Optimization of Maintenance Strategies for Diesel Locomotives: Enhancing Reliability and Performance in Transportation Systems

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Abstract

Transportation systems play a vital role in the efficient movement of goods and people, with diesel locomotives serving as a critical component of these systems. To ensure their optimal performance and reliability, it is essential to develop effective maintenance strategies for diesel locomotives. This paper presents a comprehensive study on the optimization of maintenance strategies to enhance reliability and performance in transportation systems. The first part of the study focuses on understanding the key challenges and maintenance requirements specific to diesel locomotives. Next, various maintenance strategies are analysed, including preventive maintenance, condition-based maintenance, and corrective maintenance. The strengths and limitations of each strategy are evaluated by considering factors such as downtime, and impact on locomotive performance.To address the maintenance optimization problem, mathematical models are developed to capture the relationships between maintenance actions, system performance. The proposed methodology has been applied to high power diesel locomotives in railways. The best-fit distribution of time between failures (TBF) and time to repair (TTR) of each subsystem is identified with Anderson-Darling (A-D) value and the respective parameters are calculated. These models incorporate probabilistic approaches to account for uncertainties in component degradation and failure processes. Optimization of maintenance interval for complex systems is based on the reliability and availability of the system.

To validate the effectiveness of the proposed maintenance optimization strategies, case studies and simulations are conducted using real-world locomotive data. The results demonstrate significant improvements in locomotive reliability, availability, and overall performance when compared to traditional maintenance approaches.

Keywords: Reliability; Maintainability; Time between failure; Time to repair; Diesel Locomotive

1. INTRODUCTION

Since the failure of any system cannot be prevented completely, it is important to minimize its probability of occurrence and its impact if they do occur [4]. Most of the complex mechanical systems consist of many subsystems. The performance of this system is mostly affected by reliability, availability, and maintainability of its subsystems/components.

Reliability analysis is used as a tool for the planning and operation of these systems. Reliability analysis will help to identify the critical and sensitive subsystems that have a major effect on system failure. Therefore, a focus on reliability is necessary for the improvement of equipment performance and to ensure the equipment's availability for the operation. Reliability and pattern of failures of a system/component may be affected by the external factors like operating conditions, environmental stress, and the experience of the operator. Reliability analysis of such system is required to get the realistic information from the operating environment. To maintain the designed reliability and availability characteristics and to achieve the expected performance, an effective maintenance plan is required. From the economic point of view high reliability is required to reduce the maintenance cost of systems.

Maintainability analysis is to determine the conditions under which the maintenance or repairs are to be accomplished. There are two basic categories of maintenance are there, one is scheduled (or preventative) maintenance and the other is forced (or corrective) maintenance. Scheduled maintenance is performed at constant time intervals even if the system is working satisfactorily. Such maintenance will prolong the life of components, decreases the number of failures, and increases the MTTF of the system. Corrective maintenance follows in-service failures. As soon as the failure occurs, replacement, adjustment, or repair of a component is done to bring back the system to normal operating state [9]. These maintenance actions are called as maintenance plan for a system. The first guideline for maintenance plane will be given by the manufacturer. This will then be optimized depending upon the failure rates, working conditions, desired performance levels, etc.To this end, and to develop an optimal maintenance/inspection plan, learning about the existing maintenance procedures of equipment and the statistical analysis of field data is essential.

Modelling the availability of a multi-train repairable fleet are considered in the literature that will give the description of the problem. To find applicable theories and information "Reliability and availability," "Repair," "Multi-component systems," and "Fleet of systems" have been used as keywords. After examining the literature available, an interesting point is that the most similar situations to the one described here are not necessarily in a rolling stock fleet. Models of other transit systems, general systems like (machine repair problems, communication systems, and military applications) are also considered [11].

From the analysis of operation data obtained from PKP Cargo S.A., a sample of 36 SM31 locomotives, collected in the years 2019-21, it follows that about 56% of all the failures found in SM31 locomotives are related to the diesel engine [2].Many articles are about fleet systems but out of the many two of the articles [3, 11] describe the aspects of the problems like how to analyse the TBFs and TTR data of mining trucks and hospital dialysis unit. Methodology for the reliability analysis and to get the reliability-based optimal maintenance interval for each subsystem of mining truck presented [3].

In this paper, we described a problem that has not addressed well in the literature is that the reliability and maintainability analysis of diesel locomotive with operational data from maintenance sheds.

The steps for the reliability analysis with time between failure and maintainability analysis with time to repair data are explained here. Fig. 1 show the flow of model selection for repairable systems failure data. First one is the identification of the failures with significant consequence using Pareto principle. It is often found that a large proportion of failures in a product are due to the small number of causes. The next is data collection, sorting and classification as per standards. Then the assumption validation that is independent and identically distributed (i.i.d) nature of TBF and TTR. For this common method used are trend test to detect the pattern of failure and serial correlation test for the dependency of multiple repairable systems are explained [8]. The Anderson-Darling test is used for the identification of the best-fit distribution for both TBF and TTR if the assumption is valid. If the assumption is not valid, then it may not be appropriate to do reliability analysis with statistical techniques.

Data Collection, Analysis, and results

Case study: High Power Diesel Locomotives used to haul both passenger and freight trains in railways are considered as the case study. Any locomotive, either electric or diesel, can be described as a highly complex machine with different main and sub-systems that have to interact in such a way that it has to perform in accordance with its design parameters. It can then fulfil its primary function of hauling predetermined calculated maximum loads at certain calculated running times [5].

Throughout the working life of locomotive, it must be stopped for maintenance to keep it in service. These maintenance actions are commonly known as the maintenance plan of a locomotive. A maintenance plan will cover all maintenance interventions for the entire lifespan of the system. It is a combination of running maintenance (service), component change out/overhaul's, body repair and paint programs, upgrading of subsystems, replacing of subsystems due to obsolescence and end of life (run out) maintenance.

Initially, the guidelines for maintenance plan will be given by the manufacturer. This plan will then be optimized by the maintenance manager depending on failure rates, working conditions, and desired performance levels.

Methodology for Reliability and Maintainability Analysis of Diesel Locomotives:

1. Data collection and Sorting
2. Test for the assumption independent identically distributed (i.i.d)
3. Probability distribution to get best-fit and to determine the parameters;
4. Estimation of reliability, maintainability of each subsystem at different times;
5. Identification of critical subsystems with low reliability and maintainability;
6. Determine the optimal maintenance interval for critical subsystems based on target reliability and maintainability.

1.1 Data Collection and Sorting:

Reliability and maintainability analysis of Diesel Locomotive is based on the realistic data of operation and maintenance collected on twenty-one Diesel Locomotives. Based on this Coding and classification of failures the system (Diesel Locomotive) is divided into subsystems which are given in Table I.

Table I: Diesel Locomotive subsystems and their codes

S.No	Subsystem	Code	No of failures
1	Power assemblies	A	04
2	Engine Systems	B	43
3	Other Assemblies	C	16
4	Water Cooled Compressor/CCB System	D	20
5	Traction Power Electrics	E	30
6	Electrical Control Cabinets	F	16
7	Auxiliaries	G	24
8	Vehicle and Structure	H	15
9	Maintenance Overdue/ Mismanagement by Crew	Z	42

To analyse the data for reliability characteristics of a system the basic steps have to be performed are data collection from maintenance records of maintenance shed, sorting and classification (i.e. TBF, TTR, TTF, frequency of failure, total uptime, total downtime, total maintenance hours, etc.) of data using a benchmark format. Due to paucity of space, only data from one subsystem namely Engine System (B), are given in Table II. In the column of event type, “1” means that the component failed and “0” refers to censored failures. The units of the data will effect not effect he analysis and could not be revealed due to confidentiality reasons.

Table II: Failure times of Subsystem B

S.No	Loco No	Failure time in days							
1	X1	934	1011	1626+					

2	X2	92	137	373	402	986	1633+		
3	X3	24	153	317	664	686	712	1458	1636+
4	X4	1132	1162	1615+					
5	X5	929	951	1232	1593+				
6	X6	354	617	851	1195	1606+			
7	X7	12	970	988	1563+				
8	X8	201	1141	1550+					
9	X9	1534+							
10	X10	881	969	1492+					
11	X11	228	231	843	992+				
12	X12	159	970+						
13	X13	660	953+						
14	X14	22	106	213	826	793+			
15	X15	42	215	692+					
16	X16	676+							
17	X17	603+							
18	X18	330	589+						
19	X19	598+							
20	X20	228+							
21	X21	194+							

'+' sign indicates time censoring

After sorting and classification of the data, the next is to identify the most frequent occurrences using Pareto chart for the failures system. This case study the power pack assembles subsystem (A) has only four data points, as per literature it is required a minimum of five data points for further analysis. So the assumption is that the subsystem is working perfect and it is not considered for further analysis. From the Fig 2. Engine system (21%), Maintenance Overdue/Mismanagement by Crew (20%) and Traction power electric (14%) of Locomotive has frequent failures. These subsystems must be analysed for further modification of maintenance plan to failure frequency and to improve the system availability.

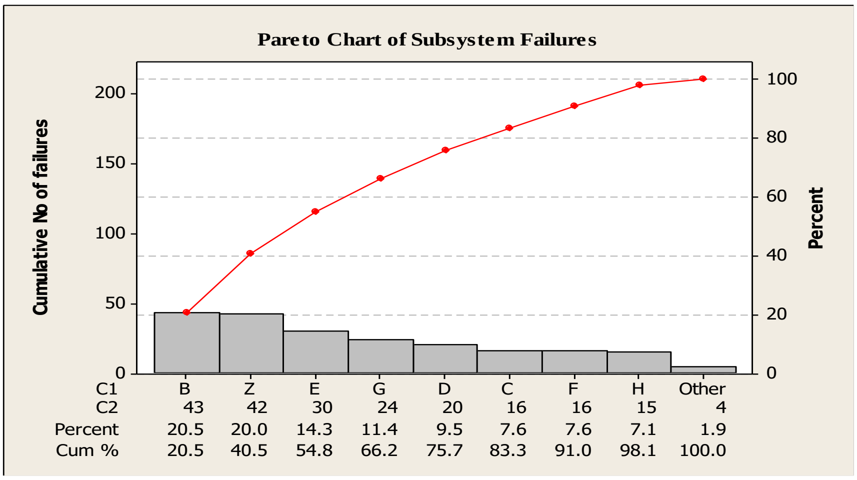

Fig 2. Pareto chart of diesel locomotive failures

1.2 Test for i.i.d nature of TBFs and TTR:

The next step is to validate the assumption i.e. independent and identically distributed nature of the TBF and TTR data of each subsystem. This validation can be done in two steps one is trend test, and another is correlation test.

Trend Tests:

Consider the null hypothesis as

H_0: no-trend in data;

H_1: trend in data.

Table III: Trend test results of subsystem								
Sub system	**Type of Data**		**MIL-Hdbk-189**		**Laplace's**			**Decision**
			TTT-based	**Pooled**	**TTT-based**	**Pooled**	**Anderson-Darling**	**for H_0**
B	TBF	Test Statistic	69.93	73.85	-0.89	-1.31	0.98	Not rejected
		P-Value	0.2	0.11	0.375	0.192	0.367	
		DF	56	56				

The tests for trend are not significant for failure times of all subsystems (P-Value > 0.05). This means that there is no enough evidence to reject the null hypothesis at 5% level of significance that means there is no trend in data. The results of the test are shown in Table III.

The results of the trend test show that failure and repair data for all subsystems are free from trend and correlation. It is obvious that the assumption of i.i.d is true for both TBFs and TTRs.

1.3 Analysis of TBF and TTR data:

If the data is independent identically distributed (i.i.d) then the data are analysed to determine the characteristics of failure time and repair time distributions of each subsystem of Diesel Locomotive to estimate the reliability and maintainability. For this, the best-fit probability distributions are used. To identify the best-fit distribution for the given failure and repair data of each subsystem the maximum likelihood estimation method with Anderson-Darling (A-D) goodness-of-fit test is used. The A-D statistics of several distributions for TBF are given in Table IV. A lower value indicates that the distribution fits the data better. The best-fit parameters for failure times of each subsystem are given in Table V.

Table IV: Parameters for time between failures (TBF) of subsystem with best-fit				
Subsystem	Best -fit	Shape	Scale	Location
B	Weibull	1.034	1199.845	-13.73

Subsystem	Log-logistic	3-Weibull	3-Lognormal	2-Exponential	3-Loglogistic	Normal	Logistic	Best-fit
B	3.06	**2.88**	3.16	3.56	3.06	4.57	4.61	3-Weibull

Table V: Parameters for time between failures (TBF) of subsystem with best-fit				
Subsystem	Fitted distribution	Parameters		
B	3-Weibull	$\beta = 0.788$	$\theta = 361.235$	$\gamma = 7.350$

1.3.1 Reliability analysis:

Reliability is the probability that the system/component can perform its intended function adequately to a specified period t understated environmental conditions.

$$R(t) = pr(T \geq t) \tag{1}$$

The system is comprised of eight subsystems, and all these subsystems are functionally arranged in a series configuration. So the system can function only if all subsystems are functioning satisfactorily. The reliability of each subsystem can be calculated with the parameters of distributions shown in Table V.

Reliability of Engine System (B) can be calculated as

$$R_i(t) = \exp^{\left(-\left(\frac{t-\gamma}{\theta}\right)^{\beta}\right)} \tag{2}$$

Where β, θ, γ are shape, scale and location parameters respectively for 3-parameter Weibull distribution as best-fit for subsystem B.

Reliability of the system can be maintained at a target value by doing the maintenance at times before its failure time. The expected failure time can be estimated for each subsystem with reliability analysis. If the maintenance is done before the failure time of each subsystem, then the system can be renewed.

Optimal preventive maintenance interval (t) for subsystem B to get expected reliability is given as

$$t = \gamma + \theta * [-\ln (R(t))]^{\frac{1}{\beta}} \tag{3}$$

The reliability of the system R (t) can be calculated by the equation given below, where $R_i$is reliability of each subsystem;

$$R(t) = \prod_{i=1}^{8} R_i \tag{4}$$

Table VI: Reliability of subsystems and system at different times

Time (days)	7.5	15	30	45	60	75	90	105	120	135	150	165	180
BR(t)	1	0.95	0.89	0.85	0.8	0.77	0.73	0.7	0.67	0.64	0.62	0.59	0.57

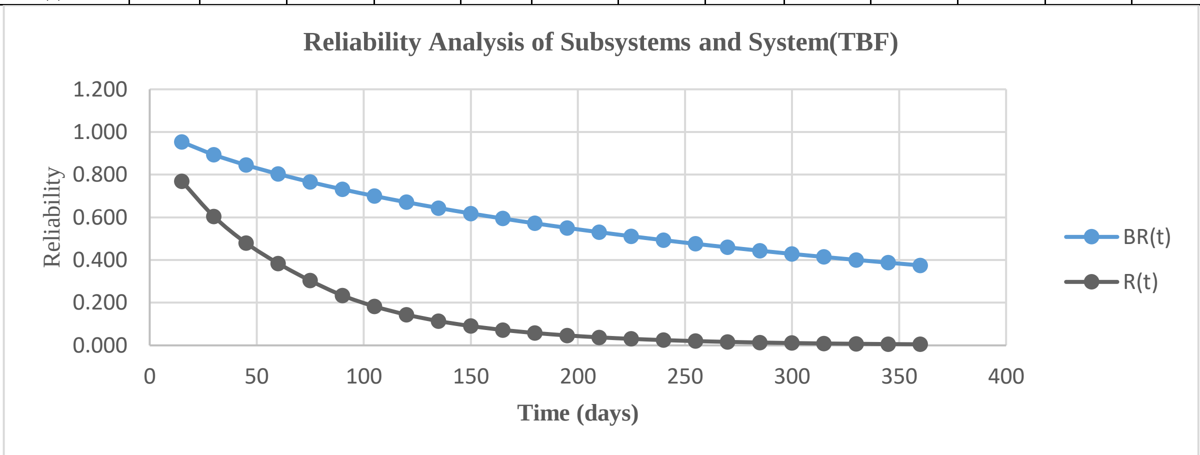

Fig 4. Reliability of subsystem B and the overall system

The reliability for each subsystem is represented along with subsystem code. (Ex: Reliability of subsystem B at time t as BR (t)). In Table VI, subsystems and the system reliabilities are determined at different times. The reliability of the subsystems B, C and E, and Z are below 70% at 180 days. This analysis will be useful for the estimation of preventive maintenance interval of each subsystem with target reliability. Ex. To achieve 90% reliability for the subsystem B, preventive maintenance must be done before 26.44 days. The reliability of each subsystem and system at different times are plotted as shown in Fig 4. This analysis will be useful to identify the bottlenecks as well as to improve the system reliability. From the analysis optimal maintenance interval for each subsystem for target reliability are determined and are shown in Table VII.

Table VII: Optimal maintenance time interval (days) for each subsystem to get target Reliability

R	0.999	0.995	0.990	0.985	0.980	0.975	0.970	0.965	0.960	0.955	0.950
B	7.41	7.79	8.4	9.12	9.9	10.8	11.7	12.6	13.6	14.6	15.7

Maintainability Analysis:

Maintainability is the probability that the repair of failed component can be done within the specified time. This is used to identify the weaknesses in maintenance operations of the system. Maintainability in respect of rail vehicles concerns corrective and preventive maintenance. Corrective maintenance enables restoration of the object's operability and putting it back into operation. Preventive maintenance, on the other hand, is done as part of an object's prescribed maintenance cycle to improve its reliability and control its wear.

Table VIII: Parameters of time to repair for subsystems with best-fit

Subsystem	Fitted distribution (A-D value)	Parameters		
		μ	σ	γ
B	3-Lognormal(0.329)	3.940	1.050	-1.900

If the time to repair (TTR) follows Weibull distribution, the maintainability at time t can be calculated by using equation 5.

$$M(t) = 1 - \exp\left(-\left(\frac{t-\gamma}{\theta}\right)^{\beta}\right) \quad (5)$$

Based on A-D value the best fit for TTRs of each subsystem is identified. The parameters of the best–fit are determined and are shown in Table VIII. Maintainability of each subsystem at different times are calculated and are shown in Table IX. From the table, the maintainability of subsystem B, C and E are below 0.7 which mean that only 70% of the repair activity will be completed within 80 hr of repair time. After 400 hr only all other subsystems expect B are attaining 90% maintainability.

Maintenance time required to get target maintainability if TTR follows Log-normal distribution and Log-logistic distribution are given in equations 6 and 7 subsequently

$$t = \gamma + \exp\left(\mu + \sigma * \emptyset^{-1}(M(t))\right) \quad (6)$$

Where μ, σ, γ are mean, standard deviation and location parameters of the log-normal distribution.

$$t = \gamma + \alpha * \left(\frac{M(t)}{1 - M(t)}\right)^{\frac{1}{\beta}} \quad (7)$$

Where α, β, γ are scale, shape and location parameters of the Log-logistic distribution.

The maintainability values are plotted for all subsystems as shown in Fig 5. This will helpful to identify the weaknesses in maintenance crew.

T (hrs)	1	8	16	24	32	40	48	56	64	72	80
BM(t)	0	0.06	0.16	0.26	0.35	0.42	0.49	0.54	0.59	0.63	0.67

M(t)	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.9	0.8	0.7	0.6	0.5
B	24.8	18.6	15.5	13.5	12.1	11	10.1	9.35	8.73	8.2	5.13	3.65	2.73	2.07

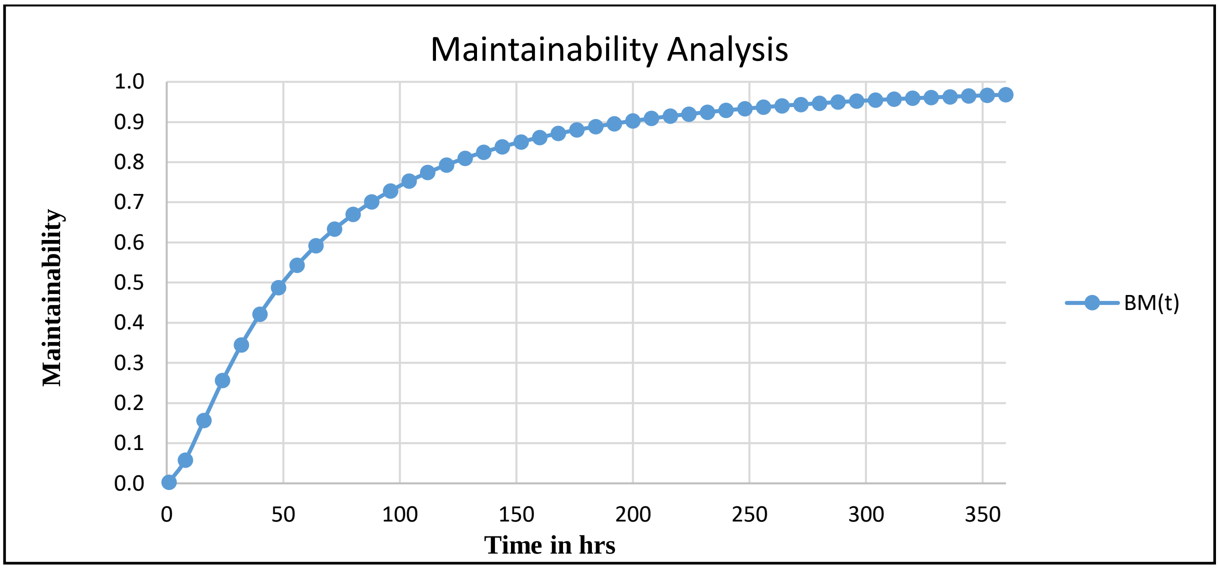

Fig 5. Maintainability of subsystems

Mean time between failures and Mean time required to repair are calculated and then steady state availability of each subsystem is determined and are shown in Table XI.

Table XI: Steady state availability of each subsystem			
Subsystem	MTBF (days)	MTTR (days)	A(t)
B	421.204	3.660	0.991

2. CONCLUSIONS

This paper presents a methodology for the identification of appropriate reliability model for system having multiple repairable units. This paper discusses different scenarios for analyzing multiple repairable units, based on trend, intensity, and dependency.The case study verified for the presented methodology on a high power Diesel Locomotive. The frame work presented in the paper enables to identify the critical subsystems that are failure frequent and having the weaknesses in maintenance activities. For each subsystem reliability and maintainability's are estimated from the i.i.d failure and maintenance data. Optimal maintenance intervals have been proposed for all subsystems of Diesel Locomotive for the target reliability and maintainability values. The results of analysis can be used to develop an inspection/maintenance schedule for subsystems and the entire system.

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