Development of Integrated Model for Assessment of Operational Risks in Rail Track

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Abstract - **Rail operating risks have been increasing due to increasing number of axle passes, steeper curves, wear-out of rails and wheels and inadequate rail-wheel grinding, poor lubrication and reduced maintenance. In 2000, the Hatfield accident in UK killed 4 people and injured 34 people and has lead to the cost of £ 733 million (AUD$ 1.73 billion) for repairs and compensations. In 1977, the Granville train disaster in Australia killed 83 people and injured 213 people. These are related to rolling contact fatigue, wear and poor maintenance. This paper focuses on development of a conceptual integrated model for rail grinding, lubrication and inspection maintenance decisions. Risk based cost benefit model is developed for optimal inspection intervals**

Keywords - **Rail Wear, Rolling Contact Fatigue (RCF)**

I. INTRODUCTION

Rolling contact fatigue (RCF) defects and rail wear occurs due to accumulated tonnage (Million Gross Tonnage) on rail track from traffic and freight movements and heavy haul services. In rail infrastructure the asset life is at risk due to continuous usage, initiation and propagation of defects, loss of material due to rail-wheel interaction and increased axle loads and train speeds.

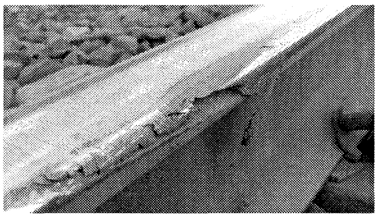

Fig 1: Rolling contact fatigue defects [1]

Head Checks, gauge-corner cracks, squats and shelling (as shown in Figure 1) are forms of rolling contact fatigue. They are caused by a combination of high normal and tangential forces between rail and wheel.

In the integrated approach, failures can be modelled as a point process. Point process is a continuous time characterised by events that occur randomly along the time continuum when an item is put into operation or it fails. $\Lambda(m)$ is an intensity function where m represents Millions of Gross Tonnes (MGT) and $\Lambda(m)$ is increasing function of m indicating that the number of failures in a statistical sense increases with MGT. $F_n(m)$ denotes the cumulative rail failure distribution modelled as Weibull distribution given by [2]:

$$F_n(m) = 1 - \exp(-(\lambda m)^{\beta}) \quad (1)$$

$$\Lambda(m) = \frac{f_n(m)}{1 - F_n(m)} = \frac{\lambda\beta(\lambda m)^{\beta-1}\exp(-(\lambda m)^{\beta})}{1-(1-\exp(-(\lambda m)^{\beta})} = \lambda\beta(\lambda m)^{\beta-1} \quad (2)$$

with the parameters $\beta > 1$ (shape parameter) and $\lambda > 0$ (scale parameter (characteristic life)). This is an increasing function of m. The total accumulated MGT, M_i, is given by:

$$M_i = \sum_{i=0}^{i} m_i \quad (3)$$

where m_i is MGT in period i. The probability of failure rate is higher in case of aged (old) rails with the increase of accumulated MGT passed though this section. Note that this corresponds to the failure rate of two-parameter Weibull distribution. As a result, $N(M_{i+1}, M_i)$ the number of failures over M_{i+1} and M_i are function of MGT and random variable. With condition on $N(M_{i+1}, M_i) = n$, the probability is given by:

$$P\{N(M_{i+1};M_i) = n\} = \{\int_{M_i}^{M_{i+1}} \Lambda(m)dm\}^n e^{-\int_{M_i}^{M_{i+1}}\Lambda(m)dm} / n! \quad (4)$$

This type of characterisation is considered appropriate because rail track is made operational through repair or replacement of the failed segment and no action is taken with regards to the remaining length. Since the length of failed segment replaced at each failure is very small relative to the whole track, the rectification action can be viewed as having negligible impact on the failure rate of the track as a whole. Then the expected number of failures over M_{i+1} and M_i is given by:

$$E[N(M_{i+1}, M_i)] = \lambda^{\beta}((M_{i+1})^{\beta} - (M_i)^{\beta}) \quad (5)$$

Chattopadhyay et al., [3] studied decisions on economical rail grinding interval for controlling rolling contact fatigue. The complexity of deciding the optimal rail grinding intervals for improving the reliability and safety of rails is because of insufficient understanding of the various factors involved in the crack initiation and propagation process. Cannon et al., [4] studied an overview rail defects. The emergence of surface-initiated rail RCF as a major cause of premature rail removal is of great concern as it indicates that operating conditions are taking the rail to and beyond its natural endurance limit.

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Despite major improvements in rail making and inspection, rail breaks still occur: for example, in the UK the annual number of broken rails remained almost constant at about 770 per year between 1969 and 2000.

Kalousek et al., [5] proposed the use of preventive rail grinding strategy. This process is applicable to both standard carbon and head hardened rails. Grinding cycles are used to remove small initiating surface cracks early and frequently with light grinding, rather than applying heavy grinding based on the surface appearance of the rail. In the preventive mode, rail grinding is a process of controlled artificial wear and through fine-tuning can be applied to restore the desired profiles and achieve the required depth of metal removal with minimal grinding effort and steel wastage. 'Fine-tuning' means both determining and applying the 'Magic Wear Rate'– that is, the combined amount of natural and artificial wear required to just remove the existing and incipient cracks that are contained within a thin skin of metal at the surface.

This paper focuses on the development of integrated model for rail grinding, lubrication, inspection, rectification and replacement. The model can be used:

- to predict and assess operational risks due to rail defects in the tack for informed managerial decisions to improve reliability and safety of rail operation,
- to estimate the expected total annuity costs for grinding, lubrication, inspection and replacement of rails,
- for cost-benefit analysis and making managerial decisions on risk based approach
- to estimate relative performance of lubricators, total curve and segment, above rail and below rail for assessing effectiveness of lubrication strategies and
- to estimate the savings with grinding, inspection intervals, lubrication, rail replacement and rectification decisions.

II. DEVELOPMENT OF INTEGRATED MODEL

The Integrated model (as shown in Figure 2) consists of grinding, lubrication, inspection, rectification and replacement models to estimate total annuity costs of maintenance. These models have been developed and analysed with illustrations and details could be found in [1]. Therefore, the total cost of maintaining a segment of rail is equal to the sum of cost for; Preventive rail grinding cost (c_g), Down time cost due to rail grinding (loss of traffic) (c_d), Inspection costs for rail grinding, (c_i), Risk cost of rectification based on non destructive testing (NDT), rail breaks and derailment (c_r) and Replacement cost of worn-out unreliable rails (c_{re}), lubrication (c_l), NDT inspection cost (Ultrasonic NDT car, NDT hand held equipment). Then the total annuity cost/m can be modelled as:

$$C_{tot}=\{\sum_{i=1}^{N-1}(G*n_i*L)/(1+r)^i\}*r_y/(1-(1/(1+r_y)^y))+$$
$$\{\sum_{i=1}^{N-1}n_{GP_i}*h_{DT}*d/(1+r)^i\}*r_y/(1-(1/(1+r_y)^y))+$$
$$\{\sum_{j=1}^{N_I}(i_c/(1+r_i)^j\}*r_y/(1-(1/(1+r_y)^y))+$$
$$\{\sum_{x=0}^{y}\sum_{i=0}^{N}E[N(M_{i+x+1},M_{i+x})]*[P_{i,x}(B)*k+(1-P_{i,x}(B))*(P_{i,x}(A)*a+(1-P_{i,x}(A))*\bar{c}]/$$
$$(1+r)^i\}*(1-(1/(1+r_y)))*(1+r_y)/(1-(1/(1+r_y)^y))+$$
$$I*(1-(1/(1+r)))/(1-(1/(1+r_y)^y))+$$
$$\{\sum_{i=1}^{N_j}(c_jM_j+Y_jc_s)/(1+r)^i\}*r_y/(1-(1/(1+r_y)^{y_j}))+xC_{NDT} \quad (6)$$

$$P_{i,1}(B)=\alpha \quad (7)$$

$$P_{i,2}(B)=\left[1-\frac{\{(1-\alpha)N_{i,x=1}+N_{i,x=2}\}(1-\alpha)}{(N_{i,x=1}+N_{i,x=2})}\right] \quad (8)$$

$$P_{i,3}(B)=\left[1-\frac{\{(1-\alpha)N_{i,x=1}+N_{i,x=2}\}(1-\alpha)+N_{i,x=3}}{(N_{i,x=1}+N_{i,x=2}+N_{i,x=3})}\right](1-\alpha) \quad (9)$$

where $P_i(B)$ is probability of detecting potential rail breaks in NDT, $P_i(A)$ is probability of undetected potential rail breaks leading to derailments, in a planned way and a is the expected cost per derailment. α is % of defects detected in NDT. G is the cost of grinding cost per pass per m, n_i number of grinding pass for i^{th} grinding, L is the length of rail segments under consideration, N be the total number of periods up to safety limit for renewal, and r is the discounting rate per period. i and j are index. y is rail life in years. x is the inspection intervals per year for a rail corridor under consideration, C_{NDT} is total expected cost for NDT inspection interval, h_{DT} is the expected downtime due to each grinding pass and d is the expected cost of down time per hour. i_c Is the cost of inspection before and after for rail grinding, $\bar{c}$ is the expected cost of each rail break repair on emergency basis. I is cost of investment in new rail. c_s is switching cost for stop/start lubrication. Y_j is decision variable for lubrication strategy (dimensionless) 0 for no or continuous lubrication (dimensionless) 1.

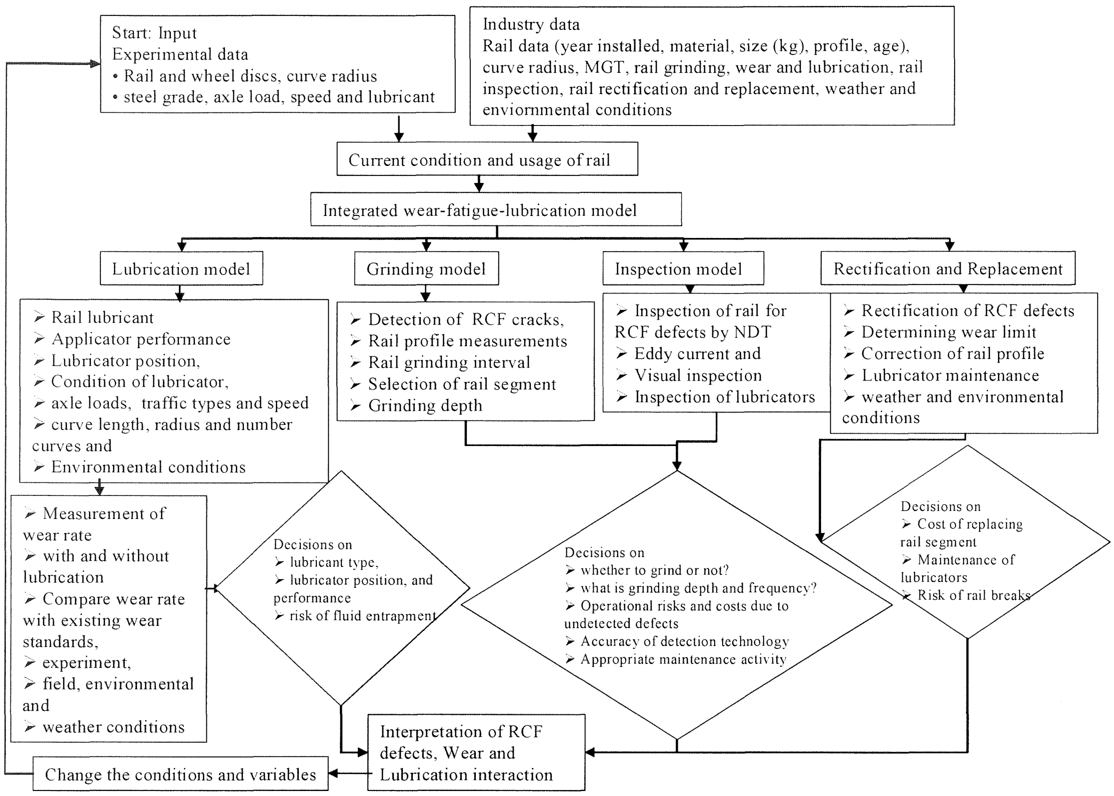

Figure 2: Integrated model for rail grinding-lubrication-inspection

III. ANALYSIS OF RESULTS

A. Estimation of Annuity Costs/m

The total annuity costs for risk and inspection are further analysed considering the expected number of failures under various inspection scenarios.

Case 1 – One Inspection per year

Data collected and analysed from industry for one inspection interval using ultrasonic NDT and verified with handheld equipment.

TABLE 1
Annuity costs/m for 12 MGT grinding interval with lubrication for one inspection per year

Radius (m)	0-300
Length (m) (Percentage)	1318 (0.0101)
Rail maintenance	Annuity costs/m ($AUD)
Grinding	6.82
Inspection for grinding	0.02
Risk	36.31
Down time	1.07
Replacement	15.48
Lubrication	0.67
NDT Inspection	1.60
Total Annuity cost	61.97

Table 1 shows annuity costs/m of rail grinding, inspection for grinding, risk, downtime and replacement and NDT inspection for 12 MGT with lubrication. Figure 3 shows annuity costs per m for 12 MGT grinding interval for curve radius 0 - 300 m with lubrication for one inspection per year and 9 MGT of traffic per 6 weeks.

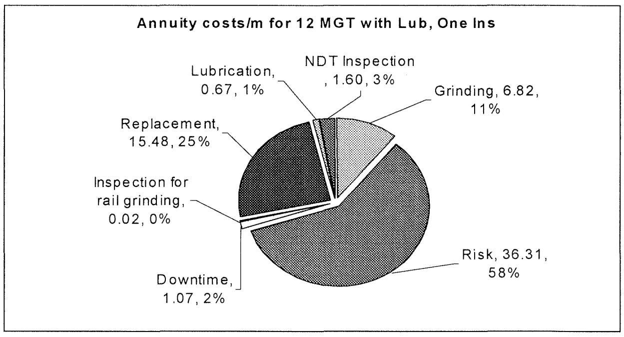

Fig 3: Annuity costs/m for 12 MGT grinding interval with lubrication for one inspection per year

It is found that risk cost is higher compared to replacement and grinding costs. This is mainly due to higher number of detected defects with NDT during the year. The risk and inspection cost has great influence on total maintenance and it much higher without lubrication compared to with lubrication. Table 2 shows annuity costs/m of rail grinding, inspection for grinding, risk, downtime and replacement and NDT inspection.

TABLE 2
Annuity costs/m for 12 MGT without lubrication for one inspection per year

Radius (m)	0-300
Length (m) (Percentage)	1318 (0.0101)
Rail maintenance	Annuity costs/m ($AUD)
Grinding	6.12
Inspection for grinding	0.000024
Risk	36.31
Down time	0.0232
Replacement	66
NDT Inspection	1.60
Total Annuity cost	110

Figure 4 shows annuity costs per m for 12 MGT grinding interval for curve radius 0 - 300 m without lubrication for one inspection per year and 9 MGT of traffic per 6 weeks.

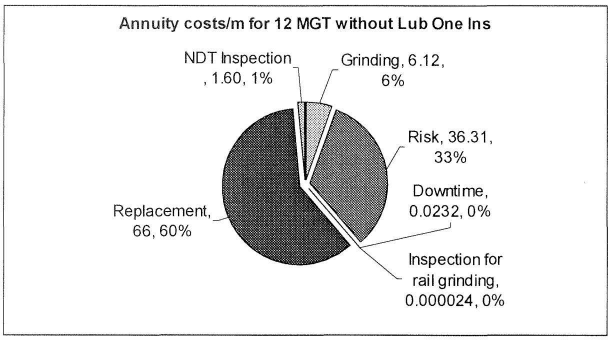

Fig 4: Annuity costs/m for 12 MGT grinding interval without lubrication for one inspection per year

It is observed that replacement cost is higher compared to all other costs. This is mainly due to early replacement of rails and higher number of defects detected with NDT during the year without lubrication.

Case 2 – Two Inspections per year

Expected number of failures estimated with stochastic models in two inspection intervals per year is 55.79508.

TABLE 3
Annuity costs/m for 12 MGT grinding interval with lubrication for two inspections per year

Radius (m)	0-300
Length (m) (Percentage)	1318 (0.0101)
Rail maintenance	Annuity costs/m ($AUD)
Grinding	6.82
Inspection for rail grinding	0.02
Risk	32.93
Down time	1.07
Replacement	15.48
Lubrication	0.67
NDT inspection	1.63
Total Annuity cost	58.62

Table 3 shows the annuity costs/m of rail grinding, inspection for grinding, risk, downtime and replacement and NDT inspection for 12 MGT. Figure 5 shows annuity costs per m for 12 MGT grinding interval for curve radius from 0 - 300 m with lubrication for two inspections per year and 9 MGT of traffic per 6 weeks. The analysis shows that risk cost and replacement costs are higher compared to other costs.

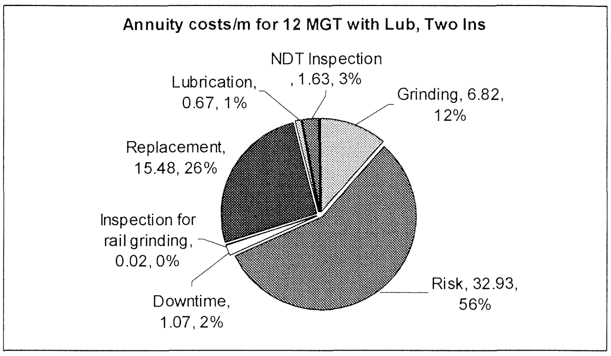

Fig 5: Annuity cost/m for 12 MGT grinding interval with lubrication for two inspections per year

It is observed that the NDT inspection cost for two inspection intervals is higher compared to one inspection interval per year.

TABLE 4
Annuity costs/m for 12 MGT grinding interval without lubrication for two inspections per year

Radius (m)	0-300
Length (m) (Percentage)	1318 (0.0101)
Rail maintenance	Annuity costs/m ($AUD)
Grinding	6.12
Inspection for rail grinding	0.000024
Risk	32.93
Down time	0.0232
Replacement	66
NDT inspection	1.63
Total Annuity cost	107

Table 4 shows the annuity costs/m of rail grinding, inspection for grinding, risk, downtime and replacement and NDT inspection for 12 MGT without lubrication for two inspections.

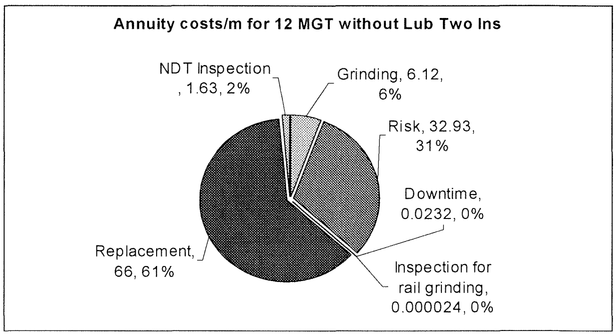

Fig 6: Annuity cost/m for 12 MGT grinding interval without lubrication for two inspections per year

Figure 6 shows annuity costs per m for 12 MGT grinding interval for curve radius from 0 to 600 m without lubrication for two inspections per year and 9 MGT of traffic per 6 weeks. The analysis shows that the replacement cost is higher compared to other costs. This is mainly due to early replacement of rails and higher number of defects detected with NDT during the year with no lubrication.

Case 3 – Three Inspections per year

Expected number of failures estimated with stochastic models in three inspection intervals per year is 27.47331.

TABLE 5
Annuity costs/m for 12 MGT grinding interval with lubrication for three inspections per year

Radius (m)	0-300
Length (m) (Percentage)	1318 (0.0101)
Rail maintenance	Annuity costs/m ($AUD)
Grinding	6.82
Inspection for grinding	0.02
Risk	31.58
Down time	1.07
Replacement	15.48
Lubrication	0.67
NDT Inspection	1.68
Total Annuity cost	57.32

Table 5 shows the annuity costs of rail grinding, risk, downtime and replacement, lubrication and NDT inspection for 12 MGT with lubrication. Figure 7 shows annuity costs/m for 12 MGT grinding interval for curve radius 0-300 m with lubrication for three inspections per year and 9 MGT of traffic per 6 weeks.

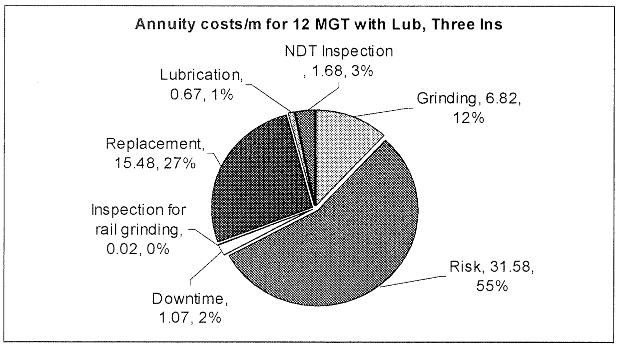

Fig 7: Annuity cost/m for 12 MGT grinding interval with lubrication for three inspections per year

The analysis shows that risk cost and replacement costs are higher compared to other costs. It is observed that the NDT inspection cost for three inspection intervals is higher compared to one and two inspection intervals per year and 9 MGT of traffic per 6 weeks.

TABLE 6
Annuity costs/m for 12 MGT grinding interval without lubrication for three inspections per year

Radius (m)	0-300
Length (m) (Percentage)	1318 (0.0101)
Rail maintenance	**Annuity costs/m ($AUD)**
Grinding	6.12
Inspection for grinding	0.000024
Risk	31.58
Down time	0.232
Replacement	66
Lubrication	0.67
NDT Inspection	1.68
Total Annuity cost	105

Table 6 shows the annuity costs/m of rail grinding, inspection for grinding, risk, downtime and replacement and NDT inspection for 12 MGT grinding interval without lubrication. Figure 8 shows annuity costs/m for 12 MGT grinding interval for curve radius 0 to 300 m without lubrication for three inspections per year and 9 MGT of traffic per 6 weeks. The analysis shows that replacement and risk costs are higher compared to other costs. It is observed that the NDT inspection cost for three inspection intervals is higher compared to one and two inspection intervals per year.

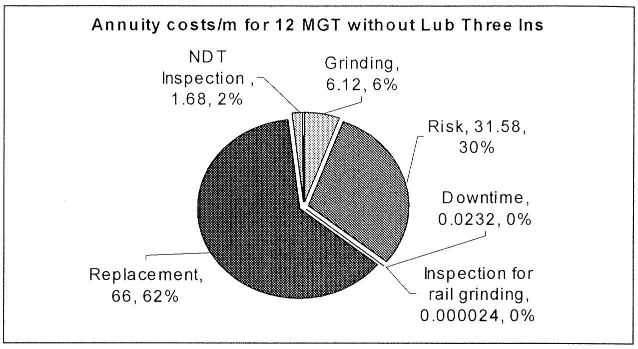

Fig 8: Annuity cost/m for 12 MGT grinding interval without lubrication for three inspections per year

IV. CONCLUSION

Conceptual integrated model is developed for costs and risks. It includes decisions on grinding interval, lubrication strategies, inspection intervals, rectification strategies and replacement of rails. Total costs are estimated using integrated wear-fatigue-lubrication-grinding-inspection-rectification and replacement. Cost savings per meter per year for 12 MGT is:

- 5.41% on total maintenance costs with two inspections compared to one inspection considering risk due to rail breaks and derailments.
- 45.06% on total maintenance costs with lubrication for two inspections compared to without lubrication.

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