Evaluation of Technical Vs Economic Decisions in Rail grinding

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Abstract - **Rail is a significant capital asset for railway companies. It contributes more than half of the capital assets of railway infrastructure. Recent rail inspection data using Ultrasonic rail testing has shown increasing number of rail defects, failures and causing disruptions to rail services. This cost can be further increased when the track quality is poor. In recent years, railroads have been purchasing over 500,000 tons of rails per year at an estimated total cost of US $1.25 billion for replacement of worn out and degraded rails. Rail grinding is considered as viable means in reducing the impacts of rail defects and failures. Rail grinding can result in improved curving performance (wheel/rail interaction) and prevents crack initiation and propagation of surface cracks due to RCF. This paper focuses on analysis of rail degradation process and development of mathematical model considering technical and economic decisions in rail grinding to rail infrastructure owners.**

Keywords: **Rail Grinding, Rolling Contact Fatigue and Rail wear**

I. INTRODUCTION

Rolling contact fatigue (RCF) of rails has increasingly become major concern to rail players due to heavy axle loads, tonnage (Million Gross Tonnes) and train speed. Combined passenger and freight train delays caused by gauge corner cracking accounts for 36.8% of the total national train delays on the Railtrack network in 2000-01 [1]. Other factors include cant, rail surface, wheel roundness, track stiffness and vehicle suspensions. Pressure and shear forces in the contact patch are particularly high during traction, braking and during curving due to lateral forces [2]. Around 60% of rail replacements in Northern Sweden are due to rolling contact fatigue and 5% are due to flange wear problems [3].

This paper focuses on rail-wheel degradation process and developing mathematical model considering technical and economic decisions in rail grinding. Section 1 provides introduction to rail defects and influence on rail network. Overview of rail-wheel degradation is discussed in Section 2. In Section 3 inspection, rail grinding, rail replacement problems are discussed. Rail data collected from Sweden and Australia for analysis and results are presented in Section 4. Economic model explained and discussed in Section 5. In concluding section summary and scope for future work are discussed.

II. RAIL-WHEELDEGRADATION

Rail degradation is generally governed by the following factors:

- Rail Wear – due to wheel/rail flange contact, especially in curves
- Fatigue – due to repetitive axle loading and tonnage
- Plastic flow – in the form of corrugation in rails, together with mushrooming of the railhead, wheel burn in rails
- Rail profile problems mainly due to design, manufacturing and maintenance [4].

The wheels problems such as wheel flats, wheel profile and wheel wear are major concerns to both infrastructure providers and train operators. Wear resistance steel with higher hardness reduces this problem but increases welding difficulties and also results in corrugation [5].

Rail corrugation increases dynamic forces, noise and discomfort to passengers due to vibration. It results in possible damage to freight, rails, sleepers and fasteners. The profile of rail and curves make a large contribution to track degradation. Wear and plastic deformation are the main contributors to profile change. In Europe, each year there are hundreds of rails are either re-profiled or replaced due to RCF defects. Rail maintenance cost within the European Union is estimated to 300 Million Euros per year.

Wear is the major factor that controls rail life in heavy haul track. It includes material removed by grinding to maintain rail profile and to remove surface fatigue cracks and spalls caused by rolling contact fatigue as shown in Figure 1 (RCF).

Nilsson [6] defined three wear regimes in the rail-wheel contact. They are mild, sever and catastrophic wear. Mild wear is observed at wheel tread and rail crown and the wear process slow similar to oxidation. Severe wear is observed at wheel flange and rail gauge face especially in sharp curves under dry conditions and it occurs at much faster rate, similar to adhesive wear. The Catastrophic wear in which wear rate is at extremely high and is unacceptable for rail operation due to safety requirements.

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Fig 1 Rolling Contact Fatigue defect

III. INSPECTION, RAIL GRINDING AND RAIL REPLACEMENT

Ultrasonic inspection of rails requires use of several probes in order to increase the probability of detecting surface and sub-surface defects. There are two types rolling contact fatigue defects generally observed during the inspection. They are cracks initiating on or very close to the surface and cracks initiating at sub-surface. Krull et al. [7] showed that eddy current technique was suitable to detect fine cracks on the surface of rails. Sawley and Reiff [8] found that current inspection technologies are capable of detecting defects of 20% to 25% sizes with about 85% reliability. After section of the track inspected, it is likely that some defects above the 25% size will remain undetected in track and continue to grow. If the next inspection cycle is too long, the likelihood of a break is high. Increase in inspection frequency significantly reduces the risk of rail breaks and derailments.

Cannon et al. [9] studied the increase of rolling contact fatigue (RCF) defects and the importance of rail grinding practice around the world. It is important to remove just enough metal to prevent the initiation of RCF cracks. High rail is grounded to a profile which is similar to wheel wear to ensure that there is relatively little wheel/ rail contact in the area around the gauge corner and shoulder of the rail [10]. Combined with a proper lubrication program, a carefully planned grinding program can extend rail life from 50% to 300% [11]. Poor maintenance of transverse profiles and wheel maintenance may lead to deterioration in curves.

Rail grinding is used to remove the existing cracks and to reduce their growth rate. Increase in frequency of rail grinding reduces the development of transverse defects and prevents rail breaks. Rail grinding re-profiles the rail transversely. Appropriate rail profile increases the susceptibility to RCF of rails with the population of wheels. Ishida et al. [12] studied the current practice on rail integrity in Japanese Railways. It is important to scientifically determine grinding interval (how frequently the grinding should be conducted) and grinding depth (how much surface material should be removed). This knowledge is useful to improve the efficiency of grinding work and decrease in the maintenance cost. It is a big challenge for rail players to best utilize the available grinding power (and grinding budget) to maximise the effectiveness of the rail grinding program. The average life of rail in track depends on many factors including rail quality, vehicle-track interaction, and renewal and maintenance policies. Table 1 gives the estimated life of rail in heavy haul sharp curve track [9]. The data is collected was from a survey of major North American railways conducted in 2002. The main factor influencing rail life varies between railways, but another survey of North American railways in 2000 indicated that rail wear was main cause of rail replacement.

TABLE 1
Estimated rail lives in heavy haul track

Curve radius (m)	Estimated rail life (MGT traffic)
388	510
318	449
269	408
233	380
206	358
184	334
<175	251

The Swedish National Rail Administration (Banverket called BV) started a rail grinding program on the 130 km ore line between Kiruna and Riksgränsen in 1997. Åhrén et al. [13] evaluated this programme and found that 12000 $\pm$ 1900 m rail (with AUD $1.55 Million) needs to be budgeted for replacement each year. The yearly cost of rail grinding of this track was estimated to be around 4 Million Swedish Krona (AUD $0.65 Million), resulting in a total yearly maintenance budget of AUD $ 2.19 Million.

Reduction of rail side and table wear with effective performance of lubrication and preventive grinding maintenance extends rail life. Research shows that with proper lubrication it would take at least two years to remove the amount of rail material that is removed in one week of dry running. Kalousek and Magel [14] proposed a light grinding at regular intervals creates a type of step system in which rail is methodically worn to remove the fatigue layer as shown in Figure 2. This firm control grinding process ensures the required amount of material to be removed depending on wear limits adopted by individual railroads. The other extreme longer grinding intervals increases risk of rail failure and rail breaks which can lead to derailments. Either of these approaches would lead to increased cost of grinding and at the same time too much material removal even in single pass when total number of grinding over the life of the rail is taken into account.

It is important to achieve effective lubrication strategies with optimal grinding intervals to enhance rail and wheel life and reduce maintenance cost. This would reduce annual rail replacement costs of rail and wheel and increase safety of rail operation [14]. The interaction of lubrication, RCF and interference by inspection and rail grinding is still not researched well. The whole situation becomes more complex with variation of speed, traction force, axle load, direction and volume of traffic. This paper focuses on technical and economic aspects in a coordinated way for optimal maintenance decisions.

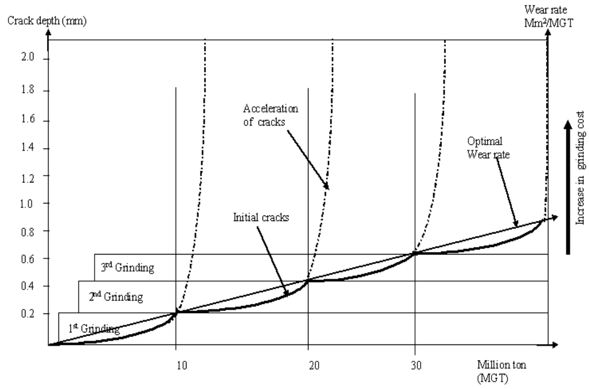

Fig 2. Achieve balanced wear by reducing cracks [14]

IV. DATA ANALYSIS

The Swedish National Rail Administration (Banverket) used the MINIPROF Rail profile system to measure the profiles before and after rail grindings. Transverse profiles are measured for outer and inner rails at 60 positions on Malmbanan line in Sweden. The rate of metal removal by rail grinding is about 0.2 mm across the railhead for every 23 MGT [13].

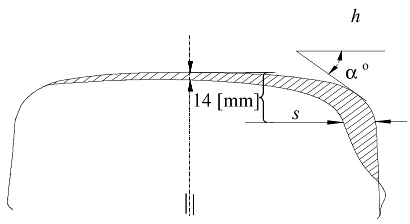

Fig 3. Central vertical wear *h* and side wear *s*

The vertical wear on the railhead *h* and the flange wear *s*, 14 mm down from the top of a new rail profile as per Regulations BVF 524.1, 1998 (Figure 3) and relationships are explained in Equation 1.

$$H = h + \frac{s}{2} \quad (1)$$

Using the relation between measured *s* and *h* one can achieve A_c, the critical railhead area. The Malmbanan line shows the annual *h/s* from traffic wear 0.16/0.24 mm and that from grinding wear 0.48/0.42 mm per year for 23 MGT intervals at curve radii R<800 meters. The relation between *s* and *h* in, *H* can be simplified to a single function of *s* or *h* as follows:

For traffic: $H = h + (0.24/(0.16*2))*h = 1.75h$ (2)

grinding: $H = h + (0.42/(0.48*2))*h \approx 1.44h$ (3)

Total: $H = h + (0.66/(0.64*2))*h \approx 1.52h$ (4)

The safety wear limit H_{limit} is set to 11 mm for the 50-kg/m BV50-rail profiles in Malmbanan line. Therefore A_c can now be obtained by:

$$A_c = h * RC_W + s * RG_W \quad (5)$$

where RC_w is the estimated Rail Crown wear width and RG_w is the estimated Rail Gauge wear width.

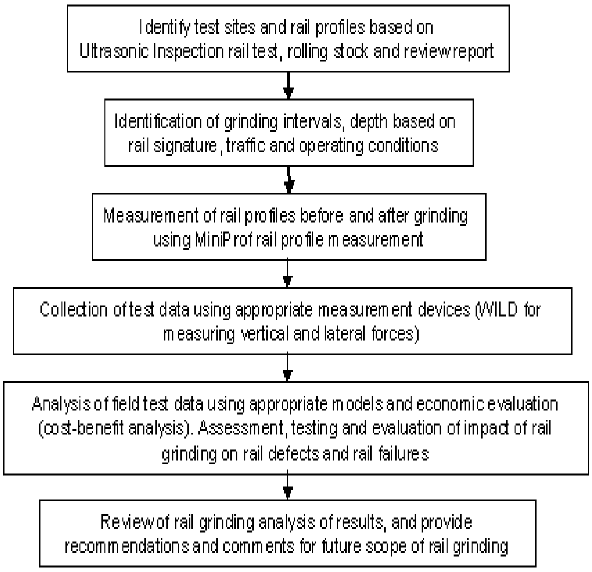

Fig 4. Assessment of methodology

Figure 4 shows the proposed methodology which can be used for the assessment of rail grinding and for making optimal maintenance decisions. Following measures and methods considered for grinding test and analysis. If the:

- targeted rail profiles are within the tolerances for rail grinding limits to prevent rolling contact fatigue cracks
- rail profile is based on rail metallurgy, track curvature, axle loads and traffic type
- decisions are based on Ultrasonic Inspection report under current traffic and rail-wheel conditions
- grinding interval and grinding depth based on rail signature.
- specification is inline with recognised good/best practice as other railways (for example Queensland Rail or Canadian Pacific Rail)
- targeted tonnage (Million Gross Tonnes) and rail life through rail grinding
- maintenance practices which are adopted before and procedures to reduce rail defects and failures
- anticipated wear due to grinding intervals and the impact of any other maintenance practices such as lubrication to reduce wear and noise

Generally using current rail grinding machines the desired profiles can be achieved in one to three grinding passes. Number of target profiles used in preventive and corrective grinding applications would be determined using MINIPROF. Average acceptance values (measured peak-to-peak) range from 0.1 mm for short wave (10 to 30 mm) longitudinal profiles to 0.1 mm for longer wave (300 – 1000 mm) longitudinal profiles after grinding as shown Figure 5 [15]. Acceptance values vary depending on line speeds. For example in Germany on lines with 160 km/h or less the acceptance value for the grinding is ± 0.5 mm. For very high speed lines with operations at 280 km/h, the maximum deviation at the gauge corner zone is ± 0.2 mm [15]. Evaluation of the test data and results will provide review of rail profiles, rail defects and grinding specifications and long term strategies to achieve optimal rail profile and reduce rail failures.

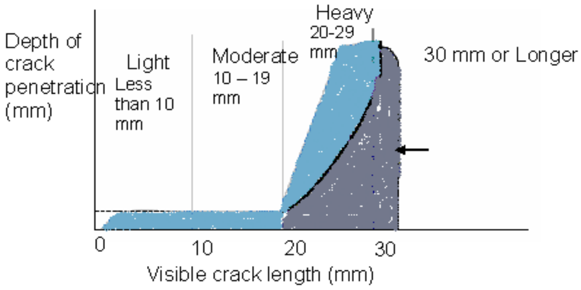

Fig 5. Visible crack length against depth of crack penetration

V. ECONOMIC MODEL

A huge share of the operational budget is spent on maintenance and replacement of rails and wheels. Although many factors contribute to degradation but the influence of wheel/rail contact conditions, the magnitude of friction coefficient and the rail wheel condition are extremely important. Advancements in materials technology and heat treatment have reduced problems related to traffic wear. It is important to develop effective maintenance strategies combining technology and optimal economic decisions based on safety standards to achieve optimal rail grinding in controlling RCF and wear. Some of the associated costs are:

- Restricted track access while grinding.
- Rail grinding cost per meter
- Replacement of worn-out rails.
- Derailment and damage of track, train, property, life, and down time.
- Repairing rail breaks in terms of material, labour, and equipment and down time.
- Inspecting rail tracks in terms of material, labour, equipment and down time.

The grinding at Malmbanan has been an increasing problem. In 2001 a new ore carrier was introduced with 30 tonne axel loads. This rise in axle load from 25 tonnes resulted in increase in RCF damages. BV carried out rail profile measurements before and after grinding activities for analysis of its effectiveness in controlling rolling contact fatigue (RCF) [13]. Rail track length is used based on actual dimensions in Swedish ore line.

In spite of aggressive grinding programs along with frequent onboard non-destructive measurements rail breaks happen. Other factors such as weld joints; rail geometry and corrugation contribute to the risk. The cost of these unplanned replacements is treated as risk cost. For an infrastructure player it is essential to measure and manage these risks by implementing cost effective traffic and maintenance management strategies. Costs associated with rail maintenance are estimated separately for low rail, high rail and curve radius and added up to obtain total cost of maintenance. 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 (NDT) c_i, Risk cost of rectification based on NDT, rail breaks and derailment c_r and Replacement cost of worn-out unreliable rails c_{re}. It is the given by

$$C_{tot} = c_g + c_d + c_i + c_r + c_{re} \quad (6)$$

where Cg is the grinding cost per pass per meter to control rolling contact fatigue and to correct the rail profile. Grinding cost is estimated for i^{th} grinding and for a particular length of rail segments (0-300, 300-450, 450-600, 600-800 meters of curve radius sections). C_d is estimated cost for downtime due to each grinding pass. This includes costs of traffic loss due to grinding. C_i is estimated cost for each inspection. C_r is estimated cost for rectification of rail breaks, accident cost and cost of derailment. In this model risk cost associated with rail break and derailment are estimated on the basis of probability of non destructive testing (NDT) detecting potential rail breaks, rail breaks not detected by NDT, derailments and associated costs. C_{re} is estimated replacement cost for a particular segment consists of labour, material, and equipment, consumables and downtime for replacement for details see Chattopadhyay [16]. Data is collected from field observations and in these calculations Weibull distribution is used with the parameters β= 3.6 and $2350 < 1/\lambda < 1250$, to estimate the rail breaks and derailments. In this case the grinding speed is set to 10 km/h with 3 passes to a total cost of AUD $2 /meter/pass. Discounting factor is used assuming 10% per year. Let G be the cost of grinding per pass per meter and n_i be the number of grinding pass for i^{th} grinding, L be the length of rail segments (0-300, 300-450, 450-600, 600-800 meters of curve radius sections) under consideration, N be the total number of periods up to safety limit for renewal, and r be the discounting rate per period. It is assumed that payments are made to subcontractors after each of the $(N\text{-}1)$ grinding. The total present value of grinding cost is spread over in equal amounts to each year of those N periods. Therefore the annuity cost for rail grinding is given by

$$c_g = \{\sum_{i=1}^{N-1}(G*n_i*L)/(1+r)^i\}*r_y/(1-(1/(1+r_y)^Y)) \quad (7)$$

Simulation model developed and data analysed using MATLAB, for details see Chattopadhyay [16]. Results for 23, 12, 18 and 9 MGT of curve radius from 0 to 300, 300-450, 450-600 and 600-800 meters are modelled for grinding and lubrication strategies (shown in Table 2).

TABLE 2
Total annuity cost/m for 0 to 800 m curves

MGT		23	12	18	9
Length (ms)	Radius (ms)	Annuity cost/m for grinding ($AUD)			
1318	0-300	5.42	6.82	11.41	14.00
1384	300-450	5.95	6.08	11.00	12.00
36524	450-600	6.00	7.12	11.00	10.00
33235	600-800	5.88	6.86	12.00	11.00

Figure 6 shows the analysis of total annuity cost/m for 23, 12, 18 and 9 MGT of curve radius from 0 to 800 m.

From the analysis it is observed that cost is higher for 18 and 9 MGT intervals. This may be mainly due to more rail replacements due to excessive grinding for lower MGT intervals. The 18 and 9 MGT intervals are based on 3 monthly and 6 weekly traffic volumes. In this case it was observed 9 MGT interval was showing technically superior results compared to other interval in controlling RCF. However, this analysis has revealed that 12 MGT is economic when all relevant factors considered in this analysis are taken care.

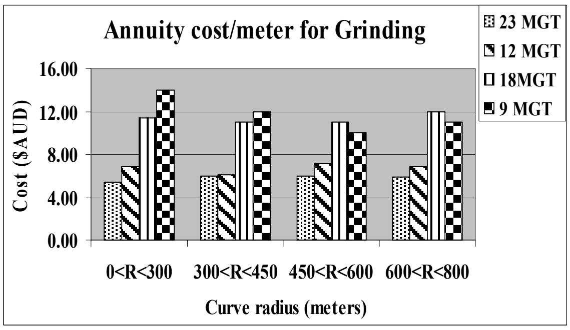

Fig 6. Annuity cost/m for grinding 0 to 800 m curves

Summary of the findings are:

- Analysis shows that total annuity cost/meter for 0-300 meters for 23 MGT is AUD $23.96, for 12 MGT is AUD $22.91, for 18 MGT is AUD $29.24, for 9 MGT is AUD $36.78. It shows that rail players can save 4.58% of costs with 12 MGT intervals compared to 23 MGT intervals.
- Analysis shows that total annuity cost/meter for 300-450 meters for 23 MGT is AUD $22.09, for 12 MGT is AUD $20.15, for 18 MGT is AUD $36.59, for 9 MGT is AUD $38.87. This shows that rail network providers can save 9.63% of costs with 12 MGT intervals compared to 23 MGT intervals.

It is observed that in steep curves rail replacement is more due to rolling contact fatigue (RCF) compared to curves with higher radius. To achieve balance between optimal rail grinding, maintenance and economic decisions it is important to consider the continual assessment of rail-wheel condition and its significant impacts of rail failures.

VI. CONCLUSION

This paper is focused on rail degradation analysis on comparison of technical and economical decisions on preventive rail grinding using real life data. Inspection, rail grinding practices and rail replacement are discussed. Rail grinding methodology proposed could be used for assessment of technical and for making economic decisions. Field data from Sweden and Australia have been used for analysis and illustration. The annuity cost/meter for grinding, risk, down time, inspection, replacement and lubrication are analysed. Results for 23, 12, 18 and 9 MGT of curve radius from 0-300, 300-450 meters are presented. Analysis shows that rail players can save with economic 12 MGT intervals compared to technical 23 MGT intervals by 4.58% for 0-300, 9.63% for 300-450 m respectively. Results from this investigation can be used for making technical and economical and replacement decisions and analysis of operating risks. There is enormous scope to extend these models for optimal maintenance decisions considering risks covering both rail and wheel, which includes profiling, lubrication and weather, traffic and operating conditions. Authors are currently working on these areas and results will be published in the future.

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