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MODELLING TRACK MAINTENANCE PLANNING USING SIMULATION

Authors: Scott Simson, BE, M Eng student;
Luis Ferreira, BE, PhD, Associate Professor
Martin Murray, BE, PhD, Senior Lecturer

Address: School of Civil Engineering, Queensland University of Technology
PO Box 2434, Queensland, Australia 4001.
Ph: 07 38641542; Fax: 65 7 38641515; email:
s.simson@student.qut.edu.au

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ABSTRACT

In Australian rail freight operations, railway track maintenance costs comprise between 25-35 percent of total train operating costs. 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 provides a simulation of the costs and benefits of degrading railway track conditions and by the maintenance work that may be conducted.

The model simulates the degrading track condition using an existing track condition 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, which is currently implemented using a series of linked EXCEL spreadsheets, can deal with up to nine adjacent track segments with differing physical characteristics. Operating costs for up to five different train types are calculated from simulated train delays and maintenance work. The latter is a function of the level of track maintenance intervention specified by the user. The model outputs the net present value of the financial benefits of undertaking a given maintenance strategy, when compared with a base-case maintenance scenario.

The model is also capable of calculating the costs of track maintenance and train operations when traffic or track conditions are changed. This capability can provide the user with an insight into various what if 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.

After describing the model inputs and the assumptions used, the paper deals with 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.

1. INTRODUCTION

Railway transportation is one of the important sectors of the Australian industry. It represents approximately 1% of the national GDP in 1992 (Bureau of Industry Economics, 1993).

The railway track maintenance cost represents 22% (A$460 million in 1992) of total operating expenditures of Australian railway systems (Bureau of Industry Economics, 1993). Therefore, infrastructure providers have strong economic incentive to minimize the railway track maintenance cost while maintaining safety standards and providing satisfactory services to the railway track users.

QUT in collaboration with Queensland Rail have initiated a project titled “A Maintenance Planning Model for the Prediction of Increased Maintenance due to the Physical Degradation of Rail Track in Australia under Greater Axle Loads and Train Speeds”. This research is a part of that project along with a parallel effort being conducted into track degradation modelling.

2. PAST WORK

A considerable number of different maintenance planning systems have been developed by American and European railways. Different approaches and methods have been used on these systems. The key features of any track maintenance planning model are:

1. A track degradation model 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. Such a model is the Integrated Track Degradation Model (ITDM), Zhang (1999).
2. The failure limit assessment functions to determine condition limits for each of the failure modes. Track maintenance models will often use only a select 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. Where it has been attempted in models, this has generally been done with expert systems such as MARPAS, Shenton and Tunna (1991) and ECOTRACK, van Leeuwen (1996). There are also examples of operations research approaches to optimise activity planning, Esvald (1989) and Zarembski (1993).
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. Therefore specific track data is used and the result is a rail system dependent planning system. Such empirical models operate with the assumption that certain maintenance, train operation practices are followed, or that specific track types or track components are in use. As discussed by Esveld (1989), an empirical approach is 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.

Simson, *et al* (1998) found that current practice needs a maintenance model to be independent of the rail system and its operating practices. In addition, it needs to keep the data input requirements to a minimum.

3. MODEL SPECIFICATION

The Track Maintenance Planning Model (TMPM) has designed to meet the objectives sited by Simson, *et al* (1998). The model is designed to simulate the costs of running and maintaining rail track on a track link. A track link being 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 links track condition obtained from the ITDM, Zhang (1999), track degradation model to train delays and other operating costs.

In order to achieve the objective 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 the accumulating costs with passing of traffic. Four distinct sub-models make up the simulation. They are:

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

The structure of the model is depicted in Figure 1.

3.2. Track Degradation Model

Zhang (1999) has developed the ITDM model, which is a mechanistic model of track degradation. The mechanistic nature of ITDM means the model is railway system independent. The model does not require detailed historical track condition data to operate. This makes ITDM an ideal candidate track degradation model to use with TMPM as it fits well with the stated objective that the model operates with a minimum of track condition and activity monitoring data.

ITDM has three sub-components of track degradation:

- Track roughness, which represents the uneven settlement of the track structure with traffic;

- Rail wear, which represents wear from passing traffic and grinding operations;
- Sleeper degradation, which represents the decay in lateral restraint that is experienced in timber sleepers from fungal decay, end splitting and wear plate cutting; in concrete sleepers it is experienced as sleeper cracking.

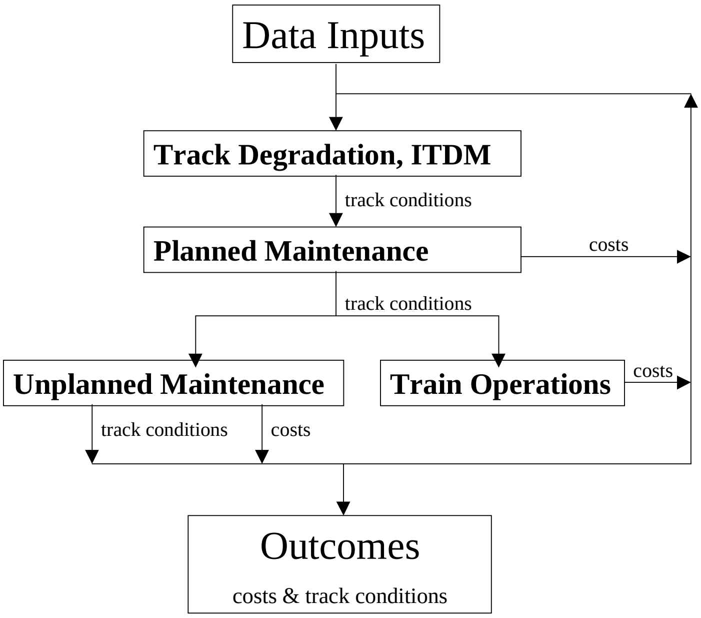

Figure 1 TMPM sub-model structure

In ITDM, it is assumed that a reasonable amount of track maintenance is performed. In this model these assumptions are replaced by the planned and unplanned maintenance sub-models that determine the timing and of maintenance interventions.

3.3. Train Operating costs

The model assigns train operating costs due to degraded track conditions based on train service delays. Train delays are the result of safety related speed restrictions. The model imposes speed restrictions based on track roughness calculated by the ITDM sub-model. The user sets train speed and track roughness limits as inputs to the model. 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 type over each consecutive track segment.

Equation 1 gives the simple train delay. Equation 2 calculates the train delays from braking when the next segment speed restriction is less then the restriction for the current segment.

$$TD_{st} = \delta_s \times \left(\frac{1}{\upsilon R_{st}} - \frac{1}{\upsilon_{st}} \right) \tag{1}$$

Where: TD_{st} = train delay for segment s and train service t
δ_s = Distance of 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

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

where: ϕ_t = the trains 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 have to be simulated. The train delay is give in Equation 3. The current train speed is accelerated by the increase in kinetic energy provided by the effective power to weight ratio. Equation 4 gives the relationship between the train speed and the train's effective power to weight ratio. Equation 5 gives the effective power to weight ratio of the train on the track segment.

$$TD_{st} = \int 1 - \frac{\upsilon(t)}{\upsilon_{st}} dt \tag{3}$$

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

$$\upsilon = 2 \times \left(\Gamma_{st} + \frac{1}{2} \upsilon^2 \right)^{\frac{1}{2}} \tag{4}$$

Where: υ = current train speed

$$\Gamma_{st} = \varphi_t - \theta_s \times \upsilon \times g \tag{5}$$

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 6. The simulation is run until the train has traveled to the end of the segment or has had to brake for the next segment as determined from Equation 6.

$$\delta_c = (\upsilon(t) - \upsilon f_{st}) / (\phi_t + \theta_s \times g) \times (\upsilon(t) + \upsilon f_{st}) / 2 \tag{6}$$

where δ_c = Critical braking distance

Train Length

This model does not account for the length of the train. The model assumes that the train length is a small fraction of the track segment length. If the train length where to similar to the segment lengths then the calculation of delays becomes much more complicated. The model would have to test for several segments behind the front of the train to determine what is the lowest speed restriction requirement for the length of the train. It is important to note the speed restrictions for track segments in the model 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 put 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 in track, very restrictive speed limits are used and repairs are performed immediately. The models iteration period is large compared to the time for these repairs, hence the repairs appear as instantaneous unplanned maintenance to the model.

Simulations of sleeper cluster formation were performed to formulate predictive equations for defective sleeper cluster repairs. Simulations where performed according to the work of Lake *et al.* (1998). Initially, Equation 7 was tested against simulated random sleeper degradation and was shown as accurate estimate of sleeper clusters numbers from the total percentage of defective sleepers.

$$\rho_n = (1 - \rho_d) \times \rho_d{}^n \tag{7}$$

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 8 was formulated as a modified version of equation 7 to provide a more accurate prediction for active sleeper degradation.

$$\rho_n = (1 - \rho_d) \times (\rho_p \times \rho_a)^{n/2} \tag{8}$$

ρ_n : probability of a cluster of n consecutive defective sleeper.

ρ_p : Probability a sleeper is defective by passive or normal decay.

ρ_a : Probability a sleeper is defective by active decay, i.e. for 50% active decay $\rho_a = \rho_p$ .x 1.5.

ρ_d : Probability a sleeper is defective.

Equation gives a better match to simulated active decay up until percentage of sleepers defective reaches 40%. This result is shown in Figure 2 From this piont onwards, the original random decay equation, equation 7 is more accurate. Equation 8 becomes less reliable for larger cluster sizes. It is consided that equation 7 is the more suited equation for predicting sleep cluster totals from a percentage of defective sleepers. At least until such time as an accurate assessment of what the active decay rate on sleepers is for each of the main sleeper degradation mechanisms.

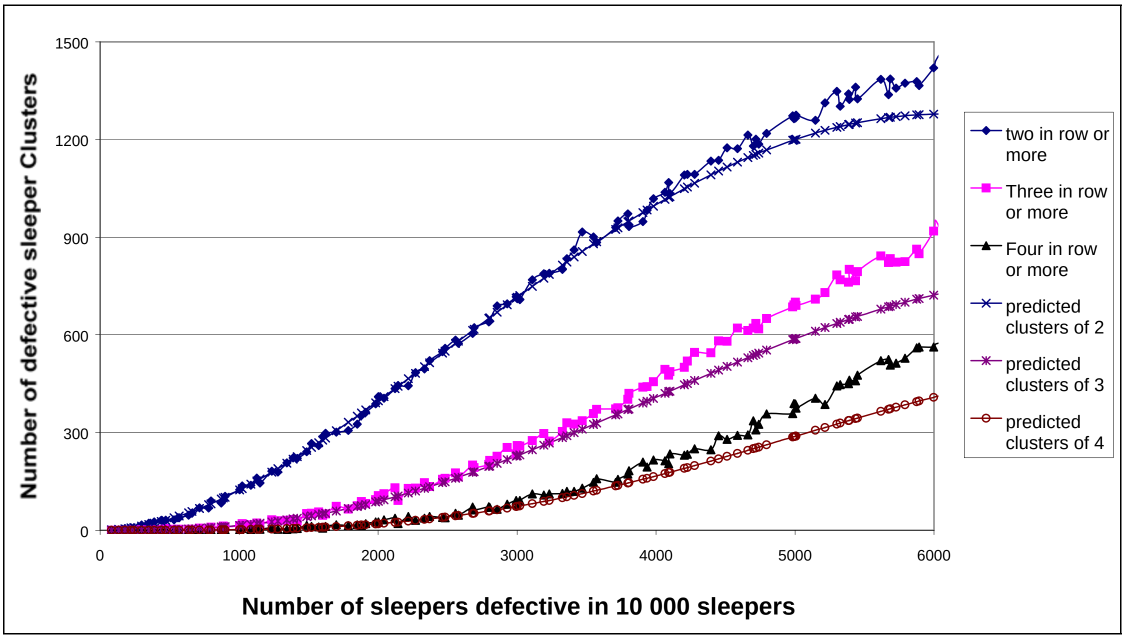

Figure 2 Defective sleeper cluster numbers for 50% active decay: simulated Vs predicted results using Equation 8

An initial proposed model known as formula one was then formed. The numbers of sleepers to be replaced is calculated from the probability of unsafe clusters as determined by Equation 7. The probability of clusters is multiplied by the number sleepers in a defective cluster and the number sleepers in a track section to give the number of sleepers to be replaced.

Two formulas for predicting the number of replaced defective sleeper clusters where tested. Both formulas use equation 7. Formula 1 assumes all the sleepers in clusters predicted above a critical size are replaced. Formula 2 assumes that sleepers replaced is one for every cluster predict to be above the critical size in the next iteration. To match typical TMPM data, the formula results were test assuming that 1% of the sleepers would become defective in the next period and sleeper replacement would be done at that time. Early data form TMPM simulations had shown no more than 3% of timber sleepers becoming defective in model iteration and that 1-2% was a typical result for high volume traffic.

Figure 3 displays the results of the simulation data against the predictive formulas. The simulation data shows that the number of defective sleepers stabilizes as cluster replacement rates increases to match sleeper decay. The formula 1 method overstates the number of sleepers from clusters being replaced. The stabilization of sleeper defective numbers occurs at a much lower percentage of sleepers defective in track. The results for formula 2 are a good representation of the full simulation of cluster replacement. The correlation between the simulation data and the total number of sleepers defective is good up until very high levels of sleeper defective numbers are reached. Figure 3 compares simulated results to the predictive formulas for cluster replacement.

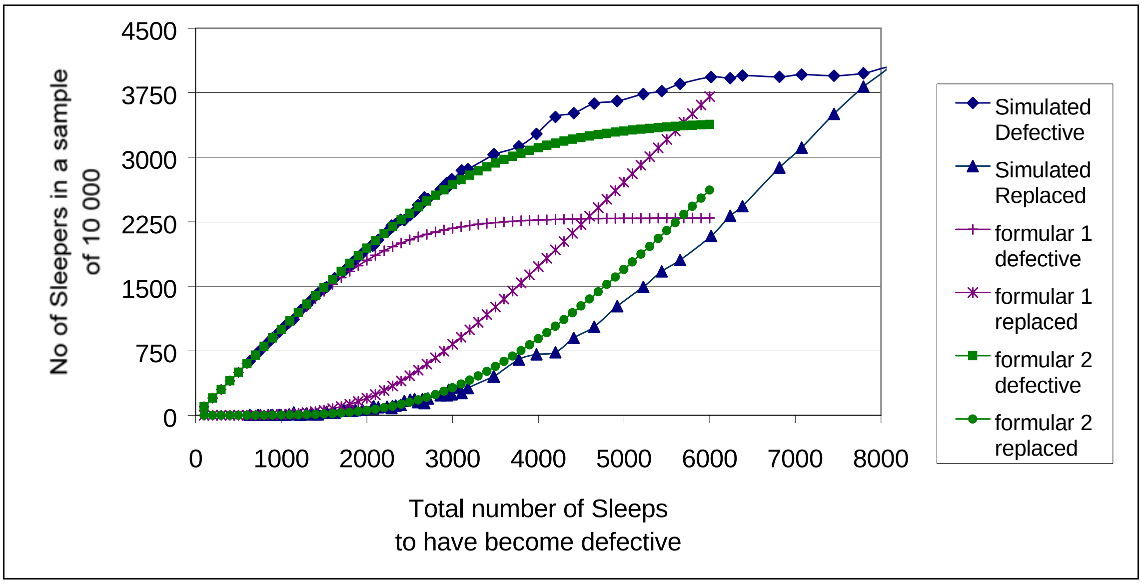

Figure 3 Sleeper Cluster Replacement, for cluster size of four consecutive sleepers and simulated active degradation at 20%

Formula 2 is used by TMPM rather than doing a full simulation for sleeper decay at each iteration. The performance of formula 2 is dependent on size of the simulation iteration. Should the failure rate of sleepers per iteration exceed 2% of sleepers formula to becomes inaccurate. A full simulation, being 10000 sleeps for each segment, Lake et al. (1999) done at each interval for each track section cannot be justified compared to the dramatic increase in computer processing that would be required.

3.5. Planned Maintenance

The model simulates the effects of three maintenance activities, namely: tamping, re-sleepering and re-railing. The model simulates the intervention of these maintenance activities based on user defined track condition limits for intervention.

Tamping interventions are made based on a track roughness limit. Sleeper replacement intervention is made on limit to the percentage of defective sleepers. Rail replacement intervention is based of a percentage life remaining to standard rail wear limits.

Opportunity maintenance is also simulated by the model. 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 MGT traffic intervals used in present computer implementation of the model. The model only allows for complete resleepering of defective sleepers under resleepering maintenance. It assumes all the replaced sleepers will be sound. Alternative strategies for resleepering such replace ever fourth sleep independent of sleeper condition are not handled by the model. This limitation in resleepering strategies can not be removed, as the degradation of sleepers is assumed essentially random. Alternative resleepering strategies are intended to prevent random pattern in sleeper degradation and thus the prospect of unsafe clusters of defective sleepers.

To handle alternative resleepering strategies the degradation of railway sleepers would need to be simulated fully similarly to the work done by Lake *at el.* (1999). Such a move would considerably increase the computer processing time of the model. It would likely increase processing by a factor of 4 to 20 times.

The maintenance sub-model allows for resleepering with rail replacement and tamping with both rail replacement and resleepering but 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.

4. MODEL APPLICATION

The model has been applied to track scenario data provided by Queensland Rail. The results are shown here for bulk coal freight operations in the Gooyella coal line. Two scenarios are shown depicting operations of 1973 and 1999. The results shows an optimal maintenance strategies for the two scenarios can be determined by the model and in this case the optimal maintenance strategy is significantly changed by the altered track structure, traffic volumes and axle loads.

4.1. Bulk minerals, Goonyella coal line, 1973

Figure 4 show the results of testing refining the tamping maintenance intervention levels. 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 5 shows the refinement of resleepering intervention. Figure 5 shows the resleepering intervention levels of 5% and 7% defective sleepers recording the same maintenance costs. These two intervention cycles both occur within two model iterations of 10 MGT. Resleepering at every second 10 MGT traffic cycle is the most economic cycle time that can be determined by the present TMPM computer program.

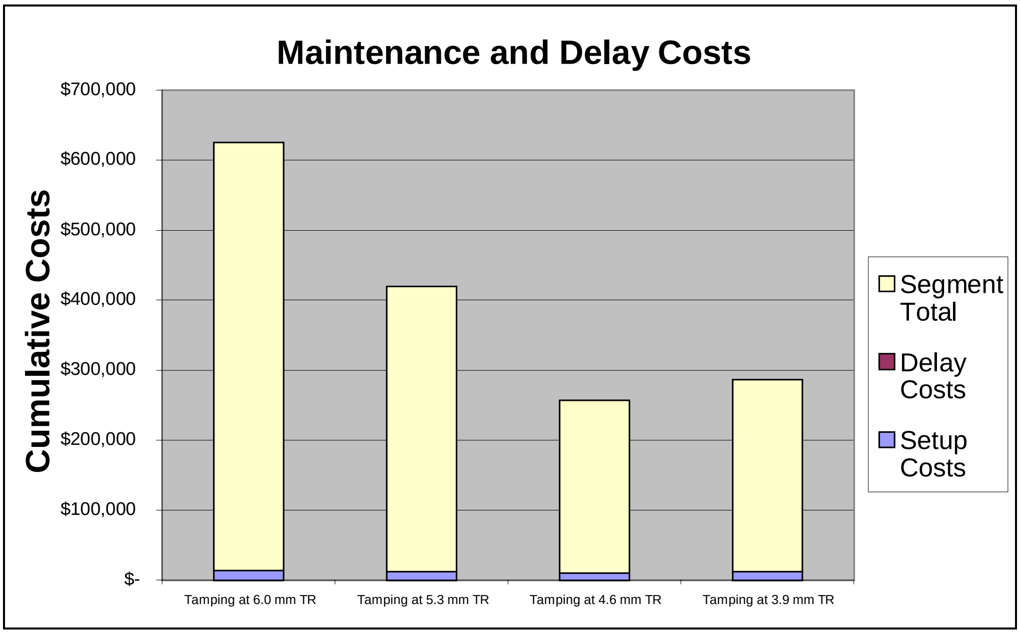

Figure 4 Bulk Minerals 1973 Scenario, Tamping intervention refinement

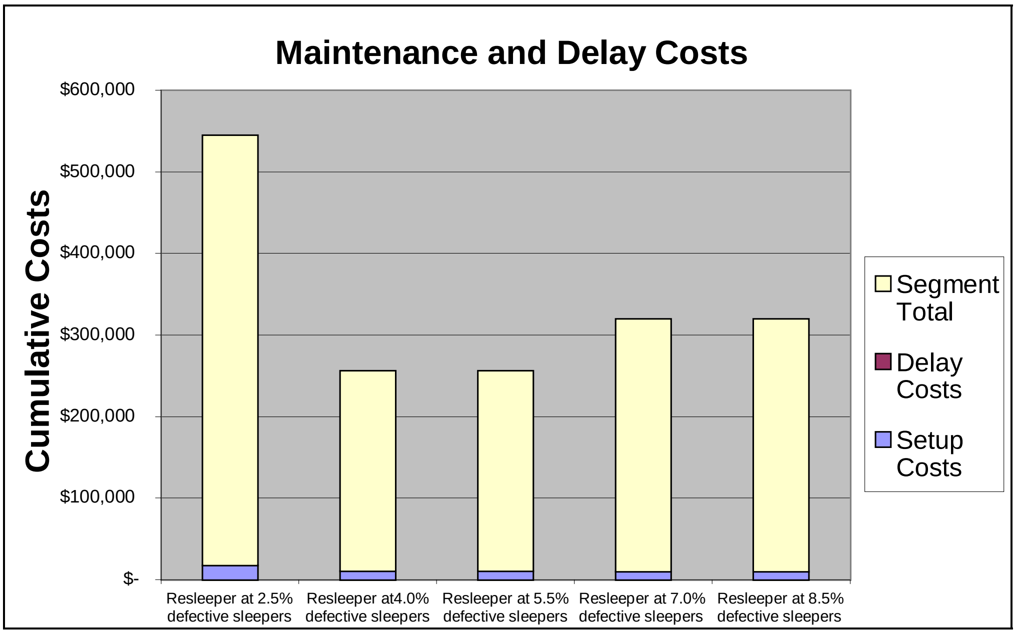

Figure 5 Bulk Minerals 1973, Sleeper Intervention Refinement

4.2. Bulk Minerals 1999

Figure 6 shows the results of the Bulk Minerals 1999 scenario under a continuous maintenance policy. A continuous maintenance policy had the lowest operating costs in the initial testing. From Figure 6, the third maintenance intervention plan is the lowest cost. Train delays are dominant to the overall operating costs in Figure 6 with no train delays until tamping intervention is set above 12 mm track roughness of the third maintenance intervention plan. This is because train speeds are already limited to 60 km/h. Train delay costs dominate due to the higher opportunity costs of train delays in the scenario. Resleepering costs dominates the maintenance expenditure with most of track segments experiencing high sleeper failure rates. The high incidence of concrete sleeper cracking is unexpected.

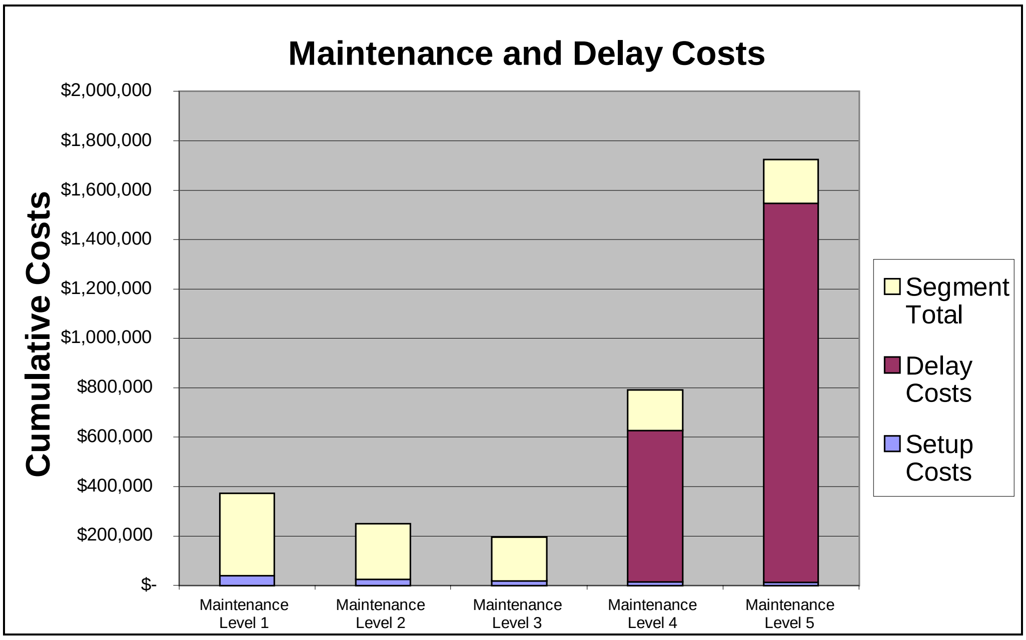

Figure 6 Bulk minerals 1999 Scenario, Continuous Maintenance

Figure 7 shows the results of further test to refine tamping intervention levels. The results show only a marginal difference in the operating costs of the different maintenance intervention levels.

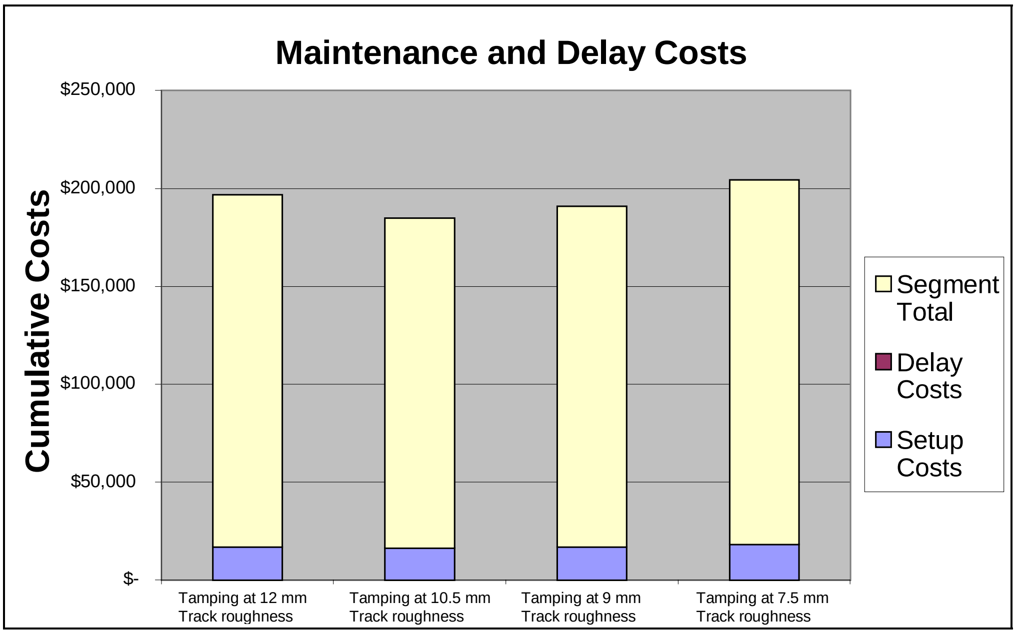

Figure 7 Bulk Minerals 1999, tamping refinement

The time variability of these costs is just as significant as the different intervention level options. Figure 7 is taken at the end of 500 MGT period of traffic. The figure suggests that intervention at 10.5 mm of track roughness is optimal. In truth there is little difference between 9 and 12 mm tamping intervention levels given the same sleeper intervention.

5. MODEL CRITICAL REVIEW

Four modeling deficiencies have been identified in the model formulation and subsequent testing. These are:

- the range of maintenance activity modelled;
- the modelling of sleeper decay and clustering; and
- the traffic volume of models iteration cycle.

Further work is required to address some of these deficiencies in the model.

5.1. Maintenance activities modeled

TMPM is currently limited in its ability to model the diversity of track maintenance activities. Regular maintenance activities currently not modeled by TMPM are:

- Rail grinding;
- Ballast undercutting; and
- Ballast blowing.

Rail grinding is not modeled but rather assumed to be occurring effectively. This is because there is no means presently available to predict rail defects except through empirically developed functions. The prevention of rail defects is often the main justification for rail grinding. Rail grinding is also performed to optimize the rail profile, particularly in curves, for wear. Again, the ITDM rail degradation model does not model the plastic flows that cause rail profile deterioration.

5.2. Sleeper decay and clustering

There are shortcomings in sleeper condition modeling in the modeling of timber sleeper age and in selective re-sleepering maintenance. Sleeper age is assumed static due to ongoing sleeper maintenance by ITDM. With timber sleepers, this could introduce a significant error due to the sensitivity of sleeper degradation to sleeper age, Zhang (1999). The model does not allow for a percentage of sleepers to be defective as an initial modeling point.

TMPM currently only models basic re-sleepering maintenance. Effective modeling of alternative resleepering policies, such as a one in four replacement policy, could be incorporated into the model. However, this would be better pursued with specific sleeper models and the formulation of equations that can model the effectiveness of such strategies in controlling defective sleeper clusters and sleeper service life.

5.3. Iteration cycle traffic volumes

The model assumes that the traffic cycle volume is appropriate when considering maintenance interventions. This is a particular problem with low volume timber sleepered track. The decay of timber sleepers being time rather than traffic dependent. Ideally, the track degradation model needs to have an adjustable cycle time to account for high timber sleeper decay rates on low traffic volume train lines. Iteration cycles need to be at or below 2% of the expected sleeper life to give reliably accurate sleeper maintenance interventions.

5.4. Future work

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 localized roughness such as pot-holing, on loading of sleepers is unknown.

Improving the modeling of sleeper age is also an area for further work. At present, the ITDM model assumes an average sleeper age. However, it is quite conceivable for TMPM to track a distribution of sleeper ages through maintenance interventions, should the track degradation model be designed to degrade a range of sleeper ages. This same issue was identified by Zhang (1999) as an area of future work for the ITDM model.

6. CONCLUSIONS

TMPM has been shown able to determine an optimal 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 both planned and unplanned, as well as train operating costs were these costs relate to the degrading track conditions. The optimal maintenance intervention levels will depend on the track and traffic information. 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.

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 what if 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 the present world leading track maintenance planning models.

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