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An adaptive opportunistic maintenance model based on railway track condition prediction

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Abstract: Maintaining a track line in a good condition is a continuous challenge since it has to deal with various track line heterogeneities that contribute to accelerate its degradation. As a result, railway tracks should be inspected regularly to detect geometry faults and to plan maintenance actions in consequence. A maintenance plan that minimizes track maintenance cost is highly desirable by infrastructure managers. This paper presents an adaptive maintenance scheduling based on track condition prediction. The degradation indicator is the standard deviation of the longitudinal (SDL) level that is sampled on every 200m-long track section. Standards define some thresholds on this indicator that correspond to different levels of severity and related penalty costs. From collected data, a degradation model that uses a random coefficient Wiener degradation-based process is built. A probabilistic model to simulate the recovery effect after the maintenance action (tamping) is also used. Based on this degradation and recovery models, a cost model is built to find the optimal time for tamping on a single track section. After that we use a Monte Carlo approach to assess the performance of the cost model for the whole track line, considering both calendar based and adaptive opportunistic tamping actions. The results show that the adaptive opportunistic maintenance strategy has a lower cost per unit of time than the systematic preventive maintenance.

Keywords: Track condition, degradation, maintenance, tamping, Wiener process, optimization, simulations

1. INTRODUCTION

It is observed that railway track will degrade over time due to ageing and usage thus reducing its functionality (Antoni (2011)). It is up to the maintenance staff to ensure that the track line still presents the requirements in terms of safety criterion. Inspection and maintenance tasks are intended to detect geometry faults, to control the degradation process, and to protect against unacceptable consequences. However, inspecting the track line too often is unacceptable since it requires a track closure to allow the monitoring machine to achieve the measurements. Therefore, one should find the minimum number of required inspections to ensure that the track condition is still below the safety thresholds.

This paper proposes an integrated model to identify the cost effective track geometry maintenance scheduling. To model track geometry degradation, a random coefficient Wiener process is used for each track section. The recovery values after tamping are modelled with a probabilistic approach by considering the effect of track geometry condition before tamping on the recovery value of tamping. An adaptive maintenance scheduling is then built based on the degradation model. While the concept of adaptive maintenance is not standardized in engineering, it has been introduced by some authors; see for example Huynh et al. (2012), Wu et al. (2010). Adaptive maintenance can be viewed as a preventive maintenance model for which the periodic intervention time is updated (i.e. shifted ahead or postponed) depending on the state of degradation indicators, external influences or strategic changes (opportunistic actions).

The parameters of the respective models are estimated using data collected by the measurement wagon STRIX/IMV200. The paper proposes an original cost model to compute the total cost, considering the costs associated with tamping actions, intervention times, and penalties for crossing the thresholds.

The rest of this paper is organized as follows. Information on the railway line used as a case study is provided in Section 2. Section 3 describes the application of the Wiener process for track geometry degradation modelling. The recovery after tamping model is presented in Section 4. The analytical cost model for one track section is presented in Section 5. The simulation method for assessing the maintenance scheduling scenarios is presented in section 6. Section 7 presents the results of this study. Finally, Section 8 provides a conclusion.

2. LINE INFORMATION AND DATA COLLECTION

The investigated track line in this study is The Main Western Line in Sweden (Västra Stambanan) between Stockholm and Gothenburg. The speed limitation of trains on the Main Western Line is around 200 km/h. Line 414 between Järna and Katrineholm Central Station is used as the case study. The Line 414 is 82 km long. This line is divided on consecutive sections of 200 m on which the Standard Deviation of the Longitudinal level (SDL) is measured. The relevant data on the line were collected from 2007 to 2015 by Optram, a system used since

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2007 by Banverket (the former Swedish Rail Administration) and Trafikverket (Swedish Transport Administration) to study measurements of the track and overhead lines (Arasteh Khouy 2013). The Figure 1 shows some real sampled paths of SDL that were recorded. The dotted ellipse highlights the tamping actions that were achieved on those track sections. Overall there are 370 track sections that were considered for this case study. The goal of the maintenance infrastructure is to ensure that the SDL do not go beyond given threshold values that are defined by standards (e.g. comfort level threshold = 1.8 mm, speed reduction threshold = 2.5 mm). The readers are referred to Arasteh Khouy et al. (2014) for more information on track monitoring methods.

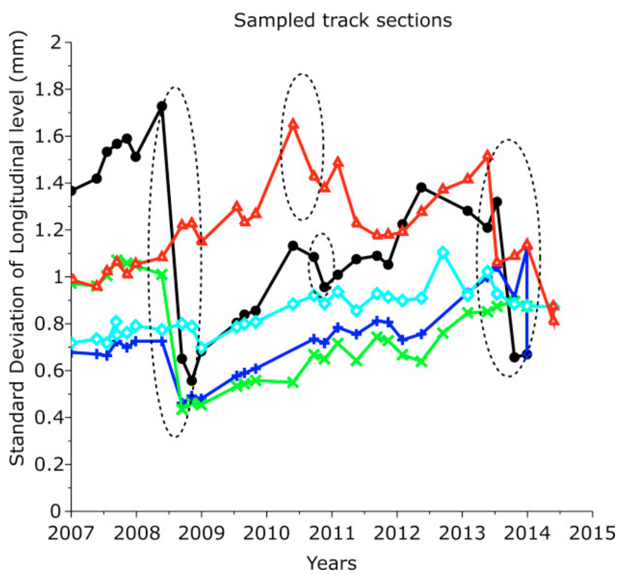

Fig. 1. Examples of real track condition (SDL) evolutions over time. Tamping actions (highlighted by the dotted oval shape) reduce the SDL value.

3. DEGRADATION MODEL AND RELIABILITY

3.1 The random coefficient Wiener process-based model

Modelling track geometry degradation can take either a stochastic or a deterministic approach. Readers are referred to Soleimanmeigouni et al. (2016) for further study on different track geometry degradation models. From collected data, one can see that there exist various degradation rates as well as noises with different magnitudes. To accurately model track geometry degradation, uncertainty must be considered in the degradation modelling process. This is why we use a random coefficient Wiener process to simulate random paths to represent different track condition evolutions over time. The main reason the Wiener process was chosen instead of typically using the gamma process is due to its ability to deal with non-homogenous behaviours that are observed in the current data set (Tang et al. 2014). The Wiener process has been widely applied to degradation modelling in various fields, e.g. bearings, laser generators and milling machines (Tang et al. 2014). The stationary Wiener process is particularly a good candidate to represent the evolution of a degradation process that is made of a linear increase over time with random Gaussian noise. It is characterized by continuous sample paths and independent, stationary and normally distributed increments (Si et al. 2013). In consequence, a Wiener process-based model has two parameters, one related to the expected value of the degradation rate and one that represents the magnitude of the random noise. According to Kahle et al. (2010), the formula for the Wiener process-based degradation model $Z(t)$ is:

$$Z(t) = z_0 + \mu t + \sigma W(t) \quad (1)$$

where $Z(t)$ is the degradation value described by the model, z_0 is the initial degradation, μ is the random drift coefficient, σ is the random diffusion coefficient, and $W(t)$ is the standard Brownian motion representing the stochastic dynamics of the degradation process. Due to its link with the normal distribution, equation (1) can also be expressed as:

$$Z(t) = N(z_0 + \mu t, \sigma\sqrt{t}) \quad (2)$$

In consequence for each section, the expected value of the Wiener process with the drift coefficient μ is $E(Z(t)) = \mu t$, and the variance is $V(Z(t)) = \sigma^2 t$. From the data collected on 370 sections, the parameters corresponding to each section are identified by maximum likelihood method (Kahle et al. 2010). After that, some statistical distributions are fitted on the values of the parameters by regression. The lognormal distribution had the highest determination factor in both cases. We also fitted the distribution of the initial degradation value z_0. Table 1 presents the values of the parameters.

Table 1. Fitted distribution for the random coefficient Wiener-based degradation model.

Parameter	Distribution	Scale	Location	R^2 (%)
μ	Lognormal	-2.777	0.896	99.3
σ	Lognormal	-2.381	0.592	96.4
z_0	Lognormal	-0.231	0.346	99.5

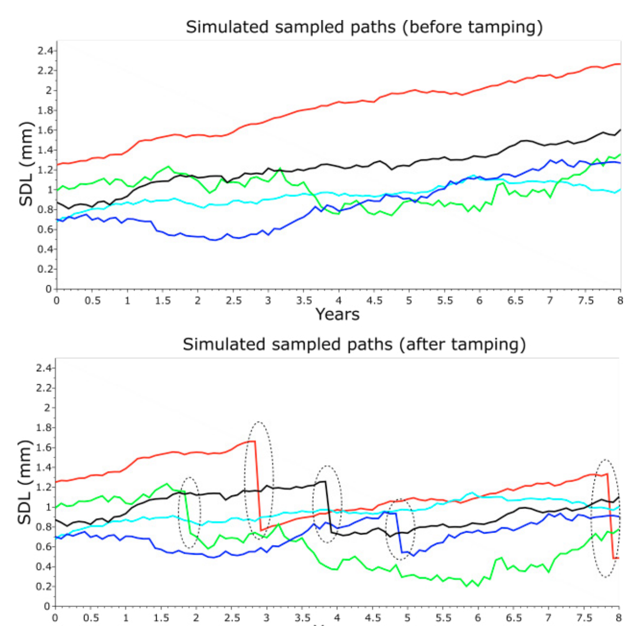

Fig. 2. Simulated data obtained with the degradation model and effect of the recovery values after tamping model.