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A stochastic model for railway track asset management

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ABSTRACT

The determination of the strategy to ensure that the geometry for railway track is kept within acceptable limits, in a cost effective manner, is a complex process. It requires the simultaneous consideration of the activities which govern inspection, maintenance and renewal. In addition to this the geometry degradation process is dependent upon the maintenance history. The condition where the track geometry is shown to have deteriorated to a level where intervention is required can be improved using a tamping machine. Tamping is carried out by a special train which measures the geometry of the rails, predicts the correction needed, lifts the rails to the required position, inserts tines into the ballast either side of the sleepers and packs the ballast such that the correct rail position is attained. Whilst improving the geometry this process has the disadvantage that it also breaks the ballast which accelerates the track geometry degradation and reduces the time between interventions.

This paper describes a modelling process to predict the state of the track geometry given any specified asset management strategy. It is based on the Petri net method and in addition to predicting the track condition over time it can also compute the expected whole life costs. By varying the parameters which govern the inspection, maintenance and renewal of the ballast as the most cost effective means to achieve the required level of performance can be predicted.

1. Introduction

Over time the passage of traffic along railway track causes the geometry to deteriorate. This affects the quality of the ride and in extreme cases, without maintenance to restore an acceptable condition, can lead to train derailment. The ballast can be adjusted using manual intervention, tamping machines or stone blowing machines to improve the geometry. A special measurement train, which passes along the network at regular intervals, can be used to assess the track geometry. It measures the location of the rails and processes this data to provide characteristics which indicate the condition of the geometry over 220 yard (1/8th mile) sections of the track. This process will report variations (expressed as standard deviations) in rail height, horizontal position, gauge and twist. In the event that the geometry deteriorates beyond a critical threshold, routine maintenance will be scheduled to restore the geometry to a good condition. Should the condition worsen before the maintenance is carried out, resulting in safety concerns, then speed restrictions or line closures can be imposed until an acceptable standard is restored. The times taken to complete the maintenance will vary depending upon the severity of the track condition and hence the priority of the maintenance. The imposition of a speed restriction or line closure provokes fast responses.

The processes used to maintain the track geometry are specified by the asset management strategy. Due to the long lengths of track present on railway networks its efficient maintenance can be a significant factor in the financial performance of the railway.

Several models have been formulated to investigate the effects of the asset management strategy parameters on the track condition. The degradation process is combined with the possible maintenance actions, usually in a stochastic model to predict the track state over time.

An artificial track quality index (TQI) has been created as a linear combination of geometry measurements to indicate the track state [1–3]. These have been used in a Markov model [4] where the TQI is calculated in a range of 0–100 based on the unevenness, twist, alignment and gauge measurements. Five states were used to represent the 100 unit TQI range in the Markov model. Transition probabilities were then calculated from changes in the TQI over time. An alternative Markov model [5] used 50 states to model the variation of twist over time, each state representing the twist on a section of track in the range of 1–50 mm. Different deterioration rates are specified in this model

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for the track section depending on if it is straight, curved or a transition section. The model was used to optimise the frequency between track geometry inspections. Podofillini et al. [6] and Kumar et al. [7] used stochastic RAMS approaches to the rail failure modelling. In Ref. [6] the RAMS modelling was used in a multi-objective optimisation approach to determine the frequency of ultrasonic inspection.

Quiroga and Schnieder [8,9] developed a statistical model integrating the deterioration process and maintenance to predict the track condition using data from the French railway operator, SNCF. Different maintenance strategies had then been investigated to determine their cost effectiveness. The statistical model takes the following form:

$$Q = Ae^{B(t-t_0)} + \varepsilon(t) \quad (1)$$

where Q is the track quality measure and A, B, and ε are parameters assumed to have lognormal, normal and normal distributions, respectively and t_0 is the time of the last intervention (tamping) activity. Once the model parameter distributions were established then the model, evaluated by Monte Carlo simulation, was used to optimise performance.

The Markov approach has assumptions which limit its ability to represent the track geometry deterioration and maintenance. For example, transitions between asset states must occur with a constant rate and the state residence times are therefore governed by the exponential distribution. The process must also be memoryless, so the future states of the model depend only on the current state and not on the history of arriving at the current state. This provides restrictions on how the degraded state of the geometry can account for the maintenance history. To overcome these limitations an alternative model has been derived using a Petri net approach [10]. The model uses time to degrade distributions for the geometry which were established from data taken from the UK railway network [11].

In this paper a Base Case model has been developed which analyses a potential track asset management strategy. Parameters which govern the inspection, maintenance and renewal processes are then varied and the effects of these changes on the asset state and whole life costs compared.

2. Track section model

The development of an asset management track section model was presented by Andrews [10]. The model, for the 1/8th mile track section, was based on a stochastic Petri net (PN) formulation, accounting for the geometry degradation, inspection, repair and renewal processes. Analysis of the model, performed using a Monte Carlo simulation technique, yields the distributions of the times for which the section will reside in different degraded states, the numbers of interventions required and the costs of maintenance activities throughout any operational period, for any specified maintenance strategy. Using such a model the effects of changes in the maintenance strategy can be evaluated and the most effective option selected in order to reduce Whole Life Costs whilst providing an acceptable level of performance.

The track section PN model is illustrated in Fig. 1. The vertical rail geometry measurements are used to indicate the quality of the track geometry. This is the mean of the left and right rail height standard deviation (SD) subtracted from a 35 m running average. It is generally these vertical geometry short-wave measurements which are the most significant when deciding the condition of the track and the requirement for maintenance. Measurements of the rail geometry are taken at regular intervals by the passage of a special measurement train along the rails. Should the need for maintenance be identified then this is carried out using a tamping machine. Tamping machines pack the ballast under the sleepers and correct the alignment of the rails to make them parallel and in level. This is done by measuring the track geometry, calculating the required adjustments, lifting the track and inserting vibrating tamping arms in either side of a sleeper. The arms are then squeezed together to pack the ballast. Tamping will improve the condition of the track geometry; however, the insertion of the vibrating arms into the ballast will cause a break-up of the stones and so at the same time as improving the track geometry it causes the condition of the ballast to degrade and so the intervals between tamping actions reduce [11]. When the requirements for geometry correction become too frequent then the ballast is renewed.

2.1. Petri net modelling

The PN model is shown in Fig. 1. The circles, or places on the model represent states of the track geometry and activities which are taking place such as maintenance and inspection. Tokens residing in the places represent the current state of the track ‘system’. The dynamics of the track section are represented by the movement of the tokens around the section model. This process is governed by transitions, represented by the rectangles on the diagram. The places are connected to transitions and vice-versa. Where places and transitions are connected the places are either input places to the transition or output places. There can be a number, known as the multiplicity, connected to the edges that link the transitions and places. When no number is specified the default multiplicity is 1. A transition indicates the time between events occurring on the model. A transition has an associated time distribution (it can be an immediate transition, with a zero time duration, for deterministic transitions) and rules for its enabling and firing. A transition becomes enabled when there is at least the required number of tokens, as given by the multiplicity of the edge, in each of the input places. Once the transition is enabled, then, following the required time duration, the transition will fire, extracting the multiplicity of tokens from each of the input places and adding the required multiplicity of tokens to each of the output places. When conditions exist to prevent a transition from firing, an inhibit edge can be used. This type of edge has a rounded head rather than the arrow of a normal edge (see the link from P2 to T4 in Fig. 1)

In order to provide an efficient PN representation of the track asset management model additional transition types have been added to those encountered in standard PN models. These are the reset transition, the conditional transition and the convolution transition [10].

The reset transition: is used to reset the tokens in part of the network. In this model it has been used to reset the PN following ballast renewal. When the ballast is renewed then tokens in places representing a deteriorated condition need to be removed from the PN. This transition is deterministic and has an associated transition time of zero and a list of places and the number of tokens that they will contain after reset.

A conditional transition: this transition type enables the transition time distribution to be adjusted dependent upon the number of tokens residing in another place on the network to which it is linked by a dashed line. For the track model this enables times to degrade to be linked to the number of prior interventions that have been performed. This type of transition appears as yellow and a typical example is illustrated in Fig. 1(T8).

A convolution transition: this is a transition where the input place indicates one level of degradation and the output place