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RAIL TRACK MAINTENANCE PLANNING: AN ASSESSMENT MODEL

Authors: Scott Simson,
Physical Infrastructure Centre, QUT
C/o School of Civil Engineering, Queensland University of Technology
PO Box 2434, Queensland, Australia 4001.
Ph: 65 7 38642848; Fax: 65 7 38641515;
Email: s_simson@powerup.com.au

Luis Ferreira,
Physical Infrastructure Centre, QUT
C/o School of Civil Engineering, Queensland University of Technology
PO Box 2434, Queensland, Australia 4001.
Ph: 65 7 38641542; Fax: 65 7 38641515;
Email: l.ferreira@qut.edu.au

Martin Murray,
Physical Infrastructure Centre, QUT
C/o School of Civil Engineering, Queensland University of Technology
PO Box 2434, Queensland, Australia 4001.
Ph: 65 7 38641542; Fax: 65 7 38641515;
Email: m.murray@qut.edu.au

RAIL TRACK MAINTENANCE PLANNING: AN ASSESSMENT MODEL

ABSTRACT

In Australia, railway track maintenance costs comprise between 25-35 percent of total freight train operating costs. Track maintenance planning models have been shown to reduce maintenance costs by 5 to 10 percent though improved planning. This paper describes a model which has been developed to deal with the track maintenance planning function at the medium to long-term levels. This model simulates the impacts of degrading railway track conditions and related maintenance work, in contrast to tradition models that mainly use expert systems.

The model simulates the degrading track condition using an existing track degradation model. Track condition data from that model is used to determine if safety related speed restrictions are needed and what immediate maintenance work may be required for safe train operations. The model outputs the net present value of the benefits of undertaking a given maintenance strategy, when compared with a base-case scenario. The model approach has advantages over current models in investigating what if scenarios. The track engineer can assess the possible benefits in reduced operating costs from upgrading track infrastructure or from the use of improved maintenance equipment.

After describing the model inputs and the assumptions used, the paper deals with the simulation of track maintenance and of train operating costs over time. The results of applying the model to a test track section using a number of different maintenance strategies are also given.

KEYWORDS

Railway
Track maintenance
Maintenance Planning
Modelling

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RAIL TRACK MAINTENANCE PLANNING: AN ASSESSMENT MODEL

1. INTRODUCTION

Railway infrastructure providers have strong economic incentive to minimise the track maintenance costs, while maintaining safety standards and providing adequate service levels to train operators. This paper describes a model which has been developed to deal with the track maintenance planning function at the medium to long-term levels. This model simulates the impacts of degrading railway track conditions and related maintenance work, in contrast to tradition models that mainly use expert systems.

This paper is structured as follows: Section 2 provides a review of the literature; section 3 describes the objectives, structure and functions of the new model; section 4 presents the application of the model and preliminary test results; the final section provides some conclusions and discusses areas where further research is needed.

2. PAST WORK

A considerable number of different maintenance planning tools have been developed by rail system in North America and Europe. Different approaches and methods have been used by these systems. The key features of any track maintenance planning model are:

(1) A track degradation model used to predict future track condition. The track degradation model needs to consider the increased loading on track components due to the interaction of degraded track conditions. An example of such a model is the Integrated Track Degradation Model (ITDM), (1);

(2) The failure limit assessment functions which are used to determine condition limits for each of the failure modes. Track maintenance models will often use only a few of these functions and ignore the other track failure modes;

(3) Maintenance activity planning to determine what is the best activity to improve track condition. This has generally been achieved with expert systems such as MARPAS, (2) and ECOTRACK, (3). There are also examples of operations research approaches to optimise activity planning, (4) and (5);

(4) Maintenance resource optimisation based on input data about the limited available maintenance resources. Such models often relate track condition to train performance data, such as locomotive fuel consumption and train delays.

Most of the existing planning systems have been designed by and for a specific railway system. Since specific track data is used, the result is a rail system dependent planning system. Such empirical models operate with the assumption that certain maintenance and train operation practices are followed, or that specific track types or track components are in use. An empirical approach is regarded as the best method to develop an accurate model, especially with regard to surface and alignment, degradation and maintenance, where local sub-grade conditions have a large influence on performance, (4). Leading maintenance planning models are expert systems dependent on or developed from historical track condition data. Maintenance planning models have shown cost savings of 5 to 10 percent to rail operators upon implementation, (6).

Current practitioners need a maintenance model to be independent of the rail system and its operating practices, since historical track condition and maintenance data is often not available (7). In addition, it is necessary to keep data input requirements to a minimum, since most rail operators do not record the required range of track condition and maintenance activity data used in leading available track maintenance planning tools.

3. MODEL SPECIFICATION

The Track Maintenance Planning Model (TMPM) simulates the costs of running and maintaining track on a link. The latter is defined here as a length of track that is subject to the same rail traffic. The model is also capable of calculating the costs of track maintenance and train operations when traffic or track conditions are changed. The model associates track condition obtained from a track degradation model (eg. ITDM), with train delays and other train operating costs.

Track degradation and maintenance interventions must be based on individual track segments, where the track has common structure, curvature, ballast, sub-grade and drainage conditions. A track link is thus made up of a number of track segments. Each tangent, curve, cutting and viaduct section will be modelled separately, whilst still being considered as part of a longer length of track.

3.1 Model Structure

The model simulates the progressive degradation and maintenance work performed on a track section and it sums the associated costs with passing of traffic. Four distinct sub-models make up the simulation, namely:

- the degradation model (ITDM), which calculates new track conditions for each successive traffic interval;
- the train operating costs sub-model, which calculates train delays and delay costs;
- the unplanned maintenance sub-model, calculates defective sleeper clusters requiring replacement;
- the planned maintenance sub-model which decides the maintenance work required and updates track conditions following maintenance.

The structure of the model is depicted in Figure 1.

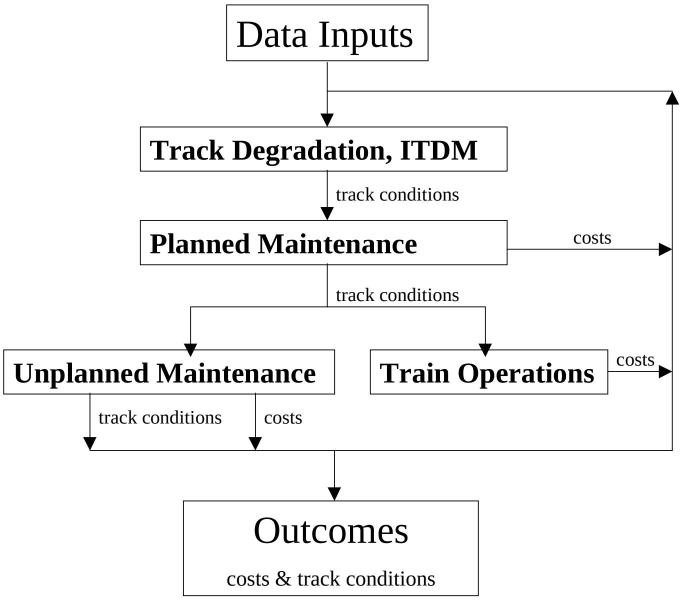

Figure 1. TMPM sub-model structure

3.2 Track Degradation Sub-Model

The mechanistic nature of ITDM means the model is railway system independent. It does not require detailed historical track condition data to operate. This makes ITDM an ideal candidate as a track degradation model to use with TMPM, as it fits well with the objective that the model operates with a minimum of track condition and activity monitoring data.

ITDM has three main sub models, (1) & (8):

- The ballast and subgrade sub-model, which is based on the work of Chrismer (9). Deterioration of ballast and subgrade is associated with differential settlement, leading on to the important parameter of track roughness, which is defined as the offset of track top line from a straight reference line. Track roughness increases with traffic and is influenced by the behaviour of track components. The equation for determining track roughness as suggested by Chrismer (9) is:

$$\sigma_{vo} = \sigma_{(vo)_{\min}} + 0.15 \times S_L \tag{1}$$

where:

σ_{vo} - standard deviation (roughness of track profile in term of vertical offsets) (mm);

$\sigma_{(vo)min}$ - standard deviation of track top line just after resurfacing (mm); and

S_L - average track settlement resulting from sum of settlement of all sub-layers (mm).

- The rail wear sub-model. Degradation of rails has long been determined by wear and fatigue defects. However, the practice of rail grinding removes many defects before they become large enough to be predictable. The current version of ITDM carries out an analysis only for rail wear. It is assumed that grinding removes fatigue defects and that the wear at rail/wheel contact area is of deformation wear type (8). The sliding between rail and wheels is considered proportional to the angle of attack of wheel set to the track. ITDM calculates wear on the rail top and the gauge face.

- The sleeper sub-model. Stress conditions in a timber sleeper are correlated with sleeper life, based on a mechanistic analysis of timber sleepers. The assumption is that each standardised wheel loading cycle causes an equal amount of sleeper damage. Hence, total sleeper replacement in a given section over a given time period is proportional to the total number of standardised wheel loading cycles, over the same track section and time period (8). The model accounts for the variable range of axle loads and environment conditions. Three main timber sleeper decay mechanisms of end splitting, wear plate cutting and fungal decay are modelled, as well as the cracking mechanism for concrete sleepers.

ITDM then has three main parameters of track degradation, namely:

- Track roughness, which represents the uneven settlement of the track structure with traffic;
- Rail wear, which represents wear from passing traffic and grinding operations; and
- Percentage of defective sleepers, which represents the number of sleepers failing to provide lateral or gauge restraint.

The planned and unplanned maintenance sub-models of TMPM determine the timing of maintenance interventions. ITDM input data is predominantly design data of the track structure, (ie rail, sleeper and ballast details, track geometry). Other inputs include annual traffic data (ie axel load, speed and annual volume) and environment data, (ie sub-grade type, drainage condition, temperature variation and average rainfall).

3.3 Train Operating costs

The model assigns train operating costs due to degraded track conditions based on train delays. The latter are the result of safety related speed restrictions. The model imposes speed restrictions based on track roughness calculated by ITDM. The user sets train speed and track roughness limits as inputs. Typically, track roughness levels will be inversely proportional to standard speed settings. However, dynamic effects and static limitations of track and rollingstock will alter this relationship, especially at extreme values. The dynamic effects are the result of vibration harmonics, whilst static effects are stability and twisting limits of the track structure and the rollingstock.

The calculations of train delays include the delays during acceleration and braking to and from restricted speed settings, as well as time lost at reduced running speed. Train delays are calculated for up to five specified train service types, each with their own maximum speed limits. Equation 2 gives the simple train delay. Equation 3 calculates the train delays from braking when the next segment speed restriction is less than the restriction for the current segment.

$$TD_{st} = \delta_s \times \left(\frac{1}{\upsilon R_{s\,t}} - \frac{1}{\upsilon_{st}} \right) \qquad (2)$$

Where: TD_{st} = train delay for segment s and train service t
δ_s = length of or distance along a segment s
υ_{st} = the maximum speed for segment s and train service t
υR_{st} = the restricted speed for segment s and train service t

$$TD_{st} = \left(\upsilon R_{st} - \upsilon f_{st}\right) / \left(\phi_t + \theta_s \times g\right) \times \frac{1}{2} \frac{\left(\upsilon R_{st} + \upsilon f_{st}\right)}{\upsilon_{st}} \tag{3}$$

Where: ϕ_t = the train's average deceleration
g = acceleration due to gravity
θ_s = Gradient of the track on segment s
υf_{st} = final speed for segment s and train service t. This will be the speed restriction for the next track segment.

Train Accelerations

Acceleration delays need to be simulated by the model. The train delay is given in Equation 4. The current train speed is accelerated by the increase in kinetic energy provided by the effective power to weight ratio. Equation 5 gives the relationship between the train speed and the train's effective power to weight ratio, whist Equation 6 gives the effective power to weight ratio of the train on the track segment.

$$TD_{st} = \int 1 - \frac{\upsilon(t)}{\upsilon_{st}} dt \tag{4}$$

Where: $\upsilon(t)$ = current train speed as a function of time

$$\upsilon = 2 \times \left(\Gamma_{st} + \frac{1}{2} \upsilon^2 \right)^{\frac{1}{2}} \tag{5}$$

Where: υ = current train speed

$$\Gamma_{st} = \varphi_t - \theta_s \times \upsilon \times g \tag{6}$$

Where: Γ_{st} = the effective locomotive power to weight ratio for segment s and train service t.
φ_t = the trains locomotive power to weight ratio for train service t.

A train might not be able to accelerate to a segment speed limit before it is forced to brake for the next track segment. The length of track required for braking is given by Equation 7. The simulation is run until the train has travelled to the end of the segment or has had to brake for the next segment as determined from Equation 7.

$$\delta_c = \left(\upsilon(t) - \upsilon f_{st}\right) / \left(\phi_t + \theta_s \times g\right) \times \left(\upsilon(t) + \upsilon f_{st}\right) / 2 \tag{7}$$

Where: δ_c = Critical braking distance

Train Length

The model assumes that the train length is a small fraction of the track segment length. Speed restrictions are applied to the entire segment length based on an average segment track roughness. In practice, the restriction will only concern peak roughness values, which are likely to be a small fraction of the segment length.

3.4 Unplanned Maintenance

Rail gauge problems associated with defective sleepers place train operations at high risk of derailment. Speed restrictions have limited effectiveness on reducing such risks because static forces are involved in gauge widening forces. Hence, when rail buckles or clusters of defective sleepers are found, very restrictive speed limits are used and repairs are performed immediately. The model's iteration period is large compared to the short time interval between identifying unsafe clusters and their repair, hence the repairs appear as instantaneous unplanned maintenance in the model.

Simulations of sleeper cluster formation were performed to formulate predictive equations for defective sleeper cluster repairs. Simulations where performed according to a method developed by (10). Initially, Equation 8 was tested against simulated random sleeper degradation and was shown to produce an accurate estimate of sleeper cluster numbers from the total percentage of defective sleepers.

$$\rho_n = (1 - \rho_d) \times \rho_d{}^n \tag{8}$$

Where:

ρ_n : probability of a cluster of n consecutive defective sleeper.
ρ_d : Probability a sleeper is defective.

Further simulation tests assessed the impact on cluster distribution of accelerated decay on sleepers adjacent to failed sleepers, (active sleeper degradation). It was found that the difference between the simulated active decay compared to random decay remained low, despite a very high level of active decay being used in testing. Equation 9 was formulated as a modified version of equation 8 to provide a more accurate prediction for active sleeper degradation.

$$\rho_n = (1 - \rho_d) \times (\rho_p \times \rho_a)^{n/2} \tag{9}$$

ρ_n : probability of a cluster of n consecutive defective sleeper.
ρp : Probability a sleeper is defective by passive or normal decay.
ρa : Probability a sleeper is defective by active decay, i.e. for 50% active decay $\rho a = \rho p$ .x 1.5.
ρd : Probability a sleeper is defective.

As shown in Figure 2, equation 9 gives a better match to simulated active decay until the percentage of sleepers defective reaches 40% (4000 defective sleepers). From this piont, the original random decay equation, equation 8 is more accurate. Equation 9 becomes less reliable for larger cluster sizes. It is consided that equation 8 is the more suited equation for predicting defective sleeper cluster totals from a percentage of defective sleepers.

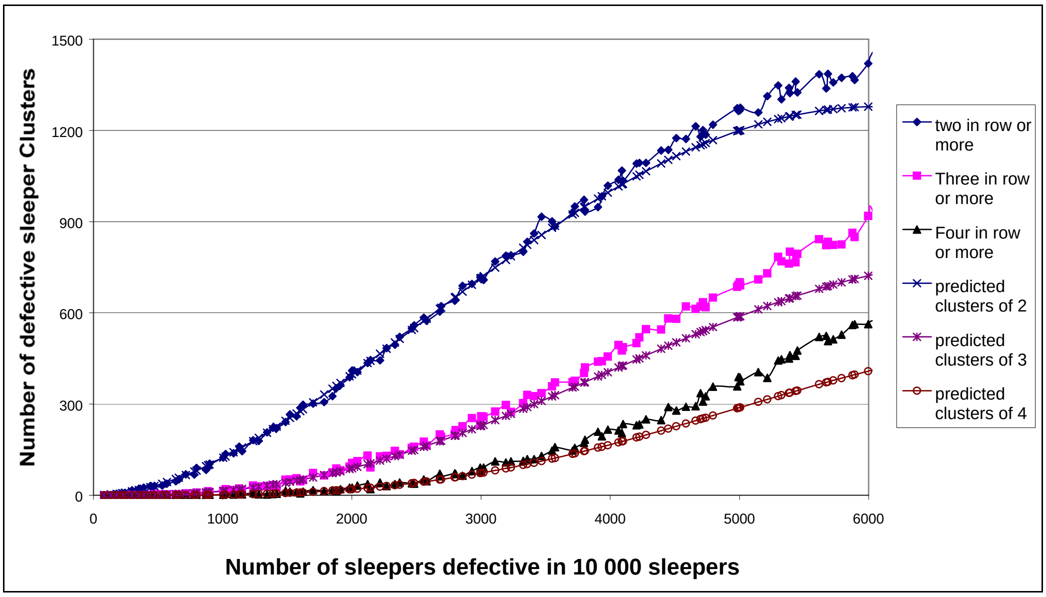

Figure 2 Defective sleeper cluster numbers for 50% active decay: simulated Vs predicted results using Equation 9

3.5 Planned Maintenance

The model simulates the effects of three maintenance activities, namely: tamping, re-sleepering and re-railing. It simulates the intervention of these maintenance activities based on user defined track condition limits for intervention on the main model parameters. Tamping interventions are based on a track roughness limit. Sleeper replacement intervention is based on a limit to the percentage of defective sleepers. Rail replacement intervention is based on the percentage life remaining to standard rail wear limits.

The model also simulates opportunity maintenance. This is when maintenance is performed on other segments in the track section under study, whilst the maintenance equipment is nearby performing regular planned maintenance on another segment.

TMPM makes some simplifying assumptions. It is assumed there is only one form of each of the main maintenance activities. The model does not calculate train delays associated with track maintenance activities, as temporary speed restrictions associated with maintenance work are insignificant in terms of the 10 Million Gross Tonnes (MGT) traffic intervals currently used. The model only allows for complete resleepering of defective sleepers under resleepering maintenance. Alternative strategies for resleepering, such as replacement of every fourth sleep independent of sleeper condition, are not handled. The maintenance sub-model allows for resleepering with rail replacement and tamping with both rail replacement and resleepering. However, it is assumed that the track roughness following such work is the same as for normal tamping operations. The sub-model assumes there is no splitting or cracking of sleepers from tamping operations.

3.6 Sensitivity Testing

The challenge with simulation models is to achieve the right balance between model complexity and the processing time for simulation. Inherently, such simulation models are only approximate and their accuracy depends on the number of iterative cycles used and on the accuracy of the inputs. Model details that have insignificant effect compared to input errors from other parts of the model are best removed to allow for an increase in the number iterations used for the simulation.

Sensitivity testing of the train delay sub-model showed it to be particularly sensitive to the relative levels of train speed and speed restriction settings. The delay sub-model also showed a strong dependency on acceleration and track gradient when segment lengths are on average less than one kilometre. No aspect of the sub-model was found to be redundant.

Sensitivity testing of the unplanned maintenance sub-model showed the sub-model to be highly dependent on the defective sleeper cluster size. The impact on the model outcomes, however, will be dependent on the cost margin between resleepering work and sleeper cluster repair. The impacts of the defective sleeper cluster size is seen as more significant to the overall maintenance costs than it is to the determination of the efficient maintenance strategy. The unplanned maintenance model was demonstrated to be integral to the model outcomes.

Sensitivity testing of the maintenance sub-model showed it to be highly dependent on the interaction between the resleepering and tamping policies. Sleeper degradation rates are highly dependent on wheel loading. As a result, train speed restrictions and tamping intervention levels can have a significant bearing on sleeper degradation rates. Sleeper degradation rates affect the level of efficient resleepering intervention. The use or otherwise of resleepering interventions to perform tamping affects the efficient tamping intervention cycle.

4. MODEL APPLICATION

The model has been applied in Australia to data provided by Queensland Rail. The results are shown here for bulk coal freight operations on a line that has seen a seven-fold growth in tonnage to 35 MGT/annum. Two scenarios are shown depicting operations for1973 and 1999. The results shows an efficient maintenance strategies for the two scenarios can be determined by the model. The efficient maintenance strategy is significantly changed by the altered track structure, traffic volumes and axle loads.

4.1 Bulk Minerals 1973 Operations

Figure 3 show the results of refining the tamping maintenance intervention levels in terms of maintenance costs. Figure 3 shows the breakdown of the costs due to train delays, planned maintenance set-up costs for the section and the maintenance costs of each segment in the model. The 4.6 mm track roughness intervention is the most economic. Tamping is actually occurring at every second 10 MGT iteration cycle of the model. The benefits in tamping in reducing dynamic wheel loads, reducing sleeper replacement costs is dominating the costs of tamping.

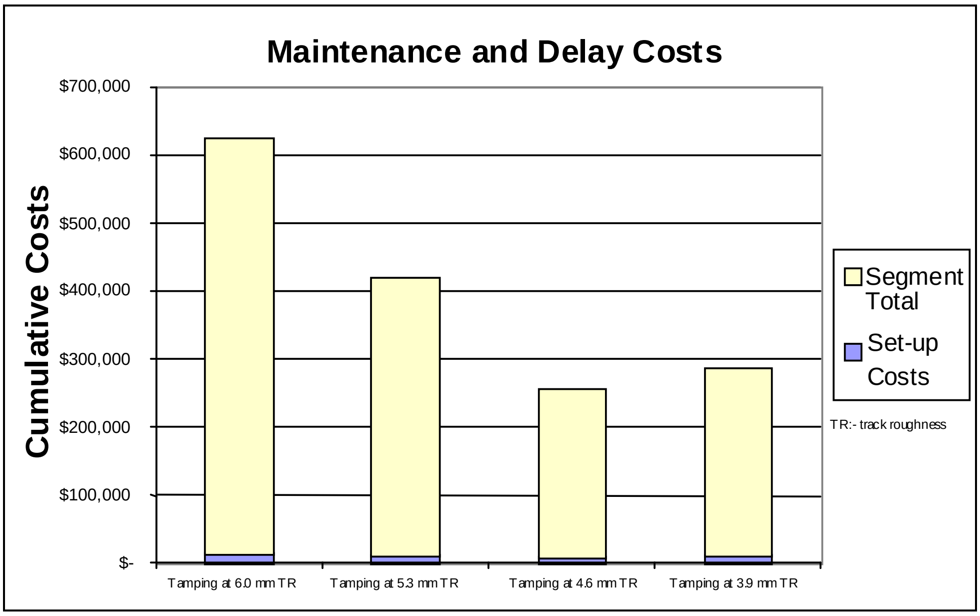

Figure 3 Bulk Minerals 1973 Scenario, Tamping intervention refinement

Figure 4 shows the refinement of resleepering intervention. Figure 4 shows the resleepering intervention levels of 4% and 5.5% defective sleepers recording the same maintenance costs. These two intervention cycles both occur within two model iterations of 10 MGT each.

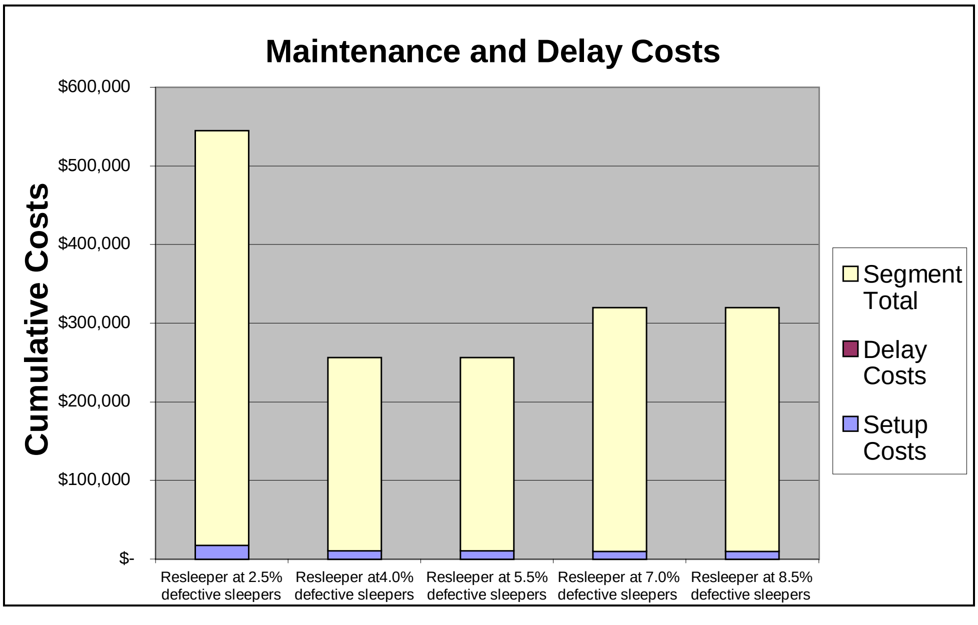

Figure 4 Bulk Minerals 1973, Sleeper Intervention Refinement

4.2 Bulk Minerals 1999 Operations

Figure 5 shows the results of the Bulk Minerals 1999 scenario. Maintenance level details are given in Table 1. Maintenance level 5 is the most relaxed maintenance with resleepering left until 25% of sleepers are defective and track roughness exceeds 18 mm.

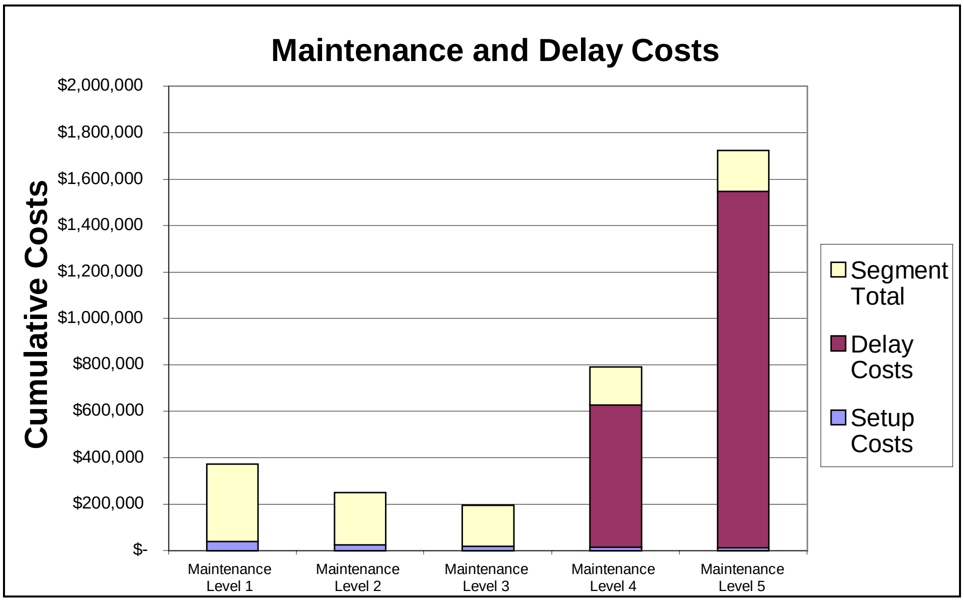

Figure 5 Bulk minerals 1999 Scenario, Continuous Maintenance

The third maintenance intervention plan has the lowest cost. Train delays are dominant in the overall operating costs (Figure 5). However, no train delays are experienced until the tamping intervention is set above 12 mm track roughness, as in maintenance plan 4 and 5. This is because train speeds in the scenario are already limited to 60 km/h. The high value of train delay costs is due to the high opportunity costs delays have in the scenario. Resleepering costs dominate the maintenance expenditure with most of track segments experiencing high sleeper failure rates.

Table 1. Maintenance Intervention: 1999 Bulk Minerals Operations

Maintenance Level	1	2	3	4	5
Tamping intervention level (mm track roughness)	6	9	12	15	18
Resleepering intervention level (percentage sleepers defective)	5	10	15	20	25

Figure 6 shows the results of further testing to refine tamping intervention levels. The results show only a marginal difference in the operating costs of the different maintenance intervention levels.

The time variability of these costs is just as significant as the different intervention level options. Figure 6 is taken at the end of 500 MGT period of traffic. The results suggest that intervention at 10.5 mm of track roughness is efficient. However, there is little difference between 9 and 12 mm tamping intervention levels given the same sleeper intervention.

6. CONCLUSIONS

6.1 General

TMPM has been shown able to determine an efficient intervention level for tamping and resleepering rail maintenance activities. In doing this, the model is not dependent on historical track condition data. The model simulates degrading track conditions, assigning costs to maintenance activities, as well as train operating costs associated with degrading track condition. The efficient maintenance intervention levels will depend on the track and traffic information (ie rail, sleeper and ballast details, track geometry, axel load, train speed, annual volume sub-grade type, drainage condition, temperature variation and average rainfall). This proves that the model can be of benefit to the maintenance planner if the cost outcomes produced can be proven sufficiently representative of actual track operating costs.

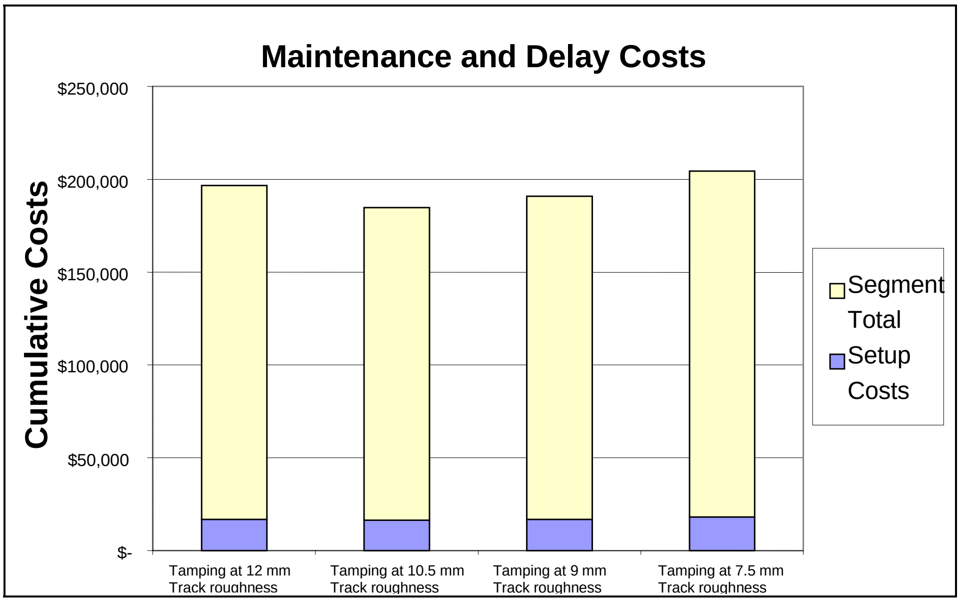

Figure 6 Bulk Minerals 1999, tamping refinement

The model is particularly useful to the track engineer in assessing “what-if” scenarios being independent of historical condition data. This capability can provide the user with an insight into various scenarios. In particular the track engineer can assess the possible benefits in reduced operating costs from upgrading track infrastructure or the impacts of changed traffic. This is an advantage over current track maintenance planning models.

6.2 Further Research

Three areas for further refinement have been identified during the model testing stage, namely:

- the range of maintenance activities modelled;
- the modelling of sleeper decay and clustering; and
- the traffic volume used for each iteration of the model.

Sensitivity testing has been performed on the model to test if any model features are redundant to the simulation accuracy. In the current computer model implementation, all the model features were found to be significant. However, the cycle time used to simulate train delays was shown to be excessive.

The main area for future work is in sleeper degradation and clustering calculations. As yet there is no proven method for predicting the distribution of defective sleepers. The interaction of failed sleepers and track roughness, particularly localised roughness such as pot-holing, on loading of sleepers is unknown.

Improving the modelling of sleeper age is also an area for further work. At present, the degradation sub-model assumes an average sleeper age. However, TMPM could track a distribution of sleeper ages through maintenance interventions, should the track degradation model be designed to degrade a range of sleeper ages.

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