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Modelling Cost of Maintenance Contract for Rail Infrastructure

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Abstract

Maintenance contracts have received significant attention in last ten years. It has huge potential to reduce the upfront investments in maintenance infrastructure, specialised maintenance facilities, and risk for owners through expert services provided by the original equipment manufacturers and/ or specialist maintenance providers. There is a growing trend for asset intensive Industries to outsource the maintenance services of their complex and critical asset through maintenance contracts due to economic pressure and technical complexities not within the capability of the owner/ user. One of the complex and critical assets in transport infrastructure is rail. To maintain reliable service through safe and uninterrupted rail operation maintenance contracts are currently being used as a cost effective option. However, there is a need to develop mathematical cost models to build into the contract price. In this paper, a conceptual rail maintenance contract model is proposed for estimating cost of outsourcing maintenance that takes into account cost of maintenance, inspection and risk of accidental failure.

Keywords
Maintenance contract, rail maintenance, cost model.

1. Introduction
Rail plays a significant role in transport infrastructure. It is expensive and complex for industries to maintain huge network services using in-house resources as it needs investment in infrastructure, experts and specialised facilities to provide the services and carry out maintenance work. Contracting out the maintenance of rail through service contracts has potential for reducing costs and enhancing reliability if applied properly. This happens by reducing upfront investments in infrastructure, expertise and specialised maintenance facilities [1-3]. The contractor in turn charges a price or premium for such services [4 -6]. There is a need to know the cost of providing service so that the contractor does not make loss in the contract and the owner/ user do not pay too much compared to the cost of in-house system [7]. Reliability analysis of rails can be carried out by understanding the failure mechanism of rail through modelling and analysis of failure data [8]. In a probabilistic sense, rail failure is modelled as a function of its usage in terms of Million Gross Tones (MGT) for certain conditions [9]. A conceptual maintenance contract model is developed for estimating owner’s cost for such contract. This can be used by contractor to ensure that they do not make loss in the contract.
The outline of this paper is: in Section 1, an introduction of outsourcing rail maintenance is provided. Section 2 deals with the Rail failure and degradations and models for predicting failures. Maintenance contracts together with various servicing strategies are discussed in Section 3. In Section 4, a conceptual cost models for rail maintenance contracts is proposed. The proposed model is analysed and illustrated with numerical examples considering real life rail failure data in Section 5. In the final section, the summaries and scope for future work are discussed.

2. Modelling Rail Failure or Degradation

First step in developing maintenance contract model is the development of rail failure or degradation model. Degradation causing failure of rail is a complex process and it depends on the rail materials, traffic density, speed curve radius, axle loads, Million Gross Tonnes (MGT), wheel rail contact, rail track geometries and importantly the servicing strategies [9]. Rail defects start developing due to the steel, axle load, maintenance of rail and wheel and material fatigue due to traffic movement. Ageing takes place in the line due to tonnage accumulation on track resulting from traffic movement. It is realistic to assume that initiated defects left in the system will continue to grow with increase in cumulative MGT.

Rail failures is modelled here as a point process with an intensity function $\Lambda(m)$, where m represents Millions of Gross Tonnes (MGT) of usages and $\Lambda(m)$ is an increasing function of m indicating that the number of failures in a statistical sense increases with MGT. That means older rails with higher cumulative MGT passed through the section is expected to have more probability of initiating defects and if undetected then through further passing of traffic can lead to rail failures. This is a realistic assumption based on real life data. This implies the number of failures for an accumulated MGT is a function of usage MGT, m, and is a random variable and can be modelled using non-homogeneous Poisson process with an intensity function $\Lambda(m)$. Let $F(m)$ and $f(m)$denote the cumulative rail failure distribution and density function respectively,

$$F(m) = P\{m_1 \le m\}$$ where, m_1 is the MGT up to a rail failure. (1)

Here we have,

$$f(m) = dF(m)/dm \qquad (2)$$

This can be modelled as:

$$F\ (m) = 1 - \exp(-(\lambda m)^{\beta}) \qquad (3)$$

and

$$f(m) = \lambda\beta(\lambda m)^{\beta-1}\exp(-(\lambda m)^{\beta}) \qquad (4)$$

with the parameters β (Known as shape parameter of the distribution) > 0 and λ (Known as inverse of characteristic life for the distribution) > 0

β greater than 1 indicates an increasing failure rate of the item under study and ageing is predominant in failure mechanism.

Then, from Equations (1) and (2), the failure intensity function $\Lambda(m)$ can be derived as

$$\Lambda(t) = \frac{f(m)}{1 - F(m)} = \lambda\beta(\lambda m)^{\beta-1} \qquad (5)$$

Rail track is normally made operational through repair or rectification of the failed segment and no action is taken with regards to the remaining length of the rail in case of detected defects and rail breaks. Since the length of failed segment replaced at each failure is very small relative to the whole track, the rectification action results in a negligible impact on the failure rate of the track as a whole [10].

3. Servicing Strategies under Contract Period

In case of rail maintenance, both Corrective maintenance (CM) and Preventive maintenance (PM) take into account different types of servicing strategies which can be used based on the failure mode and type. These strategies are classified as per degree of restorability of the rail as shown in Figure 1.

Rail servicing strategies are:

1. *Replacement*: a replacement of the segment is made when the segment is worn out and the wear limit has reached or the defect rates are more than acceptable limit. This implies that a replacement of segment restores the full reliability and turned hazard rate to zero for that segment.
2. *Imperfect repair:* Rail grinding and lubrication are the examples of this type of servicing strategy. This strategy is normally used in case of planned preventive maintenance. It can restore only a substantial portion and the hazard/failure rate due to initiation and propagation of cracks and after this type action falls in between "as good as new" and "as bad as old (see curve 'b' in Figure 1).
3. *A minimal repair:* a replacement or repair of small segment to remove the damaged or broken portion of the segment is one of the examples of minimal repair for rail. It makes insignificant improvement of the segment

and the condition after maintenance is "as bad as old" (curve 'c' in), since the hazard rate of other portion remain unchanged.

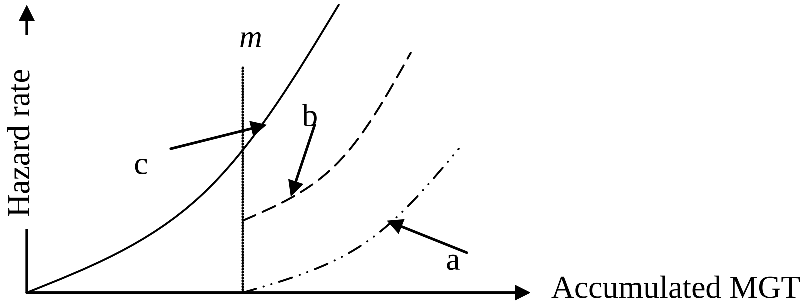
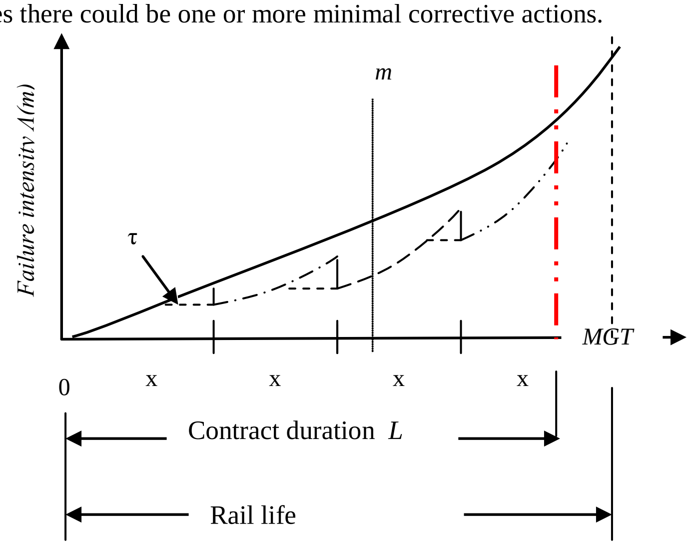


Figure 1: Failure rate with effect of various maintenance actions [2]

In a complex model it can be two dimensional due to wear and fatigue. However the wear rate due to MGT and the failure rate due to MGT can be combined and the two dimensional model can be converted to one dimensional model. For this paper the rail failures due to rolling contact fatigue (RCF) are considered and the combined model is left for future work.

4. Modelling Costs of Rail Maintenance Contract

This Section demonstrates a simple maintenance contract policy in which, *the contract terminates when contract period reaches a usage level 'L'* MGT. The contract includes provision for corrective maintenance - rectification on failure as well as constant interval preventive maintenance actions to prolong the rail reliability. The proposed maintenance model is presented graphically by the Figure 2. Preventive maintenance actions are carried out at constant interval '*x*' *MGT*, each PM restores the reliability of the asset to some extent. Between two successive preventive maintenances there could be one or more minimal corrective actions.



Figue 2. Graphical representation of the service contract Policy model 1

4.1 Assumptions

The following assumptions are made for model simplification purpose

- Failure rate increases with time /usage
- All corrective rectifications other than replacement are minimal repairs.
- Preventive maintenance actions are taken at constant interval (*x*)
- PM restores life to some extent.

- The level of restoration depends on the type and quality of the maintenance performed.
- Age restoration after each preventive maintenance (PM) is constant.
- All cost factors are constant over the contract period.

4.2 Notations

Failure intensity $\Lambda_{pm}(m) = \Lambda(m - k\tau)$ (6)

$\Lambda_{pm}(m)$: Failure intensity at accumulated MGT, *m*, with maintenance.

$\Lambda(m)$: original failure intensity at *m* when no maintenance is performed.

N: number of times the planned servicing is performed during the contract period

L: Duration (length) of service contract in MGT

k: number of times PM is carried up to *m*.

τ age restoration after each PM. $\tau = \alpha x$, *where,* α is the quality of the maintenance, α ranges from 0 to 1. When $\alpha = 1$ signifies– 'as good as new" and $\alpha = 0$ is 'as bad as old'.

C_{mr} cost for each minimal repair.

C_{pm} cost for each PM

4.3 Model Formulation

Total cost of contract over the contract period *L* can be expressed as

$$C_T = C_m + C_i + C_r + p \quad (7)$$

Where,

C_T : Total cost of maintenance contract

C_m: Cost of maintenance over the contract period

C_i: Inspection cost over the contract period

C_r: Cost of risk associated with accident if the maintenance is not performed and the reliability of the track is compromised.

p: Penalty Costs for not conforming to the contract and failure to meet agreed safety, reliability and availability standards.

Estimating Maintenance Cost (C_m)

Expected total cost of maintenance service

= (Expected total cost of all minimal corrective repairs over the contract

+ Expected cost of preventive maintenances over the contract *L*)

Expected cost of minimal repair

$$C_{mr} \sum_{k=0}^{N+1} \int_{kx}^{(k+1)x} \Lambda(m - k\tau)\,dm \quad (8)$$

Expected cost of preventive maintenance during the contract

$$NC_{pm} \quad (9)$$

The total expected maintenance cost C_m can therefore be expressed as

$$C_m = \left[C_{mr} \sum_{k=0}^{N+1} \int_{kx}^{(k+1)x} \Lambda(m - k\tau)\,dm + N\ C_{pm} \right] \quad (10)$$

***Estimating Inspection Cost* (C_i)**

Total inspection cost (C_i) over the contract can be given by

$$C_i = N_i c_i \quad (11)$$

Where, $N_i = Integer\,[\frac{L}{I_f}]$, N_i is the expected number of inspection during the contract and I_f is the optimal inspection interval throughout the contract period.

***Estimating Risk Costs* (C_r)**

The risk cost associated with system failure and accident is based on the probability of inspection detecting potential failures and failures not being detected by inspection, accident and associated costs. This can be expressed as

$$C_R = E[N(L)] * [P_n(B) * b + (1 - P_n(B)) * (P_n(A) * a] \tag{12}$$

Where,
a is the expected cost per accident;
b is the expected cost of repairing potential failure based on NDT
Pn(B) is the probability of detecting potential failure using NDT,
Pn(A) is the probability of undetected potential failure leading to accident during contract period
E[*N(L)*] is the expected number of failure over the contract period.

Total cost of maintenance contract and the Service providers premium charge **(C_T)**
Therefore, the expected total cost of contract can be obtained by adding all the above costs. The service providers can charge a premium for such service by adding a profit with the total cost of servicing divided by the contract period (number of years/months or usage in thousands hours or Million gross tonnes). This can be expressed by
Total cost of maintenance contract:

$$C_T = \left[C_{mr} \left(\sum_{k=0}^{N+1} \int_{kx}^{(k+1)x} \Lambda(m - k\tau) dm \right) + C_{pm} N_i \right] + c_i \frac{L}{I_f} + E[N(L)] * [P_n(B) * b + (1 - P_n(B)) * (P_n(A) * a + p \tag{13}$$

Service provider's premium charge per MGT can be expressed by

$$P_c = \frac{C_T + \mathrm{P}}{L} \tag{14}$$

where, L is the contract period of the Asset and P is the total profit marked up by the service provider.

5. Numerical Analysis of the Proposed Model

For the purpose of estimating and analysing the models we used a set of real life rail failure data collected from the Heavy Haul Rail Network. Crude data were first censored and rectified to make it useable. The failure or breakage MGT in the analysis is generated as follows: Usage span is considered as 720 MGT. A plot of the accumulated number of rail break versus the accumulated breakage MGT is displayed in the figure 3. The lack of linearity of the plotted data is an indication that the rate of rail break is not constant. Rather it is usage dependent. Increase of rail breaks with the increase of usage in terms of MGT implies the rail break or failure follows a First Weibull distribution or Non homogeneous Poisson process since

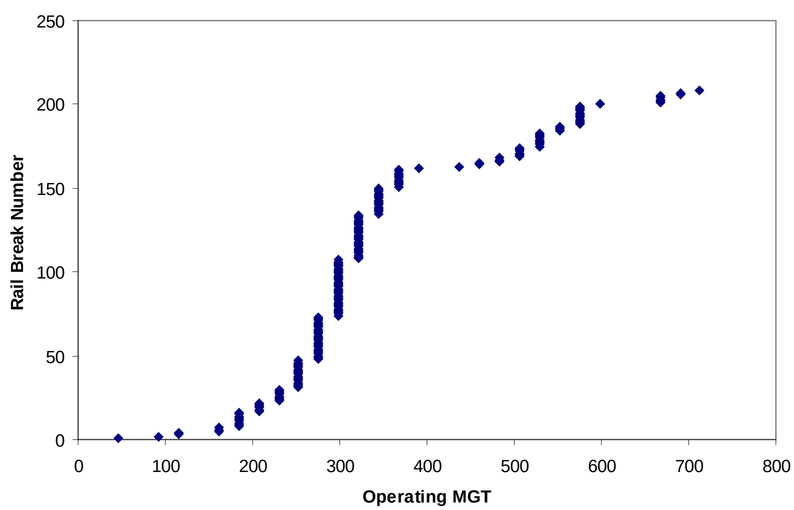


Figure 3: Cumulated Rail break vs. accumulated MGT.

Estimation of Parameters

In estimating the rail failure parameter, one can use different method such as method of Least square, method of Moments, regression analysis, and method of Maximum likelihood. The method of Maximum Likelihood (MLE) was used here to estimate the parameters λ and β. Parameters were estimated by considering a Weibull distribution (two parameters) by developing a MATLAB program. The MATLAB expression generated the Figure 4 with the Weibull graph for the used rail failure/break data. From figure 4, inverse characteristic life parameter λ = 0.00259 per MGT and the shape parameter β = 2.789 at 95% confidence interval were obtained.

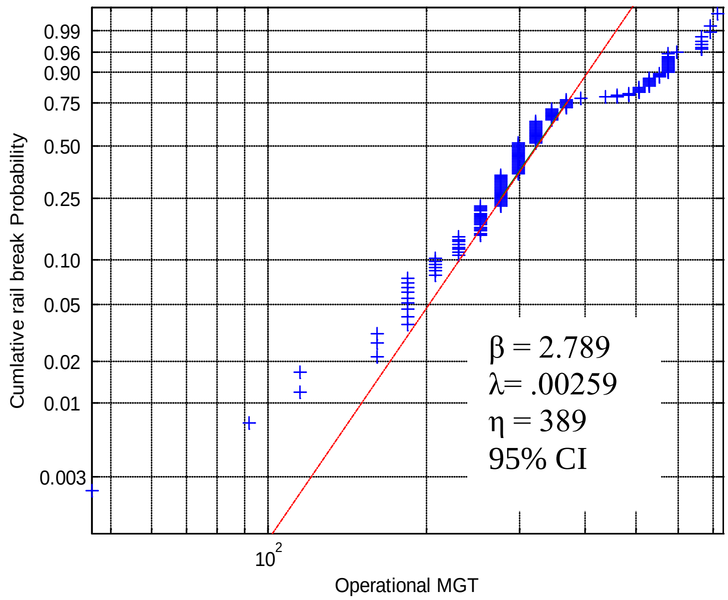


Figure 4: MATLAB generated Weibull graph for rail failure data

Estimating Costs of Rail Maintenance C_m

In this section estimated parameters were used in determining the cost of maintenance contract. It is assumed that in each Preventive maintenance action only one pass of grinding and lubrication took place.

Let us assume for illustration, Cost of minimal repair, cost of replacement/repair of one rail for any Segment due to worn out regulation C_{mr} = $150 (Approx)

Cost of each preventive maintenance (rail grinding and Lubrication), C_{pm} = ($4.00 per meter (approximately) × 110m = $440

Cost of replacement, C_{re} = $1700

Quality of each PM, α = 0.16, which implies that each PM restores only 16% of total reliability (we assume it is constant for each PM)

Let the contracted usage in MGT, L = 300 MGT.

Here, a MAPLE program has been used to determine the optimal interval and number of PMs. This provided the following results

Optimal interval between preventive maintenance x = 52.65 MGT*

Optimal number of PMs N = 5*

Expected total cost of maintenance, C_m*= AUD* 1794

Expected inspection cost

Let The mean inspection cost over the contract period be $150 (includes cost of instruments and inspectors wage)

Optimal inspection interval over the contract period 30 MGT

Total expected Inspection cost, C_i *= $1500* throughout the contract period

Expected risk cost

Let Mean cost per accident, a = *$10m*;

Mean cost of repairing potential failure based on NDT, b =$350

Probability of detecting potential failure using NDT, $P_n(B)$ = 95%
Probability of undetected potential failure leading to accident during contract periods, $P_n(A) = 10^{-7}\%$
$E[N(L)]$ is the expected number of failure over the contract period = 5
Expected risk cost associated with accident, C_R = $332.7.

Penalty cost
Here it assumed a 0 penalty cost (implies for perfect contractor dealings)

Total Cost of Maintenance Contract
Therefore, the total expected cost of maintenance contract (C_T) for a single rail (110metre long) over the 300 MGT usages is estimated as $3627.

6. Conclusion

Maintenance contracts have been widely used by industries in past ten years. Estimation of costs for maintenance contracts is a complex process and is important for both the owners and the service providers. Contractors need to know the estimated cost to avoid making loss. The owners/ users need to know it to decide contract price so that they are not paying too much compared to the cost of doing that in-house. In this paper a conceptual cost model for rail maintenance contract is proposed which takes into account both corrective maintenance in the form of minimal repairs and planned preventive maintenances as servicing strategies throughout the contract period together with the costs associated with accidental risk, inspection and a Penalty costs for not conforming to the contract and failure to meet agreed reliability, availability, maintainability and safety standards.
These models can be further extended to two dimensional problems. Some of the possible future works are: consideration of discount rate for long term contracts, utility functions for linking owner/service provider's risk preferences and impact of downtimes associated with failures.

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