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Track Degradation Predication: Criteria, Methodology and Models

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Abstract:

Australian railway transport industry lags behind the world's best practice. A potential saving in operating costs of $A80 million per annum exists if world's best practice is achieved (Bureau of Industry Economics, 1995). The increasing pressure on optimisation of track maintenance has been due to a world-wide trend to increase axle loads and train speeds. Lack of understanding of track degradation mechanisms has been an obstacle in quantitative prediction of track deterioration through changed traffic and operational conditions. This paper aims to provide an insight into problems in track degradation modelling. Criteria to be employed for degradation modelling is discussed. Methodology of track degradation is analysed from the point of view of its ability to reflect the variety of traffic and operational parameters. Existing models for track degradation are then discussed focusing on their potential to incorporate inter-relationship of degradation of different track components

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Introduction

Railway transport is an important sector in Australian transport industry, but the performance of the railway industry lags behind the world best practice. There is a potential in operating cost savings of 16% ($A80 million) if world's best practice is achieved (Bureau of Industry Economics, 1995). The increasing pressure on optimisation of track maintenance has been due to a world-wide trend to increase axle loads and train speeds. This inevitably leads to reductions in the life of track components and increases in track maintenance costs. Lack of understanding of track degradation mechanisms has been an obstacle in quantitative prediction of track deterioration through changed traffic and operational conditions.

In Australia track management decision support tools are yet to be embraced in practice (Ferreira and Murray, 1997). The effects of organisational structural changes together with customer service pressures lead to the need to predict track degradation and hence future track performance with a high degree of certainty (Ferreira and Williams, 1997).

Most existing track degradation models have failed to incorporate all modes of track degradation. Furthermore, the interrelationships between degradation modes are rarely tackled. With existing models which do not deal with all degradation modes, this aspect has been difficult to be taken into account.

This paper aims to provide an insight into problems in track degradation modelling. Track degradation mechanisms are briefly discussed. Methodology of track degradation modelling is analysed from the point of view of its ability to reflect the variety of traffic and operational parameters. Criteria to be used for degradation modelling are then described. Existing models for track degradation are examined focusing on their potential to incorporate interrelationship of degradation of different track components. Finally an integrated model incorporating interrelationships of different deterioration modes is proposed.

Railway track degradation mechanisms

The deterioration of rail tracks is a complex process, where each major component may degrade and fail due to several modes. Deterioration of one component affects that of another. For the same component, several deterioration modes often exist concurrently. Most deterioration modes of track components and degradation of the whole track, are dependent on traffic and operating conditions.

Deterioration of rails

Rail degrades in terms of wear (primarily in curves), fatigue (in the form of various defect types), and plastic flow (in the form of corrugations in rails, together with mushrooming of the rail head).

Table 1 Rail wear rates of different materials versus tonnage

Rails	Relative Rail Wear Rate to Standard Carbon Rails				
	42 MGT*	66 MGT	93 MGT	133 MGT	166 MGT
STD Carbon	1.00	1.00	1.00	1.00	1.00
Cr-Nb-V	0.79	0.89	0.93	0.93	0.93
Cr-M0	0.59	0.57	0.70	0.72	0.74
Head-Hardened	0.26	0.42	0.47	0.50	0.46

* MGT = million gross tonnes
(Source: O'Rourke, 1987, Table 1)

Wear: Excessive gauge face wear has been the major problem in curves on heavy haul railway tracks (O'Rourke, 1987). This is the controlling factor of rail life in many cases (Kalousek, 1987).

Soft steels experience higher wear rates than head hardened rails. Table 1 illustrates the relative wear rates of different materials at certain tonnage in comparison with standard carbon rails. It can be seen that at tonnage higher than 100 million gross tonnes (MGT), the wear rates tend to be stable. Head hardened rails, the most wear-resistant rails, exhibit roughly half the wear rate of standard carbon steel rails.

Lubrication has a very significant influence in reducing rail wear and increasing rail life (Clayton and Steele, 1987; and Kalousek, 1987). However, under well lubricated conditions wear rates of premium metallurgy rails and standard carbon steel rails do not vary as much as under dry conditions. Other factors influencing rail wear include track structure and traffic, e.g. grade, curvature, axle load and train speed.

Surface/Subsurface Defects: Surface initiated defects include head checking and surface cracking. Surface checking or surface initiated rolling fatigue does not itself represent a significant loss of material from the rail surface, unless it results in material spalling (Kalousek, 1987)

The initiation and growth of sub-surface flaws, which are primary factors of fatigue failures, have been regarded as important factors governing the life of rails in heavy haul lines (Blicblau and Chipperfield, 1984). On some Australian heavy haul lines fatigue defects are responsible for more rail failures than all other causes combined (Blicblau and Chipperfield, 1984). The majority of fatigue problems encountered in rails are confined to the rail head and arise from the wheel-rail contact.

Rail Corrugation: Rail corrugation gives rise to dynamic forces, causing noise, discomfort to passengers, possible damage to freight, accelerated wear of rails, and damage to sleepers, fastenings and ballast. Because the formation of corrugations is a complex process, studies into the cause of rail corrugation often lead to discrepant conclusions. One study concluded that "soft' rail materials are vulnerable to corrugations (Mair, Jupp and Groenhout, 1978), whereas another found that softer steels do not corrugate as readily as harder ones (Clark, 1984)

Deterioration of sleepers

Timber Sleepers: Timber sleepers deteriorate in terms of splits, plate/rail cut, spike-kill (damage to sleepers due to loose spikes), termite attack, and fungal decay In most cases they are replaced because of damage from termites, spike killing, rot, etc. Studies have revealed that fungal decay dominates sleeper deterioration, accounting for more than 50% of sleeper condemnations (ROA, 1990; and Davis and Chow, 1989). The second major failure mode is splitting. All the other failure modes contribute only very slightly, although plate cutting appears to be the third most important cause of failure.

Concrete Sleepers: Little evidence is available on concrete sleeper deterioration and failure. Cracking is thought to be one of the possible failure modes, which is likely to be the case when support of the sleeper is inadequate.

Attrition at the bottom edges and side faces of sleepers has been evident on Queensland Rail's Goonyella to Hay Point heavy haul line (Powell, 1989), suggesting that under certain conditions, attrition of concrete sleepers could become a dominant deterioration mode.

The area under rail pads can cause concrete sleeper degradation. Due to intrusion of fines, dust, and moisture, the area can also be worn, resulting in settlement of rail pads, and looseness of fastenings. Tests in the USA indicated that up to two millimetres of abrasion can be produced by 51 MGT traffic, and that harder rail pads cause more abrasion than softer, rubber based ones (Reiff, 1993).

Steel Sleepers: Few problems have been reported with steel sleepers A steel sleepered track carried 550 MGT without major problems (Jeffs and Mayhew, 1990). Corrosion is expected to be a deterioration mode associated with steel sleepers, but little evidence is available to date. Sleeper foot wear under repeated traffic loading can result in a cutting and digging action with its crib surfaces The ballast can be squeezed aside forming mushrooming shoulders, allowing track settlement Laboratory tests (Jeffs, 1989) suggested that ballast particle roundness has a significant effect on this action.

Ballast Deterioration

Ballast Fouling: Ballast fouling, which is a major degradation mode, is a process of ballast voids being filled with fines, from either ballast particle abrasion or foreign substance intrusion such as windblown dust, spillage from wagons, and pumped fine from underlying subgrade. Most research suggests that the majority of fines are from the ballast itself, as a result of abrasion, impact and physical and chemical weathering (e.g. Selig, Collingwood and Field, 1988). The fouling process is influenced by track loading, particle size distribution, particle shape and particle surface characteristics.

Ballast fouling is not considered to be significant until the amount of fines (particles of diameter smaller than 0.075 mm) reaches 10 percent or more (Selig, 1985) When ballast voids are completely filled with fines, the ballast becomes deformable when wet, and stiff when dry (or frozen in cool weather), preventing proper track surfacing.

Deterioration of Aggregate Material: Aggregate material deterioration is another major degradation mode, by either particle fracture or interparticle grinding/attrition. The deterioration process is closely correlated with the properties of its material. These properties are represented by various indices derived from different test procedures such as Los Angeles Abrasion number (LAA), mill abrasion (MA), and abrasion number (AN) However, it is suggested by Chrismer (1988) that these tests are deficient in accounting for chemical breakdown

Sub-grade degradation

Traffic related subgrade failures include (1) massive shear failure; (2) progressive shear failure; and (3) attrition (Stokely and McNutt, 1983; and Selig and Waters, 1993)

Mode (1) failure is usually associated with an embankment section It is likely to occur when the subgrade strength diminishes because of increasing moisture content, especially during heavy rainfall and flooding (Selig and Waters, 1993). Mode (2) failure results in loss of alignment and cross level to the same side. Mode (3) failure is likely to occur in the presence of water. Slurry will form at the ballast and subgrade interface. Where track irregularities exist, which initiate track pumping, the slurry can be pumped upwards into the ballast and reach the sleeper/ballast interface.

Methodology of track degradation modelling

In degradation analysis two basic methodologies are used namely: the statistical analysis and engineering approach (Bing and Gross, 1983). The statistical approach involves the analysis of large sample observations of actual track performance and the affecting parameters. Correlation, variance, and regression analyses may be used to develop track degradation models. The engineering approach involves establishing, by theory or by testing, the mechanical properties of track components. Track structure analysis models are used to calculate the forces and stresses in individual track components. These stress levels are then used to assess the possibility of defect development.

The advantage of the engineering approach is that the track response to traffic parameters can be incorporated. The difficulty involved in this approach is that the response to traffic parameters of some track components is hard to quantify. With the statistical analysis variations in data recording and interpretation may invalidate the models.

Criteria of track degradation modelling

Track life and track degradation

There is no clear definition of track life, and hence no means to assess it The term "track degradation" is also ambiguous It is often used as a generalised term for track geometry distortion or degradation of individual track components.

A single criterion describing track behaviour is the track condition index (TCI). The TCI is dependent on traffic, track, and maintenance parameters It is derived from data measured by track recording cars, providing a generalised indication of track quality However, it can not give information on deterioration mechanisms, neither can it reflect such track problems as rail fatigue defects, as well as sleeper and ballast deterioration

Criteria

The life of rails is often expressed in terms of the number of Million Gross Tonnes (MGT) they have carried Their renewal has long been determined by wear limits, especially in curved tracks. However, with improvement of rail materials and since rail lubrication and profile grinding were introduced, rail wear life has been prolonged significantly so that fatigue defect development has emerged as a major reason for rail replacement in heavy haul situations

Rail corrugation, though not a determining factor for rail replacement, accelerates wear and fatigue defect development. It is also used for scheduling grinding Therefore, corrugation should be a criterion in rail deterioration modelling.

The life cycle of sleepers is determined by the years of their service (ORE, 1987). Timber sleepers are replaced mainly through environmental factors. Their degradation process has been well understood except for the role of traffic parameters in degradation The dominant reason for replacement of concrete sleepers has not been established.

Ballast life is also expressed in years of service. The criterion most used is the degree of ballast voids being filled by mechanical breakdown of ballast itself. Where intrusion of foreign substances is clearly evident, degradation of ballast becomes difficult to quantify

The subgrade of railway tracks often causes problems to the super structure of the track, but it is difficult to define its degradation. The bearing capacity of subgrade varies with the moisture content of its material and with drainage conditions, leading to differential settlement of the track and distortion of track geometry. Subgrade treatment on existing tracks is more expensive than on new track.

Track deterioration modelling

Rail Wear

There are two categories of models for wear prediction, empirical and mechanistic Generally, the empirical approach for predicting rail wear life cannot account for the interactive effects developed when two or more parameters are altered to improve rail wear life. In addition, it does not allow a detailed analysis of the effectiveness of alternative methods of improving rail performance, such as rail profiling, improved vehicles, or lubrication (Tew, Marich and Mutton, 1991)

Mechanistic models are based on actual wear mechanisms of rails. This involves firstly accurate identification of these wear mechanisms. Two wear mechanisms have been proposed (Clayton and Steele, 1987): deformation wear and fatigue (progressive damage) wear Each of these two mechanisms explains some of the observed wear behaviour patterns but not all of them.

Rail Fatigue Defects

In modelling fatigue defects, cumulative probability techniques are used mostly. The probability of occurrence of rail defects as a function of tonnage (MGT) is considered to follow a Weibull distribution (Besuner, Stone, Schoenberg and de Herrera, 1978).

Australian researchers have been leading mechanistic modelling of rail fatigue (Marich and Curcio, 1978; Chipperfield and Blicblau 1984) Using a mechanistic approach in combination with Weibull distribution techniques, a fatigue population prediction model has been developed (Chipperfield and Blicblau 1984).

Rail Corrugation

There are methods for correlating the magnitude of depth and wavelength of corrugations to traffic parameters Rail related models have focused on the assessment of corrugation tendency rather than quantitative prediction. Material yield strength, ultimate tensile strength, and average contact stress have been used to assess the likelihood of corrugation occurrence (Grassie, 1994).

Statistical Analysis of Sleeper Life Distribution

Statistical analysis of sleeper life distribution has long been used in determination of sleeper replacement strategies initiated by the US Forest Service (Maclean, 1965). The percentages of sleepers that need replacement are found to be proportional to the percentage of average life. The method uses a normal distribution function to represent sleeper life. Tucker (1985) suggested that a Weibull distribution is a more suitable form for a time-to-failure distribution for railway sleepers In general, statistical analysis requires relatively large amounts of data for estimation of sleeper life distribution to fit the prediction curves closely.

Mechanistic Analysis of Sleeper Life

Timber sleeper stress conditions are correlated with sleeper life, based on mechanistic analysis of timber sleepers The presumption 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 standardised wheel loading cycles over the same track section and time period. An environmental factor also needs to be included because load-dependent factors contribute only slightly to timber sleeper failure.

Void-Filling Technique for Ballast Analysis

One technique to quantify ballast life developed by Canadian Pacific Railways assesses the allowable MGT before the ballast must be renewed (Klassen, Clifton and Watters, 1987) This concept considers the end point of ballast life to be when the inter-particle voids are filled with fine fouling material

Particle Mean Size Method

The Australian method uses mean size of ballast particles as a criterion (Ravitharan and Martin, 1996) to explain the dependency of ballast strength on the distribution of sizes of ballast aggregates. Ballast life estimation is based on axle load, wet and dry strength, gross tonnage, initial gradation and the gradation limit. Degradation due to tamping and coal intrusion is not included. The ballast life is performance-based using limited data.

It was found that below a mean size of 10 mm, ballast strength declines significantly. However, the mean size limit is considered to be conservative, because no significant ballast weakening will be evident if the fine material consists of crushed ballast alone.

Towards an integrated track degradation model

Comprehensive prediction of track degradation needs accurate quantification of in-track behaviour of each component, and more importantly a good understanding of interactions between degradation modes There is still considerable research effort needed in the area of deterioration prediction based on mechanistic relationships

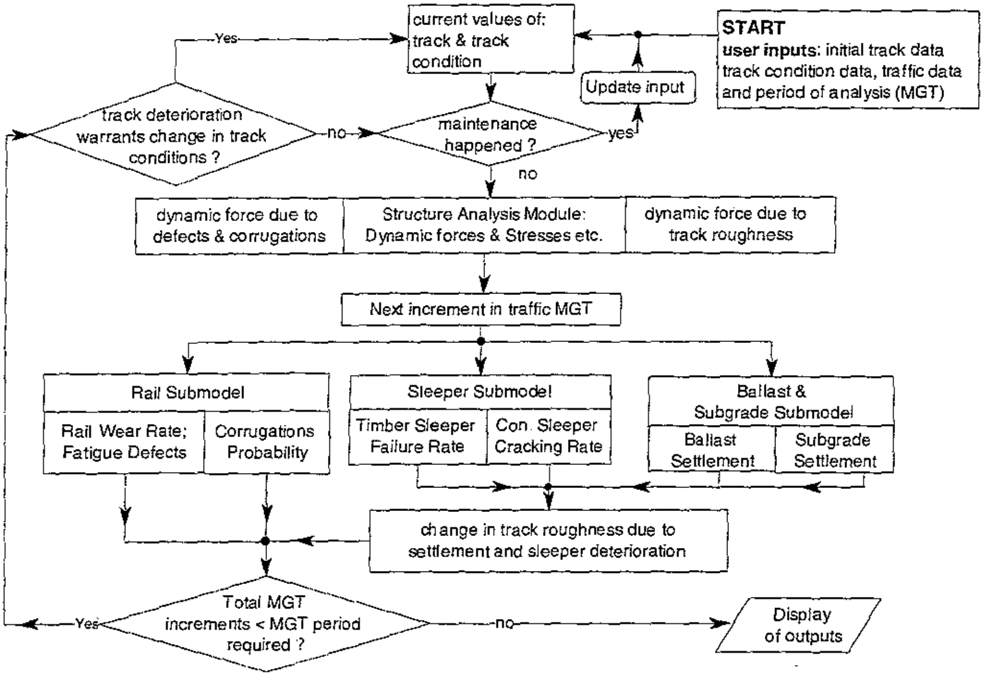

Figure 1 Framework of integrated model

Degradation prediction based on mechanistic relationships allows new technology and new research results to be incorporated into the models as they become available. The integrated model of track degradation outlined in this section will attempt to embrace all those major factors which may influence service life of track components. The philosophy for analysis of deterioration of any component will be based on mechanistic relationships wherever possible. Figure 1 shows the proposed model framework.

At the starting point the user needs to input current track conditions, traffic parameters and the period for analysis. The model will update track condition based on user inputs. It then simulates track conditions by tonnage intervals with increments of 5 to 10 MGT depending on traffic parameters. If some maintenance has been carried out since the last update, the model will update the track condition automatically. Otherwise, it will go on to calculate dynamic forces and to determine stress levels with a sub-model on track components whose degradation is dependent on stresses. The model consists of the following inter-related deterioration sub-models: rail, sleeper, ballast and sub-grade.

At the end of a given cycle, if the total tonnage has not reached the maximum tonnage for a given analysis, the output of the degradation sub-models will be assessed to determine if the track deterioration warrants a change in track conditions. If track deterioration is significant, the track condition will be updated. Otherwise the input will be directly fed into the next cycle of the estimation of deterioration. The effects of up-to-date track deterioration will be reflected in consequent calculations by way of increased dynamic loads. During each step in the cycle, an evaluation is made of the uncertainties involved in the prediction process - a risk or uncertainty factor is included in order to assess the reliability of the predictions. It is anticipated that the risk factor will grow with each cycle, to the point beyond which the prediction and therefore (more importantly) the planning processes become meaningless.

Rail sub-model

Rail Wear: The deformation based wear model (Clayton and Steele, 1987) is considered most suitable because it predicts the most important rail wear behaviour - linear dependency of rail wear on applied loads. Calibration will be carried out for Australian conditions.

Rail Fatigue: The BHP fatigue defect population prediction method (Chipperfield and Blicblau, 1984) is considered. The model, while being essentially an application of Weibull distribution technique, provides a reliable mechanistic analysis of fatigue defect initiation and growth. Incorporation of this analysis into defect population distribution analysis gives a better estimation of fatigue defects than a purely statistical method.

Corrugation: The approach proposed by Twidle, Tew, and Soeleiman (1991) will be used to determine the likelihood of corrugation occurrence.

Sleeper sub-model

For timber sleepers Lamson and Dowdall (1985) method is considered the most appropriate option. This method is less sensitive to the size of data bank than a statistical approach. This is more suitable for analysis of sleeper condition over a relatively small section of track, say as short as 200 metres, containing only a few hundred sleepers.

For concrete sleepers the analysis will be confined to the likelihood of cracking under different bending moments. Deterioration analysis for steel sleepers is yet to be included at the present stage due to lack of understanding of their deterioration mechanisms, and there being insufficient failure data for a statistical analysis of them.

Ballast and sub-grade sub-model

The deterioration of ballast may be determined either using the method proposed by Ravitharan and Martin (1996) or the AAR method (Chrismer, 1989). With the former model, ballast deterioration can not be related to any other components' performance. The AAR method, on the other hand, relates ballast, as well as sub-grade, settlement to track geometry deterioration This provides the possibility of relating ballast degradation to the performance of other track components

The level of stress in sub-grade is normally a major criterion for assessment of its condition The AAR method can also examine sub-grade condition Any settlement in sub-grade will be converted into a change in track roughness (standard deviation of track top line from a straight reference line).

Interaction of deterioration of components

The interactions between the various types of deterioration of track components is illustrated diagrammatically in Figure 2. The effect of deterioration of one component on that of the others is reflected by changes in dynamic forces on the rail. Rail deterioration will result in a rougher rail surface and increased dynamic forces The presence of rail corrugation will also increase the dynamic forces. Deterioration of sleepers, ballast and sub-grade is thought to have an effect on track roughness Track roughness is in turn a factor influencing dynamic forces The dynamic forces due to track roughness can be determined and their effect on deterioration mode will be carried forward to the cyclic simulation of track deterioration. Although the relationship between track roughness and sleeper deterioration has not been established, it is believed that deterioration of sleepers will also increase track roughness

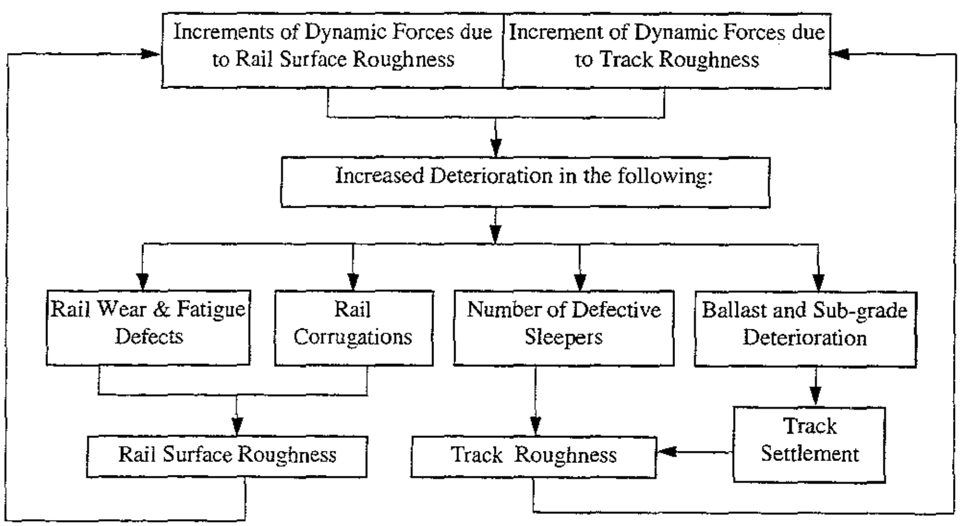

Figure 2 Interactions of deterioration of track components

Model validation and calibration

The model will be validated and calibrated using data collected from Australian railway systems. As part of data collection process, 34 trial track sections on the Queensland Rail network have been selected for monitoring track degradation In selecting the track sections, it was important to cover a wide range of track structures and traffic conditions. For comparison purposes, the test sections have been selected in pairs wherever possible, one of which serves as a control section

Conclusion

A conceptual framework for an integrated track degradation model has been developed, and is put forward in this paper. The framework has been designed to satisfy the following needs:

- the lack of available track degradation models which can serve as a single tool for analysis of deterioration of each railway track component;
- the over-simplification of track degradation in one way or another by existing degradation models; and
- the lack of attention to interactions of deterioration of one component with another.

The model proposed here, will enable comprehensive prediction of track degradation, through accurate quantification of in-track behaviour of each track component, and more importantly a good understanding of interrelationships between degradation modes

In order to incorporate the interactions of different track components, mechanistic relationships are being employed in the model, allowing new technology and new research results to be incorporated at later stages.

Future research tasks will include calibration of suitable degradation sub-models; the development of the interrelationships of degradation of individual components; and validation of the model using data collected by Queensland Rail The successful implementation of the project will pave the way for optimisation of maintenance scheduling which is a parallel research project being carried out at QUT

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