AN INTEGRATED MODEL FOR TRACK DEGRADATION PREDICTION

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Abstract

The paper presents an integrated and mechanistic method for a track degradation model using current sub-models as the basic building blocks. Unlike existing approaches, however, the modelling framework takes into account the degradation effects due to the interactions between track components, enabling analyses of either overall track condition or the condition of the individual track components. It allows prediction of future track condition from any starting track status.

INTRODUCTION

In Australia, due to a trend to privatisation and competition within government owned railway systems, there has been a move towards "vertical" separation of functions, such as the management and control of track infrastructure and train operations. Infrastructure provision is increasingly seen as a separate business to be owned, managed, and maintained. Introduction of heavier axle loads and higher train speeds has increased the need to optimise track maintenance planning, in order to encourage rail transport to compete with other transport modes by providing train operators with minimum track access costs. However, track management decision support tools which aid the optimisation process are yet to be embraced in Australian railway practice (Ferreira and Murray, 1997).

Rail operations are optimised under preventative maintenance policies. The prediction of railway track degradation is vital for the implementation of such policies. Although there are a number of useful predictive models currently in use, the factors influencing track deterioration are often limited only to a few specific parameters. The importance of linking track degradation modelling to track maintenance planning suggests that degradation criteria should be confined to parameters having the greatest influence on total track operating costs. Effective control of these parameters means better quality track, less maintenance cost and increased productivity.

A comprehensive literature investigation has revealed that there are no track degradation models generally available which can serve as a single tool for analysis of deterioration of each railway track component (Zhang *et al.*, 1997a). Most of the existing degradation models tend to over-simplify track degradation in one way or another. Comprehensive prediction of track degradation needs accurate quantification of in-track behaviour of each track component, and more importantly a good understanding of interactions between degradation modes.

This paper describes an integrated track degradation model (ITDM) using current sub-models as the basic building blocks. Unlike existing approaches, the modelling framework takes into account the degradation effects due to the interactions between track components. This enables analyses of either overall track condition or the condition of the individual track components. It allows prediction of future track condition from any initial track status.

MODEL FRAMEWORK

The ITDM model uses mechanistic relationships wherever possible. It also endeavours to embrace all the major factors which may influence service life of track components. The framework of the model is shown in *Figure 1*.

The model consists of inter-related deterioration sub-models for each of rail, sleeper, ballast and subgrade. At the starting point, the user needs to input current track conditions, traffic parameters and the period for analysis. During operation of the model, it updates track conditions based on progressive deterioration of the track. It simulates track conditions by tonnage and time with given increments depending on traffic parameters. If some maintenance has been carried out within the modelling period, the model will update the track condition accordingly. Otherwise, the model will

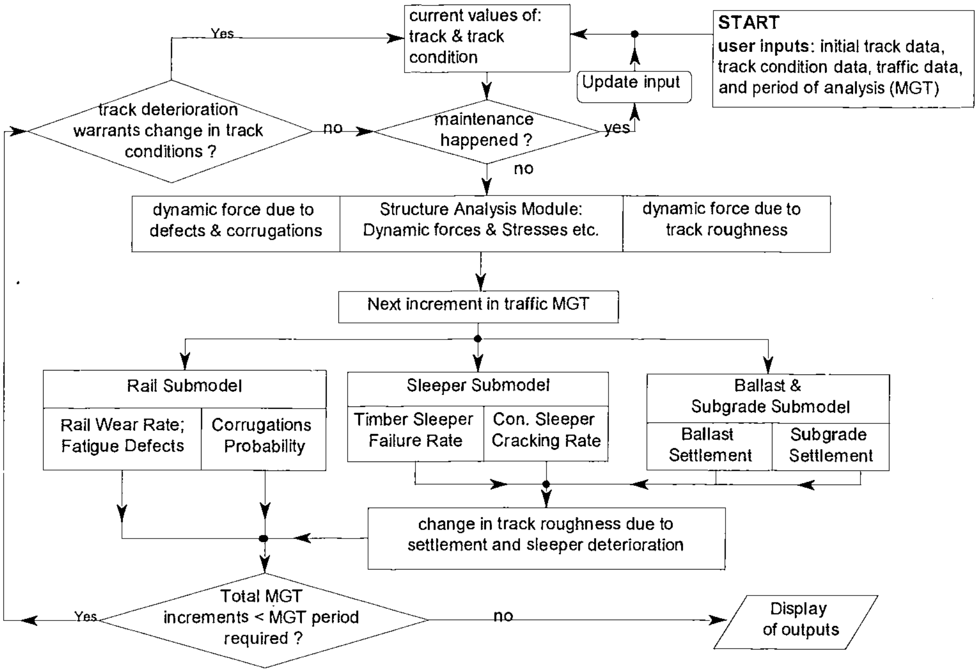

Figure 1 - Model framework

go on to calculate forces on the rail top and determine stress levels on track components whose degradation is stress-dependent.

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 is assessed to determine if deterioration of the track warrants a change in track condition. If track deterioration is significant, the track condition is updated. Otherwise, the input is fed directly into the next cycle of the estimation of deterioration. The effects of up-to-date track deterioration are reflected in related calculations by way of redistribution of axle 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 likely that risk factors will increase with each cycle, to the point beyond which prediction and therefore, more importantly, the planning processes become inapplicable.

ENGINEERING BASIS OF THE MODEL

Philosophy of track degradation modelling

To model the track degradation process, an understanding of track degradation mechanisms is necessary. Track degradation is a very complex process. Degradation of one component of the track affects that of others. The types of degradation which have major consequences on track maintenance planning are the important ones to be quantified. Many factors can affect track degradation and some of these factor may change with time. Therefore, suitable modelling techniques must be employed. Detailed investigation into these matters has been carried out and reported elsewhere (Zhang *et al.*, 1997b).

There are two basic methodologies used in degradation analysis, namely: the statistical analysis approach and the 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 then be used to develop track degradation models. With this method, variations in data recording and interpretation may invalidate the models.

On the other hand, the engineering approach involves establishing, by theory or by testing, the mechanical properties of track components. Track structure analysis models based on these properties are then used to calculate the forces and stresses in individual track components; the stresses are assessed to determine the possibility of the development of defects in the components. The advantage of the engineering approach is that the response of track to traffic parameters can be incorporated, though the response of some track components is hard to quantify.

Rail sub-model

For rail degradation analysis two aspects need to be considered: wear and fatigue defects. Rail wear has long been a dominant factor of rail replacement, especially in curves. However, due to lubrication, rail material improvement, and rail grinding, the wear rate on some tracks becomes so insignificant that fatigue defects have become the major cause for rail replacement. The ITDM model uses a set of boundary conditions to assess the possible failure mode of the rails taking into consideration effects of rail material hardness, lubrication condition, track curvature, grinding frequency, and traffic parameters. Then the sub-model carries out analysis rail wear. The rail wear prediction is based on deformation wear theory (Clayton and Steele, 1987), which is considered suitable for representing rail/wheel wear process. The fatigue defects of rails are traditionally predicted using statistical methods based on a Weibull distribution. Nowadays, however, this approach has become superseded by the practice of rail grinding which removes many defects before they become large enough to be predictable by the Weibull distribution method.

The deformation wear model suggested by Clayton and Steele (1987) is of the form :

$$W = \frac{KPS}{H} \tag{1}$$

where:

- W - wear rate;
- P - applied load;
- K - wear coefficient, a constant depending on specific test conditions;
- S - total sliding distance; and
- H - material hardness.

To determine sliding distance, use is made of the method of Ghonem and Kalousek (1984). The sliding in the wheel-rail contact region is due to microslip caused by rail and wheel geometrical constraints, and by yaw and hunting motion of the wheelset. The microslip is measured by the term creepage which has longitudinal and lateral components and spin creepage. Creepage is defined as the ratio of the difference in circumferential velocity to the mean rolling velocity. Spin creepage is defined as the difference between the angular velocities of wheel and rail about an axis normal to the plane of their contact area, divided by the mean rolling velocity. The equations representing the creepage are as follows:

$$\gamma_{long} = \frac{\Omega r_c \cos\psi - V}{V_r} \tag{2}$$

$$\gamma_{lat} = \frac{\Omega r_c \sec\alpha \sin\psi}{V_r} \tag{3}$$

and

$$\omega_3 = \frac{\Omega r_c \sin\alpha}{V_r} \tag{4}$$

$$V_r = \frac{1}{2}(V + \Omega r_c \cos\psi) \tag{5}$$

where:

γ_{long} - longitudinal creepage;
γ_{lat} - lateral creepage;
Ω - angular velocity of the wheel set (rad/s);
r_c - the generating radius of the cone (m);
ψ - angle of attack (rad);
α - cone semi-apex angle of the wheel (rad);
V_r - the rolling velocity of the wheel set (m/s);
V - the vehicle speed, (m/s); and
ω_3 - spin creepage.

Since the values of V, Ωr_c and V_r are considered similar, the above equations can be simplified:

$$\gamma_{long} \approx \cos\psi - 1 \tag{6}$$

$$\gamma_{lat} \approx \sec\alpha \sin\psi \tag{7}$$

and

$$\omega_3 \approx \frac{\sin\alpha}{r_c} \tag{8}$$

Although the original deformation wear formula (eqn (1)) represents a linear relationship with hardness, the effect of material hardness on wear is non-linear (Clayton and Steele, 1987; and Mutton *et al.*, 1982). This effect has been taken in to account. Extrapolating data from the Facility for Accelerated Service Testing (FAST) (Clayton and Steele, 1987), the following relationship is derived:

$$k_h = 51.05e^{-0.0152H} \tag{9}$$

where:

k_h - hardness factor; and
H - hardness of rail material (BH)

The effect of lubrication is also taken into account since lubrication reduces the wear rate of rails by reducing the coefficient of friction. Laboratory studies by Tyfour *et al.* (1996) indicated that the coefficient of friction ranges from 0.115 for well lubricated conditions, to 0.497 for dry friction.

These results agree well with the BHP Static-State Bogie Curving Model simulation results of 0.1-0.56 (Mutton *et al.* 1982). In practice, however, in Australian heavy haul lines, the friction coefficient is considered to vary from 0.15 (well lubricated) to 0.35 (poorly lubricated) representing a variation in wear performance of 1.6:1.

To quantify this effect, a lubrication index is used to represent lubrication conditions. Assuming a lubrication benefit ratio of 1.6:1, the lubrication correction factor is given by:

$$k_l = \frac{1}{0.15 I_l + 0.85} \qquad (10)$$

where:

k_l - lubrication correction factor; and

I_l - lubrication condition index ranging from 1 to 5

Sleeper sub-model

The sleeper (or "tie") sub-model is based on the work of Lamson and Dowdall (1985). Stress conditions in a timber sleeper are correlated with sleeper life, based on a 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.

Timber sleepers are considered to fail in two modes: spike killing and plate cutting. The number of sleepers failed due to plate cutting is assessed against the calculated cutting stress at the edge of the plate. The number of splitting sleepers is assessed against the splitting stress at the spike holes, which is a combination of the compressive stress in the fibre direction due to spike pressure and sleeper bending. An age factor is incorporated to account for the weakening of timber sleepers due environmental decay. However, due to load dependent factors contributing to only a small percentage of sleeper replacements, the accuracy of this method will largely depend on the selection of this age factor.

The advantage of this method is that the analysis is independent of historical data and length of track section selected. Furthermore, effects of track quality on sleeper failure can be readily incorporated by way of varying applied loads. This is particularly advantageous in an integrated track degradation model, where interrelationship of failure modes of each component can be quantified.

To quantify the effect of environmental factors, the decay index method is used, drawing on a decay index map developed by USA Department of Agriculture (Russell, 1986). The US regions are classified into four groups: group one areas have the lowest decay index and group four areas have the highest. The climate conditions of representative cities and states of the four groups, and Australian cities with similar climate conditions are shown in *Table 1*. The decay index map developed for Australia is shown in *Figure 2*.

Ballast and subgrade sub-model

The ballast and subgrade sub-model is based on the work of Chrismer (1994). Deterioration of ballast and subgrade is associated with differential settlement, leading on to the important parameter

Table 1 - Annual Climate Data Averages of Selected USA Districts

	City/State	Mean Temp. °C	Mean Max. Temp. °C	Mean Min. Temp. °C	Rainfall mm	Snowfall mm
USA Cities/States						
Group 1	Denver, Colorado	10.2	17.9	2.3	391	
Group 2	Clumbus, Ohio	10.8	16.2	5.3	967	736.6
Group 3	Concord, North Carolina	8.6	22.1	15.3	1159.5	129.5
Group 4	Baton Rouge, Louisiana	19.6	33.5	1.9	1546.6	
Australian Cities/States						
Group 1	Broken Hill, NSW		23.73	12.03	251	
Group 2	Hobart, Tas		16.88	8.35	626	
Group 3	Sydney, NSW		21.51	13.63	1226	
Group 4	Darwin, NT		31.98	23.22	1668	

Figure 2 - Decay Index Map for Australia Timber Sleepers

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 (1994) is:

$$\sigma_{vo} = \sigma_{vo\min} + 0.15 \times S_L \tag{11}$$

where:

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

Track settlement is calculated from plastic strains of all track sub-layers. The general equation for track settlement is given by:

$$S_L = \varepsilon_b \times h_b + \varepsilon_{sb} \times h_{sb} + \delta_{sg} \tag{12}$$

where:

- S_L - average track settlement resulting from sum of settlement of all sub-layers (mm);
- ε_b - plastic strain of the ballast layer;
- h_b - thickness of the ballast layer (mm);
- ε_{sb} - plastic strain of the sub-ballast layer;
- h_{sb} - thickness of the sub-ballast layer (mm); and
- δ_{sg} - sub-grade settlement (mm).

The plastic strain of each layer is a function of the number of load cycles, incorporating the magnitudes of wheel loads, ballast quality, and track modulus. Chrismer (1994) assumes that four wheel passes cause one load cycle for ballast and sub-ballast and eight wheel passes generate one load cycle for subgrade.

Track modulus calculation

Track modulus is a separate module of the ITDM. As the prime measure of track stiffness, it affects calculations of track deflections, rail bending stresses, bearing stresses in track components, and the response of track to dynamic loading from trains. It is, therefore, a key parameter in predicting track behaviour under passing traffic.

Traditionally, rail authorities use a range of empirical moduli drawn from measurements of various types of track, but conducting in-field measurements is time consuming and costly. A mechanistic estimation of track modulus involves analytical modelling of the physical properties of substructure layers. The accuracy is dependent on the theory underlying the track models used.

The ITDM uses a method proposed by Cai and *et al.* (1994) for estimating static track modulus using elastic foundation models, taking into consideration sleeper bending rigidity and elastic properties of layered ballast/subgrade foundation. The sleeper is modelled as a uniform beam resting on a Winkler-type foundation, with a distributed across-track modulus and subjected to two vertical loads P_{rs} at rail seats (*Figure 3*). The track modulus is a combination of the stiffness of the supporting foundation, and the combined vertical stiffness of the sleeper and the rail pad. The following is the equation elaborating these factors:

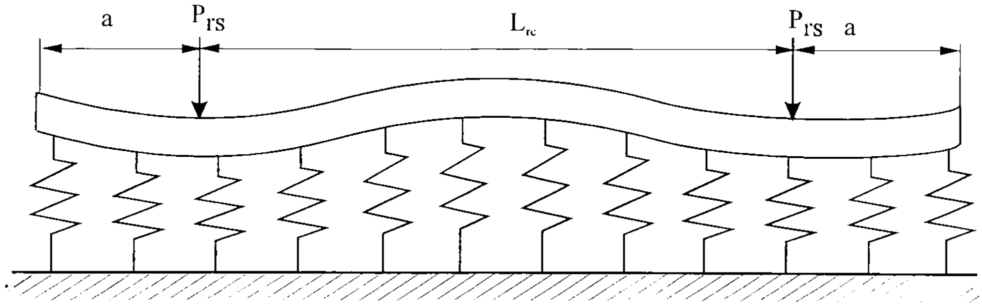

Figure 3 - Sleeper Beam on Elastic Foundation (Source: Cai *et al.*, 1994)

$$\kappa = \frac{K_{tf}}{1+ K_{tf}/K_{v}} \times \frac{1}{s} \tag{13}$$

where:

- κ - track modulus (MPa);
- K_{tf} - equivalent spring stiffness (per rail) offered by a sleeper lying on the track foundation (10^6N/m);
- K_v - combined vertical stiffness of the sleeper and the rail pad (10^6N/m); and
- s - sleeper spacing (m).

The parameter K_{tf} represents the effect on track modulus of geotechnical properties of supporting layers under the sleeper. It can be calculated as:

$$K_{tf} = \frac{P_{rs}}{y_c} \tag{14}$$

where:

- P_{rs} - is the rail seat load; and
- y_c - the sleeper deflection at rail seat.

The sleeper deflection at a rail seat is commonly determined using the Beam on Elastic Foundation (BOEF) theory, in which the ballast/subgrade modulus needs be determined. Soil mechanics theory is used in determining ballast/subgrade modulus and the equivalent elastic modulus of the layered track supporting system. Therefore, the geotechnical properties of each layer are taken into account.

The method described above has been applied to Australian conditions. Calculations were carried out for both concrete sleeper track and timber sleeper tracks of three track gauges for different ballast and subgrade conditions. The calculated results for timber and concrete sleeper tracks are given in *Table 2*.

The dominant effect on track modulus is subgrade stiffness. In the model, the depth of the subgrade is assumed to be five times the sleeper width. The effect of subgrade stiffness would be more significant if the subgrade depth was chosen to be greater, as suggested by the findings of Selig and Li (1994).

Sleeper spacing has a linear effect on track modulus: doubling the spacing will halve the modulus. *Table 2* shows that track moduli of tracks with concrete and timber sleepers do not show marked differences when subgrade is soft. However, as the subgrade stiffness increases concrete sleeper track has a much higher modulus than timber sleeper track. This is in keeping with the analysis of Cai *et al.* (1994) showing an evidence of interaction between the bending rigidity of the sleeper as a beam, and the compliance of the soil foundation: at low subgrade elastic moduli, the bending effect of the sleeper may not be appreciable. Note the curious effect in the *Table 2* that the modulus of concrete sleeper track is slightly lower than that of timber sleeper track for clay and silt subgrade: this is actually a reflection of the greater sleeper spacing of concrete sleepers than timber sleepers.

Table 2 - Track Modulus for Australian Railway Tracks, MPa

Track type	Ballast Depth mm	Subgrade type			
		Clay	Silt	Sand	Rock
Timber Sleeper Tracks (s=610 mm)					
1067 mm gauge track	100	9.2	19.8	26.2	75.2
	150	10.1	21.3	27.8	75.3
	200	11.1	23.1	29.5	75.4
	250	12.3	25.0	31.4	75.5
1435 mm gauge track	100	10.6	22.1	28.8	76.5
	150	11.5	23.7	30.5	76.5
	200	12.6	25.5	32.2	76.6
	250	13.9	27.6	34.1	76.7
1600 mm gauge track	100	10.9	22.5	29.3	76.2
	150	11.9	24.2	30.9	76.3
	200	13.0	26.0	32.7	76.3
	250	14.4	28.0	34.5	76.4
Concrete Sleeper Tracks (s=680)					
1067 mm gauge track	150	8.2	18.9	25.9	112.5
	200	9.0	20.6	27.8	112.7
	250 with capping layer	25.5	31.4	33	
	250 no capping layer	10.0	22.5	29.8	112.9
	300 with capping layer	28.7	34.7	36.8	
	300 no capping layer	11.1	24.6	32.0	113.1
1435 mm gauge track	150	9.9	22.0	30.2	126.0
	200	10.6	24.0	32.3	126.3
	250 with capping layer	29.4	36.4	38.5	
	250 no capping layer	11.4	26.1	34.6	126.6
	300 with capping layer	34	39.7	42.8	
	300 no capping layer	12.2	28.7	37.1	126.8
1600 mm gauge track	150	10.2	23.3	34.8	137.5
	200	11.3	25.4	37.6	137.8
	250 with capping layer	29.7	37.9	40.9	
	250 no capping layer	12.5	27.0	40.7	138.1
	300 with capping layer	34.0	41.1	44.6	
	300 no capping layer	14.0	30.5	44.2	138.4

INTERACTION OF DEGRADATION OF COMPONENTS

Track degradation is an integrated process in which degradation of one component affects that of the other. When rails are worn, especially in curves, the gauge will be progressively widened. Failed fasteners may also cause gauge widening. Existence of corrugations accelerates the rail wear process and promotes fatigue defects development due increased dynamic forces on the rails. Depending on the frequency of the dynamic forces, they may also penetrate rails and transmit down to sub-layers of the track thus accelerating damages to sleepers and ballast.

Deterioration of timber sleepers will lead to loss of their supporting and gauge holding capacity. A single defective sleeper may not cause any noticeable effects. However, several adjacent defective sleepers will affect the degradation of other components and the track as a whole. Material loss due to decay at sleeper top may cause excessive rail deflection or track settlement which is a cause of dynamic forces. Decay at spike holes causes loose spikes and may lead to rail gauge widening. Concrete and steel sleepers provide very good gauge holding unless they crack or break due to inadequate support or rail irregularities.

Ballast can lose its bearing capacity due to particle breakdown and fouling by fines from either the ballast itself or from foreign sources. This will cause track to settle differentially due to the deterioration not being uniform along the track. This differential settlement may lead to dynamic forces on rails and to cyclic effects on the subsequent track components. Ballast profile is also important in terms of holding the track in its position. Loss of shoulder ballast will reduce lateral track stability and encourage track buckling in hot weather.

Subgrade is the most import component in terms of its effects on deterioration of other components. It is also most inconsistent due to its great variety of materials and different geotechnical properties. The bearing capacity of subgrade varies with water content and it may cause problems during rainy reasons. Subgrade is most costly to treat when it becomes inadequate to support the track. Differential track settlement is associated more with subgrade than with ballast. Therefore subgrade is a major source of track roughness. Remedial actions such as tamping for track roughness also contribute to ballast deterioration.

Many of the interactions between the various types of deterioration of track components are incorporated in the ITDM model. As illustrated diagrammatically in *Figure 4*, the effect of deterioration of one component on that of the others is reflected by changes in dynamic forces on the rails. 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, although the relationship between track roughness and sleeper deterioration has not been established. Track roughness is in turn a

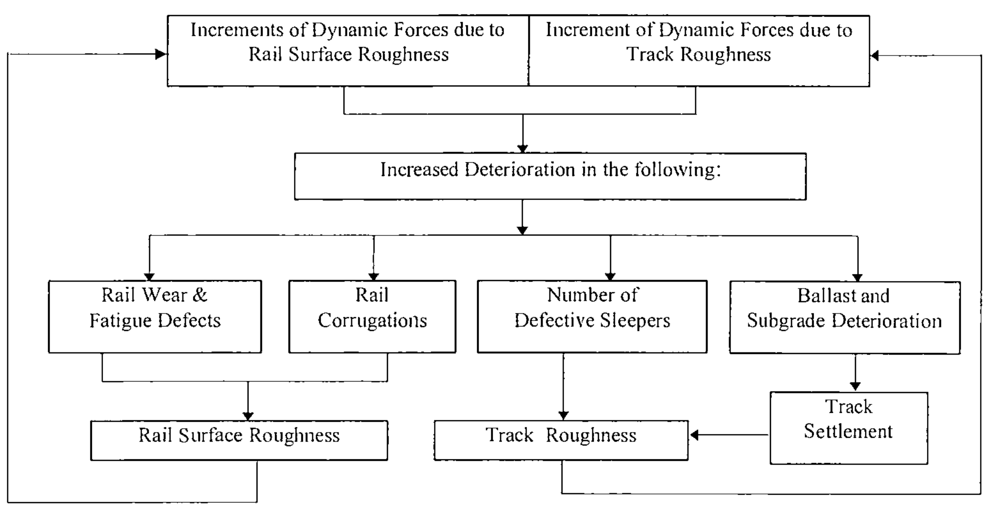

Figure 4 - Interactions of Deterioration of Track Components

factor influencing dynamic forces. The dynamic forces due to track roughness can be estimated and their effect will be carried forward to the cyclic simulation of track deterioration.

Because the ITDM model simulates track deterioration in a cyclic manner, it is possible to incorporate uncertainties in the track deterioration process. The compounding effect of those uncertainties in the modelling process can also be included in the analyses. The uncertainties, which are expected to increase with time, are mainly due to our inability to model the complex perfectly, and to the errors in forecasting the input parameters used by the model.

SUMMARY AND CONCLUSIONS

An integrated track degradation model (ITDM) has been developed for analysis of track degradation. The model can deal with the entire track system or with individual components. The ITDM model has been designed to serve as a single tool for analysis of deterioration of each railway track component. It endeavours to take into account as many affecting factors as possible to ensure reliability of prediction of track degradation.

The ITDM model enables comprehensive prediction of track degradation, through accurate quantification of in-track behaviour of each track component, and, more importantly through a good understanding of the interrelationships between degradation modes.

In order to incorporate the interactions of different track components, mechanistic relationships have been employed in the model, allowing new technology and new research results to be incorporated at later stages. The main sub-models in the ITDM model include rails, sleepers, ballast and subgrade.

One of the distinguishing features of the model is the way it deals with the interaction between degradation modes of the various components. The model also has been used to estimate the likely level of confidence associated with the estimation of degradation by analysing the errors in the input parameters.

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