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. Where the track geometry is shown to have deteriorated to a level where intervention is required the condition 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 the most cost effective means to achieve the required level of performance can be predicted.

Keywords: Railway track ballast, degradation models, maintenance models, asset management, Petri nets

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

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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. 5 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 1-50mm. Different deterioration rates are specified in this model 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 Reference 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 have then been investigated to determine their cost effectiveness. The statistical model takes the form:

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

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

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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 in reference 10. The model, for an 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 Figure 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 35m 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 are taken of the rail geometry 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 level. It does this by measuring the track geometry, calculating the required adjustments, lifting the track and inserting vibrating tamping arms 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 some 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 reduces [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 Figure 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 Figure 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 any 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 Figure 1 (T8).

A convolution transition: this is a transition where the input place indicates one level of degradation and the output place represents a second, worse, level of degradation, but the distributions of the transition times available to reach these degraded states are relative to the same base condition (for example from renewal). This type of transition is used to indicate the progression of the degraded state of the track geometry which have different implications for the system. A full description of the mathematical treatment of this type of transition is given in reference 10.
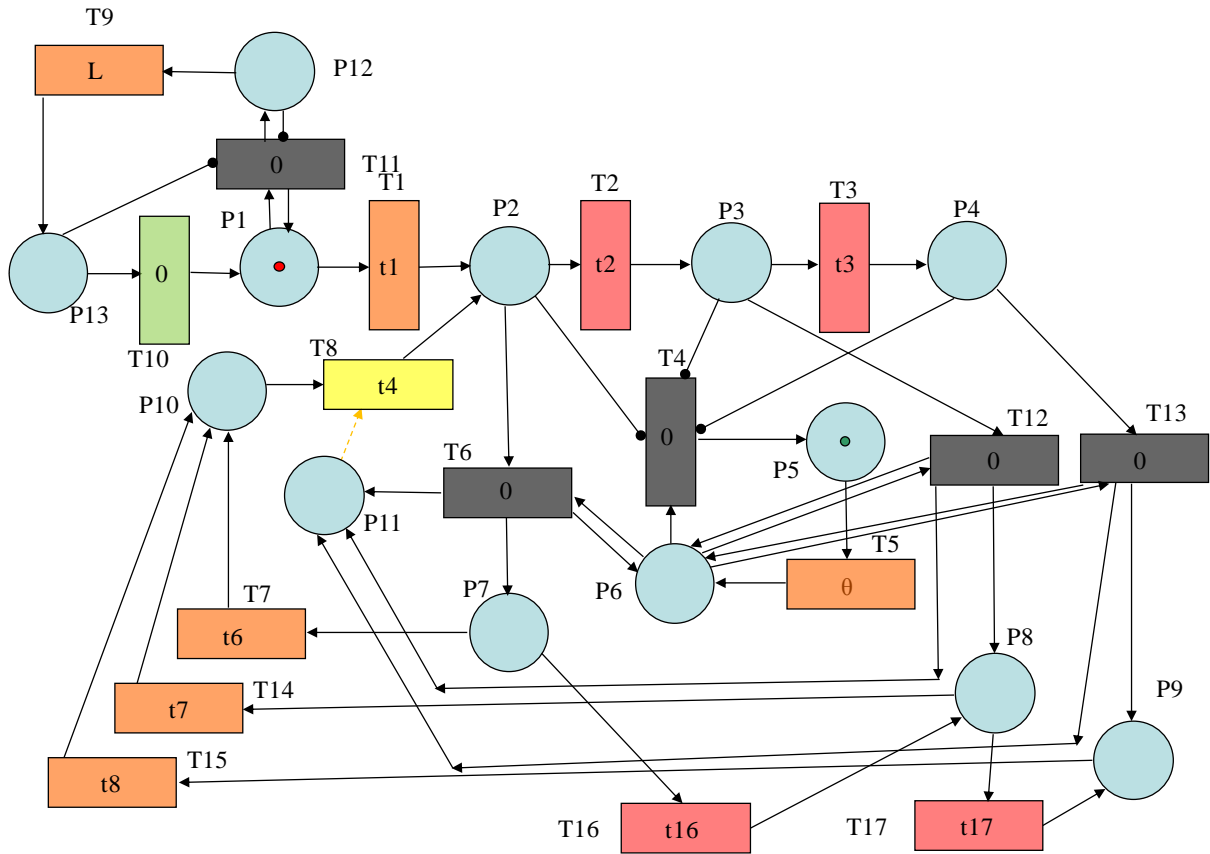
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Figure 1 Petri net of the degradation process

2.2 Track Section Model Structure

Deterioration process

This is represented in the PN section which includes places P1-P4. These places represent the geometry being: in the good condition following renewal, a minor degraded condition needing maintenance, a major degraded state requiring the imposition of speed restrictions, and a major degraded state imposing a line closure.

P2, the degraded condition needing routine maintenance is entered when the SD of the parameter representing the track geometry exceeds the critical threshold set for the track, σ_{Crit}. The transition to this state, T1, is governed by the distribution of times to reach this level of deterioration (these will be discussed in the next section). The places P3 and P4 represent the very undesirable situations where the geometry condition has deteriorated to a condition where a speed restriction or line closure has been imposed to control the risk of derailment. P3 and P4 are states defined where the track geometry SD has exceeded $\sigma_{SpeedLim}$ (the level; of SD at which speed restrictions must imposed) and $\sigma_{LineClose}$ (the level of SD at which line closures must be imposed) respectively.

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Inspection Process

When the track condition is in a state where maintenance is required (P2, P3 and P4) this condition will not be known until an inspection occurs. Inspection is accomplished by running the measurement train over the track section and will take place at regular intervals of θ. Tokens in places P7, P8 and P9 indicate that the track geometry is in a condition requiring maintenance which is either routine, to remove a speed restriction or to remove a line closure respectively. These correspond to P2-P4, however, in this case the condition is now known. Tokens are moved into P7-P9 when the measurement train has inspected the track to reveal these conditions. The measurement train activity is represented by places P5 and P6 on the PN. When the token is in P6 this section is measured. Otherwise the token is in P5. The passage between these places occurs every θ time units.

Intervention Process

Tokens in places P7, P8 and P9 indicate that maintenance is needed with different priorities. In P7 the need for normal, routine maintenance is identified. For P8 and P9 emergency maintenance has to be carried out as an urgent priority in order to restore operational services. Transitions T7, T14 and T15 return the track condition to state P10 which represents the condition where it is not as good as new but is improved to a condition that no longer requires maintenance. The time distributions for the transitions include the time to schedule the work and carry it out. The distributions of these times reflects the priority of the work with T7 experiencing a distribution of much longer ($F_{Norm}(t)$) times than T14 and T15 ($F_{Emerg}(t)$) for urgent maintenance. At the same time as completing the maintenance an additional token is added to place P11. P11 records the number of interventions carried out on the track section in order that the correct deterioration distribution is identified to cause the transition from P10 to a state requiring routine maintenance in the future.

Renewal Process

Ballast will be renewed when its condition has reached the stage where it will be more economical to renew it than continue to maintain it. This situation can be specified after a predetermined lifetime, after the condition is deemed to be too poor, after a set number of interventions, or at the point when the time between interventions becomes too short. Any of these strategies can be implemented into the PN and its effects investigated. In this PN renewal takes place after a predetermined lifetime, L. At the start of the ballast lifetime a token is placed in P12 to start its lifetime clock. When the life has expired the token moves through T9 to P13. T10 represents a reset transition which resets the tokens in the PN, where appropriate, to account for the new ballast condition.

2.3 Transition Rate Data

All events which can affect the asset management performance of the track section are represented by transitions on the PN model. These transitions govern the deterioration, inspection, maintenance and renewal processes and can be determined as outlined below.

Section Geometry Deterioration Time Distributions

An analysis of the records for each 1/8th mile section on the UK railway network has been carried out. The records contain two types of data. The first is the information recorded by the measurement train which passes along each section of the network at regular intervals and records the positions of the rails. This data is then processed to derive characteristics which represent the geometry quality and indicate when maintenance is required. The characteristic to best indicate the need to improve the geometry is the Standard Deviation of the average vertical alignment taken over a 35m wave-length. A second set of information indicates when maintenance (tamping) or renewal have been performed on each section. A typical plot of this data with the tamping history superimposed on the track quality data is shown in figure 2.
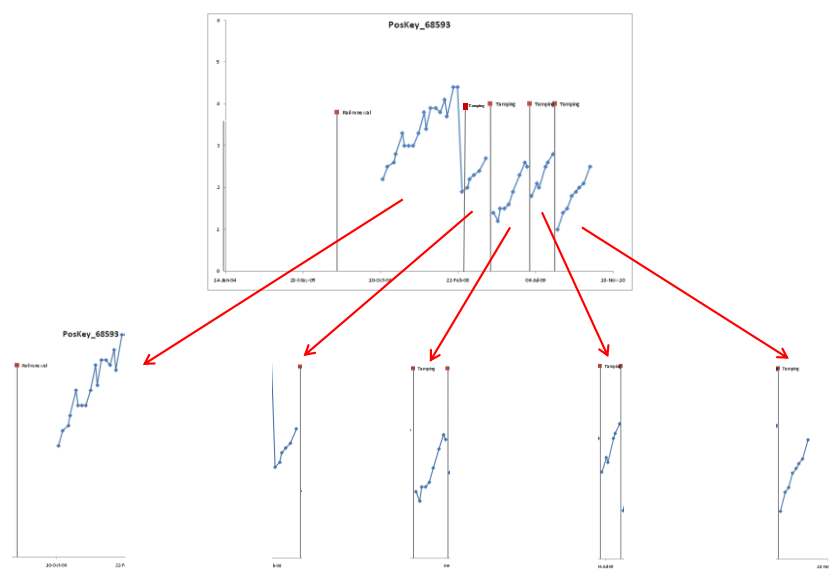

Figure 2 Degradation phase identification

The data for the track geometry can be divided up into life phases which cover the period between each intervention activity. An analysis of this data revealed that the degradation rate changes from phase to phase and is dependent upon the number of interventions that had been carried out previously. The results of the full analysis of this data are given in reference 11. These results were obtained by assuming a linear relationship between standard deviation and age over each phase. This enabled the time for each section to degrade to a specified level of performance to be estimated. By then fitting a two-parameter Weibull distribution with parameters β, the shape factor, and η, the characteristic life, the distribution of times to deteriorate to any specified standard deviation could be determined. These distributions are dependent upon the line traffic, the rail type and the sleeper type. For any specification of the track type the Weibull parameters are determined as a function of the standard deviation $\beta(\sigma)$ and $\eta(\sigma)$.

Maintenance Response Time Distributions

Two types of maintenance response times are needed for the model. These govern the times to improve the track geometry for routine maintenance, $F_{Norm}(t)$, and for situations where it is a priority, $F_{Emerg}(t)$, when speed restrictions or line closures are affecting the service provision.

The response times will vary significantly between these two situations. Routine requests for tamping machines can take a while to be carried out depending on the number of tamping machines available and their positions on the network. Emergency, priority requests, are actioned immediately.

Renewal Times

The need for renewal of the ballast can be a function of many factors and in the model shown in figure 1 it has been assumed that the ballast will have a specified life time. Alternatives would be to change the ballast based on use or condition.

Track Geometry Inspection Times

The rail geometry is measured by a special measurement train which passes around the network. The frequency at which each section of track is monitored is dependent upon the traffic usage of the route section (volume, speed and weight). A maximum time permitted between inspections is specified in the rail maintenance standards. A typical figure for important routes would be around one per month.

3 Analysis of Deterioration Time Distributions

Due to the complexity of the event interactions, particularly between the deterioration process and the maintenance process, the analysis of the section track model is accomplished by performing a Monte Carlo simulation of the model [12]. This approach conducts experiments on the computer forming potential sequences of events by taking random samples from the distributions which govern the time it takes for any event to occur. By performing many such simulations on the computer and logging key performance characteristics for each experiment the results can be interpreted, forming distributions that help to understand the system performance.

In the model of the track section maintenance and renewal key performance indicators include:

- Number of interventions

- Number of speed restrictions

- Duration of the speed restriction

- Number of line closures

- Duration of the line closure

■ Percentage of time in the good/poor/satisfactory state

■ Associated costs for preventive maintenance

■ Associated costs for corrective maintenance

4. Base Case Model

A base case model has been established which represents the situation where the parameters are set to what is considered the most likely options for the asset management process. From this Base Case alternatives can be investigated and compared to select those which offer some advantage.

The base case section analysed in this paper is that for 80-110mph speed track. The track measurement taken to represent the geometry quality is the vertical height averaged over the two rails (vertical top). The standard deviation of the value is then found over 35m wavelengths. For this type of track, the degradation distributions to any level of standard deviation and after any number of interventions is estimated from the work reported in reference 11 and is specified in Table 1. Once the track has had 7 interventions then it is assumed not to be altered by further interventions and so the distributions for 7 interventions hold.

	Standard Deviation $\sigma=1$		Standard Deviation $\sigma=2$		Standard Deviation $\sigma=3$		Standard Deviation $\sigma=4$		Standard Deviation $\sigma=5$	
No of interventions	β	η	β	η	β	η	β	η	β	η
0 (renewal)	0.86	2500	0.96	2724	1.12	3629	1.28	4311	1.33	4805
1	0.96	2200	1.0	2227	1.18	3090	1.34	3791	1.36	4283
2	1.0	2000	1.12	2222	1.2	2957	1.43	3433	1.49	3902
3	1.12	1900	1.15	2100	1.25	2700	1.48	3100	1.5	3700
4	1.15	1800	1.2	2050	1.28	2600	1.52	2900	1.55	3500
5	1.2	1700	1.25	2000	1.35	2400	1.56	2700	1.58	3300
6	1.25	1600	1.3	1950	1.38	2200	1.58	2400	1.6	3000
7	1.3	1500	1.4	1800	1.45	2000	1.6	2200	1.65	2600

Table 1 track degradation time Weibull distribution parameters

In the Base Case the definitions for the degraded geometry states in the PN model are defined in terms of the standard deviation of the vertical top measurement experienced on the track:

P2:   State needing maintenance $(3 \leq \sigma < 4.25)$

P3:   state where speed restriction is imposed $(4.25 \leq \sigma < 5)$

P4:   state where line closure is imposed $(\sigma \geq 5)$

(note these SD values have been selected as typical values to demonstrate the methodology).

The measurement train passes along the section every 28 days to determine the track geometry state.

Once maintenance has been scheduled the distribution of times to complete the repair are Normal distributions with the following parameters:

Normal priority intervention has a mean μ=100 days with standard deviation σ=15 days.

Emergency priority intervention (from both the speed restriction and line closure states) has a mean μ=0.5 days with standard deviation σ=0.125 days.

The section is renewed (track, sleepers and ballast) after an operating life of 30 years.

5. Base Case Model Analysis

The first requirement for the analysis of the PN with the data specified in section 4 is to calculate the distributions of times to make a transition between the degraded states since the data given (in Table 1) governs the time to degrade to the specified state from the point at which the intervention was carried out. It can be seen that the track condition resides in state P3 if its track quality standard deviation is in the range $4.25 \leq \sigma \leq 5$. The calculations required by the Convolution Transitions to establish the distributions of times to make a transition between the degraded states are given in reference 10 and will require the distribution of times to reach the state where σ=4.25 which is not provided in Table 1. By linear interpolation of the Weibull parameters this distribution is given in the fourth column of Table 2.

	Standard Deviation σ=2.75		Standard Deviation σ=3.25		Standard Deviation σ=3.5		Standard Deviation σ=4.25	
No of interventions	β	η	β	η	β	η	β	η
0 (renewal)	1.08	3403	1.16	3800	1.2	3970	1.293	4435

1	1.135	2874	1.22	3265	1.26	3441	1.345	3914
2	1.18	2773	1.258	3076	1.315	3195	1.445	3550
3	1.225	2550	1.308	2800	1.365	2900	1.485	3250
4	1.26	2463	1.34	2675	1.4	2750	1.528	3050
5	1.325	2300	1.403	2475	1.455	2550	1.565	2850
6	1.36	2138	1.43	2250	1.48	2300	1.585	2550
7	1.438	1950	1.488	2050	1.525	2100	1.613	2300

Table 2 Interpolated track degradation time Weibull distribution parameters for distributions not given

Using the Weibull parameters to degrade from intervention to the point where $\sigma=4.25$ and evaluating the convolution calculation procedure (ref 10) gives the distribution to get from P2 to P3 ($\sigma=3$ to $\sigma=4.25$) and from P3 to P4 ($\sigma=4.25$ to $\sigma=5$). A Weibull parameter has then been fitted to these results whose parameters are shown in Table 3.

	Transition (T2) from $\sigma=3$ to $\sigma=4.25$		Transition (T3) from $\sigma=4.25$ to $\sigma=5$		Transition (T2) from $\sigma=2.75$ to $\sigma=4.25$		Transition (T2) from $\sigma=3.25$ to $\sigma=4.25$		Transition (T2) from $\sigma=3.5$ to $\sigma=4.25$	
No of interventions	β	η	β	η	β	η	β	η	β	η
0 (renewal)	0.372	229.19	0.263	11.15	0.42	359.3	0.418	364	0.298	50.2
1	0.3664	227.27	0.254	7	0.426	392.2	0.324	113.2	0.286	45.4
2	0.462	271.8	0.272	18.14	0.492	375.2	0.39	157.6	0.338	70.6
3	0.46	248	0.2445	12.99	0.486	329.2	0.377	136.1	0.331	65
4	0.467	216.3	0.249	17.76	0.503	300.1	0.39	127.9	0.339	60.6
5	0.431	182.9	0.246	14.82	0.465	250.1	0.362	100.9	0.318	46.75
6	0.422	136.7	0.248	18.7	0.434	174.4	0.36	79	0.309	35.1
7	0.376	85.2	0.27	17.1	0.3889	111.6	0.338	50.2	0.3	21.65

Table 3 Weibull parameters for Transitions between the degraded states for the different σ variations defining the states

5.1 Analysis Results

The simulations were run for a 180 year period to ensure that the initial conditions were not influencing the results and that the numerical process had converged. 24000 simulations were performed but it was shown that convergence of the means of the parameters collected to indicate the performance were within acceptable accuracy after 6000 simulations. The results for the analysis were:

Number of interventions per lifetime 3.57

     Number of routine maintenance interventions 1.31

     Number of incidents of speed restriction: 1.10

     Number of line closures: 1.16

Percentage of time in the good condition: 98.048%

Percentage of time in the state requiring maintenance 1.842%

     Condition unknown (T2)   0.359 %

     Condition known (T7)1.483 %

Percentage of the time in a state needing a speed restriction 0.048%

     Condition unknown (T3)   0.043 %

     Condition known (T8)0.005 %

Percentage of the time in a state needing a line closure 0.062 %

     Condition unknown (T4)   0.057 %

     Condition known (T9)0.005 %

In addition to the above point estimates which represent the performance of the selected maintenance strategy, distributions of the parameters can be achieved. The distributions of the total number of interventions required per lifetime along with those for each of the emergency degraded condition states is shown in Figure 3 (for the cumulative distribution and the probability density function).
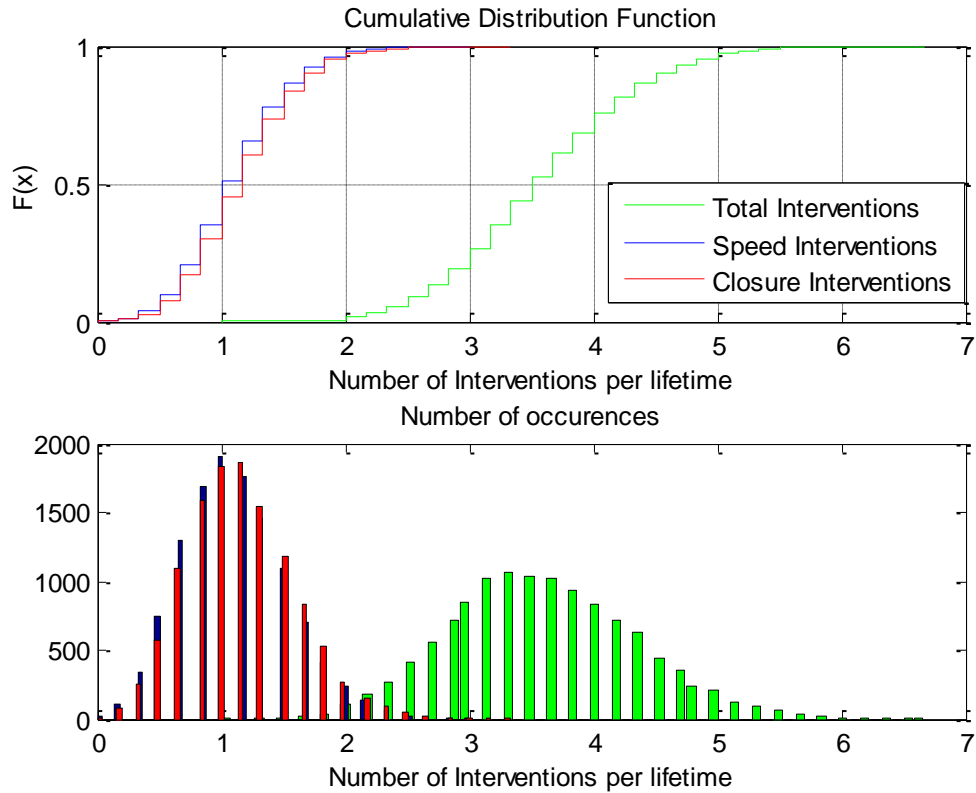
Figure 3 Distributions of the number of interventions per lifetime

6. Variations on the Base Case

Having determined the performance results for the Base Case model some of the parameters which govern the asset management strategy can be varied and the performance parameters recalculated and compared. Where the performance is improved, the financial benefits produced can be compared with the change in costs of performing the maintenance according to the specified strategy to decide if this new approach offers some advantage.

In deciding which parameters to vary it should be noted that the standard deviations which define states P3 and P4 are not variable as these will be set by the relevant codes of practice. The track condition which defines state P2 can be selected as part of the asset management strategy. If it is reduced then maintenance will be scheduled earlier and more interventions will be performed in the track lifetime. The advantage will be a reduced risk of encountering a track condition which requires a speed restriction or line closure. For the Base Case state P2 was achieved as soon as σ reached a value of 3. For this parameter, variations have been considered as: σ=2.75, σ=3.25 and σ=3.5. These require distributions of times to degrade from renewal to different values of σ than have been provided in Table 1. These distributions are given in Table 2 and the associated distributions of times to pass from the different degraded states P2, P3 and P4 have been calculated and recorded in Table 3.

The variations considered for the passage of the measurement train along any section of track are at intervals of: 7, 14 and 56 days (compared to the Base Case value of 28 days). Should a shorter measurement frequency be shown to have significant benefit, this would require the acquisition of new equipment in the form of more measurement trains. Conversely some measurement trains could be released if the frequency could be relaxed with little adverse effect.

Renewal has been considered at 20 and 40 years to compare with the Base Case value of 30 years.

Finally the mean of the time needed to perform routine maintenance (to improve on the state P2) has been investigated by setting it to 50,150 and 200 days compared with the Base Case value of 100 days. The standard deviation of the Normal Distribution of 15 days has been retained throughout the analysis. The time to repair is mainly comprised of the time between the work being requested and the tamper arriving to perform the work, the time taken for the tamp is relatively insignificant. Varying this parameter has implications to the way work is prioritised once it has been scheduled and on the number of tampers available to carry out such maintenance.

7.   Analysis of Alternative Asset Management Strategies

Based on running 24000 simulations the results of varying the inspection, maintenance and renewal parameters are shown in Table 4. The first line of the table provides the Base Case results for comparison.

		Interventions per lifetime			Percentage of time in state requiring routine maintenance		Percentage of time in state requiring speed restriction		Percentage of time in state requiring line closure		Percentage of time in good state
	Total	Routine	From speed restriction	From line closure	unidentified	identified	unidentified	identified	unidentified	identified	
Base Case											
	3.57	1.31	1.10	1.16	0.359%	1.483%	0.043%	0.005%	0.057%	0.005%	98.048%
Inspection Train Frequency											
7 days	3.57	1.47	1.18	0.92	0.099%	1.620%	0.008%	0.006%	0.007%	0.004%	98.256%
14 days	3.59	1.42	1.15	1.02	0.191%	1.600%	0.020%	0.006%	0.020%	0.005%	98.158%
56 days	3.56	1.19	1.03	1.34	0.663%	1.347%	0.094%	0.005%	0.160%	0.006%	97.725%
Renewal Times											
20 years	2.29	0.82	0.70	0.76	0.345%	1.417%	0.042%	0.005%	0.057%	0.005%	98.129%

40 years	4.34	1.57	1.36	1.41	0.375%	1.543%	0.046%	0.006%	0.059%	0.006%	97.965%
Routine Time to Repair											
50 days	3.61	1.59	0.94	1.08	0.362%	0.839%	0.044%	0.004%	0.058%	0.005%	98.688%
150 days	3.55	1.14	1.19	1.21	0.358%	2.034%	0.043%	0.006%	0.057%	0.006%	97.496%
200 days	3.53	1.02	1.26	1.24	0.357%	2.526%	0.042%	0.006%	0.056%	0.006%	97.007%
Threshold for Routine Maintenance											
$\sigma = 2.75$	3.79	1.71	1.05	1.03	0.407%	1.885%	0.035%	0.005%	0.045%	0.005%	97.618%
$\sigma = 3.25$	3.39	1.06	1.09	1.23	0.320%	1.223%	0.050%	0.005%	0.065%	0.006%	98.331%
$\sigma = 3.5$	3.28	0.54	1.17	1.56	0.249%	0.663%	0.073%	0.006%	0.098%	0.007%	98.904%

Table 4 Investigation of the Effects of Different Maintenance, Repair and Renewal Activities

7.1 Inspection Train Frequency

The results for different intervals between inspection carried out are given in Table 4 Line 1 contains the performance for the Base Case (inspection every 28 days). The first section of the table gives results for measurement intervals of 7, 14 and 56 days. Interestingly, although it would be expected that shorter inspections, which reveal the need for maintenance earlier, would result in more maintenance, this was not indicated by the results. Accounting for the fact that the analysis method has statistical variation, there is no significant difference between the total number of interventions carried out per lifetime for the range of inspection frequencies investigated. These were all around 3.57. This is explained by the fact that the periods between inspections are short in comparison to the degradation times and repair times. What does change is the track condition when the interventions are performed. As the duration between inspections increases the proportion of maintenance that is performed in the poorer track conditions increases. The longer inspection frequency of 56 days would probably not produce an acceptable financial performance where, on average, only 1.19 interventions are carried out as routine maintenance whereas on average 2.37 interventions are carried out under emergency conditions. The cost of the extra measurement trains required for more frequent inspections would be compared with the penalties incurred for speed restrictions and line closures.

The percentage of time spent in the good state (maintenance not required) is around 98% for each of the inspection values. The longer inspection values result, as expected, in a smaller percentage of time in the good state. Whilst these differences appear small they are significant when it is considered how many of the 1/8th mile track sections there are on the UK railway network. The percentage of time where track is in need of emergency

maintenance increases with the inspection interval – the proportion of this when the state is known does not change as this is governed by the repair time, which for these situations is small. For track requiring routine maintenance the larger proportion of the time awaiting repair is when the state of the track is known since the repair times for routine work are larger than the delays induced before the state is revealed by the inspection train. As the duration between inspections gets larger the times that the state is in a condition requiring maintenance also increases.

7.2 Renewal Times

Results for the renewal ages are given in section two of Table 4 for renewals at 20 and 40 years and compared to the Base Case (30 years renewal). Varying this parameter does not have a significant change in the proportion of times that the track resides in the different conditions states. For each track section, on average, 2.29 interventions are performed per lifetime for renewal at 20 years (i.e 4.58 per 40 years) compared to 4.34 interventions for a 40 year renewal. This shows that for the renewal periods considered in this study all renewals have been conducted before significant deterioration of the ballast has occurred. Larger lifetimes between renewals may be beneficial.

7.3 Routine Repair Times

The time it takes to perform a routine repair is one of the most critical factors governing the line performance. The performance indicators for the routine repair time are presented in the third section of Table 4. As the average time to repair increases from the 100 days (Base Case) the total number of interventions performed decreases. This is because the intervention takes longer to carry out and so the time that the next phase of the track life, determined from the point of maintenance completed, begins later. This trend repeated throughout all interventions means that fewer situations requiring maintenance occur in the track lifetime. It can also be seen that as the routine maintenance times increase an increased percentage of time is spent with the track in a condition known to require maintenance. This parameter has no effect on the imposition of speed restriction and line closures. This is however due to a simplifying assumption of the model where once maintenance is requested, further deterioration of the track state is not considered. This identifies a feature which would be enhanced in future models. Halving the average routine repair time to 50 days gives an excellent performance with the track in a good condition 98.688% of the time.

7.4 Threshold at which Maintenance is Performed

The final section in table 3 indicates the effects of moving the threshold at which maintenance is required. The lower the value, the less the risk of encountering a poor track condition where speed restrictions or line closures are required. It can be seen that this risk increases significantly if the threshold is raised to $\sigma = 3.5$. What appears to be good performance in the percentage of time the track condition is regarded as being good must be treated with care as changing the threshold values effectively changes the definition of what is regarded as a good condition. If the threshold is reduced to $\sigma = 2.75$ the percentage of time spent in the poor track states is very small.

8. Conclusions

- A Petri net model of an 1/8th mile track section has been used to investigate the effectiveness of the asset management strategy employed to maintain the geometry of the section to an acceptable standard. The model incorporates the deterioration process of the track and its dependence on the maintenance history together with all intervention options for inspection, repair and renewal.

- By changing parameters within the model it has been used to investigate the resulting track performance. The factors investigated include:

    i. The frequency of inspection to confirm the condition of the track geometry

    ii. The lifetime of the track

    iii. The time taken to perform routine repairs

    iv. The performance threshold at which the need for maintenance is identified.

- By determining the costs of performing the different intervention actions (measurement, tamping and renewal), together with the penalty costs of experiencing line closures and speed restrictions, the life cycle costs of each of the possible asset management strategies can be evaluated and the most effective one chosen.

- Factors which affect the implementation of the different intervention options would also have to be included in the selection of the best asset management strategy. Options i and iii above would require more measurement trains and more tampers to be available respectively if values of lower durations than the Base Case were selected.

- The model can be refined to take into account lengths of track made of many 1/8th mile sections. This would enable the conflicting requirements of the tamping machines to be incorporated together with the ability to perform opportunistic maintenance for which a second threshold would be incorporated where maintenance would be performed on a section to take advantage of the tamper being in the vicinity when it would not normally be performed.

9. References

1. Hamid, A. and Gross, A., Track-quality indices and track degradation models for maintenance-of-way planning, Transportation research Board, 802, p2-8,1981.

2. Bing, A.J. and Gross A., Development of railway track degradation models, Transportation research Board, 939, p27-31, 1983.

3. Sadehghi, J. And Askarinejad, H., 'Development of Improved Railway Track Degradation Models', Structure and Infrastructure Engineering, Vol 6, No 6, pp675-688,2010.

4. Shafahi, Y. and Hakhamameshi, R., Application of maintenance management model based on Markov chain and probabilistic dynamic programming for the Iranian railways, Trans A: Civil Engineering, Vol 16, No 1, pp87-97, 2009.

5. Lyngby N., Hokstad, P. and Vatn, J., RAMS Management of Railway Tracks, published in the Handbook of Performasbility Engineering (Ed Krishna Misra), Springer Press, 2008, pp1123-1145.

6. Podofillini, L., Zio, E., and Vatn, J., Risk-informed optimisation of railway tracks inspection and maintenance procedures, Journal of Reliability Engineering and System Safety 2006, 91, 20–35.

7. Kumar, S., Espling, U., and Kumar, U., A holistic procedure for rail maintenance in Sweden, Proc. of the IMechE, Part F: J. Rail and Rapid Transit 2008, 222 (4), 331-344.

8. Quiroga, L.M., and Schnieder, E., 'Monte Carlo Simulation of Railway Track Geometry Deterioration and Restoration', to be published in the Journal of Risk and Reliability, Part O of the Proceedings of the IMechE.

9. Quiroga, L.M., and Schnieder, E., 'A Heuristic Approach to Railway Track Maintenance Scheduling', WIT Transactions on The Built Environment, Vol 114, pp687-699, 2010

10. Andrews, J.D., 'A Modelling Approach to Railway Track Asset Management', Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, Volume 227 Issue 1, January 2013

11. Audley, M. and Andrews, J.D., 'The Effects of Tamping on Railway Track Geometry Degradation' submitted to Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit.

12. Rubinstein, R.Y. and Kroese, D.P., Simulation and the Monte Carlo Method, 2nd Edition, Wiley, 2008.

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