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Data-driven optimization of railway maintenance for track geometry[☆]

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ABSTRACT

Railway big data technologies are transforming the existing track inspection and maintenance policy deployed for railroads in North America. This paper develops a data-driven condition-based policy for the inspection and maintenance of track geometry. Both preventive maintenance and spot corrective maintenance are taken into account in the investigation of a 33-month inspection dataset that contains a variety of geometry measurements for every foot of track. First, this study separates the data based on the time interval of the inspection run, calculates the aggregate track quality index (TQI) for each track section, and predicts the track spot geo-defect occurrence probability using random forests. Then, a Markov chain is built to model aggregated track deterioration, and the spot geo-defects are modeled by a Bernoulli process. Finally, a Markov decision process (MDP) is developed for track maintenance decision making, and it is optimized by using a value iteration algorithm. Compared with the existing maintenance policy using Markov chain Monte Carlo (MCMC) simulation, the maintenance policy developed in this paper results in an approximately 10% savings in the total maintenance costs for every 1 mile of track.

1. Introduction

Rail across the world is experiencing an increase in demand that is driven by increased global trade (Li et al., 2014). In the United States, railways are one of the major modes of freight transportation. In the 2007 Commodity Flow Survey, rail accounted for 46% of total national ton-miles (Bureau of Transportation Statistics, 2014). Rail is also used, to a fair extent, by people to commute between two places. Therefore, there is increasing pressure on railways to maintain a high service level at all times. Railway tracks are essential components in the rail industry. As typical mechanical systems, tracks are prone to faults and failures with time and usage. In 2009, out of 1890 train accidents, 658 were due to track defects (Peng et al., 2011). Major failures of railway tracks can cause heavy economic losses, lawsuits, huge delays in recovery operations and, in extreme cases, fatalities. The severe consequences due to track defects increase the pressure to maintain rail tracks in a good state of repair. In addition, with the advance of new communication and sensing tools, big data is becoming increasingly emerging in railway transportation (Nunez and Attoh-Okine, 2014).

The main objective of this paper is to develop a data-driven track preventive maintenance strategy, which also takes spot corrective maintenance into account, to maintain the best service level of railway track with minimal costs. Preventive maintenance helps to prevent major failures from occurring. The primary objective of preventive maintenance is to preserve system functions in a

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cost-effective manner (Tsang, 1995). Preventive maintenance can be further classified as condition-based or interval-based (time interval or tonnage interval) (Yang, 2003). In interval-based preventive maintenance, maintenance activities occur after a certain period of time, and the system is restored to its initial state. In condition-based preventive maintenance, maintenance actions are taken depending on the current state of the system after each inspection (Su et al., 2016). The focus of this research is related to condition-based preventive maintenance at discrete time intervals. After an inspection, this paper considers three maintenance actions: no action taken on the system, minor maintenance work to restore the system back to the previous working state, or major maintenance work to greatly restore the system to much better conditions (Chen and Trivedi, 2005). In this study, minor maintenance refers to preventive tamping, while major maintenance refers to corrective tamping (Khouy et al., 2014).

This paper adopts the track quality index (TQI) as an overall track-state indicator for decision making in preventive maintenance. TQI is a numeric representation of the ability of railroad track to perform its design function, or, more precisely, to support the required train movements (Fazio and Corbin, 1986). In short, TQI indicates whether the track is in a good state or a bad state. If the track is in a bad state, the railroad performs appropriate maintenance activities to improve its condition and restore it to the good state. The railroad can plan the actions depending on the TQI value. This makes it easier to develop a state using a range of TQI values. Assuming the future state of the track only depends on the current state, one can regard the track as a Markovian system. Additionally, there are more than one actions that can be taken for a state so that the problem can be formulated as a Markov decision process (MDP). This paper aims to assist the railway industry in maintaining a state of good repair for existing track systems. The proposed maintenance strategy will help in reducing the cost expenditures by railroads as well as preventing failures that may lead to derailments and accidents.

In contrast to preventive maintenance, corrective maintenance aims to recover the track into a state in which it can perform a required function after fault recognition. In this paper, we refer corrective maintenance as rectifications of spot defects reported by daily manual inspections or scheduled track inspections. Over time, the spot conditions of railway track can degrade from a good state to an unusable state, either gradually or abruptly. This can occur due to cumulative tonnage, defective wheels, and the impulsive force on tracks.

Railway track spot defects can be classified into two different types, namely, track structural defects (also known as rail defects) and track geometry defects. Track structural defects occur when the structure and support system of the railway tracks, comprising sleepers, joints, fasteners, ballast and other underlying structures, fail. Track geometry defects arise due to irregularities in the various track geometry measurements (Zarembski, Einbinder and Attoh-Okine, 2016). In practice, railroads collect massive raw inspection data on several dozens of track geometry parameters. However, due to data limitations, this paper focuses on track geometry defects that exceed the threshold. The majority of track geometry defects fall into a few types of geometry measurements. Without loss of generality, this paper only investigates the following five prevailing track geometry measurements: (1) Cant: the amount of vertical deviation (in radians) between two flat rails from their designed value; (2) Cross-level: the difference in elevation between the top surfaces of the rails at a single point in a tangent track segment; (3) Gage: the distance between the heads of the inner surface of the rails; (4) Surface: the uniformity of the rail surface measured in short distances along the tread of the rails; (5) Twist: the difference between two cross-level measurements a certain distance apart. Fig. 1 illustrated these five defects. The dashed lines in Fig. 1 indicate the deviation from the normal state. Therefore, one can tell how each type of defects deviates from the normal state. One can refer to He et al. (2015) for more detailed explanations of track geometry measurements.

A flow chart of this study is presented in Fig. 2. In this paper, Policy is a course of action or decision proposed by the model for track maintenance. Starting from raw track related data, this study examines both optimal policy and existing policy for track maintenance. Regarding optimal policy, this paper considers both corrective maintenance and preventive maintenance. First, a random forest is employed to forecast the occurrence of geo-defects that have to be rectified after inspections. Second, we use an equation to measure TQI model by aggregating raw geometry measurements and build a Markov model based on field observations. The occurrence of geo-defects is then modeled as a Bernoulli process. Then, we define actions in track maintenance and derive an MDP model which incorporates both maintenance costs and geo-defect repair costs. We use a value iteration algorithm to solve the MDP model and determine the optimal policy. In contrast, the existing policy is derived directly from the raw track data. Finally, we employ Markov chain Monte Carlo (MCMC) simulation to calculate and compare the total cost of different policies. This paper makes the following three contributions: (1) as a first attempt, it builds a prediction model for the occurrence of geo-defects with massive foot-by-foot track geometry data, traffic in million gross tonnage (MGT), track speed limit, and historical maintenance activities. The relationships between the values of TQI and the arrival probability of geo-defects are quantified; (2) it establishes a Markov chain to model the track deterioration process and calibrate the transition probability with the real-world data; (3) it develops a Markov decision process (MDP) for track maintenance decision making, incorporating both preventive maintenance based on TQI and spot corrective maintenance based on geo-defects.

2. Literature review

2.1. Track quality index

The track quality index (TQI) is one of the most widely used indices to represent the track state. Traditionally, TQI is derived from foot-by-foot track geometry measurements, which reflect how well the track structure is performing. An overall track maintenance planning model can be developed easily if the geometry TQI data are supplemented with additional data pertaining to the structural data (Fazio and Corbin, 1986). TQI also helps in maintaining a track deteriorating record (El-Sibaie and Zhang, 2004).

The track geometry is measured for each foot by a track geometry car, an automated track inspection vehicle on a rail transport

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