EFFECTIVE TIME INTERVAL FOR RAILWAY TRACK GEOMETRY INSPECTION

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Abstract:

A proper decision-making scheme for track geometry maintenance requires a knowledge of the real condition of track geometry. Therefore, the track must be inspected by measurement cars at different time intervals. The frequency of track geometry inspection plays a crucial role in decision-making and has always been a big concern for infrastructure managers. The inspection interval should be chosen properly, it means that the small period can decrease the capacity of line and affect the operation of network and the big period can result in low quality of track and in some cases derailments and possible loss of human lives. The aim of this paper is to determine the effective inspection interval such that the total maintenance cost is minimized. In the proposed cost model, the costs of inspection, preventive maintenance, corrective maintenance and the penalty for exceeding the corrective maintenance level are considered. A case study is performed on a real dataset collected from a railway line in Iran. The standard deviation of longitudinal level is considered to measure track geometry degradation. A widely applied linear model is used to model track geometry degradation over time. Monte Carlo technique is used to simulate the track geometry behavior under various track geometry inspection intervals. In addition, a set of sensitivity analyses are carried out to assess the effect of various inspection intervals on different terms of maintenance cost. The results indicate that not only can substantial costs be saved by setting effective inspection intervals, but also the time during which the track suffers from bad conditions is dramatically reduced. The result of this study has shown the appropriate inspection interval for the studied case can result in 13.6 percent decrease in maintenance cost in comparison with the current maintenance policy. Besides, it would lead to more reliable railway track by preventing the system exceed the corrective threshold.

Keywords: *track geometry, inspection interval, maintenance, degradation, maintenance cost*

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1. Introduction

Railway infrastructure managers (RIM) have to provide a reliable and safe track system to ensure the safety of passengers (Osman, 2018; Matusevych et al., 2018, Rudyk et al., 2019). An important criterion which should be maintained in an acceptable level is the track geometry. To this end, the track geometry must be inspected so as to compare the current level with standard thresholds. Such inspections can help RIM make better decisions in the short and long term. Certain measurement machines such as EM120 (inspection car) are utilized to measure track geometry (Andrews et al., 2014; Famurewa et al., 2016). Only few measurement cars exist in the railway network of Iran (about 10 sets of EM120), hence the real need to determine the effective inspection interval. For example, performing track geometry inspection with low frequency may lead to more serious maintenance actions, i.e., corrective maintenance, increase in system downtime, risk of unexpected failures in the system, derailment and loss of human life in the worst case. On the other hand, in case of excessive inspections, the RIM fails to inspect the whole railway network regularly due to the limitation of measurement machines. Moreover, inspection at short intervals can affect the line capacity. In recent years, several studies have been conducted on determining the effective inspection interval of railway track geometry. (Lannez et al., 2015) studied inspection frequencies and operational constraints such as working shift durations, restrictions, vehicle flow, track outages and a heterogeneous fleet on minimizing the total deadhead distance. In another research Kim et al. (2011) presented an approach for determining the optimum inspection and monitoring interval for fatigue-sensitive structures by considering cost functions regarding the costs of inspection or monitoring and the expected failure cost. They studied the effect of failure cost on inspection and monitoring scheduling. In another research Konur et al. (2014) was considered inspection and travel time as cost functions. Their constraint were minimum inspection frequency and time gap between two consecutive inspections on the same track. Meier-Hirmer et al. (2009) attempted to determine a tradeoff between inspection interval and maintenance threshold, leading to minimum track maintenance cost. The costs related to inspection and interventions were considered in their

model. Arasteh khouy (2013) optimized track geometry inspection interval with the aim of minimizing total ballast maintenance cost (Sysyn et al., 2018). Moreover, Lyngby et al.(2008) conducted a research on optimizing the intervals of track geometry inspection with the same objective. For analyzing the effective inspection interval, a maintenance model must be developed including a degradation model, a recovery model and intervention levels. Researchers such as Jovanovic (2004), Quiroga and Schnieder (2010), Guler (2014), Zhu and et al. (2015), Yousefiki and et al. (2014), Shafahi and Hakhamaneshi (2009) and Andrade and Teixeira (2011; 2012; 2013) proposed different degradation models in the maintenance field. Some others proposed recovery models such as Gustavsson (2015), Famurewa and et al. (2015), Meier-Hirmer and et al. (2005), Vale and et al. (2011), Oyama and Miwa (2006), Li and et al. (2015), Miwa (2002), Audley and Andrews (2013) and Quiroga and Schnieder (2012).

The crucial role of effective inspection interval in decision-making (Rudyk et al., 2019) for RIM motivates the authors of this article to present an effective inspection interval for a specific case of Railway network of Iran. In this study, a maintenance model is presented by considering the linear degradation model, recovery model and cost model. The model is developed for planning the maintenance actions over a long term. The cost model includes the inspection cost, preventive maintenance (PM), corrective maintenance (CM), while a penalty cost for the case of surpassing the CM level is considered to control the failure risk. Three factors can be used to assess the track geometry quality based on the recorded measurement data by inspection trains. These include mean value, standard deviation over a specific length, and extreme values of isolated defects (Arasteh Khouy, 2013). In this article, the standard deviation of longitudinal level is considered to measure the track geometry degradation (Famurewa, 2016; Soleimanmeigouni et al., 2018; Quiroga et al., 2012).

This article is organized as follows. Section 2 describes the problem involving Railway network of Iran. In section 3, an indicator is determined for analyzing the degradation level and choosing an appropriate action. Section 4 describes the importance of studied railway track. The next section expresses the maintenance models and their components, i.e. the degradation model in section 5.1, the recovery

model in section 5.2 and the cost model in section 5.3. Section 6 offers the results and explains the effect of inspection interval on maintenance cost. In the end, the conclusion is presented in Section 7.

2.   Problem description

A railway track bears different forces that finally result in track geometry degradation. Furthermore, there is an increasing demand for using railway as a means of transport. The degradation level must be maintained in a certain range which is a function of safety, train punctuality, overall capacity utilization and expenses. Accordingly, track maintenance is generally planned and executed to meet a certain range of safety (Helak et al.,2019). Track maintenance is a pricey activity, convincing the development of a track maintenance model. This model must include the capability of predicting future track geometry conditions. A specific property of this model is the inspection interval. The importance of inspection interval lies in its effect on cost function and detection of system state. Actually, there is a

trade-off between inspections: more frequent inspections result in higher costs and lower probability of exceeding the maintenance levels (PM or CM), while less frequent inspections result in lower costs and higher probability of exceeding maintenance levels (Wolde et al., 2013). The aim of this article is to present an effective inspection interval for the specific case of a railway network in north-eastern Iran that can minimize the cost while maintaining the conditions in safe levels.

3.   Selection of the degradation indicator

Geometry specifications include longitudinal level (profile) for right and left rails, alignment for right and left rails, gauge, cant, and twist (Figure 1). The longitudinal level is the geometry pertaining to the track centerline projected onto the longitudinal vertical plane. The alignment denotes the track centerline projected onto the longitudinal horizontal plane. The gauge defines the distance between the inner sides of the rail heads. Cant (cross-level) is the is the difference in height of the adjacent running tables
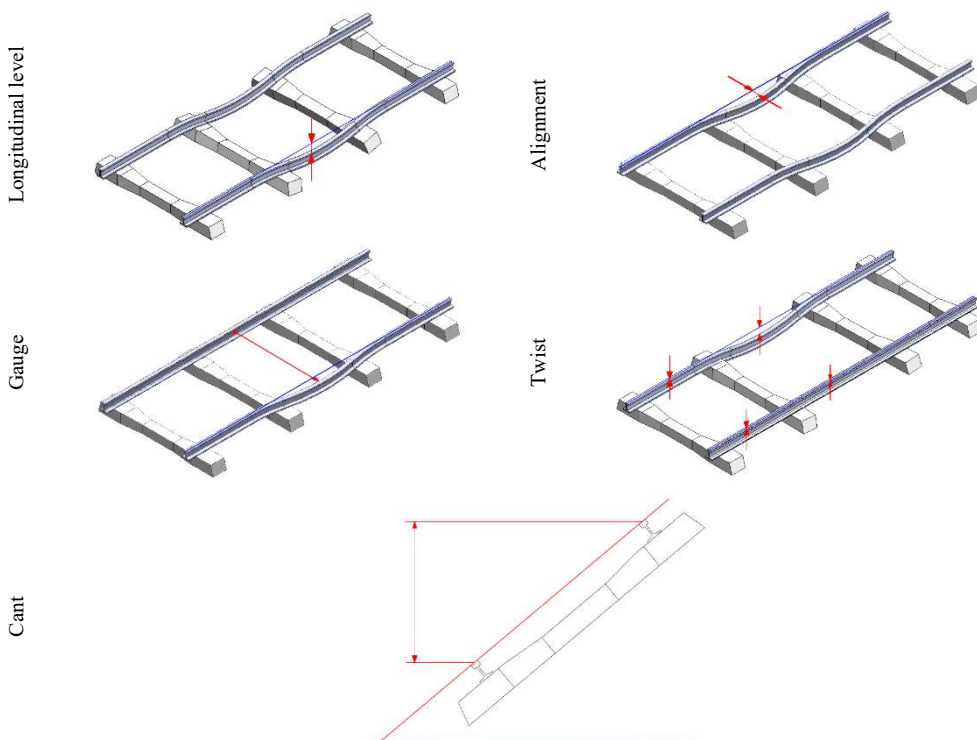

Fig. 1. Track geometry parameters (Khajehei et al., 2019)

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 two points of measurement (EN 13848-1, 2008). Code EN 13848-5 (2010) defines 3 levels of intervention as follows:

– Immediate Action Limit (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 correcting the track geometry;

– Intervention Limit (IL): refers to the value which, if exceeded, requires corrective maintenance so that the immediate action limit shall not be reached before the next inspection;

– Alert Limit (AL): refers to the value which, if exceeded, requires analyzing the track geometry condition and regularly considering the planned maintenance operations.

According to the literature, the longitudinal level is one of the important parameters that can be taken for maintenance analysis (Famurewa 2016; Soleimanmeigouni et al. 2018; Caetan et al. 2016).

Therefore, the standard deviation (SD) of longitudinal level over a section of 1 km is considered as the degradation indicator. The calculated indicator at each inspection time will be compared with defined levels. The thresholds and the maintenance model will be presented in another section.

4. Description of selected line as the case study

The total length of Railway network of Iran is about 13000 km. One of its important tracks is Tehran-Mashhad line, connecting two important cities with prominent situations and supporting a heavy traffic. In terms of passengers, this track is the most significant line of Iran railway network. About 14,212,493 passengers (equal to 28,539 passenger trains in year or about 78 trains every day) were transported from Tehran to Mashahd and vice versa during the course of March 2018–March 2019. Therefore, the quality and safety are highly critical in this track. The average interval of data analysis in this line was 180 days over the period of 2011–2017. The considered line segment for evaluation is presented in red in Figure 2, starting from the Neqab station to the Mashhad station with a length of 271 km for the considered segment. The superstructure of this line includes the rail UIC60, concrete sleeper B70 and fastening systems Vossloh and Pandrol.
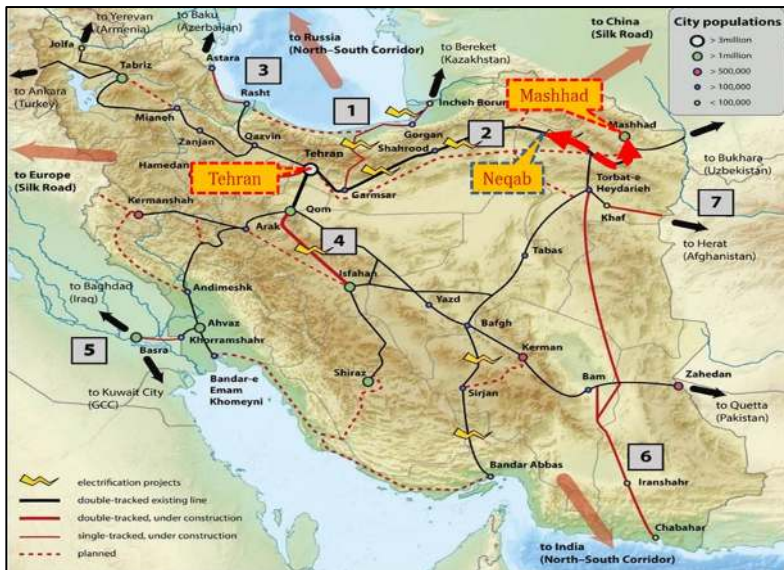

Fig. 2. Railway network of Iran and the considered segment for study (from archive of Islamic Republic of Iran Railways)

5. Maintenance model

The presented model relies on data measurement. In this section, the structure and parameters of the model are presented as shown the Figure 3 including the modeling procedure and its convergence. As the first step, the input parameters such as time horizon, inspection interval, and maintenance thresholds can be seen.
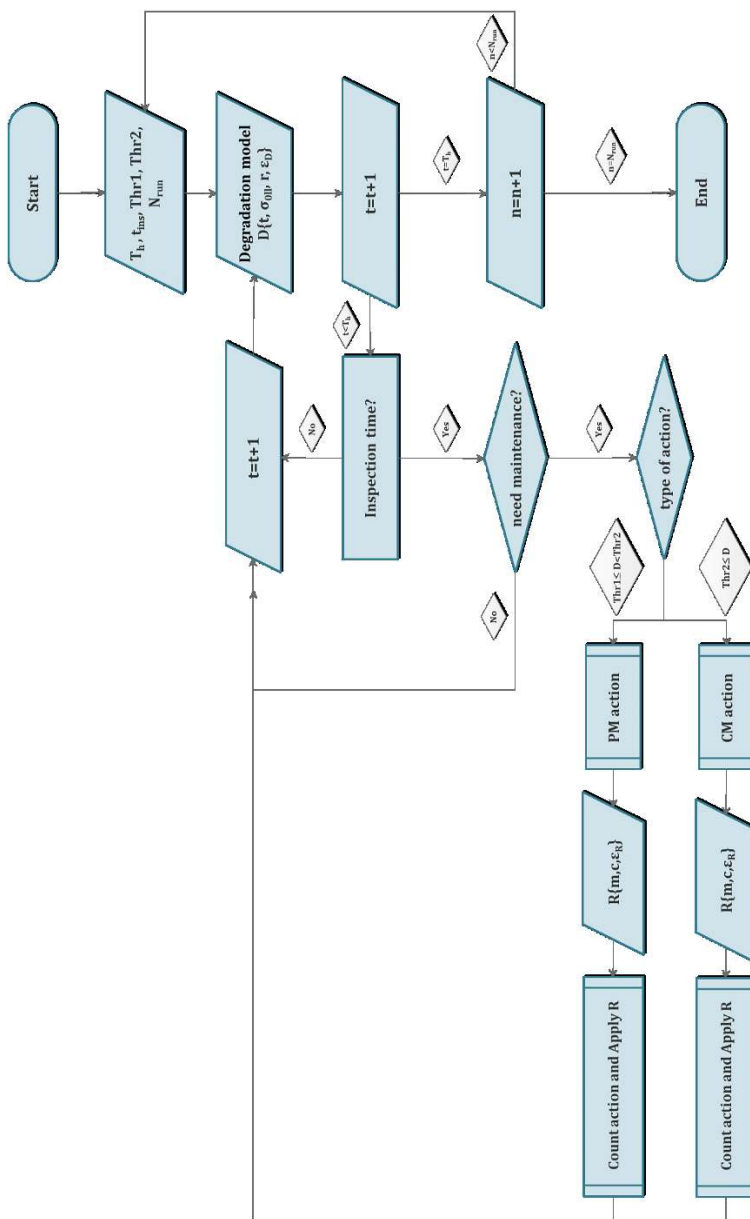

Fig. 3. Modeling procedure and its convergence

At each inspection time, the track geometry degradation is monitored and decisions are made regarding the level of degradation (PM, CM or no action). After specifying the type of action, a recovery (restoration) model is applied to restore the degradation according to the type of needed operation. This procedure will be continued for the time horizon (T_h). Due to the existence of uncertainty and variation in input parameters, the Monte Carlo technique is used to estimate the expected mean number of preventive and corrective actions as well as the mean time at which the system exceeds PM or CM levels (Khajehei et al., 2019).

Here, two maintenance levels are considered: threshold 1 ($\delta1$/PM level) and threshold 2 ($\delta2$/CM level). The degradation curve based on these two levels will then be compared. When the degradation curve exceeds $\delta1$, PM action is necessary, while CM action must be performed when exceeding $\delta2$. These conditions are described with the following inequality equations:

If $\sigma_{LL}(t) \prec$: the track section does not need maintenance activity,

If $\delta1 \preceq$: PM activity with specified maintenance response time (MRT: the time to perform PM action from its detection) will be applied to the track section,

If $\delta2 \preceq$: CM activity with no MRT will be applied to the track section.

$\sigma_{LL}(t)$ is the degradation value for longitudinal level. With respect to the described model, the following steps are implemented:

1- Considering inputs
2- Obtaining the degradation curve with continuous, constant increments (one day)
3- Inspecting the degradation curve at specific moments (inspection intervals)
4- Comparing the degradation with specified thresholds ($\delta1$ and $\delta2$)
5- Acting according to the level of degradation by considering MRT for PM actions
6- Counting the number of PM or CM action and the time the system has exceeded each level.

Figure 4 shows the process of inspection and action according to the degradation level. In the present study, a linear model is used to model the track geometry degradation and Figure 5 shows the degradation parameters and restoration in this maintenance model schematically. In the proposed model, the degradation parameters (degradation rate **r** and initial value after tamping σ_{0ll}) are considered as random variables. The next sections describe the degradation and recovery models.
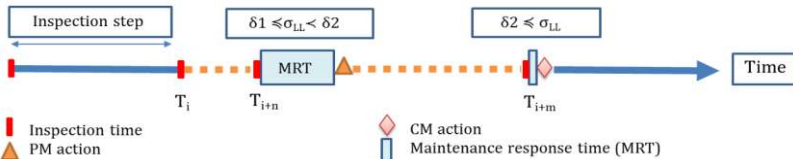

Fig. 4. One-dimensional schematic description of maintenance model
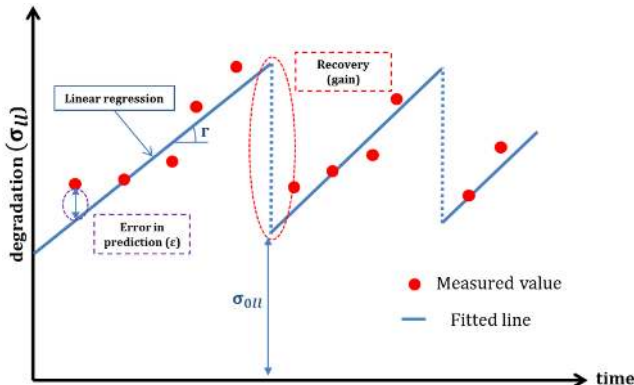

Fig. 5. Schematic degradation parameters of track geometry

5.1. Degradation model

There are two general approaches for describing degradation: 1) mechanistic models (Zhang et al., 2000) and 2) statistical models. In mechanistic models, the mechanical properties of track that cause degradation are used and the aim is to predict track degradation with few geometrical data. In other words, the mechanistic approach is described as modeling the mechanical reactions in the track that result in track degradation. The mechanistic model faces certain issues including uncertainty as an intrinsic characteristic. Statistical models are based on data measurement to describe the model.

Statistical models give a full representation of data generation, i.e. the data are representative of the situation that track has experienced over time. According to Elkhoury et al. (2018), a statistical model can be termed a mathematical model with a set of statistical assumptions coming from a big population of samples or similar data. What differentiates statistical models from other mathematical and non-statistical models is the inherent probability distribution. As highlighted by Soleimanmeigouni et al. (2018), a significant property differentiating statistical models from mechanistic models is how the track geometry exhibits uncertain behaviors. These uncertainties are important in making maintenance decisions. Therefore, to achieve effective and accurate degradation modeling, concepts from statistical modeling, probability theory, and stochastic processes are considered to be beneficial. To do so, it is important to have sufficient data from track degradation distributions (Muinde, 2018). In this article, a statistical model is used for describing the maintenance model. The linear degradation model is chosen as

$$\sigma_{ll} = \sigma_{0ll} + r(t - t_0) + \varepsilon_D(t) \qquad (1)$$

where σ_{ll} is the standard deviation of degradation (longitudinal level), σ_{0ll} is the initial degradation value after tamping, r is the degradation rate between two maintenance cycles, t is time, $\varepsilon_D(t)$ is the Gaussian random error term with an average of zero and a constant variance $\varepsilon_D \sim N(0, \sigma)$; the error term is the deviation between the measured and predicted values (as shown in Figure 5).

Histogram plots of the standard deviation of longitudinal level after tamping and degradation rate are shown in Figure 6.
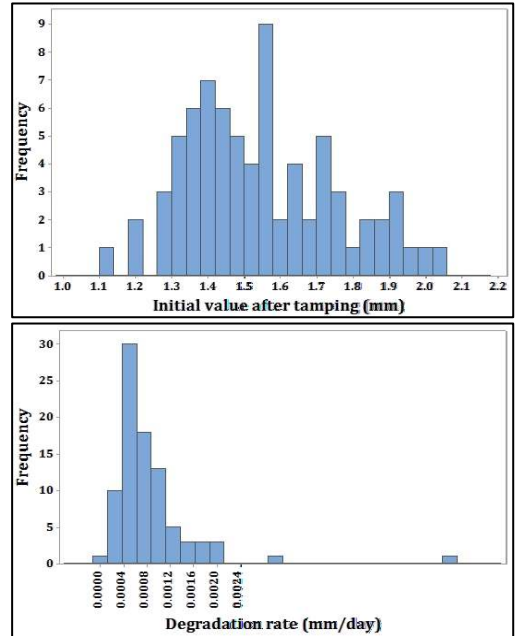

Fig. 6. Histograms of initial value after tamping and degradation rate

Based on the histogram plots in Figure 6, the degradation level after tamping and degradation rate are assumed to follow lognormal distribution. Accordingly, Anderson Darling (AD) test is performed to assess the standard deviation of longitudinal level after tamping and degradation rate. Using the standard deviation of longitudinal level after tamping $\{\sigma_{0ll}\}$ and degradation rate $\{r\}$, AD and p-values are generated for normal, lognormal, and Weibull distributions. Based on the tests, the best-fitted distribution is selected by considering the value with the smallest AD-value and p-value greater than significance level. This means that the selected p-value must be greater than the critical value α. To perform AD test, the following hypotheses are made:

-   $H0$ (*Null hypothesis*): follows the specified distribution
-   $H1$ (*Alternative*): does not follow the specified distribution
-   Significance level: $\alpha = 0.05$

From the tested values (as shown in Table 1), it is found that $\alpha < P - value$, hence not enough evidence to reject the null hypothesis.

Estimation of model parameters is achieved using maximum likelihood estimators (MLEs). Normally, MLE is used in parameter estimation owing to its ability to approximate parameters without considering prior distributions, but it only considers estimates from the statistical model and observations. Using Minitab, the estimation for degradation level after tamping and the degradation rate are calculated and recorded in Table 2:

The mean and variance of the error term in the degradation model are determined using Minitab 18. The value of error term is equal the $\varepsilon_D \sim N(0,0.06)$.

5.2. Recovery model

As shown in Figure 5, once track geometry degradation reaches a predetermined maintenance threshold, a maintenance action is performed on the track in order to return the track quality to a better condition. Tamping is currently the main common maintenance procedure used across the globe to restore tracks to the desired geometrical state (Janaka et al. 2016). Generally, tamping has two major effects on track geometry including changes in the degradation rate and track geometry jump reduction (Soleimanmeigouni et al., 2018). There are two main approaches for modeling recovery (gain) after tamping, namely deterministic and probabilistic approaches (Martey et al. 2018). The recovery model is considered as a linear regression model. The regression formula is written as

$$R = c + m\sigma_{ll}^* + \varepsilon_R , \varepsilon_R \sim N(0,\sigma) \qquad (2)$$

where R is the real gain (restoration), σ_{ll}^* is the standard deviation of longitudinal level deterioration just before the intervention, c is the intercept, m is the slope, and ε_R is the error term with a normal distributed random variable with standard deviation σ. The error term is the deviation between the measured and predicted values. This model is used for all types of interventions. The result of linear regression is shown in Figure 7. The gain in the figure indicates the restoration after tamping which is used in maintenance modeling as a recovery model. The results for recovery model are given in Table 3.

Table 1. Results of AD test for degradation model parameters

Degradation rate $\{r\}$			Initial value after tamping $\{\sigma_{0ll}\}$		
Distribution	Anderson-Darling	P-value	Distribution	Anderson-Darling	P-value
Normal	6.947	<0.005	Normal	0.705	0.063
Lognormal	0.533	0.168	Lognormal	0.35	0.464
Weibull	2.616	<0.010	Loglogistic	0.431	0.243

Table 2. Maximum likelihood estimation of parameters distribution for degradation model

Degradation rate $\{r\}$			Initial value after tamping $\{\sigma_{0ll}\}$		
Distribution	Location	Scale	Distribution	Location	Scale
Lognormal	-7.29488	0.65224	Lognormal	0.42783	0.13322

Table 3. Specifications of linear regression

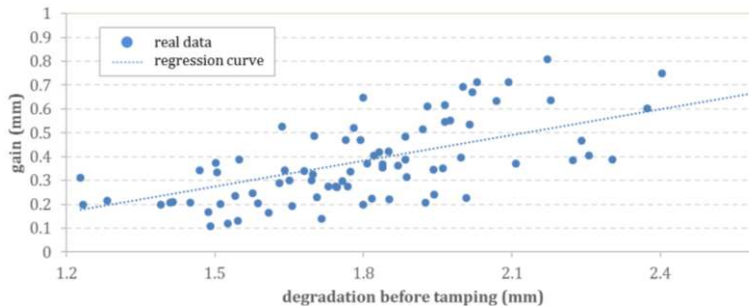|	Intercept (c)	Slope (m)	Standard Deviation (σ)	R^2
Maintenance recovery	-0.26	0.36	0.13	0.57

Fig. 7. Linear regression result and real data

5.3. Cost model

After determining the mean number of different actions, various scenarios are compared with each other. To this aim, maintenance cost function is considered. The cost function includes the costs of inspection, PM and CM as well as the penalty for exceeding the CM threshold, as described by:

$$E(C_{tot}) = N_I . C_I + E(N_{PM}) \cdot C_{PM} \\ + E(N_{CM}) \cdot C_{CM} + E(P_{CM}) \qquad (3)$$

where $E(C_{tot})$ is the expected maintenance cost, N_I and C_I are the number and cost of each inspection in horizon time, respectively, $E(N_{PM})$ and C_{PM} are the expected mean number and cost of PM, respectively, $E(N_{CM})$ and C_{CM} are the expected mean number and cost of CM, respectively, and $E(P_{CM})$ is the expected mean number of penalties for exceeding the CM threshold.

The mentioned model is developed using Matlab R2016a and computed on a personal computer utilizing Intel Corei5-3340M CPU @ 2.70GHz. For each simulation, 45,000 runs are performed to make sure the simulation would converge. Figure 8 shows a sample plot of a simulation for the inspection interval = 120 days and MRT = 63 days.

6. Results and discussion

The focus of this article is on determining the effective inspection interval; therefore, the effect of varying the inspection interval is investigated on the costs. Table 4 lists the costs of inspection, PM, CM and the penalty for exceeding the CM level. Here,

the threshold 1 ($\delta 1$) and threshold 2 ($\delta 2$) are set to 1.6 and 2.0 mm, respectively, for standard deviation of longitudinal leveling, MRT = 63 days and the modeling horizon time of 12 years.

Table 4. Considered costs of different items

Inspection cost (USD/km)	88
PM action cost (USD/km)	1,765
CM action cost (USD/km)	4,235
Penalty for exceeding CM level (USD/day)	85

Figure 9 shows the effect of inspection interval on the maintenance cost. As noticed, with increasing inspection interval, the maintenance cost also increases. One also observes that the minimum maintenance cost for considered scenarios happens for the inspection interval = 120 days (blue line). The studied railway line at the time of study was inspected about every 180 days (green line). The following results demonstrate that the maintenance cost for this case can decrease by 14%. This example indicates that implementing the proposed strategy can be notably effective in decreasing the maintenance cost.

Table 5 presents the variation of maintenance cost with respect to inspection interval. The variation is calculated with regard to the optimum scenario, i.e. inspection interval=120 days. The table shows that changing the inspection interval from 120 to 270 days results in an increase of 64.2 percent increasing and decreasing inspection interval from 120 to 30 days increases the maintenance cost by 42.5%.
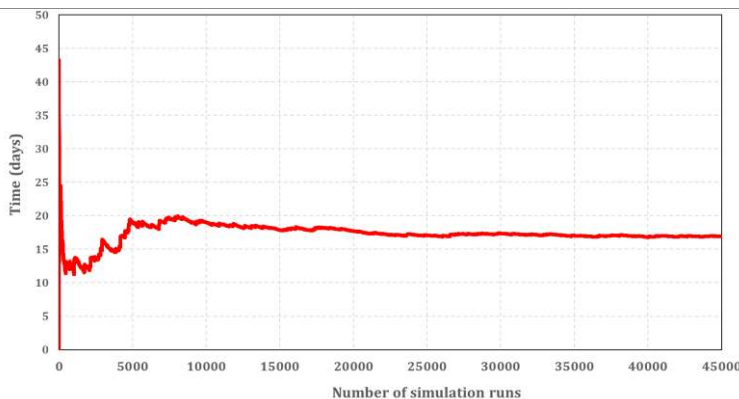

Fig. 8. Sample convergence of the mean time exceeding CM level (for inspection interval = 120 days, MRT = 63 days)
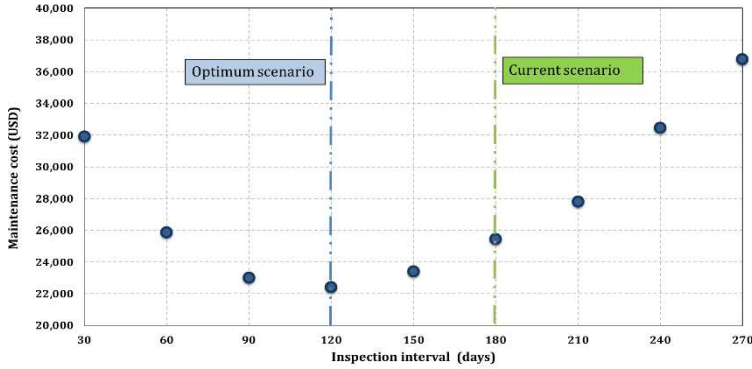
Fig. 9. Total maintenance cost for different inspection intervals

Table 5. Effect of inspection interval variation on total maintenance cost

Inspection interval (days)	30	60	90	120	150	180	210	240	270
Cost variation* (%)	42.5	15.5	2.7	0.0	4.5	13.6	24.2	44.9	64.2

*Cost variation with respect to the minimum scenario of inspection interval = 120 days

Figure 10 illustrates the effect of inspection interval on the different terms of maintenance cost function over horizon time (12 years). As depicted, with increasing inspection interval from 30 days to 270 days, the PM cost has decreased by about 30%, while CM cost and the considered penalty for exceeding CM level have increased dramatically.

Figure 11 shows the effect of altering the inspection interval on exceeding the level of PM and CM over time horizon. It is inferred that increasing the inspection interval results in increasing time during which the system requires maintenance actions. For example, for the inspection interval = 30 days, the system has exceeded the PM and CM levels for 831 days (out of 4380 days or 12 years). This means that the system has been in PM and CM states for about 19% of the horizon time. However, approximately 99.7% of them is found to be the PM state. With increasing inspection interval, exceeding the CM level is also increased. This analysis shows that increasing inspection interval can decrease the system reliability. For instance, at the inspection interval = 270 days, the system is in maintenance need for about 43% of the time.
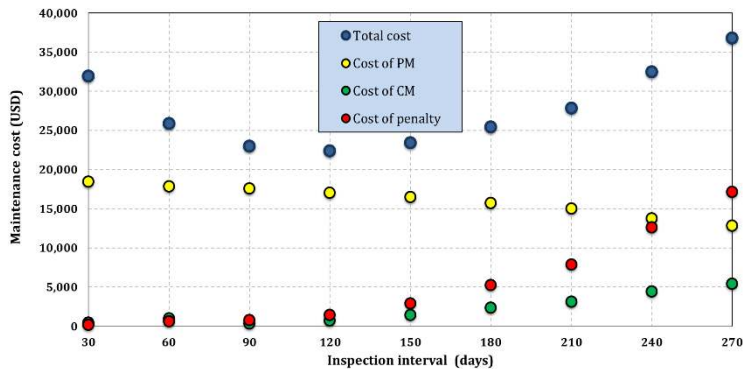

Fig. 10. Effect of inspection interval variation on different parts of maintenance Cost
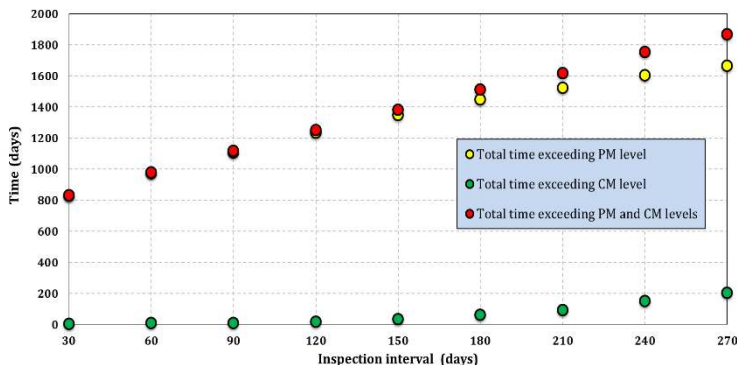
Fig. 11. Effect of inspection interval variation on time exceeding maintenance levels

7. Conclusion

This article developed a maintenance model for a railway track located in the north-east of Iran. The proposed model included a prediction scheme for the track geometry condition and a cost model. Linear regression was used to model the track geometry degradation and restoration. The Linear degradation model was developed according to the probabilistic distribution function for the initial value after tamping and degradation rate. The objective was to determine the optimum inspection interval for planning the railway track geometry maintenance. The standard deviation of longitudinal level was considered as a quality indicator to assess the degradation level for choosing preventive and corrective maintenance. To analyze the variation of inspection interval, a specific cost model was defined including the costs of inspection, PM and CM along with the penalty for exceeding the CM level. The sensitivity analysis performed on the inspection interval showed that the frequency of inspection can greatly affect the total time during which the system exceeded the PM and CM levels. The optimum inspection interval which results in minimum maintenance cost happened at 120 days, i.e. the system should be inspected every 120 days and appropriate actions must be planned according to the track condition. This strategy for a specific case resulted in a lower cost maintenance with a drop of 13.6% in comparison with the current strategy. Employing this strategy over the entire network can help infrastructure managers focus and develop on other sections of maintenance management like improving infrastructures and upgrading monitoring systems.

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