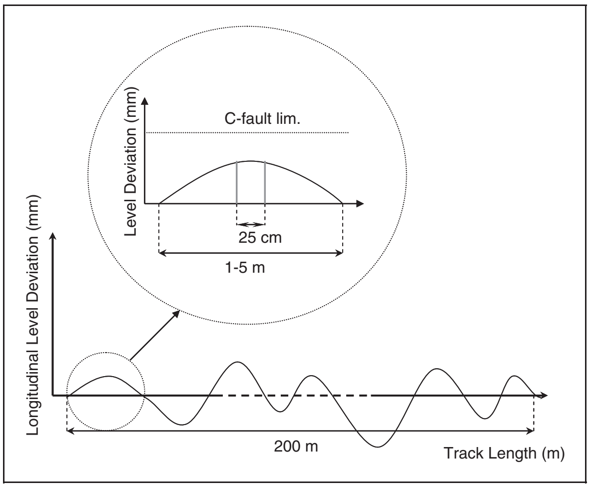

Figure 3. Illustration of C-fault limits.

dissimilar fault thresholds and varying comfort limits for local trains (see Table 1).

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

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

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

Tamping is done as either preventive or corrective maintenance. Execution of tamping due to a C-fault is considered corrective maintenance; tamping performed because of the *Q*-value is preventive. This means that if the *Q*-value of the track section falls below the contractual limit and/or there is a deviation in the track greater than the C-fault limits (Intervention limits), tamping is required.

Data collection and data treatment

To ensure comparable data from the selected track section, segments of 1000 m from both quality classes K2 and K3 were selected. Stations and other track sections before or after stations with a length shorter than 1000 m were excluded.

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

The study used two of Trafikverket's databases: Ban Information System (BIS) (Trafikverket asset register) and Optram (Optimised track management system). Information about substructure characteristics was obtained from BIS, and data for the geometry condition of segments were extracted from Optram. BIS contains information on infrastructure and facilities, agreements, the history of tamping (such as location of tamped section, length of tamping, date, etc.), grinding and curves.[14] Optram is a maintenance decision support system implemented in 2009 that can be used to graphically show the results of track geometry measurements. Only measurement data after 2007 are available in this database. The system also provides functionality for analysis and displays data trends.[10] To gain access to all available information on tamping, it is essential to consider both systems.[2]

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

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

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

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

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

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

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

Degradation of track geometry

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

For a track section with similar traffic, the rate of degradation varies depending on construction and differences in substructure. Figure 5 shows the variability of longitudinal level degradation rate in different 200-m tangent segments of the studied track for the time interval 2007–2009. The figure clearly shows the high variability of degradation rates for the track with the majority of the sections having low degradation rates that can be controlled by preventive tamping at infrequent intervals. However, the tail of the distribution consists of sections with high degradation rates that need to be accurately monitored and restored with corrective tamping to reduce risks. The balance between preventive and corrective tamping must be based on an appropriate cost analysis, as suggested in this paper.

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

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

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

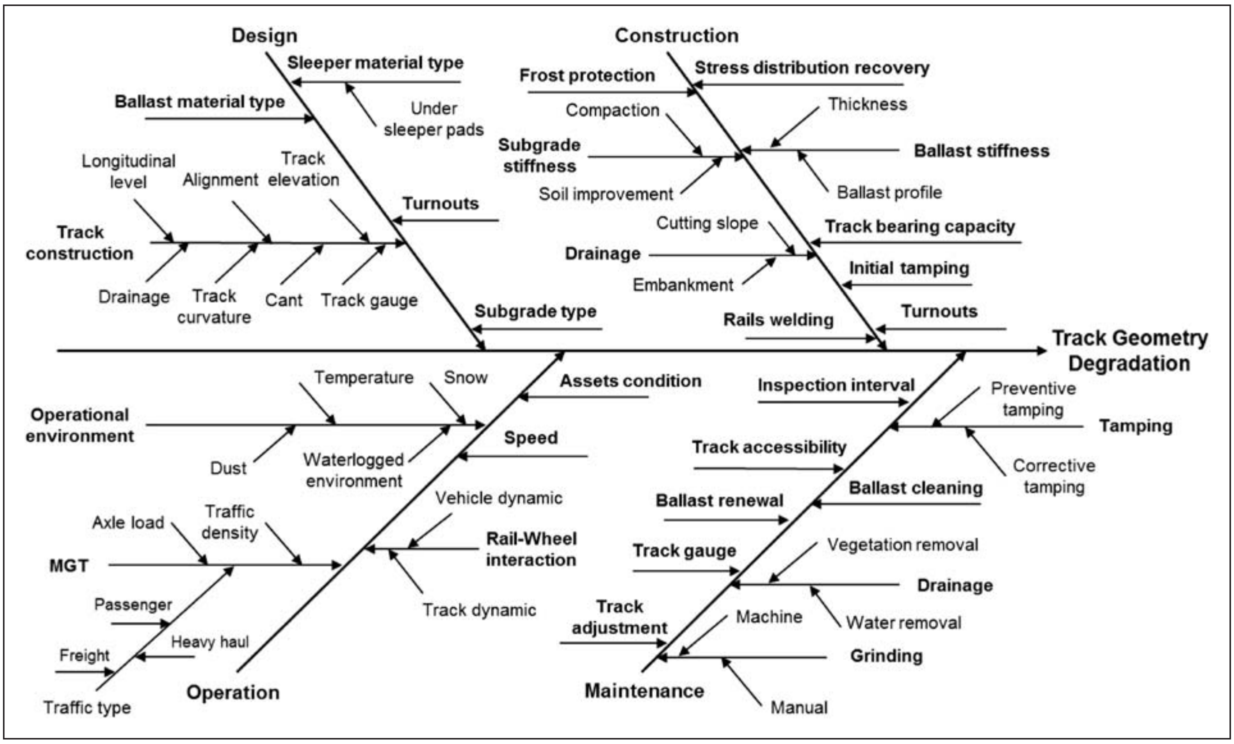

Figure 4. Ishikawa diagram (cause and effect diagram) of the factors influencing track geometry degradation.

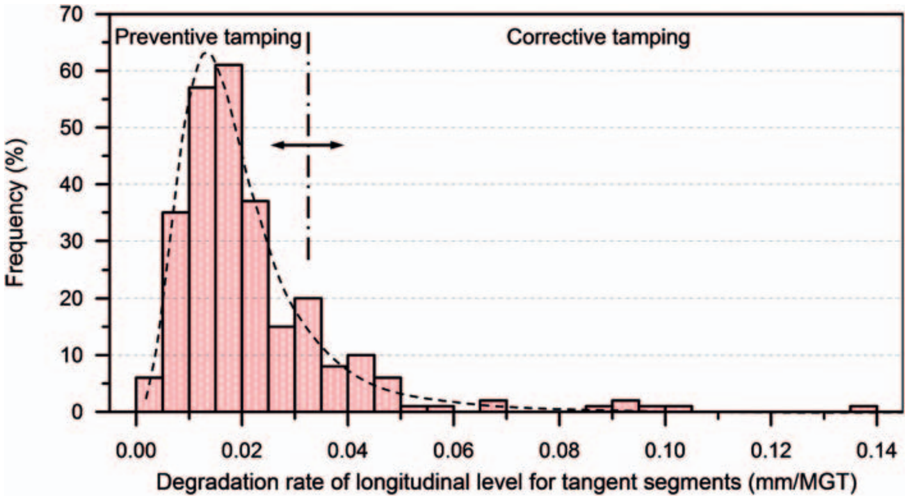

Figure 5. Histogram of longitudinal level degradation rates in tangent segments between 2007 and 2009.

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

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

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

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

Proposed inspection model

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

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

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

The following assumptions underpin the proposed model.

1. The execution of inspection and maintenance has no effect on the availability and capacity of the line. Therefore, the cost of unavailability of the line due to inspection or maintenance execution is not considered.

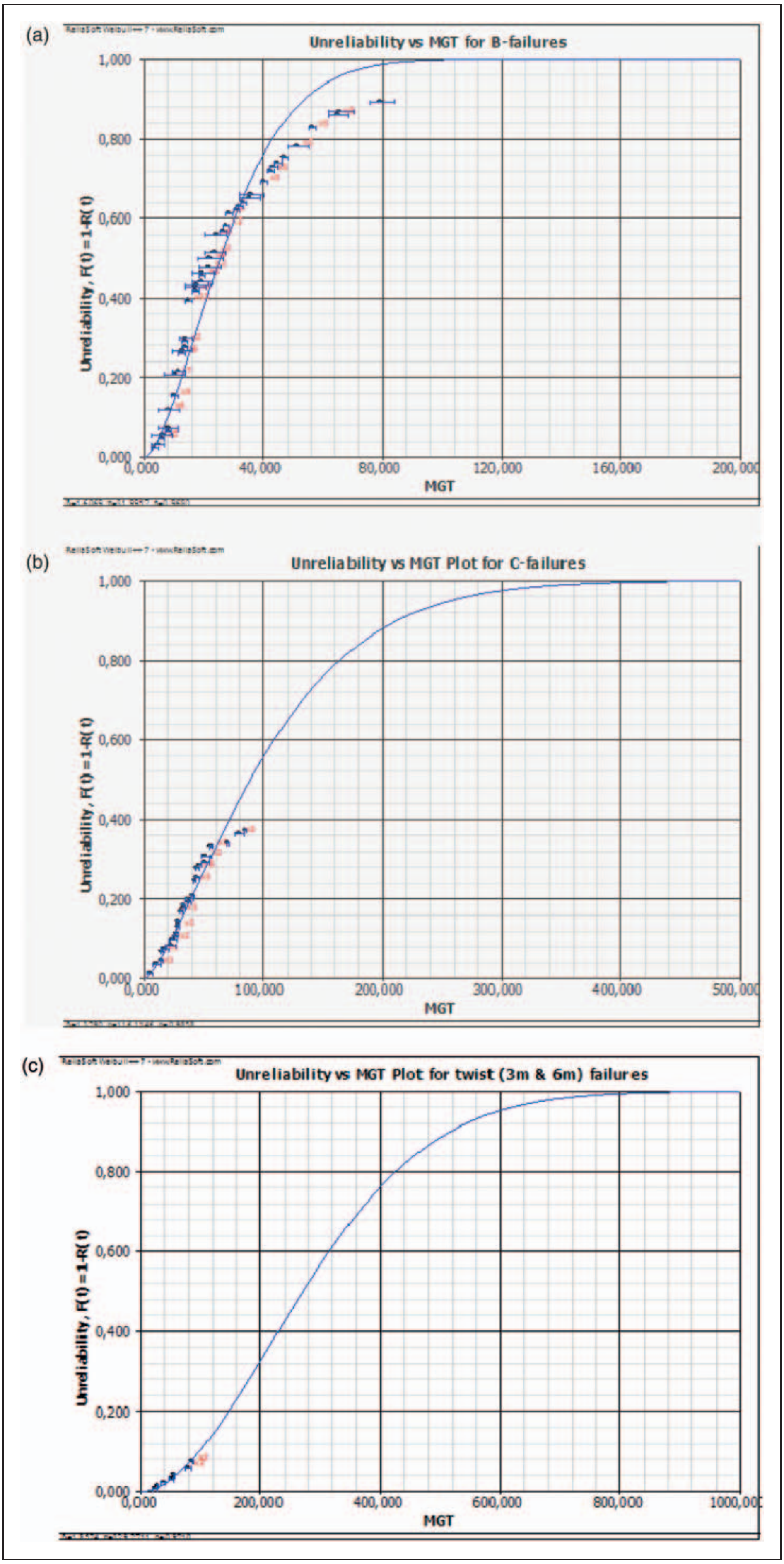

Figure 6. CDF of geometry faults versus MGT (a) B-faults, (b) C-faults and (c) twist (3 & 6 m) failures.

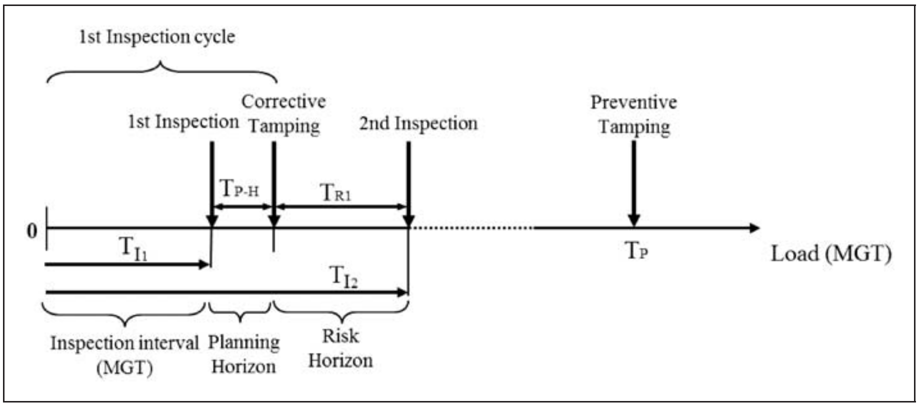

Figure 7. Schematic model of inspection cycles.

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

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

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

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

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

Application of the model on the studied line

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

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

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

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

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

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

Discussion

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

The obtained results are based on certain assumptions. It was assumed that all track segments are identical regardless of geometric characteristics, location (curve or tangent), substructure characteristics and construction time and maintenance history. However, as shown in Figure 5, the degradation rates of the tangent segments vary significantly. To reduce the risk and ensure the safety level, sections with high degradation rates should be carefully monitored and restored. In other words, more frequent inspections and preventive maintenance should be performed in segments with higher degradation rates.

The effectiveness of the maintenance was also assumed to be perfect. However, when the tamping intervention graph developed by the Austrian Railway[20] was used to evaluate the efficiency of tamping on 200-m tangent segments, results showed high

Table 3. The costs considered in the model.

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

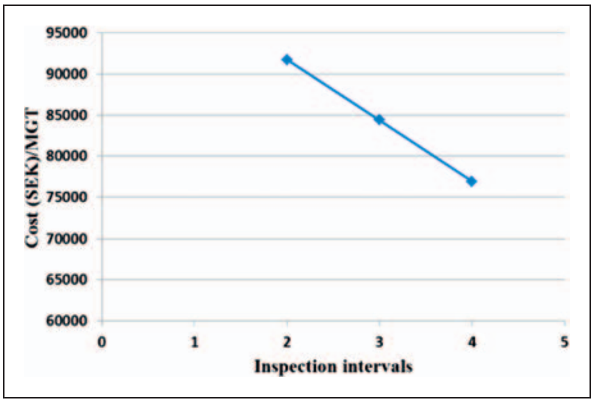

Figure 9. Comparison of maintenance cost per MGT for different inspection intervals.

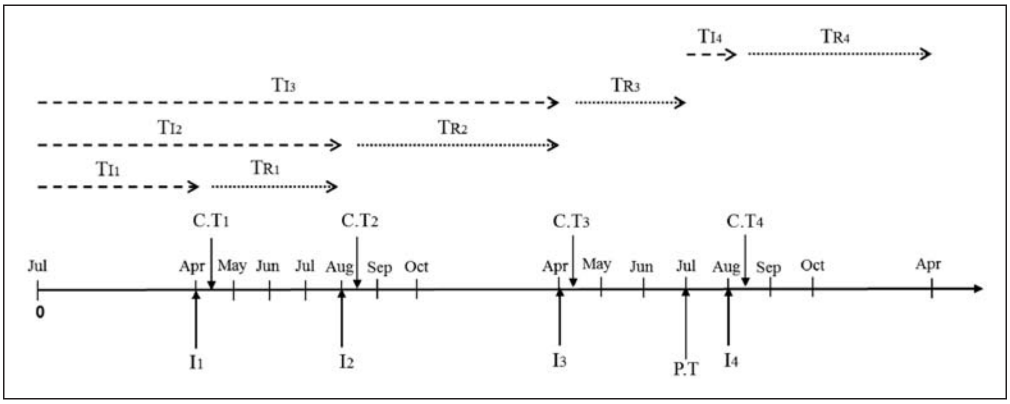

Figure 8. Schematic illustration of third scenario (inspection every 4 months).

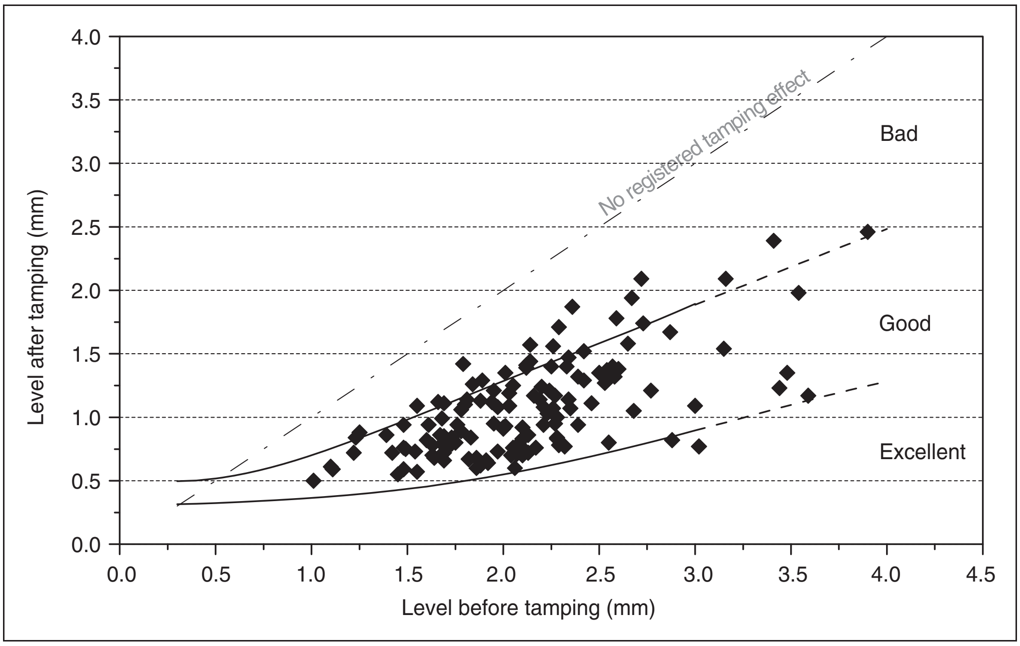

Figure 10. Efficiency of tamping on 200-m tangent segments.

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

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

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

Conclusions

The following conclusions are drawn from this study.

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

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