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Decision on economical rail grinding interval for controlling rolling contact fatigue

G. Chattopadhyay[a], V. Reddy[a] and P.-O. Larsson-Kråik[b]

[a]*School of Engineering Systems, Queensland University of Technology, 2 George Street, Brisbane, Qld 4000, Australia,*
[b]*Swedish National Rail Administration, Technical Department, PO Box 43, SE-971 02 Luleå, Sweden*
E-mails: g.chattopadhyay@qut.edu.au [Chattopadhyay],
v.reddy@qut.edu.au [Reddy], per-olof.larsson-kraik@banverket.se [Larsson-Kråik]

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Abstract

Rail players around the world have been increasing axle loads to improve the productivity of freight and heavy haul operations. This has increased the risk of surface cracks at curves because of rolling contact fatigue. Rail grinding has been considered an effective process for controlling these cracks and reducing risks of rail breaks. 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. This paper focuses on identifying the factors influencing rail degradation, developing models for rail failures and analyzing the costs of various grinding intervals for economic decision making. Various costs involved in rail maintenance, such as rail grinding, downtime, inspection, rail failures and derailment, and replacement of worn-out rails, are incorporated into the total cost model developed in this paper. Field data from the rail industry have been used for illustration.

Keywords: maintenance cost; mathematical modelling; rail grinding; wear; rolling contact fatigue (RCF)

Nomenclature

A_c	Critical railhead area when rail replacement is recommended (mm^2)
A_i	Cross-sectional rail profile area ith interval (mm^2)
A_{GW_j}	Cross-sectional area loss because of grinding in period j (mm^2)
A_{TW_j}	Cross-sectional area loss because of traffic wear in period j (mm^2)
A_0	Cross-sectional profile area of a new rail (mm^2)
A	Expected cost/derailment (AUD)
C_r	Cost/rectification of rail breaks on emergency basis (AUD)
C_{tot}	Total cost (AUD/year)

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C	Cost of each rail break repair on emergency basis (AUD)
$\bar{c}$	Expected cost of each rail break repair on emergency basis (AUD)
c_{d}	Downtime cost (AUD/year)
c_{g}	Grinding cost (AUD/year)
c_{i}	Inspection cost (AUD/year)
c_{r}	Risk cost (AUD)
c_{re}	Replacement cost (AUD/year)
D	Expected cost of downtime due to traffic loss (AUD/h)
$E\,[M_{i+1},\ M_i]$	Expected number of failures over M_i *and* M_{i+1} (dimensionless)
$F_n(m)\ [f_n(m)]$	Rail failure distribution [density] function (dimensionless)
$G(c)$	Distribution function of cost of each rail break repair (dimensionless)
GD_j	Wear depth due to rail grinding after period j (mm)
G	Cost of grinding/pass/m (AUD/pass/m)
H	Weighted side- and height wear (mm)
H_{limit}	Critical H when the rail must be replaced (mm)
h	Vertical central wear on the railhead (mm)
h_{DT}	Expected downtime due to each grinding pass (h)
I	Cost in investment of rail for segment L (AUD)
I_{f}	Inspection frequency in millions of gross tonnes (MGT) (dimensionless)
i	Index (dimensionless)
i_{c}	Cost of each inspection (AUD)
j	Index (dimensionless)
K	Cost of rectification of potential rail breaks based on NDT (AUD)
L	Length of rail segment under consideration (m)
M_i	Total accumulated MGT of the section studied up to decision I (kg $\times\ 10^6$)
M_N	Total accumulated MGT for rail life up to end of period N (kg $\times\ 10^6$)
m	Millions of gross tonnes (kg $\times\ 10^6$)
m_j	MGT in period j (dimensionless)
N	Total number of periods up to safety limit for renewal (dimensionless)
$N(M_{i+1},M_i)$	Number of failures over M_i and M_{i+1} (dimensionless)
N_I	Number of inspections over rail life (dimensionless)
n	Number of failures (dimensionless)
n_{A_j}	Number of accidents in period j (dimensionless)
n_{Gp_i}	Number of grinding passes for ith grinding (dimensionless)
n_{NDT_j}	Number of detected potential rail breaks using NDT (dimensionless)
n_{RB_j}	Number of rail brakes in between two NDT inspections (dimensionless)
$P[\cdot]$	Probability (dimensionless)
$P_i(A)$	Probability of undetected potential rail breaks leading to derailment (dimensionless)
$P_i(B)$	Probability of detecting potential rail breaks using NDT (dimensionless)
R	Track circular curve radii (m)
RC_{w}	Estimated rail crown wear width (mm)
RG_{w}	Estimated rail gauge wear width (mm)
r	Discounting rate between preventive rail grindings (%)

r_i	Discounting rate between inspections using NDT (%)
S	Flange wear (mm)
TD_j	Wear depth due to traffic after period j (mm)
WOL_i	Worn out level of rail after ith grinding (%)
α	MINIPROF degrees (deg.)
β, λ	Weibull parameters (dimensionless)
$\Lambda(m)$	Failure intensity function associated with m (dimensionless)
ρ	Parameter of repair rail cost function (dimensionless)

1. Introduction

Rail players around the world have been increasing axle loads to improve the productivity of freight and heavy haul operations. Recent reviews show that rolling contact fatigue (RCF), such as squats and head check defects, have been increasing because of the introduction of longer and heavier trains (increased axle loads), and also because of the greater speeds of freight trains. The European Union has estimated that premature rail removal, renewal and maintenance costs because of these factors amount to 300 million Euros (AUD 420 million) per year (Sawley and Reiff, 2000). Rail grinding has been considered an effective process in controlling these cracks and reducing the risks of rail breaks. The complexity in deciding optimal rail grinding intervals for improving reliability and safety of rails is because of insufficient understanding of the various factors involved in the crack initiation and propagation process. It is important to identify the factors causing degradation, measure these factors and develop a model for economic rail grinding intervals for controlling RCF and rail replacements. Squats, shelling and head checks, and various forms of RCF defects develop in curves and switches because of increased slippage towards the gauge corner and the decreased area of wheel–rail contact. These RCF-initiated cracks are major challenges for railtrack owners (Hiensch et al., 2001). Four people were killed and 34 were injured on October 17, 2000 when an Inter City Express train travelling at 115 miles/h derailed on a curve near Hatfield on Britain's East Coast Main Line. The analysis of this accident showed that the cause was gauge corner cracking/head checking because of RCF, leading to a £580 million (AUD 1.4 billion) bill for the cost of the re-railing and compensation for the affected people and companies (Grassie, 2001). Kalousek and Magel (1997) proposed a magic wear rate in preventive rail grinding to control RCF without wasting too much rail life by excessive rail grinding. Magel and Kalousek (2002) then applied contact mechanics to rail profile design and rail grinding. Ringsberg (2001) and Ringsberg et al. (2000) further developed crack initiation models. Jendel (2002) developed prediction models for wheel profile wear.

In this paper, factors influencing rail degradation are identified, models for rail failures are developed, and costs for various grinding intervals are analyzed for economic decisions. Various costs involved in rail maintenance such as rail grinding, downtime, inspection, rail failures and derailment and replacement of worn-out rails are incorporated into the total cost model developed. Field data from Swedish National Rail and Queensland Rail have been used for illustration. The results of this research can be used for economic rail maintenance and replacement decisions.

The outline of this paper is as follows: In Section 2, modelling rail breaks are discussed. Section 3 provides modelling of rail section loss. In Sections 4–9, rail grinding, downtime, inspection, risk cost, replacement and total cost of rail maintenance are modelled. Section 10 provides a numerical example along with simulation results. In the final section, the scope for future work is discussed.

2. Modelling rail breaks

In this paper, failures are modelled as a point process with an intensity function $\Lambda(m)$ where m represents millions of gross tons (MGT) and $\Lambda(m)$ is an increasing function of m, indicating that the number of failures, in a statistical sense, increases with MGT. As a result, $N(M_{i+1}, M_i)$, the number of failures over M_i and M_{i+1}, is a function of MGT, m, and is a random variable. Let the MGT of rail, m, be known, and $F_n(m)$ denote the cumulative rail failure distribution, modelled as Weibull distribution given by

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

The failure intensity function $\Lambda(m)$ is given by

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

with the parameters $\beta > 1$ and $\lambda > 0$.

With the condition that $N(M_{i+1}, M_i) = n$, the probability is given by

$$P\{N(M_{i+1}; M_i) = n\} = \left\{\int_{M_i}^{M_{i+1}} \Lambda(m)\,\mathrm{d}m\right\}^n \mathrm{e}^{-\int_{M_i}^{M_{i+1}} \Lambda(m)\,\mathrm{d}m}/n!. \tag{3}$$

This type of characterization is appropriate because rail track is made operational through repair or replacement of the failed segment, and no action is taken with regard to the remaining length of the whole track. As the length of the failed segment replaced at each failure is very small relative to the whole track, the rectification action can be viewed as having a negligible impact on the failure rate of the track as a whole; see Barlow and Hunter (1960). Then the expected number of failures from period i to $(i+1)$ is given by

$$E[N(M_{i+1}, M_i)] = \lambda^{\beta}((M_{i+1})^{\beta} - (M_i)^{\beta}), \tag{4}$$

where the total accumulated MGT, M_i, is given by

$$M_i = \sum_{j=0}^{i} m_j. \tag{5}$$

3. Modelling rail section loss

MINIPROF was used to measure the profiles of rail just before and after preventive rail grinding with an accuracy in the order of ± 0.015 mm (Åhrén et al., 2003). Marks on the edge of the rail

Fig. 1. Rail Profile Measurement [MINIPROF, Greenwood, Denmark].

are used to ensure that the measurements are performed at the same location each time; see Fig. 1. For details, see Esveld and Gronskov (1996).

The area after the ith period is modelled as

$$A_i = A_0 - \sum_{j=o}^{i} ((RC_w + RG_w)TD_j + (RC_w + RG_w)GD_j), \quad (6)$$

where A_0 is the cross-sectional profile area of a new rail, RC_w is the rail crown wear width, RG_w is the rail gauge wear width, TD_j is the wear depth because of traffic after period j and GD_j is the depth of wear because of rail grinding after period j. It can be expressed as

$$A_i = A_0 - \sum_{j=0}^{i} A_{TW_j} + A_{GW_j} \quad [A_i \geq A_c], \quad (7)$$

where A_{TW_j} is the cross-sectional area loss because of traffic wear and A_{GW_j} is the cross-sectional area loss because of grinding wear in period j.

The percentage of worn out rail after the ith period is given by

$$WOL_i = 100 \times \frac{A_0 - A_i}{A_0 - A_c}, \quad (8)$$

where A_c is the critical railhead area for rail replacement based on safety recommendations. The Swedish National Rail Administration (Banverket) follows regulation BVF 524.1 (1998) for railhead wear. The vertical wear on the railhead h and the flange wear s is taken at a level of 14 mm from the top of a new rail profile, see Fig. 2 and Equation (8).

The annual traffic wear and grinding is used to estimate the proportion of rail life consumed and to indicate when the rail should be replaced:

$$H = h + \frac{s}{2}. \quad (9)$$

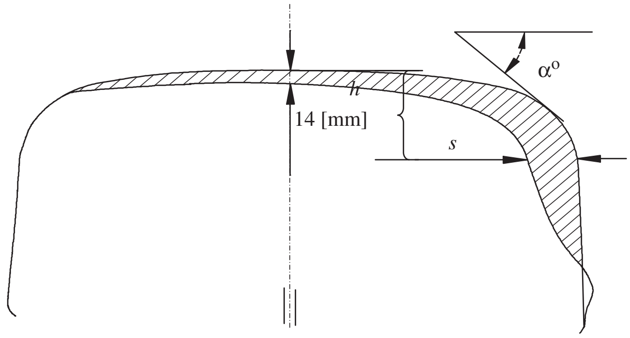

Fig. 2. Central vertical wear h and side wear s.

The terms s and h can be used in place of A_c (the critical railhead area) for deciding rail replacements. A_c can be obtained by

$$A_c = h \times RC_w + s \times RG_w, \tag{10}$$

where RC_w is the estimated width of rail crown wear and RG_w is the estimated width of rail gauge wear.

4. Modelling rail grinding cost

Let g be the cost of grinding per pass per meter and n_{GP_i} be the number of grinding passes for ith grinding, L be the length of rail segment under consideration, N be the total number of periods up to the safety limit for renewal and r be the discounting rate. The rail grinding cost/year is then given by

$$c_g = \left\{ \sum_{i=1}^{N-1} (g \times n_{GP_i} \times L)/(1+r)^i \right\} \times r_y/(1 - (1/(1+r_y)^y)), \tag{11}$$

where $1/(1+r)^i$ is used to calculate the present value of the grinding cost occurring after period i and $r_y/\left(1 - \left(1/\left(1+r_y\right)^y\right)\right)$ is applied to estimate the equal amount of the total cost over the rail life y in years. r_y is the annual discounting rate and r is the discounting rate for any period.

5. Modelling downtime cost

Let h_{DT} be the expected downtime because of each grinding pass, n_{GP_i} be the number of grinding passes for ith grinding and d be the expected cost of downtime/h. Then downtime cost because of loss of traffic is given by

$$c_{\mathrm{d}} = \left\{ \sum_{i=1}^{N-1} n_{\mathrm{GP}_i} \times h_{\mathrm{DT}} \times d/(1+r)^i \right\} \times r/(1 - (1/(1+r)^N)). \tag{12}$$

6. Modelling inspection cost

Let I_f be the inspection per MGT and i_{c} be the cost of each inspection. Then the annual inspection cost over the rail life is given by

$$c_{\mathrm{i}} = \left\{ \sum_{j=1}^{N_I} i_{\mathrm{c}}/(1+r_i)^j \right\} \times r/(1 - (1/(1+r)^N)), \tag{13}$$

where

$$N_I = Integer\left[\frac{M_N}{I_f}\right] \tag{14}$$

and r_i is the discounting rate associated with the interval of nondestructive testing (NDT).

7. Modelling risk cost

Let C_{r} be the cost per rectification of rail breaks on an emergency basis, modelled through $G(c)$, and is given by

$$G(c) = P[C_{\mathrm{r}} \le c]. \tag{15}$$

As an example, if $G(c)$ follows exponential distribution, then it is given by

$$G(c) = 1 - \mathrm{e}^{-\rho c}, \tag{16}$$

where $\bar{c}$ denotes the expected cost of each rail break repair on an emergency basis and is given by

$$\bar{c} = [1/\rho]. \tag{17}$$

Let k be the expected cost of repairing potential rail breaks based on NDT in a planned way and a be the expected cost per derailment. Then, k and a could be modelled in a similar manner. The risk cost associated with rail break and derailment is based on the probability of NDT detecting potential rail breaks, rail breaks not being detected by NDT, derailments and associated costs.

Let $P_i(B)$ be the probability of detecting potential rail breaks using NDT, $P_i(A)$ be the probability of undetected potential rail breaks leading to derailments, n_{NDT_j} be the number of detected potential rail breaks using NDT, n_{RB_j} be the number of rail brakes in between two NDT inspections and n_{A_j} be the number of accidents in period j. Then, the risk cost is given by

$$c_{\mathrm{r}} = \left\{ \sum_{i=0}^{N} E[N(M_{i+1}, M_i)] \times [P_i(B) \times k + (1 - P_i(B)) \right.$$
$$\left. \times (P_i(A) \times a + (1 - P_i(A)) \times \overline{c}]/(1+r)^i \right\} \times r/(1 - (1/(1+r)^N)), \qquad (18)$$

where $P_i(B)$ and $P_i(A)$ could be estimated based on n_{NDT_j}, n_{RB_j} and n_{A_j}.

8. Modelling replacement cost

Let c_{re} be the expected cost of replacement for segment L and consist of labor, material, equipment and consumable and downtime 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

$$c_{\mathrm{re}} = I \times (r/(1+r))/(1 - (1/(1+r)^N)). \qquad (19)$$

9. Modelling total cost of maintenance

Costs associated with rail maintenance are estimated separately for low rail, high rail and different curve radii. These are added to obtain a total cost of rail maintenance. Therefore, the total cost of maintaining a segment of rail is equal to the sum of costs for: preventive rail grinding, downtime because of rail grinding (loss of traffic), inspections (NDT), rectifications based on NDT, repair of rail breaks, derailments and replacement of worn-out and unreliable rails. It is given by

$$C_{\mathrm{tot}} = \overline{c}_{\mathrm{g}} + \overline{c}_{\mathrm{d}} + \overline{c}_{\mathrm{i}} + \overline{c}_{\mathrm{r}} + c_{\mathrm{re}}. \qquad (20)$$

10. Numerical example

The data related to track path, wear and RCF and cost data are given in Tables 1, 2 and 3, respectively.

10.1. Simulation results

Chattopadhyay et al. (2003) used profile data to predict contributions from traffic wear, grinding wear and the number of grind passes and area that the grinder needs to take away in each rail

Table 1
Track path divided into sections

Section	Curve radii (m)	Length (%)
1	$0<R<300$	1.01
2	$300<R<450$	1.06
3	$450<R<600$	27.98
4	$600<R<800$	25.46

Table 2
Measurements of grinding for high rail

Average traffic wear (mm^2)	11.2
Average traffic wear depth (mm)	0.18
Average grinding wear (mm^2)	24.6
Average grinding wear depth (mm)	0.40
Average rail crown wear width (RC_w) (mm)	40
Average rail gauge wear width (RG_w) (mm)	20
Average no. of grinding passes (dimensionless)	3
Critical railhead area loss (BV-50) (A_c) (mm^2)	585
Critical railhead area loss (UIC-60) (A_c) (mm^2)	745
Critical railhead area loss (80 kg/m profile) (A_c) (mm^2)	1000
Total length of the section (L) (km)	130

Table 3
Estimated costs

Cost of grinding per pass per meter (AUD/pass/m)	2.00
Cost of replacement of one rail for segment L because of worn out regulation (AUD/m)	152
Expected costs of repairing rail brakes (AUD/brake)	1700
Expected cost per derailment (accident) (AUD/accident)	3,000,000
Expected cost of downtime per hour (AUD/h)	3136
Inspection cost (AUD/m/MGT)	0.0043
New rail cross-sectional area (mm^2)	2960
Critical area for replacement decision (BV50) (mm^2)	2520–585
Critical area loss for replacement decision (UIC60) (mm^2)	2400–745
Critical area loss for replacement decision theoretical 80 kg/m profile (mm^2)	1960–1000

grinding. The parameters of the Weibull distribution are $\beta = 3.6$ and $2350 < 1/\lambda < 1250$ (see Besuner et al., 1977) to estimate the risks associated with rail breaks and derailments. The grinding speed is set to 10 km/h and four passes on the section length annually removes 24.6 mm^2 (see Table 3) for a total cost of 43 SEK/m (AUD 7.8/m) track. The total track length L is 130 km. Other costs are given in Table 3. The total present value of the costs is then used for estimating the equal amount of spread over all the years of the rail life and is known as the annuity cost.

Grinding cost is estimated using the grinding cost per meter per pass and the number of passes required to address the RCF-related surface cracks, and is shown in Fig. 3.

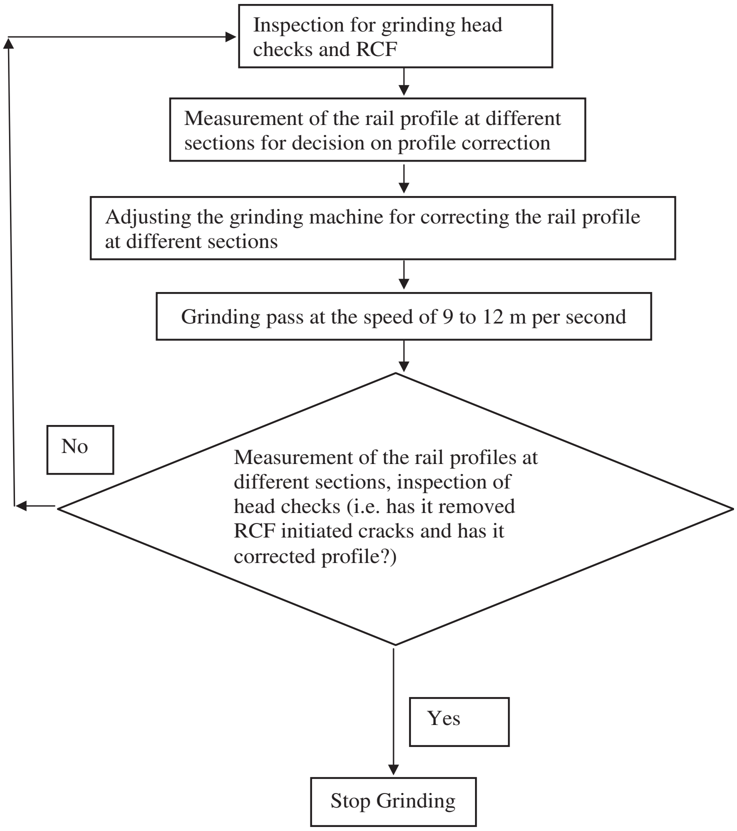

Fig. 3. Grinding cost estimation method.

10.2. Annuity cost/m for 12 MGT

Analysis of the annuity cost/m of grinding, risk, downtime, inspection and replacement for 12 MGT of curve radius from 0 to 800 m is compared. The results are shown in Table 4.

Figure 4 shows the analysis of annuity cost/m for 12 MGT of curve radius from 0 to 800 m. It is observed that the cost is higher for replacement and grinding.

10.3. Annuity cost/m for 18 MGT

Analysis of the annuity cost/m of grinding, risk, downtime, inspection and replacement for 18 MGT of curve radius from 0 to 800 m is compared. The results are shown in Table 5.

Figure 5 shows the analysis of annuity cost/m for 18 MGT of curve radius from 0 to 800 m. It is observed that the costs for replacement and grinding are higher compared with other costs.

10.4. Annuity cost/m for 9 MGT

Analysis of the annuity cost/m of grinding, risk, downtime, inspection and replacement for 9 MGT of curve radius from 0 to 800 m is compared. The results are shown in Table 6.

Table 4
Annuity cost/m for 12 MGT

Radius (m)	0–300	300–450	450–600	600–800
Length (m)	1318	1384	36,524	33,235
Maintenance costs	Annuity cost/m (AUD)			
Grinding	6.82	6.08	7.12	6.86
Risk	0.00	0.00	0.00	0.00
Downtime	1.07	0.95	1.12	1.08
Inspection	0.02	0.02	0.02	0.02
Replacement	15.00	13.10	11.63	11.49

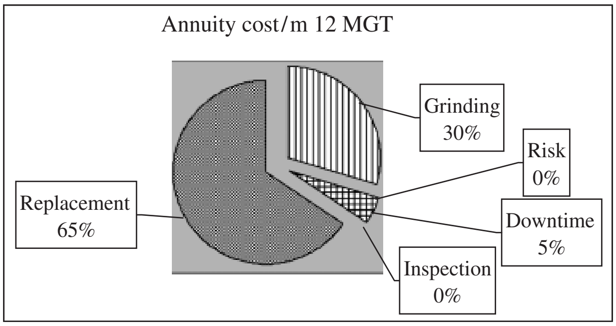

Fig. 4. Annuity cost/m for 12 MGT.

Table 5
Annuity cost/m for 18 MGT

Radius (m)	0–300	300–450	450–600	600–800
Length (m)	1318	1384	36,524	33,235
Maintenance costs	Annuity cost/m (AUD)			
Grinding	11.41	11.00	11.00	12.00
Risk	0.00	0.00	0.00	0.00
Downtime	1.79	1.56	1.77	1.83
Inspection	0.03	0.03	0.03	0.03
Replacement	16.00	24.00	32.00	24.00

Figure 6 shows the analysis of annuity cost/m for 9 MGT of curve radius from 0 to 800 m. It is observed that the grinding costs are higher compared with other costs.

10.5. Total annuity cost/m

Analysis of the total annuity cost/m for 12, 18 and 9 MGT is compared for curve radius from 0 to 800 m. The results are shown in Table 7.

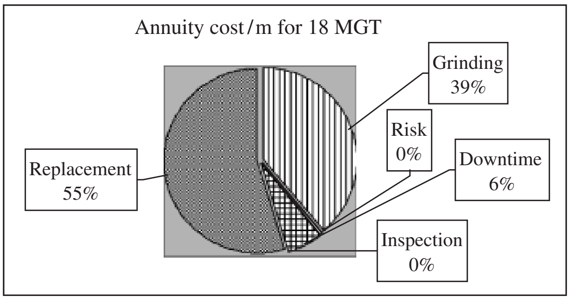

Fig. 5. Annuity cost/m for 18 MGT.

Table 6
Annuity cost/m for 9 MGT

Radius (m)	0–300	300–450	450–600	600–800
Length (m)	1318	1384	36,524	33,235
Maintenance costs	Annuity cost/meter (AUD)			
Grinding	14.00	12.00	10.00	11.00
Risk	0.00	0.00	0.00	0.00
Downtime	2.14	1.85	1.57	1.74
Inspection	0.02	0.02	0.02	0.02
Replacement	20.62	25.00	28.00	28.00

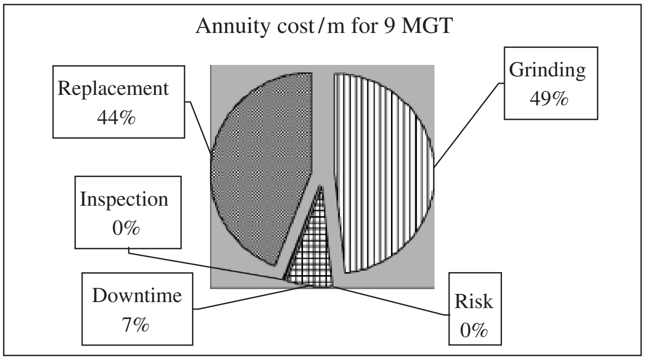

Fig. 6. Annuity cost/m for 9 MGT.

Figure 7 shows the analysis of total annuity cost/m for 12, 18 and 9 MGT of curve radius from 0 to 800 m. From the analysis it is observed that the cost is higher for 18 and 9 MGT intervals. This may be mainly a result of more rail replacements because of excessive grinding for lower MGT intervals. The 18 and 9 MGT intervals are based on 3 monthly and 6 weekly traffic volumes resulting in higher annuity costs. However, costs per MGT could be comparable. It is also observed that costs are greater for the segments with steeper curves.

Table 7
Total annuity cost/m

MGT		Total annuity cost/m (AUD)		
Length (m)	Radius (m)	12 MGT	18 MGT	9 MGT
1318	0–300	22.91	29.24	36.78
1384	300–450	20.15	36.59	38.87
36,524	450–600	19.89	44.80	39.59
33,235	600–800	19.45	37.86	40.76

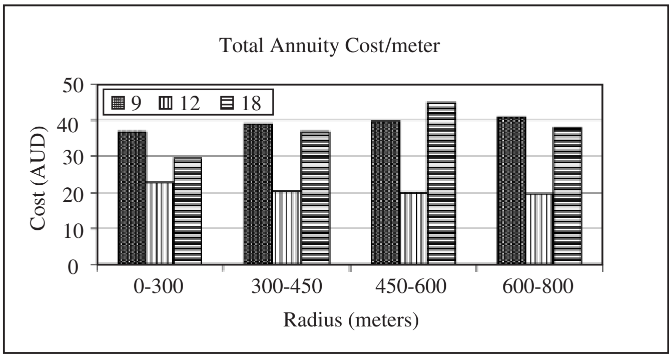

Fig. 7. Total annuity cost/m for replacement.

11. Conclusion

In this paper factors influencing rail degradation are identified, models for rail failures are developed and costs for various grinding intervals are analyzed for economic decisions. Various costs involved in rail maintenance such as rail grinding, downtime, inspection, rail failures and derailment and replacement of worn-out rails are incorporated into the total cost model. Field data from the rail industry have been used for illustration.

The analysis shows that total annuity cost/m increases for steeper curves

- 0–300 m for 12 MGT is AUD 22.91, for 18 MGT is AUD 29.24, for 9 MGT is AUD 36.78.
- 300–450 m for 12 MGT is AUD 20.15, for 18 MGT is AUD 36.59, for 9 MGT is AUD 38.87.
- 450–600 m for 12 MGT is AUD 19.89, for 18 MGT is AUD 44.80, for 9 MGT is AUD 39.59.
- 600–800 m for 12 MGT is AUD 19.45, for 18 MGT is AUD 37.86, for 9 MGT is AUD 40.76.

The above analyses show that rail players can save money by using 12 MGT intervals instead of 9 or 18 MGT intervals. For steeper curves, replacement is more expensive because of RCF. There is enormous scope to extend these models, considering rail-wheel profiling, lubrication (track and/or on board) and weather conditions for economic rail grinding and replacement decisions. The authors are currently working on this, and the results will be published in the future.

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