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# System-wide assessment of intervention strategies for railway infrastructure

D. Rama and J. Andrews

*Nottingham Transportation Engineering Centre*

*Faculty of Engineering*

*University of Nottingham, University Park*

*Nottingham, NG7 2RD*

[dovile.rama@nottingham.ac.uk](mailto:dovile.rama@nottingham.ac.uk)

[john.andrews@nottingham.ac.uk](mailto:john.andrews@nottingham.ac.uk)

**Abstract.** The existing railway infrastructure exhibits faster degradation rates and requires more maintenance effort as a result of increased utilisation. At the same time, due to increased numbers of freight and commuter trains obtaining access to the railway infrastructure to carry out maintenance and repairs, not to mention major enhancements, is becoming more problematic. Furthermore, safety measures put in place in the event of infrastructure faults or delayed completion of intervention activities will cause greater disruptions to train services in the parts of the network with intense train traffic. Taking a system wide view is, therefore, vital for developing efficient intervention strategies that could deliver the desired infrastructure outputs. In this paper we propose a modelling approach for simulation and analysis of railway track asset management strategies integrating different elements of the whole railway system. The approach uses a Petri net modelling technique to construct the railway system model. The model is built in a hierarchical, modular fashion, meaning that the system can be represented at any level of granularity and complexity, ranging from a single-asset system in a small segment of the network to a complex multi-asset system in a large geographical region. The impact of different asset management strategies on the infrastructure functionality and the operation of train services is assessed using the Monte Carlo simulation technique.

## 1. Introduction

Railway infrastructure owners are facing a great challenge of increasing capacity on the aging infrastructure without compromising its reliability and safety under strict financial constraints. This drives the need for the application of asset management principles as a framework for delivering infrastructure functionality subject to operational and financial constraints. In the railway industry asset management decisions are explicitly focused on the maintenance, enhancement and renewal of assets in order to ensure a required level of dependability and improvement in services at the lowest cost (Kirwin & Gradinariu, 2010).

Modelling tools play a major role in supporting asset management/intervention decisions. The models used usually focus on either operative (most often finite and short to medium-time horizon) decisions or tactical, i.e. long-term, planning problems. In the finite horizon railway track maintenance models proposed by Budai et al (2006) and Higgins et al (1999), the maintenance work was used as an input in order to develop the optimal maintenance schedule. Vale et al (2012) and Quiroga et al (2011) in their operative maintenance decisions models used a different approach. The authors incorporated deterioration modelling of the track to define the resulting demand for intervention work and using this information solved maintenance scheduling problems.

Modelling tools developed to solve long-term intervention problems are aimed at supporting a decision-making process when several intervention alternatives are available. One such model was proposed by Podofillini et al (2006) to analyse the effects of different inspection frequencies and waiting times before rail repairs are carried out. Quiroga et al (2012) proposed a simulation based approach to investigate different maintenance strategies with constant and dynamic intervention thresholds. Zhao et al. (2009) studied the long-term track intervention planning problem and investigated options for synchronisation of renewal activities for different track components.

Although considerable effort has been made in developing tools for modelling asset degradation and interventions, any decisions about railway infrastructure cannot be made without considering the impact the decisions will have on the day to day running of trains. Adoption of the whole-system approach has been identified as one of the main foundations of future developments in the railway industry in Great Britain (Future Railway, 2012). Asset management decisions should therefore be reached by evaluating all driving

causes of interventions, intervention enabling factors, alternative intervention options and resulting effects on other elements of the system (e.g. train operation). Little work has been done to integrate all of the elements of the whole-system approach in a single asset management model.

In this paper a modelling approach is presented for the investigation of asset intervention strategies within the whole-system context. The approach uses the Petri net (PN) modelling technique where the analysis is performed by means of Monte Carlo (MC) simulations. The case study presented in the paper focuses on the railway track ballast management.

## **2. Modelling Techniques**

The forecasting and planning of railway asset intervention activities is a complex problem which can possess both deterministic and stochastic features. For those reasons resorting to a simulation based modelling framework was thought to be a more practical option than constructing an analytical model.

### *2.1. Standard Petri Net Formalism and its Extensions*

A PN is a bipartite directed graph constructed by using four types of objects: transitions, places, arcs and tokens. A detailed description of PNs is provided by Murata (1989). Transitions, drawn as bars, depict actions, events or processes and represent the dynamic behaviour of the system (e.g. component degradation, failure) or performance of a certain activity (e.g. component repair, train movement). Places, drawn as circles, represent preconditions and post conditions of the actions and processes (e.g. operational system state, maintenance completion). Transitions are linked to places and vice versa by directed arcs. Tokens move between places through transitions according to transition firing rules and mimic a dynamic behaviour of the system. A transition is enabled for firing if each of its input places contains at least as many tokens as the multiplicity of the input places. An enabled transition fires by removing as many tokens as the multiplicity of the input places from each input place, and adding as many tokens as the multiplicity of the output places to each output place.

In order to make the model representation more compact and to enhance the modelling power of the PN technique, the standard PN formalism has been extended by introducing additional concepts. One of the extensions introduced is often encountered in the literature and is called inhibit arc (Murata, 1989). Some more complex extensions relying on logical interactions between objects of PN were initially proposed by Prescott and Andrews (2012) and have been used in this work with further enhancements. Additionally, three new extensions to the standard transition formalism have been introduced namely, place priority transitions, periodic transitions and multifunctional transitions. Place priority transitions have the standard execution rules modified in the sense that among all such transitions enabled in a given marking and sharing the same input place(s) their firing sequence is determined based on the marking of the specified associated input places (conditional input places). Place priority transitions in the model are used to prioritise resource allocation among different parts of the network. A transition with a periodical firing delay time represents an event that is triggered by other events and/or activities which occur at regular time intervals. For example, the periodical transition is used to determine the time when a localised ballast defect, e.g. void, would be detected as part of the routine track inspection that is performed on a regular basis. A multi-functional transition combines time-related and place marking-related transition features. For example, a place conditional transition which when it fires, resets the marking of certain associated places is a multi-functional transition combining features of the place conditional and reset transitions.

### *2.2. Petri Net Simulation*

For a large and complex PN, discrete-event simulation is commonly used to gain insights into the behaviour of the modelled system. The simulation process involves executing PN by firing enabled transitions with the minimum firing delay time. After every firing the simulator clock is updated and changes in the PN marking are assessed to determine which transitions are to be fired next. The process is repeated until the simulator clock reaches a predetermined value representing a lifetime of the system being modelled. The algorithm for the execution of the PN was implemented in C++. Due to the enhanced features introduced to the PN technique, commercial software could not be used in this case.

The simulation process produces a range of outputs that facilitate the assessment of the dynamic system behaviour. In the case of a PN containing stochastic delay transitions, each simulation will produce performance parameters of the modelled system which will be stochastic in their nature. For this reason a

MC simulation technique (considering a simulation of the modelled system lifetime constitutes a single experiment) is used to obtain the expected values of the parameters. During the experiment delay times of stochastic transitions are randomly sampled from appropriate distributions and performance parameters of interest are obtained. The experiments are repeated until the convergence of the parameters of interest is confirmed, i.e. when the coefficient of variation of a specified performance parameter is less than the prescribed tolerance value.

### 3. Ballast PN Model

The ballast, a formation of loose and coarse grained aggregate, is one of the principal components of the track substructure. Its main functionality is to provide support to the superstructure (rails and sleepers) against vertical, lateral and longitudinal displacement. (Lam & Wong, 2011).

#### 3.1. Modelling Framework

The ballast model has been constructed using the infrastructure state modelling framework presented by Rama and Andrews (2013) and additionally integrating resource utilisation and train service modules. It has a hierarchical modular architecture that is aligned with the hierarchical representation of the network and therefore can model the infrastructure at different levels of granularity with the varying degree of complexity.

A 50 mile railway line of a high quality track in the 80–110 mph speed band is analysed in this case study. Using a top down approach the line is divided into 5 sections each one comprising 80 1/8th mile homogeneous segments. The state of an individual asset object is modelled at a segment level. In this context, a segment is equivalent to the smallest unit of the network for which ballast degradation and intervention processes can be determined. Segment PNs are then used as building blocks for constructing the infrastructure PN models for higher levels of granularity. Segment models are jointly integrated into a single PN model by considering the asset management principles specific for a particular level of the network hierarchy.

#### 3.2. Model Construction

##### 3.2.1. Infrastructure State Module

The ballast state module itself consists of three interlinked sub-modules namely degradation, inspection and a rule based sub-module for maintenance management.

**Ballast degradation.** In the model two modes of ballast degradation are considered: the overall track geometry degradation and the development of isolated defects, such as voiding or wet-beds. The two degradation modes are assumed to be independent. Each degradation mode is modelled using a finite number of discrete degradation states (depicted as places in the PN) representing changes in the ballast condition in a single segment of the track. In the geometry degradation module the states are associated with track geometry degradation levels that correspond to specific threshold values of the vertical track alignment parameter. States in the isolated defect module represent the severity levels of defects. The distribution of times to reach each degradation state is sampled from an appropriate distribution related to the track category and maintenance history.

**Ballast Inspection.** The state of the ballast condition becomes revealed only during its inspection. Visual inspections and track geometry monitoring using an instrumented train that records the positioning of the rails are the two activities modelled. It is assumed that inspection schedules for both types of activities are prepared for individual sections. Thus when building a scaled up infrastructure PN each segment will have a set of places and transitions modelling the detection of track geometry states and ballast defects in that segment and these will be linked to an appropriate inspection subnet associated with the section containing the segments in question.

**Ballast Maintenance.** The timescales for carrying out corrective geometry maintenance are determined based on the severity of the geometry condition. They are assumed to follow a lognormal distribution. The same applies to ballast defects. When the scheduled intervention is due to start appropriate resources are allocated and a suitable time window with available track access is determined. The duration of the intervention is sampled from an appropriate lognormal distribution which again depends on the severity of the ballast condition or the type of resources used. A part of the ballast geometry maintenance PN is shown in Figure 1 as an example.

With time the ballast maintenance becomes less effective and eventually ballast renewal, i.e. cleaning, becomes more cost-effective than maintenance. A predetermined intervention frequency has been implemented as the benchmark for initiating ballast cleaning. The concept of modelling the ballast cleaning is similar to that used to model the ballast geometry and defect maintenance activities.

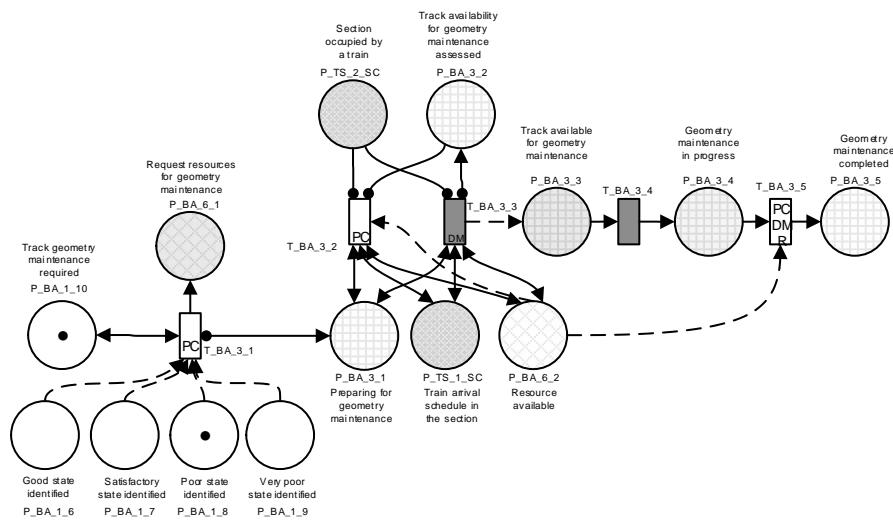


Figure 1. Track Geometry Maintenance

### 3.2.2. Resource Management Module

Four types of resources are considered in the ballast model namely a tamper, a stoneblower, a ballast cleaning machine and a maintenance crew. Individual PNs exist for modelling the availability and allocation of each type of resources to a particular section of the line, assuming that all jobs in one section, allocated to a single resource type are completed before moving to another section. A set of rules is introduced to govern the allocation of appropriate resources to specific tasks and their order among sections and within sections. The allocation of resources within the section, i.e. to particular segments, is carried out in an arbitrary order assuming that only one type of resource can be allocated for ballast maintenance in the same segment.

### 3.2.3. Train Service Module

The purpose of using the train service module is to analyse and assess the impact train services will have on maintenance activities and subsequently on the performance of the infrastructure and vice versa. As the access to infrastructures for maintenance is limited, the scheduling of maintenance activities needs to be coordinated with the train service timetable. Thus the train service module is activated so that the simulation of train movements is initiated prior to the start of any maintenance activities given the maintenance resources requested have been deployed in the line.

To align with the proposed hierarchical representation of the infrastructure, during the simulation a train journey begins in the first section of the line and finishes in the last one by sequentially traversing intermediate sections as shown in Figure 2 (considering a 2 section line). A cyclic train timetable is assumed with trains scheduled at a specified frequency during the day and night service hours. Train arrival schedules are specified for each section to be able to determine track availability for maintenances interventions as discussed in Section 3.2.1. It is assumed that if at the start of a train journey maintenance activities are underway, the train will be re-routed and a resulting deviation from the initial timetable will be observed.

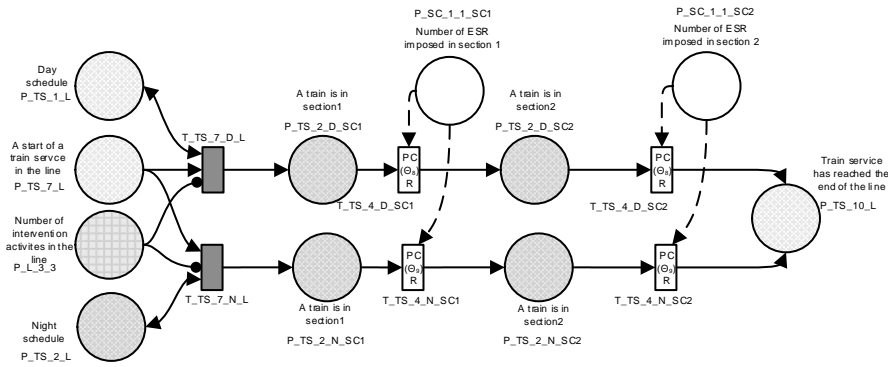


Figure 2. Train Journey during Day and Night Service Hours

#### 4. Case Study

To illustrate the application of the ballast model three scenarios have been analysed using the MC simulations. The first one is a baseline case. The second scenario has several modifications introduced to the baseline intervention policy resulting in more ballast cleaning activities, improved efficiency of intervention activities and additional tamping and engineering resources available. Finally, the third scenario is the same as the second one but has more intense train traffic during service hours and shortened (from 6 hours to 4 hours) train service-free periods during night time when maintenance can be carried out. Input parameter sets used for MC simulations of the given PN have been modified accordingly to reflect the changes mentioned. Selected performance parameters evaluated over a 100 year lifetime for the 50 mile long railway line are presented in Table 1 and Table 2.

Table 1. Expected values of the performance parameters of the infrastructure and train services over the lifetime

	Total downtime, days	Mean time between interventions, days	Total duration of speed restrictions, days	Duration of line closures due to poor condition, days	Total number of train diversions	Duration of delays due to maintenance, days
Baseline	335.13	1.82	1124.14	14.78	781.76	12.70
Option1	336.61	1.82	1091.50	12.08	8.32	0.12
Option2	336.82	1.82	1095.31	12.11	75.79	2.04

Table 2. Expected values of the utilisation parameters of maintenance resources over the lifetime

	Usage duration of a tamper, days	Usage duration of a stoneblower, days	Commitment of engineers' resources, days	Usage duration of a ballast cleaner, days
Baseline	719.44	1.81	782.98	0.22
Option1	595.61	0.81	601.99	33.12
Option2	594.62	0.79	602.40	33.11

As results demonstrate, changes introduced under the second scenario would have the biggest impact on train delays caused by overrun maintenance activities (reduction from 13 days to less than a day). The time that the line would be closed due to poor asset condition would also be reduced by about 18% under the second scenario. As expected, the total number of days that resources of each type (excluding the ballast cleaning machinery) are used for maintenance (including traveling times, waiting times for access and actual maintenance performance) would reduce, as the work would be carried out more efficiently and ballast cleaning interventions would be more frequent.

Infrastructure performance parameters obtained using the second and third data sets are similar. The only significant difference as a result of reduced traffic-free intervals would be observed in train delays that increase from less than a day to two days.

None of the alternatives considered would have any impact on the average frequency of interventions though. Mean time between interventions remains the same in all three scenarios meaning that neither changes proposed to the intervention policy nor changed train operation conditions would impact the rate of ballast condition degradation.

## 5. Conclusions

Railway infrastructure managers are faced with big challenges of preserving and managing the aging infrastructure while meeting the requirements, needs and expectation of all its stakeholders which are very often conflicting. Mathematical models have been increasingly used to provide information about infrastructure assets in support of asset management decisions to deliver the needed infrastructure outputs.

The ballast model presented in this paper has been constructed to simulate the operational lifetime of the ballast on the railway track moving away from an asset-focused to a system-wide approach. The model estimates a range of infrastructure performance parameters under a specified maintenance and train operational regimes further constrained by the availability of resources. Integration of the train service and resource elements in the model provides additional sources of information for the decision making process enabling a holistic assessment of benefits and drawbacks of alternative decisions. Furthermore, being built in a modular fashion, the model can support the asset management decisions at different levels of the infrastructure hierarchy.

The model application was demonstrate by analysing two asset management decision alternatives under different train operation conditions. Based on the results produced by the model, not only the infrastructure performance parameters but also the demand for maintenance resources can be compared for different train operation scenarios.

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