LIFE-TIME MANAGEMENT OF RAILS BASED ON STRUCTURAL RELIABILITY APPROACH

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ABSTRACT

Preventing derailment due to broken rails is an area of high priority for keeping a safe rail industry. The common method to control the risk of rail breaking is a frequent rail inspection through nondestructive testing technologies and a replacement of rails based on the remedial action plans. However, determining the effective (optimal) inspection frequency is not an easy task and setting exact inspection intervals requires critical decisions in railway infrastructure management.

In this research paper, the rail model is developed using ABAQUS/CAE and FRANC3D software and fracture mechanics is used for the determination of critical crack -size at a rail head, web and base as well as fatigue life of rail. First order reliability analysis is carried out and reliability of rail as well as a mechanism of remedial action is recommended to help an infrastructure manager's decision. Event-tree analysis and life cycle cost estimation is also conducted.

Based on the analysis results, an annual, uniform and effective rail inspection frequency is assessed with 99.5% rail reliability for the applied stress and tonnage using non-destructive technologies which result in minimal total cost. Finally, critical cracks of rail before failure are determined as1mm for rail head, 5 mm for the rail web and 2 mm for the rail base to help infrastructure managers' (track engineers or rail inspectors) decision for replacement.

***Keywords**: Rail Inspection, Reliability Index, ABAQUS/FRANC3D, Fracture Mechanics and Life-Cycle Cost.*

INTRODUCTION

Among the major industry sectors where fatigue and fracture of structural components are of critical concern is the railway industry. Railway infrastructures are assets which represent a high investment. They are designed to work in a very demanding safety conditions and must display an extremely low-risk of failure. Rails are the most significant and basic components of railway systems. However, different factors affect the rail degradation process which gradually reduces the performance, reliability and safety of the railway infrastructure.

In spite of the fact that railway companies around the world have attempted to reduce the number of broken rails by making use of various management techniques, failure is still high and a substantial proportion of railway budget is spent on rail track inspection and maintenance [11].

By considering the above facts, this paper takes the case of the Ethiopian railway infrastructure by taking into consideration the following observations:
Rails deteriorate over time due to vast movement of passengers and goods especially in the import-export corridor of the railway line.

Ethiopian railway transport has now a well-developed rail life-time management technique. In order to prevent rails from breaking during their service life, there are generally two policy options in rail defect management; The first is improving the material quality (i.e. choosing durable material), and the second is increasing the frequency of rail inspection. However, it is a difficult task to develop a new material that will not result in cracks in its service-life. As for the frequency of rail inspection, it is also expensive for the Ethiopian Railways Corporation to Increase significantly the frequency of rail inspection increase significantly the frequency of rail important for risk and cost reduction inspection activities. Therefore, appropriate scheduling of inspection activities and remedial action plan is important for risk and cost reduction.

In this study an attempt was made to develop a life-time rail management technique for the Ethiopian railway infrastructure based on structural reliability theory such as determination of remedial action plan, optimal inspection interval and adaptation of rail maintenance model or procedure. This will enhance the reliability of Ethiopian railroad systems and reduces the possibility of costly failures in the future, reduce maintenance work and cost without increasing the risk of passengers and freight. To achieve these objectives/outputs, literatures were reviewed to document the validation of the reliability based approach for determination of optimal rail inspection frequency by conducting a four-step analysis,.

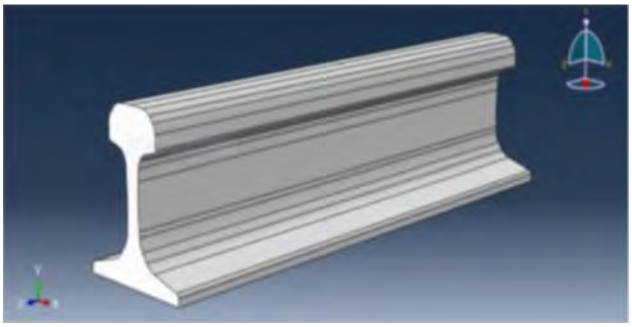
- **Step 1**: **Linear elastic fracture mechanics (LEFM) -**predicts the fatigue life of rail. A important for risk and cost reduction inspection. Therefore, appropriate scheduling of inspection activities and remedial action plan is important for risk and cost reduction. Rail is modeled by beam on elastic foundation principle to determine the rail stress and to predict the critical crack-size.
- **Step 2: First order reliability method (FORM)** creates the reliability profile of rails using critical crack size determined before as a reliability index, β. The reliability index of rails determines the criteria for the mechanism of remedial action of rails.
- **Step 3: Event-tree analysis (ET)** resolves all possible consequences of detecting defects and remedial actions with probability using the above step results.
- **Step 4: Life-cycle cost Estimation (LCC)** determines the optimum number of inspection using data obtained before.

ANALYSIS

LINEAR ELASTIC FRACTURE MECHANICS

ANALYSIS

Figure 1: Profile and Geometric model of T50 rail created in ABAQUS



Rail is modeled by Winkler's beam on elastic foundation theory and modulus of track support is obtained by a pyramid method as 38.7 kN/m per area = 8700 N/m/area.By using the Hertz contact patch theory, hertz stress contact pressure is obtained as 1511.22

To determine the magnitude of stress at the rail head, web and base, finite element modeling and analysis of T50 (50 kg/m) rail for the national railway network of Ethiopia is carried out by using commercial software, ABAQUS .

MPa and elliptical contact area is 0.0086 m x 0.00687 m which is 59.08 mm2. The stress distribution results are obtained in the form of Von-Misses stresses and a maximum value is found to be 1036 MPa.

Figure 2Von misses stress distribution for rail (Pa).

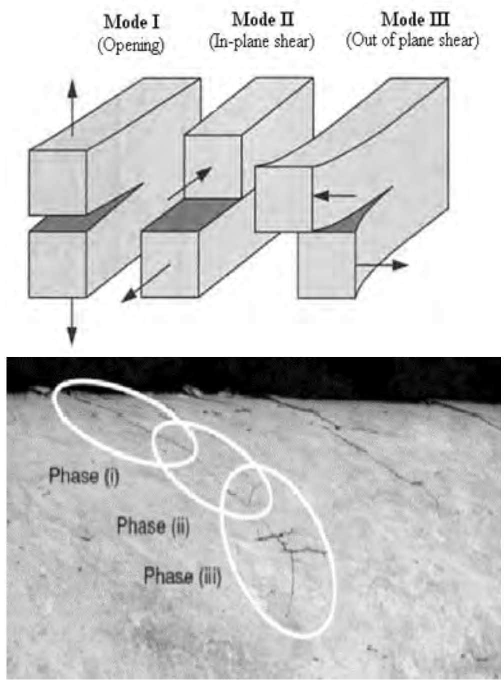
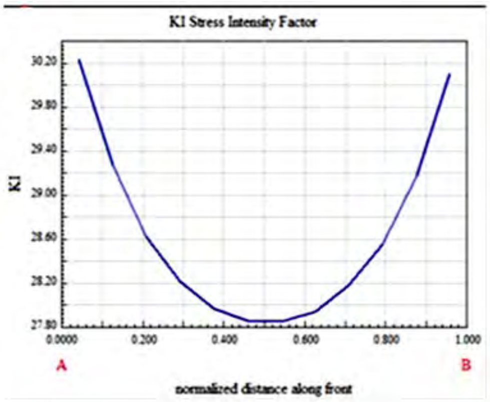


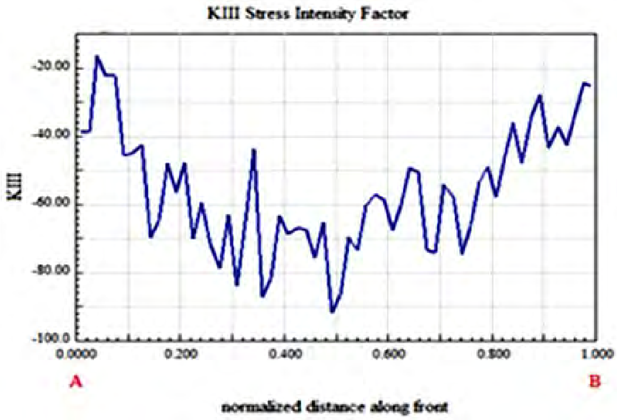
Figure 3*The three crack propagation modes (phases) [13].*

Due to the complexity of the rail geometry, FRANC3D (Fracture Analysis Code 3 Dimensional) software is used to determine stress intensity factor of rail.
The Chinese standard recommends the fracture toughness of rail steel as *'The minimum single value of fracture toughness K_{IC} of rails shall be 26 MPa√m and the minimum mean value shall be 29 MPa√m'*. The FRANC3D software mode 1 stress intensity factor value obtained before is much closer. So, a fracture toughness value of 29MPa√m is taken for the T50 rail of national railway network of Ethiopia.

There are three crack propagation modes for rails and Mode I is the predominant loading mode.



(a)



(c)

Figure 4 (a) *Mode I, (b) Mode II, (c) Mode III stress intensity factor created by FRANC3D soft ware*

Since the fracture criterion is: K_I=K_{IC}, the critical crack size at the head, web and base of the T50 rail steel can be determined as follows:

CASE 1: At rail base:

$$a_c = \frac{1}{\Pi}\left(\frac{k\xi}{1.12\sigma_c}\right)^2 = \frac{1}{\Pi}\left(\frac{29*2.464}{1.12*1036}\right)^2 = 2mm$$

CASE 2: At the rail head:

$$a_c = \frac{1}{\Pi}\left(\frac{k\xi}{1.12\sigma_c}\right)^2 = \frac{1}{\Pi}\left(\frac{29*2.464}{1.12*1511.22}\right)^2 = 1mm$$

CASE 3: At the rail web

$$a_c = \frac{1}{\Pi}\left(\frac{k\xi}{1.12\sigma_c}\right)^2 = \frac{1}{\Pi}\left(\frac{29*2.464}{1.12*523.4}\right)^2 = 5mm$$

crack size,a(mm)	SIF,KI (MPa√mm)		
	Head	Web	Base
0.0	0	0	0
0.5	861.284	298.3	590.43
1.0	1218.04	421.86	835
1.5	1491.79	516.67	1022.66
2.0	1722.57	596.6	1180.87
2.5	1925.89	667.02	1320.25
3.0	2109.71	730.68	1446.26
3.5	2278.74	789.23	1562.14
4.0	2436.08	843.72	1670
4.5	2583.85	894.9	1771.3
5.0	2723.62	943.3	1867.12

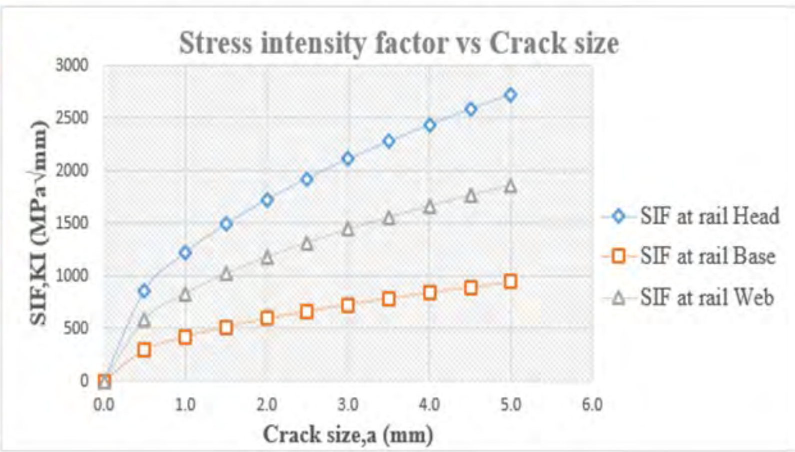


Figure 5 Stress Intensity factor versus crack size

FATIGUE LIFE OF RAIL

A fatigue life analysis is performed based on Paris law. As mentioned above, the Paris law states that the crack growth rate is an exponential function of the stress intensity factor, ΔK:

$$\frac{da}{dN} = C\Delta Km = C\left(\Delta\sigma Y\sqrt{\pi}\right)^m \quad (1)$$

Table 1Crack-length vs. Number of cycles for rail web

Crack length (a_o) (mm)	Crack length (a) (mm)	DN (cycles)	N (cycles)
1	2	21,995	21,995
2	3	20,990	42,985
3	4	19,151.57	62,136
4	5	17,568.9	79,705

The annual traffic density for the national Railway Network of Ethiopia is taken as 22.67 MGT (Million Gross Tones). To determine the number of trains per day, Vope Centre empirical formula is used which is as a function of annual traffic density as follows:

$$No\ of\ trains\ per\ day = \frac{T}{(0.006312*365)}$$

$$N = \frac{22.67}{0.006312*365} = 10$$

Assume one train passes a certain tra ck section two times per day. So, the total number of cycles per year for loaded standard vehicle with four axles or eight wheels is 8*(10*365) =29,200 cycles/year.
29,200 Cycles = 22.67 MGT
79,705 Cycles =?
From the above proportioning, the fatigue life of rail based on the maximum critical number of cycles for rail web is taken as **61.88MGT.**

FIRST-ORDER RELIABILITY METHOD (FORM) OF ANALYSIS

Rail defects are directly related to the serviceability of tracks so that the limit state of serviceability exists on a state of crack growth. When the critical crack size, a_c is specified, limit state functions for rails subjected to N stress cycles can be defined as:

$$Z = g(x) = a_c - a(N)) \quad (2)$$

Where,

a(N) is a crack size after a rail is subjected to N stress cycles.

Therefore, the above limit state function, after substitution of required data for the rails determined in section 2.1,was determined as:

Therefore,

$$g(x) = \frac{a_C^{1-\frac{m}{2}} - a_o^{1-\frac{m}{2}}}{\left(1-\frac{m}{2}\right)\left(1.12\sqrt{\pi}\right)^m} - \frac{\sqrt{2\pi} * C * N * (1169)^m * \left(\frac{m}{2}\right)^{\left(\frac{m}{2}+\frac{1}{2}\right)}}{e^{\frac{m}{2}}} \quad (3)$$

Table 2 Statistical characteristics of variables for first-order reliability method of analysis

Variables	Notation	Type	Mean Value (mm)	COV
Critical crack size at head	a_{ch}	lognormal	1.0	0.3
Critical crack size at web	a_{cw}	lognormal	5.0	0.3
Critical crack size at base	a_{cb}	lognormal	2.0	0.3
Initial Crack size	a_o	lognormal	0.2	0.3

Where,

a_c and a_o are critical and initial crack size of rail, C and m are material constants and N is the number of cycles.

Instead of rail safety evaluated by rigorous probabilistic prediction of failure, a kind of index, that is, the Hasofer- Lind reliability index: beta assesses the reliability of rails used in this paper.

In order to determine the reliability index β, recursive iteration was carried out using Rosenblatt transformation for the rail web and base. Since iteration of the algorithm is very tedious for hand calculation, efficient spreadsheet algorithm has been developed for the determination of exact reliability index value as follows:

Table 3 Summary of Hohebichler-Rackwitz Iterations

	INPUT			RESULT
Iteration	**y*(design point)**	**x*(New design point)**	**g(x*)(limit state function)**	**β (Reliability index)**
1	(0.2,1)	(0.3184,1.0092)	0.16813	2.4176
2	(0.3184,1.0092)	(0.3716,0.9078)	0.05065	2.7778
3	(0.3716,0.9078)	(0.3610,0.8462)	0.00311	2.7891
4	(0.3610,0.8462)	(0.3581,0.8379)	-0.00036	2.7867
5	(0.3581,0.8379)	(0.3580,0.8376)	4.60E-07	2.7867
6	(0.3580,0.8376)	(0.3580,0.8375)	-7.8E-09	2.7867
7	(0.3580,0.8375)	(0.3580,0.8375)	-8.3E-11	2.7867

The structural reliability theory can be performed both at the single failure mode and at multiple failure modes. When implementing the analysis with respect to multiple failure modes, rail defects are modeled as a series.

Table 4 Information concerning failure elements

I	*At rail head*	*At rail web*	*At rail base*
β	2.7867	5.8710	4.2697
ϕ(-β)	$4.6*10^{-3}$	$9.7*10^{-8}$	$1*10^{-5}$

$$-\phi^{-1}\left(\sum_{i=1}^{m}\phi(-\beta_i)\right)\leq\beta^s\leq min_{i=1}^{m}\beta_i \tag{4}$$

$$\beta^s\geq-\phi^{-1}(0.0046)=2.78$$

$$\beta^s\leq min(2.7867,4.2697,5.8710)=2.7867$$

$$\mathbf{2.78\leq\beta^S\leq2.7867}$$

Therefore, β^s (Reliability index) = 2.78 and P_f *(Probability of failure)* = $4.6*10^{-3}$

Finally, the reliability of rail for the provided rail type with respect to the applied stress is

$$\begin{aligned}R &= 1-P_f \\ &= 1-0.0046 \\ &= 0.995\end{aligned} \tag{5}$$

Therefore, the rail is 99.5% reliable for the applied stress and tonnage and the range of crack size for the remedial action plan of rail was decided based on this result as follows:

Table 5 Remedial Action plan table developed for rails of national railway network of Ethiopia based on rail reliability value.

Types of rail defects	Criteria (mm)	Remedial Action
Vertical split head	0<a≤0.4	Marking for check
	0.4<a<1	Maintain and Plan to replace
	1≤a	Replace immediately
Split Web	0≤a<2	Marking for check
	2≤a<5	Maintain and Plan to replace
	5≤a	Replace immediately
Broken Base	a<2	Marking for check
	2≤a	Replace immediately

EVENT-TREE ANALYSIS

Event tree is used for condition assessment and repair decision-making process. Even if there are many rail inspection methods available, Nondestructive testing (NDT) plays an essential role in a condition assessment in-service and repair decision-making process. The remedial action plan gives two opportunities regarding replacement for the track engineers. One is planning replacement policy and the other is immediate replacement policy corresponding to the critical repair level. The decision about these options can be interpreted in a probabilistic form, probability of repair (POR) that implies track engineers' actual response after inspections.

$$i(x)=a_r-a(N) \tag{6}$$

Where,

a_r is the critical repair level,

a (N) is the estimated crack size at N stress cycle.

The $P_{rep/det}$ can be obtained by using FORM with respect to the above LSF.

Where;
$P_{rep/det}$ is probability of repairing rail defects given a detection of defects;
P_{det} is probability of detecting rail defects

It is expected that as a crack size increases, its detectability also increases. It was found that the log-logistic distribution was the most acceptable distribution for the determination of Probability of detection of metals and the *PoD (a)* function can be written as:

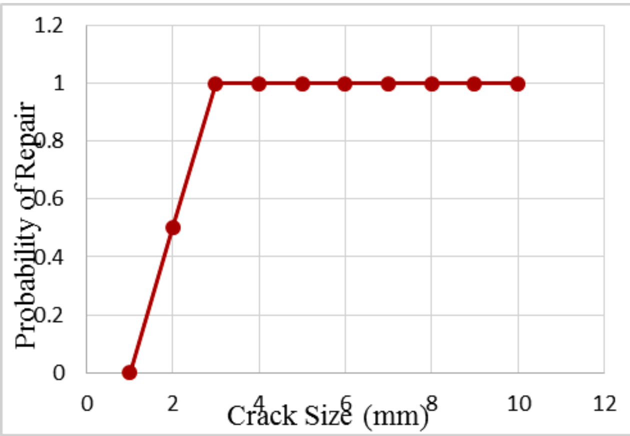
$$POD(a) = \frac{e^{\frac{\pi}{\sqrt{3}}\left(\frac{\ln a - m}{\sigma}\right)}}{1 + e^{\frac{\pi}{\sqrt{3}}\left(\frac{\ln a - m}{\sigma}\right)}} \quad (7)$$

Where a is the crack size and m and σ are the median and standard deviation respectively.
Finally,

$$P_{r(repair)} = P_{det} \times P_{rep/det} \quad (8)$$

$$P_{r(No-repair)} = P_{det} \times (1 - P_{rep/det}) + (1 - P_{det}) \quad (9)$$

Figure 6 Probability of repair



For any inspection, if the actual crack size at the time of inspection is smaller than a detectable crack size when a given NDT technique, the defect is not expected to be detected [14]. The event which is no crack is detected during the inspection when the rail has been subjected to N stress cycles, can be expressed as:

$$a_d \geq a(N) \quad (10)$$

Where,
a_d is the capability at the time of inspection,
a(N) is the estimated crack size at N stress cycle.

It is assumed that the critical repair level, a_r follows a uniform distribution, where the maximum value of the POF is the size on which track engineers must replace the damaged rail and the maximum value of the PDF is the size on which the engineers will take some management actions.

Table 6 Probability of failure and repair of rail

Location of crack for Rail	$P_{r(repair)}$	$P_{r(no-repair)}$
Head	5%	95%
Web	100%	0%
Base	50%	50%

The above table shows that, probability of repairing the rail head after detection of critical crack-size before failure based on remedial action plan was obtained as 5% only and probability of no repair for the rail head is 95% due to rail heads critical crack-size is much smaller than web and base of rail. This shows that the failure of rail head is critical and reach earlier than web and base failure. So, immediate management action is required to prevent the failure of the rail. Similar considerations were taken for the rail web and base.

LIFE-CYCLE COST ESTIMATION

Life-cycle cost estimation provides an economical evaluation of all current and future costs associated with investment alternatives. Life- cycle cost estimation enables comparison of the costs of alternatives regarding inspection interval. The idea behind cost estimation is that decision related to inspection/repair intervention should consider all the costs incurred by the Ethiopian Railways Corporation during the period over which the alternatives are compared. The costs regarding the rail maintenance should consist of inspection and repair costs as well as costs due to the risk of rail broken accidents using an economical technique known as discounting. These costs are converted into the present value in the life cycle cost estimation.

The data used for the determination of total cost were taken from the documentation of feasibility study of the national railway network of Ethiopia as well as the current Ethiopian cost. But some data which are not available in Ethiopian database were taken from other countries' experience.

The total costs related to rail- defect inspection include:

- Costs for operating inspection vehicles.
- Costs for repairing detected rail defects and the corresponding train delay cost.
- Costs for repairing broken rails and the corresponding train delay cost.

$$C_{total}(K) = C_{INSP} + C_{def} + C_{bro} + C_{derail} \quad (11)$$

$$C_{total}(K) = \frac{kL}{V} C_{ins} + \frac{S(k)L}{\lambda\left(\frac{T}{K} - \theta\right)}\left(DDC + C_{DDT}\right) + \quad (12)$$
$$S(K)L(SDC + C_{SDT}) + S(K)L\phi(\mu DA + C_{DA})$$

Where:
C_{total} = total cost related to rail defect inspection (\$) (Life cycle cost).
K = rail defect inspection frequency per year
S (K) = number of broken rails per track-mile by annual rail defect inspection frequency.
Φ = proportion of broken rails causing train derailments, 0.85% [10].
DA = average track and equipment damage cost per broken-rail-caused train derailment (\$3,000,000) [12].
μ = multiplier for accounting for other related derailment costs (excluding train delay cost), 1.65 [7] and other variables as previously defined.

The total cost (including rail defect inspection, rail defect or broken rail repair, track and rolling stock damage and train delay due to derailments or repair activities) is minimized at a certain inspection frequency. The following equation presents a general model to estimate the total number of rail breaks per year between two successive rail defect inspections assuming that no complementary broken rail prevention technique (e.g., rail grinding or rail lubrication) is used.

(13)

$$MINIMIZE\left[\left(\sum_{i=2}^{k} S_{(i-1,i)}\right) + S_{(k,end)}\right] \text{ Where, } \sum_{i=2}^{k} x_i \le T \quad (14)$$

$$S_{(i-1,i)} = R\frac{\frac{\alpha\left(0.5N_{i-1} + 0.5N_i\right)^{\alpha-1}}{\beta^{\alpha}} e - \left[\frac{0.5N_{i-1} + 0.5N_i}{\beta}\right]^{\alpha}}{1 + \frac{1}{\lambda\left(x_i - \theta\right)}} x_i \quad (15)$$

$$S_{(k,end)} = R\frac{\frac{\alpha\left(0.5N_k + 0.5(N_o + T)\right)^{\alpha-1}}{\beta^{\alpha}} e - \left[\frac{0.5N_k + 0.5(N_o + T)}{\beta}\right]^{\alpha}}{1 + \frac{1}{\lambda\left(T - \sum_{i=1}^{k} x_i - \theta\right)}}\left(T - \sum_{I=1}^{k} x_i\right) \quad (16)$$

$S_{(i-1,\ i)}$ = number of broken rails per track-mile between the (i-1) th and i^{th} inspection
$S_{(K,\ end)}$ = number of broken rails between the K^{th} inspection and the end of year
R = rail segments per track-mile = 61
X_i = Inspection interval (MGT) between the (i-1) th and i^{th} inspection
T = annual traffic density (MGT) = 22.67MGT.
α = Weibull shape factor, 2.94 [6]
β = Weibull scale factor, 1396 [6]
λ = slope of the number of rail breaks per detected rail defect (S/D) vs. inspection interval curve, 0.0108 [9]
θ = minimum rail defect inspection interval is assumed to be 1MGT
N_i = rail age (cumulative tonnage on the rail) at the i^{th} inspection, $N_i = N_{i-1} + X$

Figure 7 Annual total cost for different rail inspection frequencies (initial rail age is 61.88 MGT and annual traffic density is 22.67 MGT, 1-mile route).

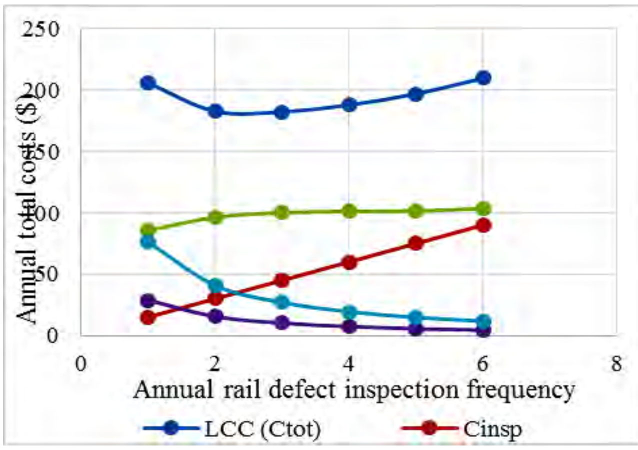


Table 7 Total annual cost for different rail inspection frequencies

Annual Rail Inspection Frequency	Cost Category($)				
	Total Cost	Rail Inspection Cost	Rail Defect Repair Cost	Rail Break Repair Cost	Derailment Damage Cost
1	205.68	15.00	85.67	28.83	76.18
2	182.54	30.00	96.26	15.45	40.83
3	182.19	45.00	100.06	10.19	26.94
4	187.77	60.00	101.08	7.33	19.36
5	196.89	75.00	101.58	5.53	14.73
6	209.6	90.00	103.36	4.46	11.78

There is a tradeoff point at three inspections at which LCC is minimized.

CONCLUSIONS

- The effective (optimum) inspection interval is assessed for the national railway network of Ethiopia. By applying the exact inspection frequency based on exact rail failure data base, it is possible to prevent the occurrence of rail failure by taking the required action at the right time, and extend the rail life expectancy, and reduce the rail maintenance work and its cost.
- Based on the present situation and determined remedial action plan for the national railway network of Ethiopia, Infrastructure Managers (track engineers or rail inspectors) shall decide to replace any rails that include head cracks of more than 1 mm, web cracks of more than 5 mm and base cracks of more than 2 mm.

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