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ScienceDirect
Int. J. Production Economics 105 (2007) 475–482
international journal of production economics
www.elsevier.com/locate/ijpe

Modelling and analysis of rail maintenance cost

Venkatarami Reddy[a,*], Gopinath Chattopadhyay[a,*], Per-Olof Larsson-Kråik[b], Doug J. Hargreaves[a]

[a]School of Engineering Systems, Queensland University of Technology, P.O Box 2434, Brisbane QLD 4001, Australia
[b]Swedish National Rail Administration, Technical Department, P.O. Box 43 SE-971 02 Luleå, Sweden

Received 15 April 2004; accepted 24 March 2006
Available online 15 June 2006

Abstract

Lubrication at wheel flange and rails on sharp curves is considered as an effective solution for reducing wear loss of material from effective cross-section of rail and wheels. Rail administrations around the world have been increasing axle loads and traffic densities in rail networks. This has led to traffic initiated wear, fatigue initiated surface cracks and rail breaks. Limited research has been carried out on the overall impact of combining lubrication strategies and rail grinding. This paper presents a model for lubrication strategy and rail-grinding interval to reduce wear and rolling contact fatigue (RCF). Data from rail industry is collected and used for numerical illustration.

Keywords: Wear; Rolling contact fatigue (RCF)

1. Introduction

Rail players around the world have been using lubrication to reduce rail wear at the gauge-corner of the high rail in curves (Kalousek and Magel, 1997). There is further scope for better wear control and safety, (Welty, 1988; Allen, 1999). Axle loads in many rail networks have increased from 25 to 32.5 tonnes. An experimental test program of wheel/rail friction and wear was undertaken by Kumar et al. (1996). The influencing parameters identified are:

- rail curvature or angle of attack,
- friction coefficient,
- axle loads.

Thelen and Lovette (1996) investigated the lubricant transport mechanisms at the wheel–rail interface. Sims et al. (1996) measured the coefficient of friction. Nilsson (2002) discusses important factors for modelling rail wear. These are: friction coefficient (humidity, temperature, surface texture), type of lubrication equipment (on-board or way-side), grease contamination from dust, leaves, worn away metal particles, water, rail and wheel profile maintenance, track irregularities (vertical, lateral, cant, gauge), curve radius, magnitude of creep in wheel/rail contact as well as braking and acceleration.

Annual grease consumption for rail lubrication varies between 0.7 and 2.5 kg/km for different countries, (Larsson, 2000). The variation depends on number of trains, track curvature, type of application equipment such as stationary or on-board. The annual lubricant consumption in Russia (2nd largest in the world with 87,000 km of main

*Corresponding authors. Tel.: +61 7 38645106; fax: +61 7 38641469 (V. Reddy); Tel.: +61 7 38642865; fax: +61 7 38641469 (G. Chattopadhyay).
E-mail addresses: v.reddy@qut.edu.au (V. Reddy), g.chattopadhyay@qut.edu.au (G. Chattopadhyay).

0925-5273/$ - see front matter
doi:10.1016/j.ijpe.2006.03.008

Nomenclature

a	expected cost per derailment (AUD)
c_{tot_j}	total cost (AUD/year)
c_{d_j}	down time cost (AUD/year)
c_{g_j}	grinding cost (AUD/year)
c_{i}	inspection cost (AUD/year)
c_{l_j}	cost of lubrication (AUD/year)
c_{r_j}	risk cost (AUD)
c_{re_j}	replacement cost (AUD/year)
c_{s}	switching cost for stop/start lubrication (AUD /changeover)
$E_j[M_{i+1}, M_i]$	expected number of failures over M_i and M_{i+1} for jth strategy (dimensionless)
$F_j(m)$ $[f_j(m)]$	rail failure distribution [density] function for jth strategy (dimensionless)
j	lubrication strategy (dimensionless)
L	length of rail segment under consideration (m)
MGT	million gross tonnes (tonnes)
M_j	total accumulated MGT for the section studied up to decision j (tonnes)
m	millions of gross tonnes (tonnes)
m_q	MGT in period q (tonnes)
N_j	total number of periods up to safety limit for renewal for strategy j (dimensionless)
$N_j(M_{i+1}, M_i)$	number of failures over M_i and M_{i+1} as per strategy j (dimensionless)
n	the number of failures (dimensionless)
q	index (dimensionless)
R	track circular curve radii (m)
β_j, λ_j	Weibull parameters for failures in jth strategy (dimensionless)
$\Lambda_j(m)$	failure intensity function associated with m in jth strategy (dimensionless)
Y_j	decision variable for lubrication strategy (dimensionless) 0 for no or continuous lubrication (dimensionless) 1 for stop/start lubrication (dimensionless)

track and 77.7% of freight lines) is 30% higher per MGT compared to other rail systems in the West (Habali, 1999). Gangloff (1999) mentioned that lubricants used in railroad applications primarily consist of petroleum-based greases and special graphite lubricants. Tests in the USA have suggested that a significant portion of the grease used is lost during wayside lubrication. It has potential of ground water contamination. There is a need for an optimal amount of grease based on traffic and environmental conditions. Goyan et al. (1997) discussed environmental regulations required to be considered for suitable rail lubrication. Biodegradable grease has favourable environmentally adaptable properties such as low toxicity along with excellent extreme pressure, low wear rate (friction coefficients for lubricated contact is 0.025–0.038, ten times lower than non-lubricated contact), low temperature pumpability, suitable dropping point, and the ability to be transported (1.5 km) down the track. (Kramer, 1994), found that grease-based lubrication, typically used on main lines is prone to waste and several companies have already started developing solid lubrication (i.e. a solidified version of a traditional-type lubricant, or a substantively different technology such as self-lubricating, oil-infused polymers). These new lubricants ought to eliminate the problems of waste and inefficiency making them more effective than the existing lubricants (Larsson, 2000). In the European rail research project ICON (Integrated study of rolling CONtact fatigue), Nilsson (2002), showed that the railhead wear rate is low during the wet seasons of the year and is high during other periods.

This paper is on development of models for analysis of rail track maintenance cost considering rolling contact fatigue (RCF), traffic wear and lubrication.

The outline of this paper is as follows:

Section 1 provides introduction with background of the problem. Section 2 gives an overview of rail lubrication. Modelling and analysis of rail track maintenance cost are developed in Section 3. Numerical examples are used for illustration in Section 4. In the final section contributions of this paper are summarised along with scope for future work.

2. Overview of rail lubrication

The rail wear rate decreases with increase in curve radius for both high and low rails as shown in Fig. 1. The wear rate ratio between non-lubricated and lubricated sites decreases for the curves with larger radius.

Kalousek and Magel (1997) introduced preventive rail grinding to grind away a thin layer of material from rail surface before surface cracks can

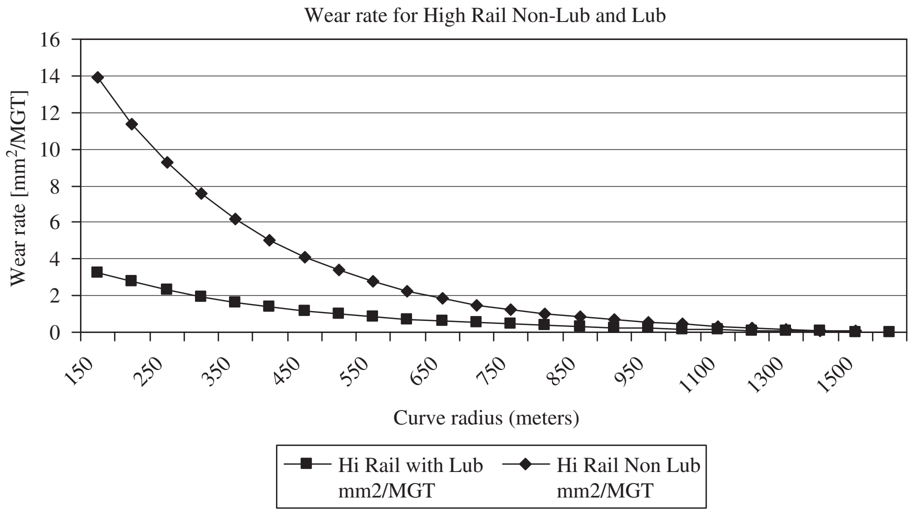

Fig. 1. Traffic wear rate for high rail non-lubricated and lubricated (Kramer, 1994).

propagate. The depth of the cut is determined by the depth at which surface cracks appear. On an average, about 0.004–0.008 in is removed from the gauge corner and 0.002–0.006 in from the crown of rail before surface cracks propagate. It is found that the costs of any grinding program are simply too high and there is a need of better understanding of rail surface cracks and develop economical grinding to minimise the costs and improve the grinding efficiency. In the ICON project, Nilsson, (2002) compared the wear rate and observed that the effect of lubrication in curves is significant. For example, the wear rate for a lubricated curve at 200 m distance from the lubricator is approximately twice compared to the wear rate at 50 m distance from the lubrication device. There is need to develop better understanding of lubrication effectiveness of entire rail curvature and evaluate the lubrication performance.

3. Modelling and analysis of maintenance cost

This section looks into rolling contact fatigue, lubrication strategies to reduce traffic wear and the influence of rail grinding in preventing crack propagation for developing a total cost model for rail maintenance.

3.1. Modelling cost of lubrication

This is based on the following strategies:

- *No lubrication*: Wear is higher in sharp curves and the replacement of rails occurs too frequently.
- *Lubrication throughout the year*: Per MGT cost of lubrication in curves is higher; however there is no cost of switching to stop/start for lubrication throughout the year.
- *Start/stop lubrication*: Per MGT cost of lubrication is less; however there is cost of switching to stop/start lubrication.

Cost of lubrication without considering risk is given by

$$c_{l_j} = \left\{ \sum_{i=1}^{N_j} (c_j M_j + c_s Y_j)/(1+r)^i \right\} *(1-(1/(1+r)))*(1+r)/\left(1-\left(1/(1+r)^{N_j}\right)\right), \tag{1}$$

where r is the discounting rate, c_j the cost of lubrication per MGT for strategy j, $j = l$ means lubricated, $j = \mathrm{s}$ means start/stop lubrication, and $j = \mathrm{nl}$ means no lubrication.

3.2. Modelling total cost of rail maintenance

It is important to develop effective maintenance strategies combining technology and safety methods for optimal rail grinding in controlling RCF and wear. Some of the associated costs are:

- Restricted track access while grinding.
- Rail grinding cost per meter or per meter removed railhead area.
- Cost for replacement of worn-out rails.

- Derailment and damage of track, train, property, life, and down time.
- Cost for repairing rail breaks in terms of material, labour, and equipment and down time.
- Cost for inspecting rail tracks in terms of material, labour, equipment and down time.
- Lubrication cost.
- Switching cost for stop/start.

The total cost of maintaining a segment of rail is equal to the sum of cost for: preventive rail grinding, loss of traffic due to rail grinding, rectification based on non-destructive testing (NDT) using ultrasound probes, rail breaks and derailment, lubrication and replacement of worn-out unreliable rails (for details see Chattopadhyay et al., 2003). It is the given by

$$C_{\text{tot}_j} = c_{\text{g}_j} + c_{\text{d}_j} + c_i + c_{\text{l}_j} + c_{\text{r}_j} + c_{\text{re}_j}. \quad (2)$$

4. Numerical example

Data related to cost and life is collected from Swedish Rail and Queensland Rail. The simulation model developed by Chattopadhyay et al. (2003) was extended including lubrication cost. Results from investigation by Swedish State Railways (at SJ Track division) found that rail wear in curves has been reduced by as much as 98% with a very small amount of grease, only 17 g (0.06 oz)/1000 wheels. The result showed that the wear on wheel flanges decreased with as much as 50% after a large-scale installation of SRS CLICOMATIC. The use SRS CLICOMATIC electric lubricators have reduced grease consumption significantly compared to mechanical lubricators CLICOMATIC.

Nilsson (2003) observed a lubrication benefit factor of 9 for 300 m curves and a factor of 4 for 600–800 m curves. The rate varied over the year due to the possible effect of natural lubrication changes resulting from changes of weather and precipitations. Waara (2000) reported gauge face wear in northern Sweden heavy haul lines can be reduced 3–6 times with proper full year lubrication. On-board lubrication evaluated by Cantara (1993) in a Spanish study revealed that flange wear is reduced by a factor of 4.5 by on-board lubrication. Table 1 shows the operating scenario of heavy haul trains.

Table 2 shows the characteristics of freight wagons. Data is used to estimate average number of cars for each freight train, average weight of freight train, amount of lubrication required for each train and number of trains for each metric tonne (MT) of load. From the above data we have:

- Amount of lubrication/train = (17∗68∗8)/1000 = 9.248 g.
- Number of trains/MT = 1∗1,000,000/(68∗100) = 147 trains
- Amount of lubricant/MT = 147∗9.248 = 1360 g

Lubrication cost which is collected from supplier of lubricants (Australasia) is on an average $AUD 4.5/kg of grease based lubricant (Zarembski and Paulsson, 1998).

4.1. Lubricators

Number of lubricators used can be estimated with the length of rail for each curve radius:

Number of lubricators for

- 0–300 m curve = 7;
- 300–450 m curve = 5;
- 450–600 m curve = 96.

4.2. Total annuity cost/meter for rail maintenance

This is estimated using simulation approach. The process is explained in Fig. 2. Various cost, wear

Table 1
Operating scenarios of heavy haul trains (Zarembski and Paulsson, 1998)

	Base case	Heavy axle load case	Longer train case
Cars per train	52	68	85
Net weight (load)	4160	6800	6800
Axle load	25	30	25
Tonnes ore/yr	22,900,000	22,900,000	22,900,000

Table 2
Characteristics of freight wagons (Zarembski and Paulsson, 1998)

	Base wagon	High capacity wagon
Length (mm)	8400	10,300
Tare weight (wagon weight) (tonnes)	20	20
Net capacity (load) (tonnes)	80	100
Gross weight (tonnes)	100	120

and fatigue data from rail industry is used for analysis of various strategies.

Annuity cost/meter for lubrication for 23 and 12 MGT are estimated. Results for lubrication costs are compared for different curves. Analysis of annuity costs/meter for lubrication results is shown in Table 3.

Fig. 3 shows the analysis of annuity costs/meter for 23 and 12 MGT curve radius from 0 to 600 m. It is found that the annuity cost/meter is higher for curve radius 0–300 m compared to higher radius. This is due to excessive usage of lubrication to control traffic wear and noise in sharp curves and also due to quicker replacements at sharp curves.

4.3. *Stop/start lubrication*

Total annuity cost/meter for non-lubricated and stop/start lubrication for curves is estimated based on increase of traffic wear for 0–300 m curve by 10 times, 300–450 m curve by 5 times and 450–600 m curve by 2 times, respectively (Nilsson, 2003).

Let α be reduction of rail grinding cost for controlling RCF. For modelling start/stop lubrication let us consider Y_j as the decision variable for

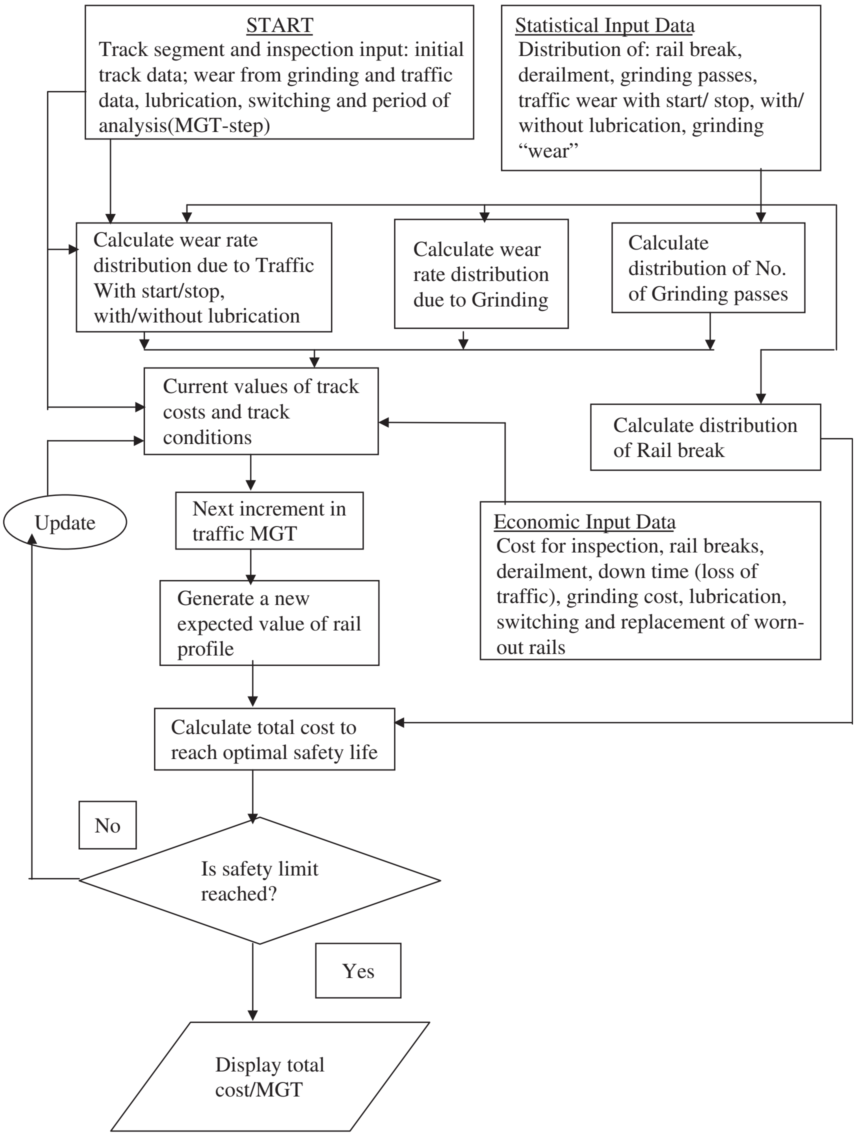

Fig. 2. Simulation approach used in total cost model.

Table 3
Annuity cost/meter for lubrication 23 and 12 MGT

MGT		23	12
Accumulated length (m)	Radius (m)	Total annuity cost/meter ($AUD)	
1318	$0<R<300$	0.68	0.67
1384	$300<R<450$	0.46	0.46
36,524	$450<R<600$	0.33	0.34

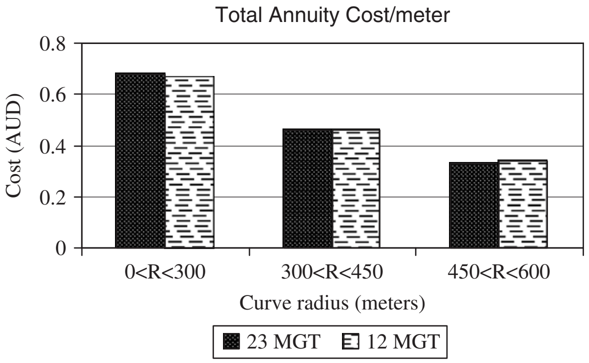

Fig. 3. Annuity cost/meter for lubrication of curve radius 0–600 m.

lubrication strategy. Where $Y_j = 1$, for $j = s$ and the decision is switching off and on of the lubricators. If $Y_j = 0$, for not using stop/start lubrication option. Let cost for switching on or off = $AUD 250

Total annuity cost/meter for start/stop lubrication considering risk = total annuity cost/meter with lubrication + number of switching∗cost/switching/meter−cost of lubrication∗$\sum_{N=1}^{n_s} \text{Lub}_i - \alpha$∗saving in rail grinding annuity cost/meter + probability of spalling∗annuity cost/meter for risk + % of increase in wear during the stop period (increase in replacement cost) where i = index.

Let $\alpha = 0.05$, where α is percentage of saving in annuity cost/meter for grinding.

Total annuity cost/meter with lubrication = grinding cost + inspection cost + down time cost + risk cost + replacement cost + lubrication cost.

Number of switching per stop/start = 2,where n_s = number of stop periods.

It is assumed that number of stop periods are 1 per year.

Stop period per year in percentage = 16%

Savings in lubrication = 16%

Lub_i = Lubrication amount during ith stop periods.

Let probability of spalling due to stop/start lubrication strategy = 0.02

Increase of wear during the stop period-130% = 1.3

For the analysis it is assumed that there may be 5% savings in grinding cost/meter and 16% reduction in lubrication cost/meter for stop seasons. However, there may be increased risks of rail break and rail failures.

4.4. *Total annuity cost/meter for 23 MGT for rail maintenance*

Analysis of total annuity cost/meter for rail maintenance for 23 MGT with lubrication, no lubrication and stop/start lubrication is shown in Table 4.

Fig. 4 shows the analysis of total annuity cost/meter for rail maintenance for 23 MGT with lubrication, without lubrication and stop/start lubrication from curve radius 0–600 m. From the analysis it is observed that the cost/meter is higher for curves without lubrication. This is due to early replacement of rails at the sharp curves due to increase of RCF and traffic wear.

4.5. *Total annuity cost/meter for rail maintenance for 12 MGT*

Analysis of total annuity cost/meter for 12 MGT with lubrication, no lubrication and stop/start lubrication is shown in Table 5.

Fig. 5 shows the analysis of total annuity cost/meter for rail maintenance for 12 MGT with lubrication, without lubrication and stop/start lubrication from curve radius 0–600 m. It is found that the cost/meter is higher for curves without lubrication. From the analysis it is found that the costs are higher for curves without lubrication

Table 4
Total annuity cost/meter for rail maintenance for 23 MGT

Total annuity cost/meter for 23 MGT ($AUD)				
Length (m)	Radius (m)	With lubrication	No lubrication	Stop/start lubrication
1318	0–300	24.65	171	28.32
1384	300–450	22.51	168	25.66
36,524	450–600	23.38	87	26.38

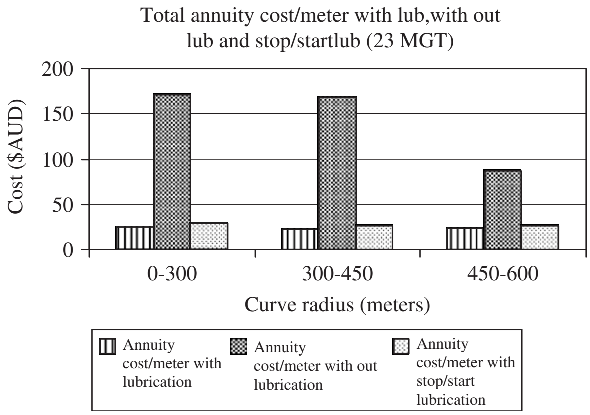

Fig. 4. Total annuity cost/meter for rail maintenance for 23 MGT.

Table 5
Total annuity cost/meter for rail maintenance for 12 MGT

Total annuity cost/meter for 12 MGT ($AUD)				
Length (m)	Radius (m)	With lubrication	No lubrication	Stop/start lubrication
1318	0–300	24.06	73	27.11
1384	300–450	20.62	60	23.33
36,524	450–600	20.23	54	22.25

because they wear at faster rate and need early replacement. The curves with lubrication and stop/start lubrication show significant influence in reducing rail degradation and noise. Costs may vary with the variation in grinding costs and increase the risk due to spalling with stop/start lubrication. It is found that total annuity cost/meter with lubrication for 12 MGT is economical interval. It is also found that stop/start lubrication is not cost effective as a strategy. However, there is enough scope for carrying out detailed research in this area. There is scope for considering cost of environment pollution due to ground water contamination from excessive lubrication to build more realistic models and is left for future work.

5. Summary

Cost model developed in this paper presents an integrated approach for rail maintenance based on rolling contact fatigue (RCF), traffic wear, rail grinding interval and lubrication. This integrated system approach in analysing and solving real life complex problem is the original contribution of this paper. This research shows that

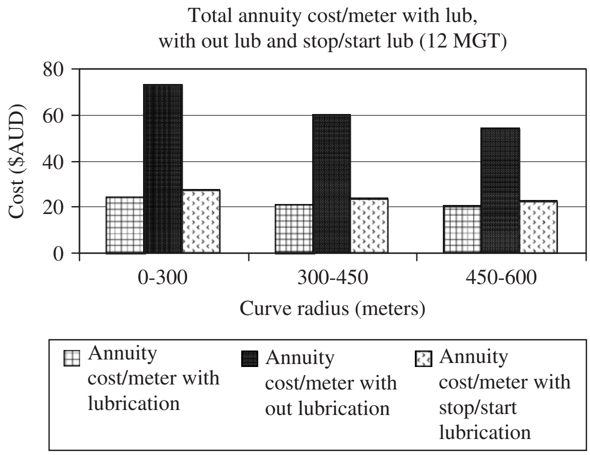

Fig. 5. Total annuity cost/meter for rail maintenance for 12 MGT.

- For both 12 and 23 MGT grinding interval costs of
  - o no lubrication is extremely high compared to rail curve with lubrication for all 0–600 curves.
- For 23 MGT grinding interval costs of
  - o stop/start lubrication is 14.9% higher compared to rail curve with lubrication for 0–300 m, 14% higher for 300–450 m and 12.8% higher for 450–600 m.
- For 12 MGT grinding interval costs of
  - o stop/start lubrication is 12.7% higher compared to rail curve with lubrication for 0–300 m, 13.1% higher for 300–450 m and 10% higher for 450–600 m.

From the analysis it is found that rail players can save around 2.45% for 0–300 curves, 9.1% for 300–450 m curves and 15.5% for 450–600 m curves, respectively, by planning 12 MGT interval for rail grinding compared to 23 MGT intervals. The annuity cost/MGT/meter can be used by rail players for benchmarking asset utilisation. Total annuity cost/meter with lubrication can be further analysed in terms of wayside, on-board lubrication methods for benchmarking applicators and lubricants. The authors are currently working on this area and results will be published in the future.

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