Reliability Investigation for a Fleet of Load Haul Dump Machines in a Mine

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Abstract

The recent deployment of complex and capital intensive equipment in mines has resulted in increased interest in the maintenance and operational reliability of these equipments. This is because random equipment failure has consequences that influence the total operating cost of this system. This case study analyses the reliability of a fleet of load haul dump machines in a Coal India mine situated in Nagpur There are three goals of this case study: To estimate the operational reliability of these machines secondly to Locate items or assemblies that need improvement in design to enhance the reliability. Thirdly to decide whether preventive maintenance should be applied. Failure data of one year of load haul dump (LHD) machines are analyzed and other analytical methods are used in the analysis.

Keywords: *Reliability, TTT Plot, Maximum likelihood estimator (M.L.E.), time between successive failures (T.B.F.)*

1- Introduction

As automation in mines is increasing, the importance of having highly reliable operating systems is being recognized in the mining industry. High reliability results in lower maintenance costs of the system. Earlier, maintenance was not considered to be a major problem in the mining industry because the consequences of equipment failure were negligible. But as more capital intensive machines are being applied and mineral prices are falling, higher reliability is desired. The Coal India mine in Nagpur is interested in doing more research on how to make their systems more efficient. A recent study of the Indian mining industry showed that the maintenance costs, both direct and indirect, often constitute 50-60% of the equipment operating cost. Indirect costs are costs resulted due to losses in production and machine idleness.

2- Mine Operating System

The mining operations can be thought of as system comprising subsystems connected in a series. Therefore this means that if one unit is down, the whole system has to be stopped and indirect cost due to lost production is incurred. First fragmentation occurs through drilling and blasting. Then the fragment rock is loaded into trucks or ore passes. The ore is crushed and then transported to the ore dressing plants for sorting and enrichment. The Process is stated below

1. Drilling
2. Blasting
3. Loading
4. Crushing
5. Transportation

2.1 The Load Haul Dump (LHD) Machines

These are the dominating machines used in underground mines in India. They are used to pick up ore or waste rock from the mining points and dump it into trucks or ore passes depending on the distance. Most of the LHD machines works on diesel but electric LHDs are being introduced in the Indian mines as well. The strategic location of the LHD machine in the mine operating system and its high cost of operation and maintenance is what motivated the selection of this machine for this study. The goal is to identify the items, subassemblies of assemblies of the machines that need improvement in design and come up with optimal maintenance policies. The machine has many subsystems that are shown as

1. Engine
2. Transmission
3. Hydraulic

4. Brake
5. Others

2.2 - LHD subsystems

The time between successive failure (TBF) data for a period of one year were sorted and analyzed. Several statistical distributions were examined and their parameters were estimated using the Maximum Likelihood (ML) method. TTT plots are used to analyze the TBF□s and the results are compared to the one obtained by the ML method.

3 - Basic Concepts

3.1 - Techniques for failure data analysis

In this study, ML method will be used together with TTT plots to analyze the TBFs. This method requires the use of computer programs for using Minitab and Microsoft Excel. The method of TTT plotting is based on the assumption that the TBF are independent and identically distributed (iid). All these methods are explained during the analyses.

3.2 - Assumption of iid for the TBFs

Since it cannot be assumed that the data is independent and identically distributed, proper tests would be used to test for the presence of structures or trends in the data. If there is no trend, the assumption will be deemed correct. Another important thing is to test the successive inter-arrival times for independence by testing them for serial correlation. It will be done using graphical methods.

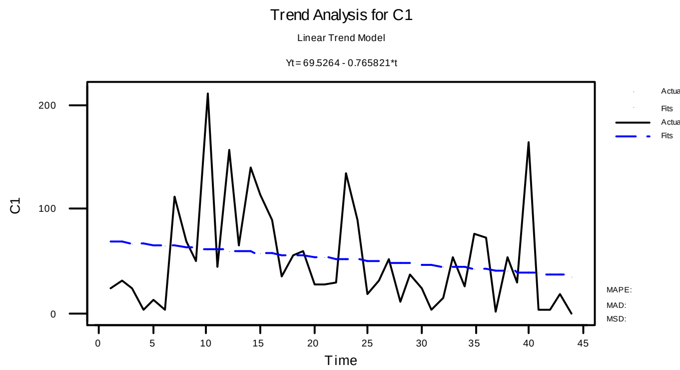
3.3 - Data Collection, Sorting and Classification

To obtain information about the time between successive failures, operation and maintenance cards of a fleet of LHD machines were collected from a period of one year. From these cards, data such as times to failure, the engine clock hour, the reported failures, the time to repair and the actual repairs performed, was collected. Only the TBF data for the first machine is analyzed in this study. The data is presented in Table A in Appendix B. It is important to point out here that the machines were neither too old nor too new. From the cards, the TBFs for the engine, brake, transmission and hydraulics subsystems were calculated. The TBFs for the engines of all the three machines is presented in Table B in Appendix B. Many times, more than one subsystem is repaired. For this study, the failure reason was assigned only to those subsystems for which the machine was stopped and the rest will be considered censored failures. For example, in case of LHD A, at serial number one, the subsystems repaired are engine, hydraulics and body, the engine will be assigned the reason for failure and the rest are censored failures. The TBFs for the other subsystems for LHD A is presented in Table C of Appendix B. Also when the machine is stopped for routine maintenance, the TBFs obtained due to these stoppages are considered censored failures.

4 - Methodology of Data Analysis

4.1 - Trend Analysis for the TBFs

To see if there is any presence of structure in the TBFs of the LHD machines and their subsystems, the cumulative time between successive failures was plotted against the cumulative number of failures in each case. An example of the curve is shown in **Figure 3**. Since the curves were linear, no trend or structure was observed in most of the TBF data sets.



Scatter plot of cumulative TBF VS CUMULATIVE NUMBER OF Failures for LHD B

```
      -
  2400+
      -                              x xxx
C1    -                            x xxx
      -                         xx
      -                   xx xxxx x
  1600+                    x xx
      -               xx
      -            xxx x
      -          xx x
      -         x
   800+          x x
      -       x
      -       x
      -     x x
      -   xx xxx
    0+  x xx
       +---------+---------+---------+---------+--------
-+------C2
      0.0     8.0    16.0    24.0    32.0    40.0
```

Figure 3 –Trend analysis of failures and Scatter plot of cumulative TBFs against cumulative number of failures for LHD B

The TBF data for some of the subsystems, like the hydraulic subsystem of LHD A, shows the presence of a structure. But for simplicity, they will be treated as having no trend. However, it can lead to a wrong conclusion about the failure rate. It is also required to test the TBFs for independence by testing the failure data for serial correlation. To do this, the (i-1)th TBF is plotted against the ith TBF. No serial correlation was observed for most of the data sets as shown in **Figure 4.**

```
                       -



C1    -
     -    x
     -      x
  140+      x     x
     -
     - x                  x
     -
     -                  x   x
   70+     x       x     x       x
     - x  x  xx   x  x
     -  x          x                 x
     -   xxx2xx   2x
     - 3        x     x
    0+  x x x2        x              x
       +---------+---------+---------+---------+--------
-+------C2
      0      40      80     120     160     200
```

Figure 4 - Scatter plot of ith TBF against (i-1)th TBF for LHD A

4.2 - Maximum Likelihood Estimation

Now it is known that iid assumption for the data sets is not contradicted. Exponential, Weibull and Lognormal were tried to describe the nature of the TBFs distribution. Kolmogorov-Smirnov (K-S) test is used as a measure of goodness-of-fit of the different distributions. The results can be seen **in Table 1**. To conduct this test, the following steps are followed:

a) i: serial number n = number of failures F(i) = TBF at i

b) Find D^{-*} = F(i) – [(i-1)/n] and Find D+ = (i/n) – F(i)

c) Find D-max = max{D-} and D+max = max{D+}

d) Find D = max{D-max, D+max}

Table 1: K-S test results

System /Subsystem	K-S statistics D_{max}			Best fit Distributions
	Exp	Weibull	Lognormal	
LHD	0.081	0.069	0.118	weibull
Engine	0.215	0.193	0.220	weibull
Brake	0.125	0.101	0.110	Weibull
Hydraulics	0.200	0.198	0.180	Lognormal
Transmissions	0.410	0.237	0.307	Weibull

In most of the cases, the two parameter Weibull distribution provides the best fit model for describing this data because it has the lowest Dmax. The parameters were estimated using the ML method in Minitab. The results can be seen in Table 7.1.2. To use ML method, the following steps are followed:

(a) Enter the TBF data in a column

(b) Highlight and Go to Graph □Probability plots □OK

(c) Select the column from the left side and Go to Distribution

(d) Select distribution and then click OK □OK

(e) We can see the shape and scale parameters of this distribution on the right hand side of the graph.

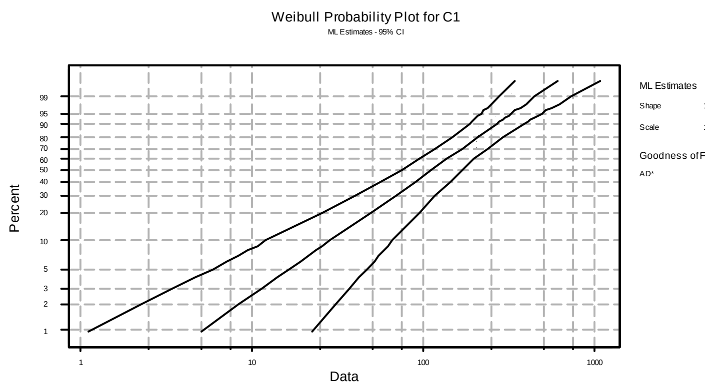


Figure 5 Probability Plot of engine TBF of LHDA

This plot is a Weibull probability plot of the brake TBF of LHD A. It can be seen that the shape parameter (β) and the scale parameter (α) are shown on the right side of the plot. In this case, they are 1.35and 146.4 which is also shown in the

5.0 - Analysis by TTT-plotting

TTT-plots are used to check the validity of the results obtained by the ML method and for obtaining the shape of the failure rate function. To develop TTT-plots, the following steps are followed:

a) TBF is structured as 0 <= t(0) <= t(1) .... <= t(n) and i = 0,1,2,…,n

b) Find S(i) = nt(1) + (n-1)(t(2) - t(1)) + …. + (n – i + 1) (t(i) - t(i-1)) for all the i□s till n

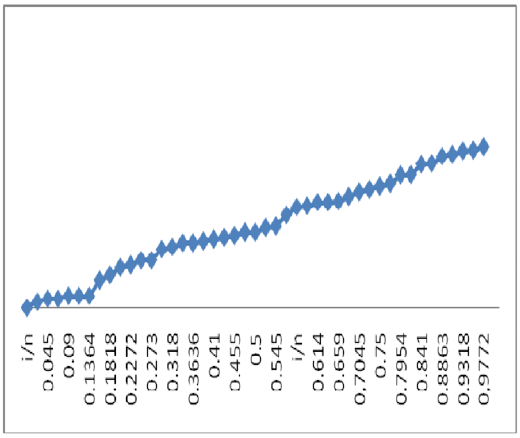
c) Y – axis: (S(i)/ S(n))

(d) X – axis: (i/n)

Calculation of TTT plot is available in Appendix A .The TTT-plots for LHD A, B and C are shown below in Figure 6, 7 and 8 respectively. Figure 6 was made in Microsoft Excel using the calculation method mentioned above. The other TTT plots are made by the same process..

TTT PLOT OF LHD A

Si/Sn



i/n

Figure 6 - TTT-plot of LHD A

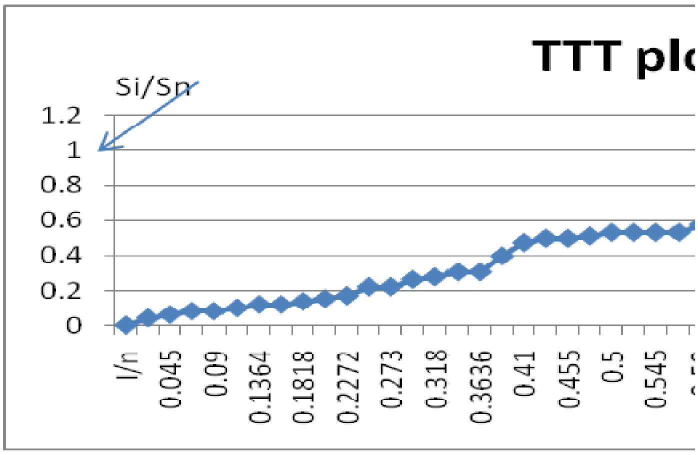


Figure 7: TTT-plot of LHD B

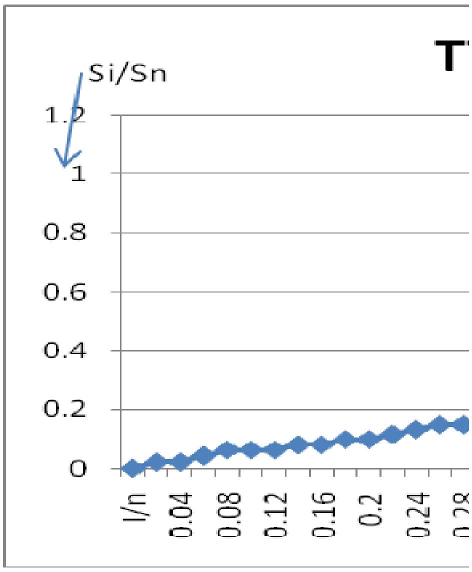


Figure 8 TTT-plot of LHDC

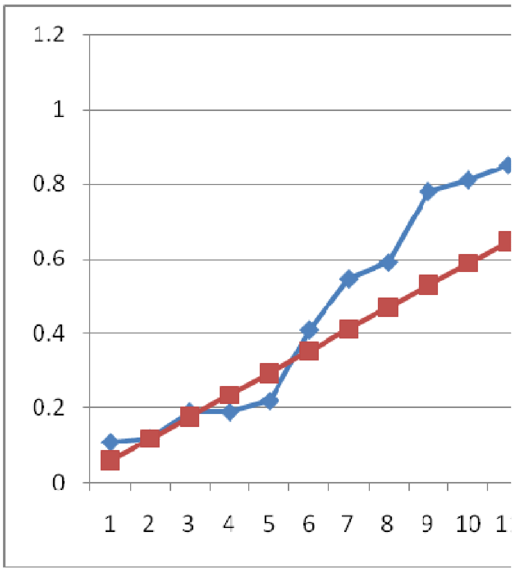


Figure 9 TTT- plot for engine of LHD A when censor time is treated as failure time

For the TBFs of the engines of all the machines, TTT-plots for three different situations are created: when all the TBFs are treated as a complete sample.The TTT-plots for the engine of LHD A for the above three situations are shown in Figure 9, 10 and 11 respectively. TTT-plot for engine of LHD A when censor time is treated as failure time

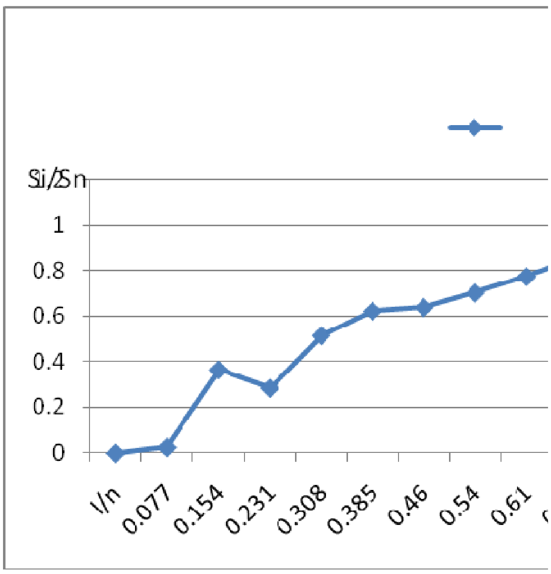


Figure 10 TTT- plot for engine of LHD B when censor time is treated as failure time

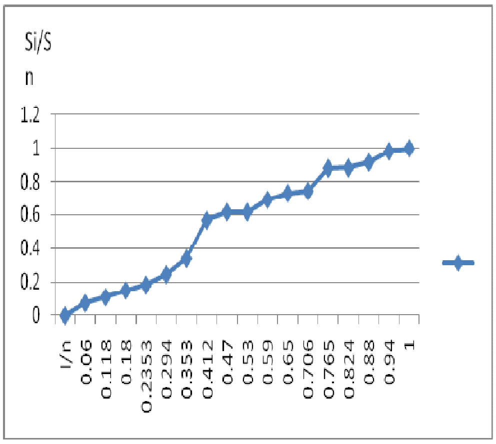


Figure 11: TTT- plot for engine of LHDC when censor time is treated as failure time

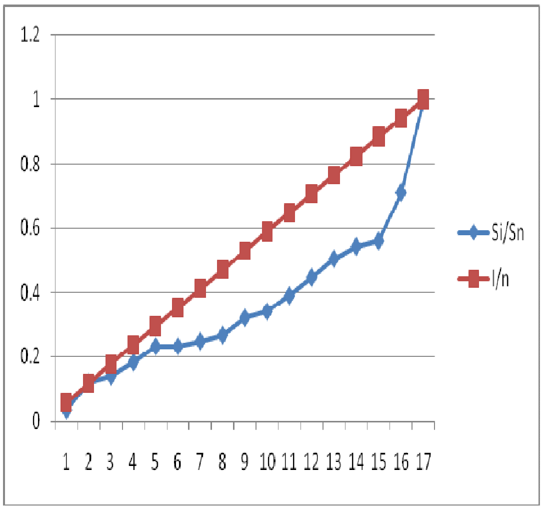


Figure 12: TTT PLOT OF Brake LHD A

TTT-plots of brake, transmission and hydraulics system of LHD A are also developed in **figure 10, 11 and 12** respectively where the TBFs of these systems are treated as complete samples.

TTT Plot of Brake LHD A

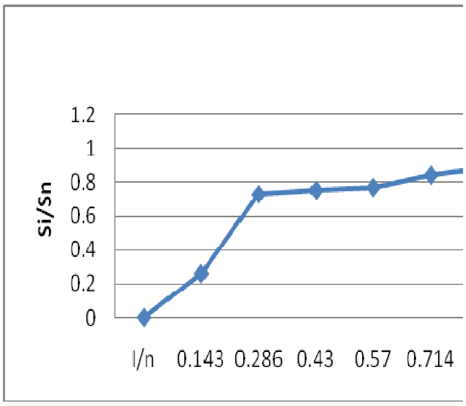


Figure 13 - TTT-plot of transmission of LHDA

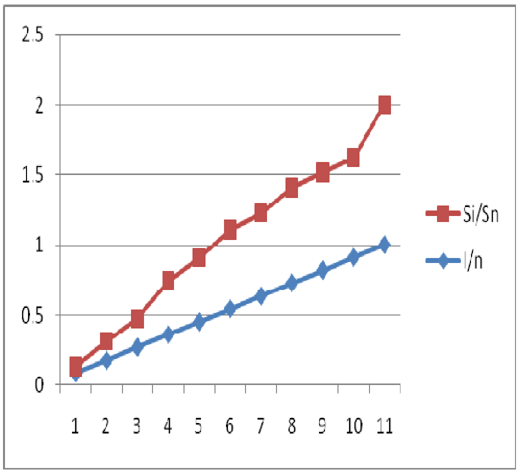


Figure 14 TTT plot of Hydraulics of LHD A

6.0 - Discussion Of The Results

(1) From the test for trend and serial correlation for the failure data of the LHD machines and other subsystems (from figure 3 and 4), it is clear that the assumption of iid is not valid for all the machines. In this case, three machines selected have shown a trend. Presence of trends is more frequent in the failure data of the subsystems. But most of the data sets seem to be iid. Calculation of TTT plot is available in Appendix A

(2) From Table 2 and Figures 6, 7 and 8, it seems that TBFs of the machines as a whole are exponentially distributed. But for LHD C, the Weibull distribution has a shape parameter of 0.86 (less than one) and also from the TTT-plot (Figure 8), it is indicated that the TBFs follow a life distribution with a decreasing failure rate.

(3) The TBFs for the engine of LHD A exhibit increasing failure rate distribution because its TTT-plot is concave. This means that preventive maintenance is economical in this case. The increasing failure rate observation is in sync with the ML shape parameter for the engine of 1.35 which being greater than one shows increasing failure rate.

(5) From Figures 10 and 12 and the ML shape parameter estimates in Table .2, it seems like the brake and hydraulic systems of the machines have approximately constant failure rates since shape parameters are close to one. But since a trend has been noticed earlier in the TBFs of the hydraulic subsystem of LHD A, the assumption of iid is not justified. Therefore, a non-stationary model like the Poisson process model might be better. The steps are:

(a) Estimate shape parameter: $\beta = n/(\sum^{n-1}_{i=1} \mathrm{In}\,(t_n/t_i))$

(b) Estimate scale parameter: $\alpha = t_n/(n)^{1/\beta}$

(c) Failure intensity= $\lambda(t) = (\beta/\alpha)(t/\alpha)^{\beta-1}$

where n is the number of failure events, t_n is the total running time and t_i is the running time at the occurrence of failure number i.

(6) From Table 2 and Figure 11, it can be seen that the transmission of LHD A shows dominant increasing failure rate characteristics.So Preventive maintenance will be useful in this case.

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7.0 - Constraints and Limitations

One of the constraints was the availability of reliable and sufficient data. Another limitation was that even if data was available, it was not stored in a way that it can be easily used for reliability analysis. Due to time constraints, not all the TTT plots were created by us. We created some like Figure 6 and Figure 9 to show as an example.

8.0 - Conclusion

From our investigation, it seems that preventive maintenance of the engines of LHD machines could reduce maintenance costs. The investigation has also shown that it is very important to check the data sets for the presence of trends and serial correlation, otherwise wrong conclusions can be made. It is difficult to make a long-term decision about the whole fleet based on TBF data for one year but if data is available in sufficient quantity, decisions about preventive maintenance can be taken.

9.0 References

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