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Optimisation of maintenance track possession time: A tamping case study

Stephen M Famurewa[1], Tao Xin[1,3], Matti Rantatalo[1,2] and Uday Kumar[1,2]

Abstract

Optimum allocation and efficient utilisation of track possession time are becoming important topics in railway infrastructure management due to increasing capacity demands. This development and other requirements of modern infrastructure management necessitate the improvement of planning and scheduling of large-scale maintenance activities such as tamping. It is therefore necessary to develop short-, medium- and long-term plans for performing tamping on a network or track section within a definite time horizon. To this end, two key aspects of infrastructure maintenance planning are considered in this paper, deterioration modelling and scheduling optimisation. An exponential deterioration function is applied to model the geometry quality of a series of 200 m segments of a 130 km line section, and an empirical model for recovery after tamping intervention is developed. These two models are subsequently used to generate a methodology to optimise a schedule for tamping intervention by minimising the total cost of intervention including the cost of track possession while geometry quality is ascertained to be within a desirable limit. The modelling considers two types of tamping interventions, preventive and corrective, with different intervention limits and tamping machines. The result of this paper suggests a tamping plan which will lead to optimum allocation of track possession time while maintaining the track geometry quality within specified limits.

Keywords

Tamping, track possession time, degradation, longitudinal level, optimization

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Introduction

The improvement of the technical performance of track structures is essential to support the design capacity and at the same time improve the service quality of railway transport. Moreover, increasingly stringent safety requirements and demand for capacity for both freight and passenger traffic requires adequately supported intervention measures with optimum allocation and utilisation of track possession time. These intervention measures are categorised into track maintenance and track renewal tasks.[1] Among the most important maintenance concerns for track structures are how to predict and control degradation of track structure and how to maintain the geometrical quality of the track.[2] These factors influence ride quality and passenger comfort during operation, and also make a major contribution to the dynamics of the entire train/track system. Tamping is considered to be a maintenance task that has a large impact on the capacity of a railway network due to its particular requirements such as track possession time, quality demand, heavy machinery involved and scheduling challenges.

Effect of tamping operations on capacity

The time required to restore the geometry characteristics of a track is significant when the capacity of an existing network is considered. Depending on the maintenance philosophies and track management strategies, the track possession demand for tamping can vary for similar track sections. If an effective tamping strategy is not deployed, the track design capacity might not be achieved. Similar to other maintenance activities on railway infrastructures, the parameters that affect the total track possession time are the duration of the white period for each possession, travelling speed of the machine, working speed, preparation time and time for logistics considerations.[3] Even though the duration of each possession

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window and working speed are important, scheduling procedure is of particular interest in this study because redesign and innovation aspects are not within the scope of this work.

In the past, different principles have guided the planning, scheduling and implementation of maintenance actions: these include manufacturers' recommendations, experience within the railway organisation, assumed deterioration, availability of maintenance equipment and other basic factors. However, these factors are not able to support the growing demand for capacity, safety, cost-effectiveness and other service quality requirements for railway transport. To this end, several techniques and methods have been developed for optimum planning and scheduling of railway infrastructure maintenance.

Track possession scheduling and optimisation

Developments in railway management have led to increasing need for optimum planning and scheduling of maintenance activities. The parameters of interest in several maintenance optimisation tools and techniques include maintenance costs, labour cost, life cycle cost, asset performance, track possession time, punctuality and other service quality parameters.[4,5] Basically, maintenance optimisation of railway infrastructure gives short-, medium- or long-term plans for how preventive maintenance will be performed, on which segments and within which time horizon. To this end, an overview of railway infrastructure maintenance planning has highlighted two vital aspects of infrastructure maintenance planning: deterioration modelling and maintenance scheduling.[6] On the aspect of track deterioration, important parameters to be taken into consideration for prognostics are initial quality, initial settlement and rate of deterioration.[3,7–10] The significance of the initial quality of the track at the time of installation was investigated by Veit[7], where the life cycle management perspective of track structures was also studied. The rate of deterioration is governed by an integrated process of material degradation, traffic-induced degradation and maintenance. These phenomena are due to the design and layout of the track, rail profile, condition of the ballast, bearing capability of the subgrade, drainage problems, axle loads and traffic volume.[3,11] On the scheduling aspect, maintenance activities are allocated to available time intervals, or optimum track possession windows are created for maintenance during the timetable schedule. Higgins[4] proposed a model to determine the best allocation of maintenance activities and crews to minimise traffic disruption and completion time. Miwa[9] developed a mathematical programming model for an optimal tamping schedule; it indicated the track division for which tamping must be implemented within a specified horizon. Cheung et al.[12] developed a track possession assignment program to assign railway tracks to a given set of scheduled maintenance tasks according to defined constraints. The objective of the program is to create an assignment plan that maximises the assignment of job requests based on priorities while satisfying all imposed constraints. A preventive maintenance scheduling program was presented by Budai et al.[5] to cluster routine activities and projects for a link over a certain period such that the sum of possession costs and maintenance costs is minimised. They developed some heuristics such as 'most frequent work first' and 'most costly work first' to solve the formulated preventive maintenance schedule problem. Andrade and Teixeira[10] created a preventive maintenance scheduling program connected to track geometry quality using a bi-objective integer formulation that balanced renewal and maintenance costs with train delays. Vale et al.[8] developed a binary linear program to schedule tamping taking into consideration track degradation over time, track layout, quality recovery of track and track quality limits based on standards.

Several mathematical programs for preventive maintenance scheduling problems have been formulated, and solutions have been proposed using multi-objective algorithms, artificial intelligence approaches, heuristic algorithms and other techniques. There is need to further address the optimum allocation and utilisation of track possession time for maintenance to enhance operational capacity. The contribution of this paper is an investigation of differential deterioration along a length of a track and quantification of tamping intervention on a specific length of track over a finite horizon. Also, a methodology for optimum scheduling of tamping is proposed to minimise the direct cost of intervention and cost of track possession while maintaining geometrical quality within the desired level.

Theory and model formulation

The lifetime of track structure, as well as the quality of the track at any point in time, can be described in terms of deterioration and recovery phenomena.[7,9] There are some basic principles and theories that are essential to the modelling of these phenomena.

Track degradation

The passage of a train over a track generates enormous forces. This leads to deformation and wear of track components such as rails, sleepers, fasteners, ballast and subgrade, and consequently, long-term deterioration of the track geometry.[13] This phenomenon is one of the most important aspects of railway infrastructure maintenance. Thus, it is a vital requirement to adequately understand the pattern of deterioration of track geometry quality due to the accumulation of plastic and elastic deformation as a result of traffic loading.

The geometry quality and irregularity of ballasted tracks are monitored by some key parameters including longitudinal level, alignment, gauge, cross level and twist.[3,14,15] To manage track geometry problems, infrastructure managers (IMs) and academic researchers have monitored the evolution of principal parameters such as longitudinal level and alignment[2,8,15,16] while others have used derived indices such as variation of acceleration (due to irregularity)[7] and combinations of quality parameters to monitor the growth of track quality defects. Moreover, the standard deviation of the irregularity in the vertical direction of the track coordinate system has been proven to be sufficient to model the track geometry quality and also to support maintenance decisions and actions. [3,15,17]

The life cycle behaviour of track has been explained using different empirical models based on measurement records and load or time. These models include the grey model, linear model, exponential model and other empirical models.[2,7,8,11,15,16] The exponential model in equation (1) is preferred in this study considering the established behaviour of track; high-quality track or new track deteriorates slowly while low-quality track or ageing track deteriorates rapidly. The standard deviation of a vertical irregularity for a segment s at time t is given as

$$\sigma(s,t) = \sigma(s,0)e^{b(s)t} \tag{1}$$

where $\sigma(s,0)$ is the initial standard deviation for segment s estimated from vertical irregularity values from the recording car over a length of 200 m and $b(s)$ is the exponential constant or degradation rate for segment s estimated from a series of measurements over time.

Tamping and recovery

The quality of the track geometry eventually deteriorates beyond the allowable threshold for maintenance and safety giving rise to the need for intervention to restore it to the design specifications. The intervention level depends on the tamping strategy deployed. Common strategies in use by IMs include correction of isolated defects and restoration of lines when specified thresholds are reached. The details of recommended intervention limits can be found in EN-13848-5.[17] Ideally, from a life cycle perspective these thresholds should be dynamic, thereby becoming dependent on the age of the track structure or the number of interventions carried out. This practice will enhance the durability of track quality and also extend the lifespan of the track. Other factors considered in tamping are the availability of tamping machines and the maintenance philosophy of the owner of the asset. When a prognostic tamping strategy is to be deployed, the recovery or amount of improvement to be achieved by the tamping must be known in advance.

In reality, the recovery or efficiency of tamping depends on several factors such as track quality at tamping, age of track components, tamping technique, number of previous tamping operations, ballast condition and human factors. In the present study, an empirical regression model based on data collected in previous research on the investigated route has been developed.[18] The model describes the relation between the standard deviation of the longitudinal level before tamping and the improvement following tamping after passage of some traffic for stabilisation of the track. The model is used to predict changes in the geometry parameter at any point in time when tamping is carried out. Figure 1 shows a plot of the observed recovery and quality at intervention. The regression model is given in equation (2), and it has an R^2 value close to 0.7. In order to improve the prediction accuracy of the simple regression model, a 90% prediction limit was estimated for the model to account for other parameters that could affect the recovery value

$$\text{Recovery } R = 0.5445\sigma(s,t) - 0.8893 \tag{2}$$

The linear model shown in Figure 1 suggests that recovery depends on the quality at the point of intervention. Only the observation data that fall within the region considered most likely for good substructure and ballast condition in the best-practice guide for optimum track geometry durability[15] are shown in the figure.

Assumptions

The following assumptions underpin the model developed in this paper.

1. Deterioration follows an exponential model based on the explanation given earlier that high-quality track deteriorates slowly, whereas low-quality track deteriorates rapidly and irreversibly (see equation (1)).
2. The degradation rate of each 200 m track section is considered to be constant within the time horizon considered for the scheduling in this study.
3. The track section is considered to have good ballast conditions because the track structure is relatively new. Thus, tamping recovery is assumed to lie within the region considered likely for efficient tamping in a good ballast condition and to follow the model described in the previous section. The same recovery model is used for all the segments.
4. Segments with switches and crossings and other critical units will be maintained using spot tamping considering them as isolated defects. The

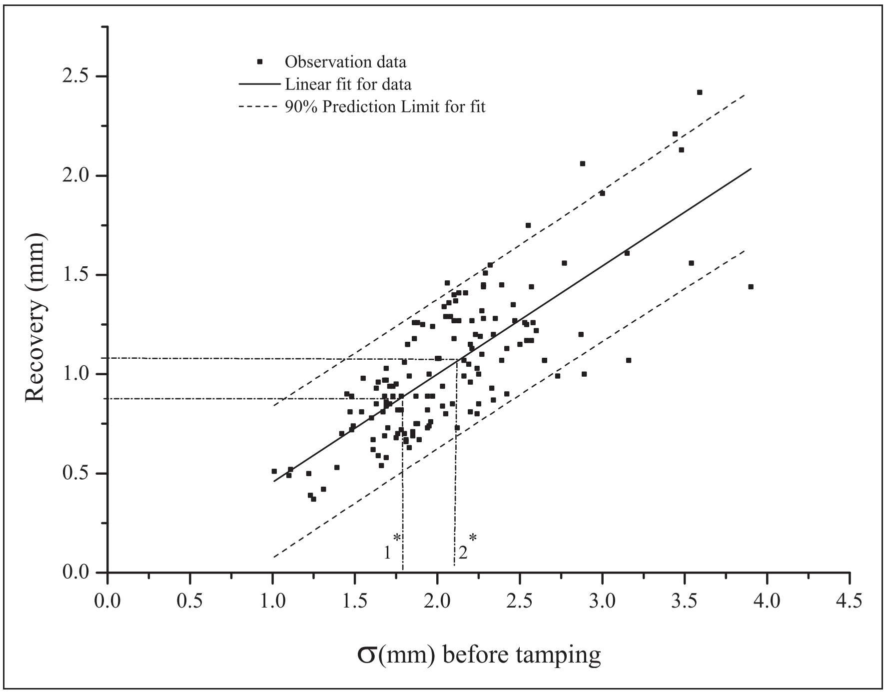

Figure 1. Recovery of track geometry quality after tamping interventions. (1*- preventive intervention threshold and 2*- corrective intervention threshold.).

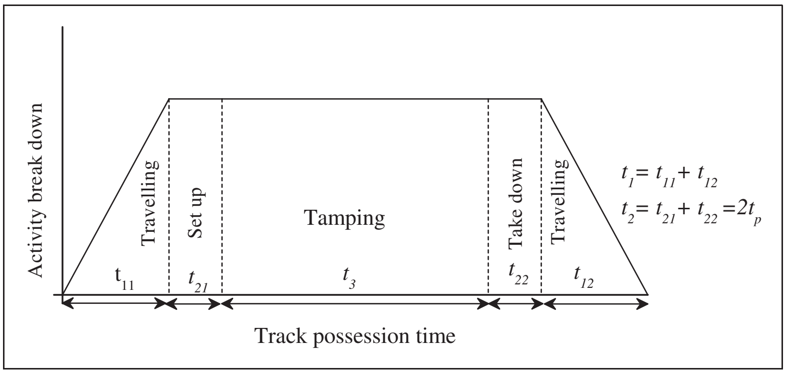

Figure 2. Track possession time for interventions.

reason for this is because so many engineering works are carried out on these segments; thus to model their deterioration, additional measurement is required.

5. There are two tamping machines, one has limited availability, high tamping efficiency, and it is used for early or preventive intervention. The second one is more available but has a relatively low tamping efficiency and is suitable for late intervention or corrective tamping. Optimum allocation seeks a balanced mix of the two possibilities in terms of cost, quality and time on the track.
6. There are four different stations that can provide temporary parking for the machines before and after tamping.

Optimisation procedure

The activity breakdown structure shown in Figure 2 is a simplified intervention process for both preventive and corrective policies. The travelling time depends on the speed and location of the tamper before the shift, while the set-up and dismantling times are fixed.

A simplified representation of the optimization procedure is given by the flow chart shown in Figure 3. An algorithm was developed in FORTRAN to obtain a solution for the model formulated in equations (3) to (8). The notation is defined in Appendix 1.

The objective function for intervention decisions is

$$t_w(N(t)) = \max\{t_1 + t_2 + t_3\} \tag{3}$$

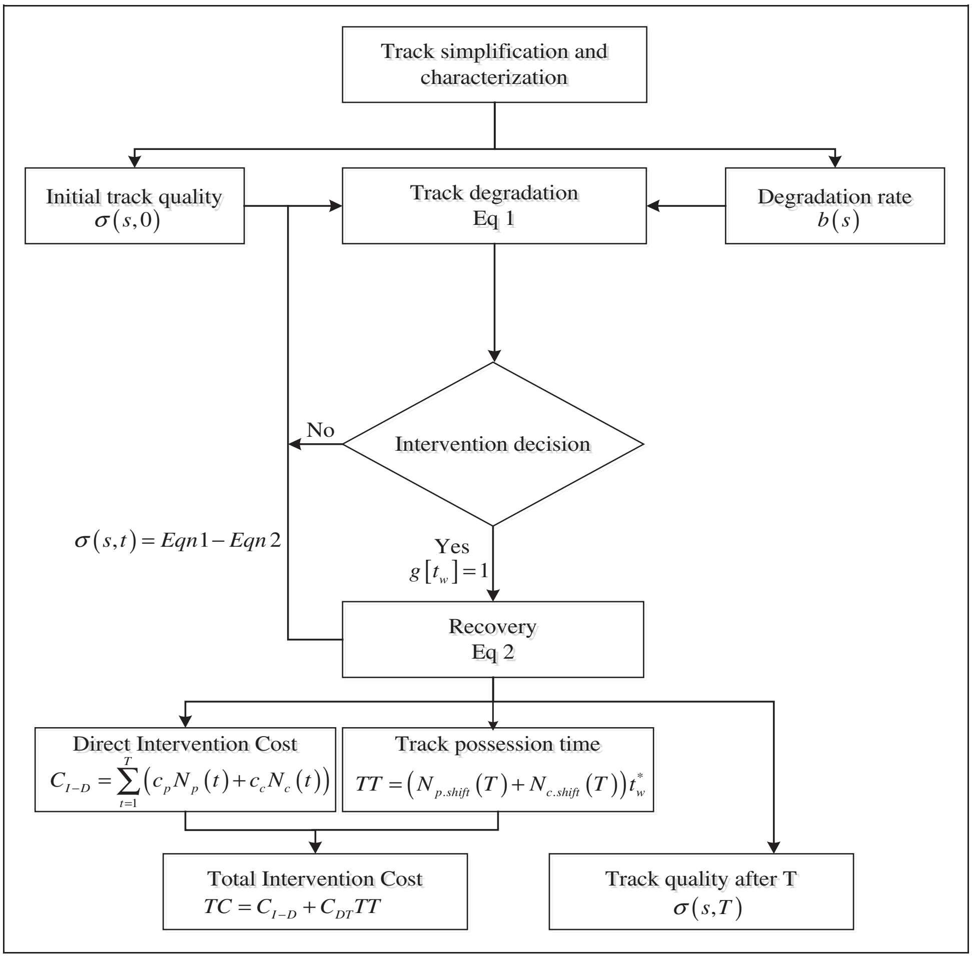

Figure 3. Flow chart for the optimisation of track possession and cost of tamping.

s.t.

$$\begin{cases} t_w(N(t)) < t_w^* \\ t_w(N'(t+1)) > t_w^* \\ N'(t) = \sum_{s=1}^{S} f\left[\sigma(s,t) - \sigma^*\right] \\ f[x] = \begin{cases} 1, & x \geqslant 0 \\ 0, & \text{else} \end{cases} \\ N(t) \leqslant N'(t) \end{cases}$$

The decision function is

$$g[t_w] = \begin{cases} 1, & t_w(N(t)) = \max\{t_1 + t_2 + t_3\} \\ 0, & \text{else} \end{cases} \tag{4}$$

where

$$t_1 = \left[\min\left(\left|s(1) - p(i)\right| + \left|s(N) - p(j)\right|\right) + s(N) - s(1) - (N-1)\right] \times \frac{d}{v'} \quad \left(i, j \in 1, \ldots, n_{park}\right) \tag{5}$$

$$t_2 = 2t_p(N - n_a) \tag{6}$$

$$t_3 = \frac{Nd}{v} \tag{7}$$

The number of corrective intervention shifts required to maintain the line section, given a specific number of preventive maintenance shifts is

$$N_{c.shift}(T) = \sum_{t=1}^{T} g[t_w(N_c(t))] \qquad g[t_w] = \begin{cases} 1, & t_w = \max\{t_1 + t_2 + t_3\} \\ 0, & \text{else} \end{cases} \tag{8}$$

Case study

Description of case study

A line section in the network of the Swedish Transport Administration (Trafikverket) is considered in the case study. The line section is 130 km of single track from Kiruna to Riksgränsen. It is basically a freight line because the majority of the traffic is iron ore freight, although passenger trains and other freight trains also use the line. Thus, the

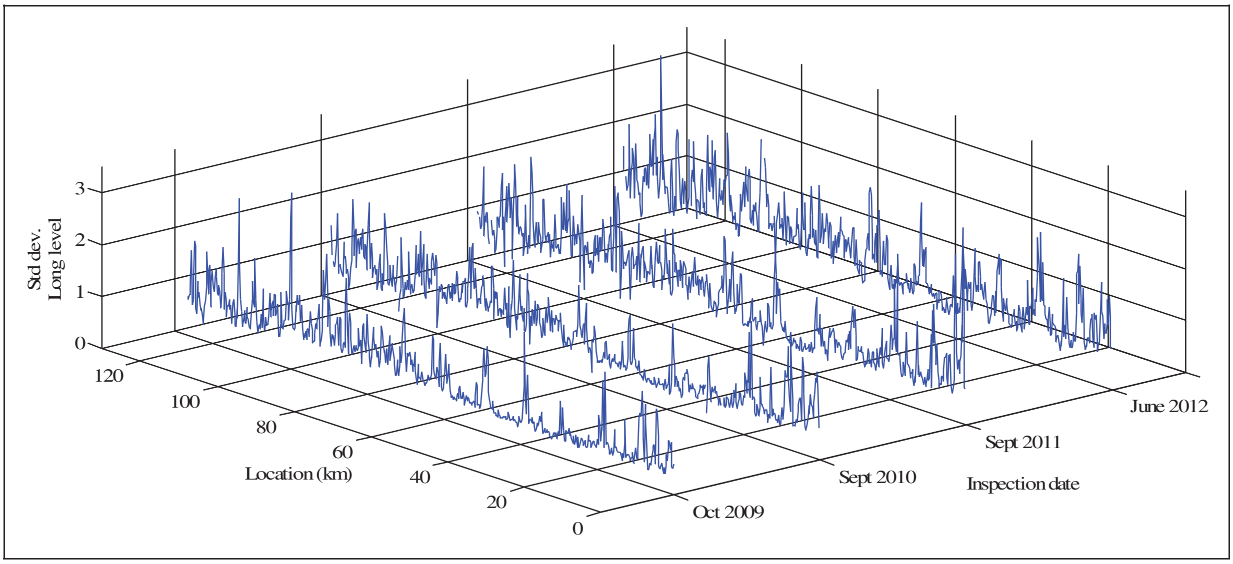

Figure 4. Standard deviation of longitudinal level over the 130 km line section.

line has a high socio-economic importance and high maintenance requirements. The train speed on the line is between 80 and 120 km/h. The maximum allowable axle load on the line section is 30 t and the annual accumulated tonnage is over 22 MGT. The line has continuous welded rail, head hardened 60E1 rail type, with concrete sleepers and Pandrol fasteners. It is highlighted that the track structure on this line section was renewed between 2006 and 2009; this major work also included ballast renewal. It should also be noted that this line section operates in extreme climatic conditions which can influence the reliability, availability, maintainability and safety characteristics of the infrastructure. The winter season sees snowfall and extreme temperatures. The annual temperatures vary between −40 °C and +25 °C.

Inspection data

Inspection is an important element of any effective preventive maintenance programme. Track geometry inspection is needed for planning a tamping strategy that is optimum in the allocation and utilisation of track possession time. It also gives useful information to avoid tamping too early or too frequently, which degrades the ballast condition, and at the same time to warn against intervening too late, which can result in a temporary speed restriction or failure. Track inspection is done by the IM based on two factors, speed and annual accumulated tonnage on the section. For the case study, track quality inspection was done three to six times a year, generally between April and October. The available inspection data extend from 2007 to 2012, and for each 200 m segment, only data after the completion of renewal were considered. Several geometry parameters were recorded by the train measurement vehicle, but only the standard deviation of the longitudinal level over each 200 m track length was used for the geometry quality prognosis and maintenance optimisation. The standard deviations of the longitudinal level (3–25 m wavelength) for a 200 m track segment from four measurements on the 130 km line section investigated in this study are shown in Figure 4.

Results and discussion

The results and findings of the modelling and predictions of deterioration and recovery phenomena in this study are presented in this section.

Non-homogeneity of track sections

The degradation rate of the longitudinal level for each 200 m segment was estimated using the exponential model explained in the previous section and the 2007–2012 inspection data. The degradation rate is an indication of the evolution of the track geometry quality for each segment. The distribution of the degradation rates for all 592 segments is shown in Figure 5. It is heavily skewed to the right, indicating the existence of critical spots with rapid degradation in their geometric quality. More than 50% of the track section has an exponential degradation rate between 0.00024 and 0.00060. The differential degradation rate along the track sections reflects non-homogeneity and variation of track components along the track length. In fact the 200 m track segments can be regarded as non-identical units in terms of quality deterioration.

An inference that can be drawn from this plot is that continuous tamping of the whole length of the track section might not be the best strategy in terms of life cycle management of the track. An essential maintenance requirement revealed by the figure is the balance of preventive and corrective tamping, since a higher exponential rate will require more

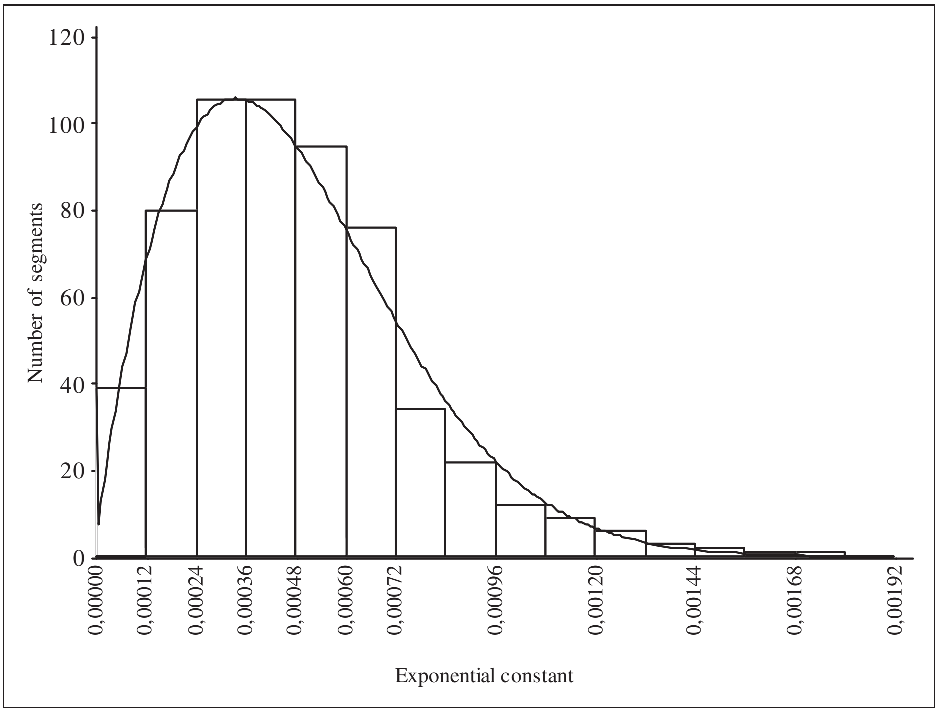

Figure 5. Distribution of exponential constant or degradation rate.

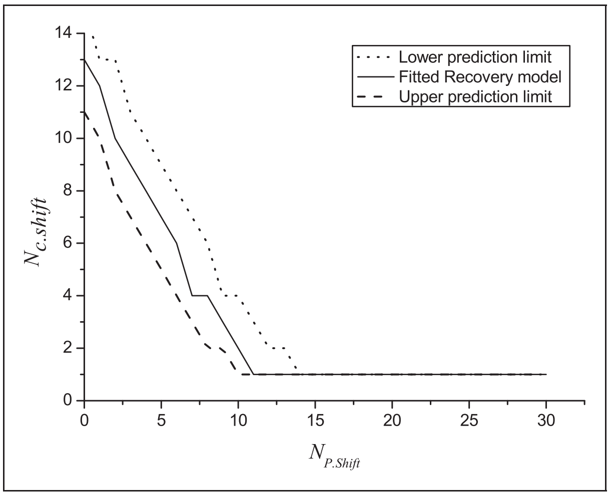

Figure 6. Corrective interventions and scheduled preventive interventions.

interventions than a lower exponential rate, this is also noted by Arasteh Khouy et al.[18]

Tamping strategy

Based on the observation of a differential degradation rate along the track length, there is a need to optimise the preventive and corrective tamping interventions on the track section. Using the model procedure described in the flow chart (Figure 3) and equation (8), the number of corrective interventions that will be required in 2 years for different numbers of allocated preventive tamping shifts was estimated, and the result is shown in Figure 6. The sensitivity of the result is also shown using the 90% prediction limit of the recovery model fit. Increasing the number of allocated shifts for preventive tamping decreases the consequent number of corrective tamping shifts up to a point where there is no need for corrective tamping after the initial one which was necessary at the beginning when few sections were above both intervention thresholds.

Direct cost of intervention

Using the proposed optimisation procedure shown in Figure 3 with different cost ratios for the two tamping policies, the total cost for tamping interventions over a short period of 2 years is given in Figure 7. A high value of the ratio c_p/c_c results in a higher cost of intervention when the number of preventive maintenance shifts increases.

For all cost ratios, the direct cost of intervention is constant after 16 shifts because no more segments will exceed the preventive maintenance threshold within the 2 year period of planning. For low corrective maintenance costs, the economic optimum plan in a short period will always be to carry out corrective maintenance. However, this is not always the best policy, particularly during the early life of the track, because it will reduce the service life. From Figure 8 the economic optimum policy considering a cost ratio of $c_p/c_c = 1$ is to have only a few preventive intervention shifts. However, track possession time and quality of the track are other parameters that need to be considered.

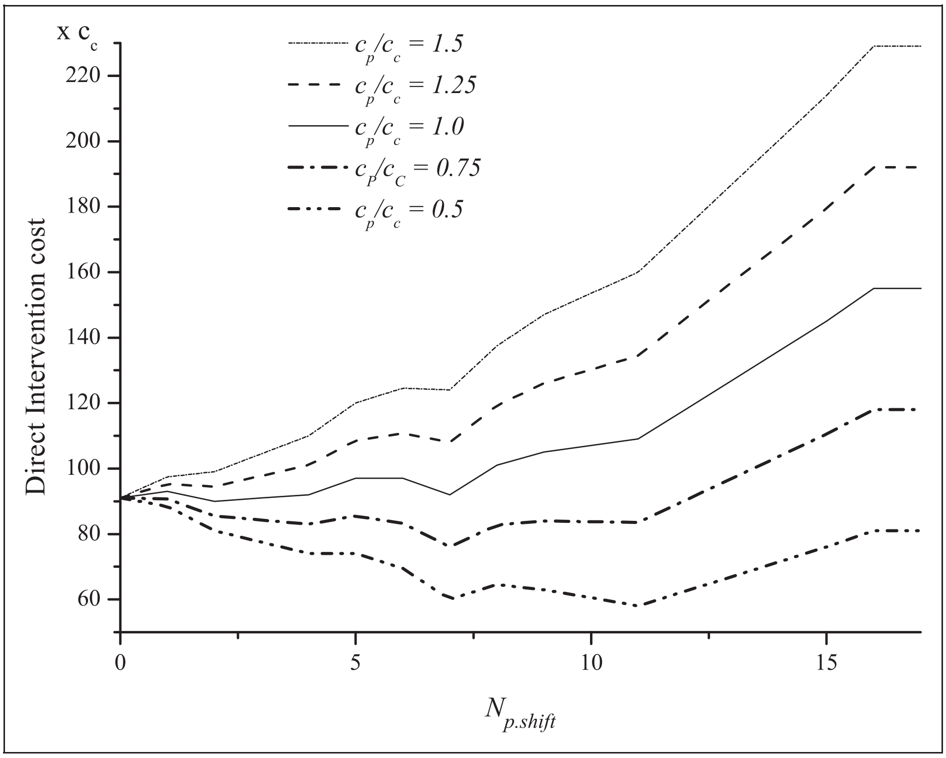

Figure 7. Total maintenance costs at different cost ratios.

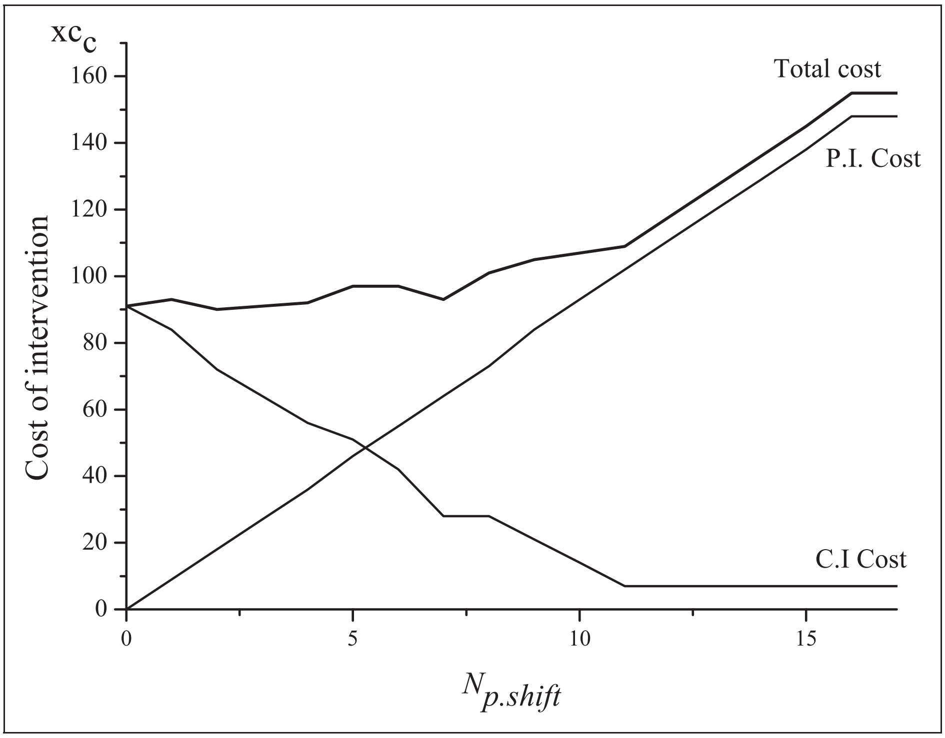

Figure 8. Maintenance costs for a finite horizon using a cost ratio $c_p/c_c = 1$. (P.I. = preventive intervention; C.I. = corrective intervention).

Cost of intervention and track possession

The present demand on railway infrastructure requires augmented allocation and utilisation of track possession time, and thus there is a need to implement optimum maintenance practice. In view of this, the global cost model proposed in Galar et al.[19] was adapted to estimate the total cost of intervention by adding the direct and indirect costs of intervention. Following the model procedure outlined in Figure 3 and using stochastic simulation for the recovery model (equal chance of obtaining recovery

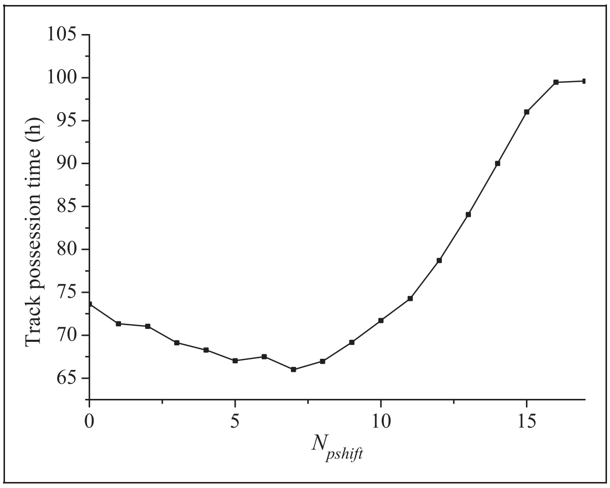

Figure 9. Track possession time.

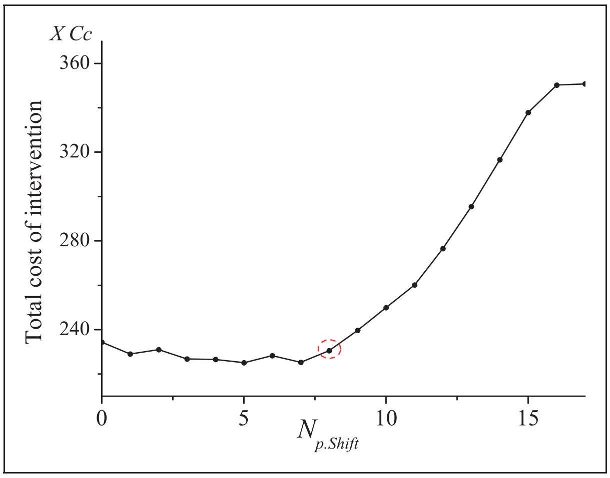

Figure 10. Total cost of intervention.

within the prediction limits, see Figure 1), robust estimation of track possession time was obtained and also the indirect cost of intervention (using $C_{DT} \approx 2c_c$). Figure 9 shows the total track possession time over a short period of 2 years for different numbers of preventive intervention shifts. Strategies with an $N_{p\cdot shift}$ value of between five and eight are efficient because they are in the range of the values of the minimum track possession time. Furthermore, Figure 10 shows the total cost of intervention with different numbers of shifts allocated for preventive intervention. According to the results shown in Figure 10, selecting strategies with more than eight preventive maintenance shifts will result in additional cost due to overly frequent track possession. An optimum strategy should have a high economic performance, process efficiency and satisfy the required effectiveness in terms of track quality. In view of this, strategies with $N_{p.shift}$ values up to eight are cost-efficient because they are in the neighbourhood of the minimum total intervention costs. However, it is necessary to confirm the optimality of any of these strategies by assessing the resulting quality characteristics to see if they meet the quality requirement of the infrastructure manager. In this study $N_{p.shift} = 8$ is suggested because it is cost-efficient and produces better quality than other strategies with lower preventive maintenance shifts.

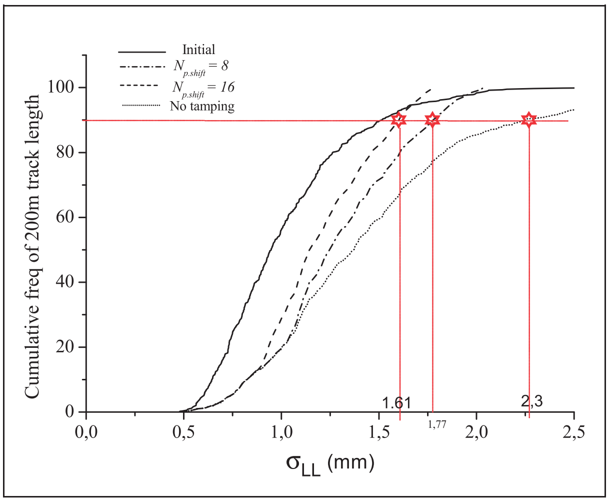

Figure 11. Cumulative frequency distribution of track quality indicator.

Track quality characterisation

The tamping strategies were evaluated by characterising the predicted geometry quality using the procedure in the current state-of-the-art description for track geometry quality.[20] Figure 11 presents the cumulative frequency distribution of the predicted longitudinal level defects over the length of the entire track section. The figure characterises the initial quality and also track quality after 2 years for three different scenarios: no tamping, $N_{p\cdot shift} = 8$ and $N_{p.shift} = 16$. If it is required by the IM that at least 90% of the total segments on the track section should not exceed track quality class C ($\sigma_{LL} < 1.8\,\text{mm}$) for safety, comfort, ride quality and life cycle management reasons, then from Figure 11 having $N_{p\cdot shift} = 8$ is adequate.

Table 1 gives the detailed description and extended classification of the track section into track quality classes for the 2 years under consideration using the procedure mentioned previously. If the requirement of the IM puts a limit on the proportion of the track segments expected to be in each quality class within a certain time horizon, then this can be checked.

Conclusions

The demand on the allocation and utilisation of track possession time is increasing, and there is a need to develop a model to support maintenance decisions, particularly for maintenance tasks with high possession requirements. This paper has presented an

Table 1. Percentage of the track falling into each quality class (A is the best, and E is the worst).

Scenario	A < 0.75 mm	B 0.75–1.1 mm	C 1.1–1.8 mm	D 1.8–2.5 mm	E > 2.5 mm
Initial	24.12	41.48	30.02	4.21	0.17
$N_{p.shift} = 8$	5.40	26.98	58.68	8.94	0.00
$N_{p.shift} = 16$	5.40	37.27	57.16	0.17	0.00
No tamping	5.39	23.94	49.07	14.68	6.92

optimisation tool to support the allocation of track possession time in a short-term plan for tamping. It considered the exponential function to model the deterioration of each 200 m segment in the case study.

The study found a varying degradation rate of the longitudinal level over the studied 130 km track section with about half of the segments having an exponential degradation rate of between 0.00024 and 0.0006. The objective of the optimisation model is to minimise the direct costs of intervention and track possession while geometry quality is maintained at a desirable level. In the case study, the optimum tamping strategy for a 2 year planning horizon will be to allocate eight shifts for preventive tamping while additional quality failures will be restored using a corrective intervention policy. This will support adequate planning and resource allocation including ordering of tamping machines. This approach provides: knowledge of track behaviour; quantification of tamping requirements; and a suggested tamping strategy that reduces track possession time and associated costs.

Finally, in future work a long-term plan will be developed that considers dynamic intervention threshold levels for the two policies: low threshold levels at the early stage of the track life and high thresholds at the later part.

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Appendix 1

Notation

c_p, c_c	cost of preventive and corrective intervention per segment
C_{DT}	cost of downtime per hour (depends on line class)
C_{I-D}	direct cost of intervention in T days
C_{I-I}	indirect cost of intervention in T days
d	length of segment $= 200\,\text{m}$
n_a	number of adjacent segments among tamped segments
n_{park}	total number times tamping machine is parked (in this study $n_{park} = 4$)
N	number of segments tamped in preventive intervention shift $\left(N_p\right)$ or corrective shift (N_c)
$N_{c.shift}$	number of corrective intervention shifts required for a specified number of preventive intervention shifts $N_{p.shift}$
$N'(t)$	number of segments above preventive threshold (N'_p) or corrective threshold $\left(N'_c\right)$ on day t
p	location of start parking lot $p(i)$ and end parking lot $p(j)$ $\left(i, j \in 1, \ldots, n_{park}\right)$
$s(i)$	location of tamped segments $\forall s(i) \in S$ and $i = 1, \ldots, N$
t_p, t_1	time for each set-up and disassemble $=$ 10 min, total travelling time during a shift
t_2, t_w	total set-up and disassemble time for a shift, duration of shift. (minimum duration $t_w^* = 6\,\text{h}$)
TC	total cost of intervention in T days
TT	total track possession time
v	tamping speed for preventive tamper $v_p = 1.4\,\text{km/h}$ and corrective tamper $v_c = 0.8\,\text{km/h}$
v'	travelling speed for preventive tamper $v'_p = 90\,\text{km/h}$ and corrective tamper $v'_c = 80\,\text{km/h}$
σ^*	threshold for preventive interventions $\sigma_p^* = 1.8\,\text{mm}$ and corrective interventions $\sigma_c^* = 2.1\,\text{mm}$ from EN-13848-5.