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Integrated Model for Assessment of Risks in Rail Tracks under Various Operating Conditions

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Abstract. Rail breaks and derailments can cause a huge loss to rail players due to loss of service, revenue, property or even life. Maintenance has huge impact on reliability and safety of railroads. It is important to identify factors behind rail degradation and their risks associated with rail breaks and derailments. Development of mathematical models is essential for prediction and prevention of risks due to rail and wheel set damages, rail breaks and derailments.

This paper addresses identification of hazard modes, estimation of probability of those hazards under operating, curve and environmental condition, probability of detection of potential hazards before happening and severity of those hazards for informed strategic decisions. Emphasis is put on optimal maintenance and operational decisions. Real life data is used for illustration.

Key Words : *risk assessment, maintenance costs, mathematical modelling, wheel /rail wear and rolling contact fatigue.*

1. INTRODUCTION

Maintenance of rail track involves large costs for track owners, in terms of investment, reinvestment, and maintenance, cancelled / delayed traffic, and derailments. Surface fatigue, rail/wheel wear, increased speed and higher axle loads result in surface cracks in curves. It is significant for rail players to identify hazard modes, estimate probability of those hazards under operating curve and environmental conditions, probability of detection of potential hazards and severity of those hazards for informed

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strategic decisions. This paper focuses on developing integrated model for analysing risks and associated costs in rail tracks.

Outline of this paper as follows: Section 1 gives introduction of this investigation; Section 2 gives Identification of hazard modes. In Section 3, Estimation of probability of hazards under operating, curve and environmental condition is discussed. In Section 4 probability of detection is discussed. Section 5 develops models for cost benefit analysis based on risks. In the final section, scope for future work is discussed.

2. NOMENCLATURE

a	Expected cost per derailment	[AUD/year]
C_r	Cost per rectification of rail breaks on emergency basis	[AUD/year]
C_{tot}	Total cost	[AUD/year]
$\bar{c}$	Expected cost of each rail break repair on emergency basis	[AUD]
c_d	Down time cost	[AUD/year]
c_g	Grinding cost	[AUD/year]
c_i	Inspection cost	[AUD/year]
c_r	Risk cost	[AUD/year]
c_{re}	Replacement cost	[AUD/year]
c_j	Cost per unit time for running each train in period j	[AUD]
D_j	Demand for period j	[-]
F_j	Feasible time per year j	[-]
I	Cost in investment of rail for segment L	[AUD]
I_f	Inspection frequency in period j	[-]
i_c	Cost of each inspection	[AUD]
j	Number of years	[-]
k	Cost of rectification of potential rail breaks based on rail head area, RCF, and speed of train	[AUD]
L	Length of rail segment under consideration	[m]
n	Number of Wagons	[-]
N	Total number of periods	[-]
N_I	Number of inspection over rail life	[-]
p	Revenue per MGT	[-]
$P[.]$	Probability	[-]
$P_i(A, Fatigue, s)$	Probability of undetected potential rail breaks leading to derailment	[-]
$P_i(B)$	Probability of detecting potential rail breaks using NDT	[-]
r	Discounting rate	[%]
r_i	Discounting rate between inspections using NDT	[%]
s	Speed of train	[Km/h]
S_j	Supply for year j	[-]
t	Trave time for each wagon is based on variable speed s	[-]
W	Wagon capacity	[-]

3. IDENTIFICATION OF HAZARD MODES

Rail track experiences repetitive loading of the axles and continued pressure of ever increasing speeds of both commuter and heavy haul trains. This results in wear and surface fatigue. Ringsberg and Lindback [7] show that longitudinal residual stress changes from tension to compression under high axle load. Greatest fatigue damage was found at the railhead surface for the prevailing contact load conditions. A rail failure assessment report by the TTCI, Pueblo, Colorado, USA, Sawley and Reiff [6] analysed the causes of broken and defective rails.

Table 1. Causes of defective Rails Sawley and Reiff [6]

Railway	Four common causes of defective rails percentage of railway total			
	First	Second	Third	Fourth
Rail track (99/00)	Squats 21.7%	Vertical/transverse 20.1%	Horiz./longitudinal 12.5%	Bolt holes 9.6%
SNCF (1999)	Squats 23.4%	Internal fatigue 11.5%	Shells 8.4%	Thermite welds 4.7%
HSPC (1999)	Thermite welds 31.5%	Wheel burns 17.2%	Horizontal split webs 13.3%	Bolt holes 11.3%
NS (1997)	Insulated Joints 59.4%	Transverse defects 18%	Thermite welds 15%	Fatigue Failure 5.2%
DB (1996)	Thermite welds 29%	Sudden fracture 18%	Fatigue Failure 16%	Electric bonds 4%
Banverket (1998)	Transverse fracture 55.1%	Welded joint 32.7%	Horizontal defect 6.1%	Vertical split 2.0%
HH1 (1999)	Vertical split heads 34.7%	Thermite welds 20.3%	Detail fractures 13.1%	Bolt holes 12.2%
HH2 (1999)	Transverse defects 23.6%	Thermite welds 15.5%	Wheel burns 13.2%	Shells 9.6%

Table 2. Causes of Broken Rails Sawley and Reiff [6]

Railway	Four common causes of broken rails by percentage of railway total			
	First	Second	Third	Fourth
Rail track (99/2000)	Vertical/transverse 39.5%	Thermite welds 22.4%	Bolt holes 14.9%	Horiz./longitudinal 7.4%
SNCF (1999)	Thermite welds 35.3%	Internal fatigue 18.6%	Squats 8.8%	Rail manufacture 6.1%
Banverket (1998)	Transverse fracture 44.1%	Vertical split 19.4%	Welded joint 19.4%	Horizontal defect 17.2%
HH2 (1999)	Transverse defects 37.9%	Thermite welds 35.6%	Bolt holes 5.8%	Flash welds 5.6%

Table 1 & 2 explain the risk due to rolling contact fatigue, welding performance, rail material, traffic type and heavy axle operation in railway network.

3. ESTIMATION OF PROBABILITY OF HAZARDS

Predicting the hazards under operating, curve and environmental conditions is extremely complex. It is important for inspection, maintenance and speed decisions to enhance safety and reliability of rail infrastructure. Swedish iron-ore mining group LKAB and the two rail infrastructure players, Banverket in Sweden and Jernbaneverket in Norway, conducted a study in 1995 for assessing the economical, technical and environmental consequences of 30 tonne axle load instead of 25 tonne axle loads on existing tracks. The economic analysis of Malmbanan indicated that about 50% of the total cost for maintenance and renewal was related to traffic and balance was related to factors such as signalling, electricity, snow-clearance etc. Based on the analysis the mining company LKAB introduced 30 tonne axle load with new wagons and locomotives on the Malmbanan line since 2001. Subsequent technical findings revealed that Squats and Shelling occurred due to RCF and Head Checks (HC) occurred in curves and switches due to increased slip towards the gauge corner and decreased area of wheel-rail contact. These surface initiated cracks are major challenges of heavy haul lines Hiensch et al [1].

The Swedish National Rail Administration (Banverket called BV) introduced a grinding program in 1997 at Malmbanan, 130 km ore line between Kiruna and Riksgränsen. Åhren et al [2] evaluated the grinding on Malmbanan and estimated that 12000±1900 m rail costing 9.6 million SEK (USD$1.05 million) needs to be budgeted for replacement each year. The yearly cost of grinding of this track was estimated around 4 million SEK, giving a total yearly maintenance budget of 13.6 million SEK.

To avoid accidents due to inbuilt risks in various sub systems detail analysis of factors affecting operations need to be understood. Muttram [4] addresses importance of following issues:

1. Understanding of the nature and distribution of the current risk;
2. Risk information and risk profiles to:
    - assist in the development of Railway Safety
    - provide risk information for risk assessments
3. Prioritise for safety improvement over a planned period;
4. Revise Railway Group Standards for risk reduction and mitigation;
5. Cost benefit analyses:
    - to assist in the decision-making process regarding the merits of technical changes or modifications and new infrastructure and
    - to assist in the development of safety justifications for proposed changes;
6. Control measures that would reduce risk;
7. Contribution of a particular item of equipment or failure mode to the overall risk;
8. Validation of Railway Safety;
9. Identification and prioritisation of issues for audit;
10. Prioritisation of areas for safety research.

This paper presents an integrated approach for assessment of risks in rail track under various operating conditions. Train/track simulations, in combination with monitoring field measurements and a system approach is developed in Chattopadhyay et al [3]. Results from this investigation are able to reduce probable rail breaks and derailments.

4. PROBABILITY OF DETECTION OF POTENTIAL HAZARDS

North American railroads runs up an annual bill of around USD 80 million to inspect rail for internal flaws to avoid catastrophic derailment caused by a rail problem leading to a broken rail, Judge [5]. The factors involved with wear and fatigue estimates the risk (likelihood and consequence) associated with potential crack propagation and leading to rail breaks/ derailments. In spite of preventive grinding programs along with frequent onboard non-destructive measurements, rail breaks happen. The factors such as weld joints, rail geometry, wheel burns, and corrugation contribute to the risk. The cost of unplanned replacements due to these problems is treated as risk cost in this paper. For an infrastructure player it is essential to monitor and control these risks by implementing cost effective traffic and maintenance management strategies. Questions commonly asked are:

- How much is the current risk of derailment on a specific track section?
- Will it change with changed operating, traffic conditions and maintenance activities?
- What is the cost/benefit ratio of various combinations of these factors?

The total cost of maintaining any segment of rail for wear and fatigue control is equal to the sum of; rail grinding cost, down time cost due to rail grinding (loss of traffic), rectification and associated cost with rail breaks, cost of derailment, inspection costs and replacement cost of worn-out rails, see Chattopadhyay et al. [3]. Costs associated with rail maintenance are estimated separately for low rail, high rail and different curve radii. These are added to obtain total cost of rail maintenance. The total cost of rail maintenance is modelled as:

$$C_{tot} = c_g + c_d + c_i + c_r + c_{re} \tag{1}$$

For each MGT increment the profile degradation of the railhead needs to be estimated. Using the statistical data on derailments, rail breaks (speed, railhead area, RCF at that time of derailment/rail breaks) and rectifications initiated by routine inspections the expected costs can be estimated.

5. INTEGRATED MODEL FOR COST BENEFIT ANALYSIS(CBA) AND ASSESSMENT OF RISKS

Figure 1 shows the proposed risk model for rail operation, and the factors that influence the rail degradation, rail breaks and derailments.

Wheel-rail contact; wheel and rail wear, rolling contact fatigue, lubrication, curve radius, axle load, number of axles passed through rail segment, Million Gross Tonnes

(MGT), traffic intensity, speed, rail material, track geometry, rail dynamics, inspections and wear limits play vital role in rail wheel degradation and leads to increased operational risks and adds to operational costs for rail players. These are modelled in the following sub sections.

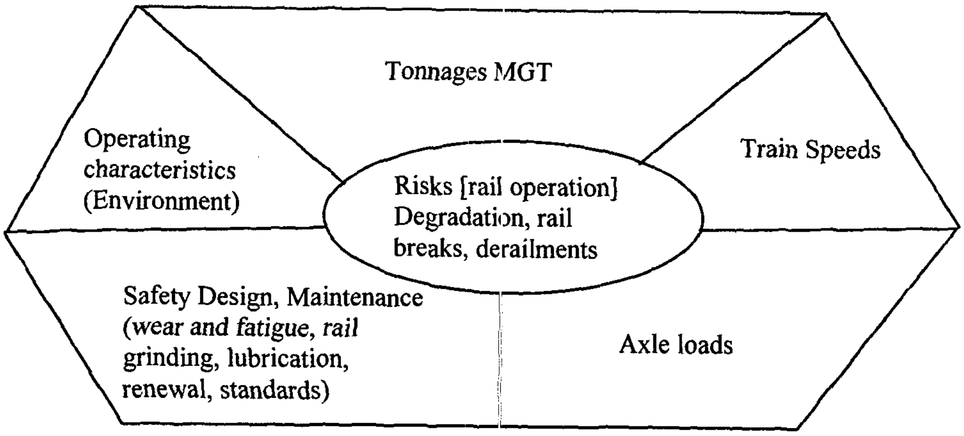

Figure 1. Proposed Risk Model for Rail operation

5.1 Modelling inspection cost

Let I_f be the inspection per MGT and i_c be the cost of each inspection. Then annual inspection cost over the rail life is given by:

$$c_i = \{\sum_{j=1}^{N_I} (i_c/(1+r_i)^j\} * r/(1-(1/(1+r)^N)) \tag{2}$$

where $N_I = Integer[\frac{M_N}{I_f}]$ and r_i is discounting rate associated with interval of Non Destructive Testing (NDT).

5.2 Modelling risk cost of rail breaks and derailment

A stochastic rail life model is developed using traffic and grinding wear data from profile measurements. The area after i^{th} period can be modelled as:

$$A_i = A_0 - \sum_{j=o}^{i} \left((RC_w + RG_w)TD_j + (RC_w + RG_w)GD_j\right) \tag{3}$$

where A_0 is the cross sectional profile area of a new rail, RC_w is Rail Crown wear width, RG_w is Rail Gauge wear width, TD_j is the wear Depth due to Traffic after period j, GD_j is the Depth of wear due to rail grinding after period j. Replacement occurs when $A_i \geq A_c$ (Where A_c is the critical area for replacement).

Let $\bar{c}$ denote the expected cost of each rail break repair on emergency basis. Let k be the expected cost of repairing potential rail breaks based on railhead area, RCF, and speed of train. a be the expected cost per derailment. The risk cost associated with rail break and derailment is based on railhead area, RCF and speed of train.

Let $P_i(A, Fatigue, s)$ be the probability of undetected potential rail breaks leading to derailments based on rail head area, RCF and speed of train. $P_i(B)$ be the probability of detecting potential rail breaks based on rail head area, fatigue and speed of train. Rolling contact fatigue is given by Million Gross Tonnes (MGT). Railhead area is determined by wear and preventive rail grinding based on MGT. When expected number of failures are modelled as Non Homogeneous Poisson process and is given by $E[N(M_{i+1}, M_i)$ then the risk cost is given by:

$$\begin{aligned} c_r \;=\; & \{\sum_{i=0}^{N} E[N(M_{i+1}, M_i)] * [P_i(B) * k + (1 - P_i(B)) * (P_i(A, Fatigue, s) * a \\ & + (1 - P_i(A, Fatigue, s)) * \bar{c}] / (1+r)^i \} * r / (1 - (1/(1+r)^N)) \end{aligned} \tag{4}$$

5.3 Modelling replacement costs of worn-out unreliable rails

Let c_{re} be the expected cost of replacement for segment L and consists of labour, material, equipment, and consumable and down time cost for rail replacement. Let I be the cost of current investment in new rail. In this paper the cost of replacement is assumed to be occurring at the beginning of each year and is simplified as the annual cost of investment for new rails.
Then c_{re} is given by:

$$c_{re} = I * (r/(1+r)) / (1 - (1/(1+r)^N)) \tag{5}$$

5.4 Modelling Cost Benefit Analysis

Cost benefit analysis is modelled based on demand and supply for the year j. Revenue of the organisation depends on supply S_j and the operating condition of the rail head area, fatigue, and speed of the train. When travel time (t) is variable based on speed s, then t is given by $t = L/s$

Supply is given by $S_j = min\ \{D_j, (F_j/t) * W * n\}$ (6)

Then net present value (NPV) over rail life is given by

$$NPV = \sum_{j=1}^{N} [S_j [p - (1/W.n) * (L/s) * c_j] / (1+i)^j - C_{tot} \tag{7}$$

This is analytically intractable and a simulation to be used to arrive at train speed, inspection frequency and MGT interval for preventive rail grinding.

6. SUMMARIES AND SCOPE FOR FUTURE WORK

In this paper model for cost benefit analysis for decisions on train speed, inspection frequency, and MGT interval for controlling rolling contact fatigue is developed. Real life data from Australia and Sweden are currently being analysed for managerial decisions and results will be published in future.

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