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Reliability analysis of a fleet of mining trucks (A case study in Iran)

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ABSTRACT

Loading equipment is one of the most essential equipment in open-pit mining operations. Any failure of all or some of these equipment leads to a decrease in the production and profitability of the mine. Trucks are one of the well-known machines applied for mineral transportation. The occurrence of any kind of failure in trucks leads to the stop of the loading operation and, finally the complete stop of the mining operation. Knowing the operating conditions of the mineral transport unit is one of the critical parameters to prevent unwanted stops and accordingly improve the operational performance of the equipment. Therefore, it is necessary to check the reliability and maintainability of loading machines to provide a maintenance and repair program and control the productivity of mineral transportation operations. In this paper, the reliability of seven trucks in Sungun Copper Mine, Iran, was evaluated and discussed. To achieve this, the statistical approach was used to obtain the best reliability function, and then the reliability-based preventive maintenance scheduling was proposed. The results of this paper showed that the reliability of the fleet of mining trucks decreased to 80% in 47 hours and reached zero after about 300 hours. The results of this study are helpful for mine managers and contractors to have a safe and reliable mineral transportation system.

KEYWORDS

Mining trucks, reliability, statistical analysis, Songun Copper Mine

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I. INTRODUCTION

Mineral transportation is one of the most critical stages of open-pit mining operations. Any failure of loading machines and equipment will eventually lead to the stop of the whole mining operation. Therefore, it is necessary to investigate failures of mineral transportation equipment/systems/machines and analyze their reliability to provide a proper maintenance policy. Maintenance and repairs of mineral transportation equipment lead to reducing the operating costs, increasing the machine availability, protecting the mining profitability by reducing losses due to machine stoppage, and increasing the machine's remaining lifetimes, as well as the mining rate. Reliability evaluation is a scientific and practical approach to detecting the bottleneck of the systems. Reliability analysis is one of the powerful tools to evaluate the performance of a system and choose the most appropriate maintenance program. Using a reliability approach, it is possible to prevent unexpected failures and accordingly increase the remaining useful life of the system (Bevilacqua and Braglia, 2000).

In the mineral transposition operation, reliability is a practical method to check the breakdown of equipment to increase the mining operation rate. Using this method, it is possible to provide a detailed plan for preventive maintenance and prevent unplanned breakdowns. Since the size and complexity of the mineral transportation equipment are increasing, the unplanned stoppage can lead to an increase in operation costs; it is crucial to protect the consequences of their failures (Allahkarami et al., 2016).

There are different mineral transportation systems applied in both underground and surface mines. They can be categorized into two types; continuous such as belt conveyors, semi-mobile and mobile in-pit crushers, and noncontinuous, including the dump truck-shovel, and truck-loader. The truck-shovel is an economical, flexible, and efficient mineral transportation system (Rahimdel, 2022).

Reliability analysis has been gradually considered a standard tool for the planning and operating automatic and complex mining systems since the mid-1980s (Billinton and Allan, 1992). Nowadays, reliability analysis of mining equipment and machines such as mining trucks has been studied. Rahimdel et al. (2016) applied the Markov modeling approach for RAM analysis of four rotary drilling machines in Sarcheshmeh Copper Mine, Iran. In the mentioned study, the drilling machine was decomposed into five main subsystems, including hydraulic, electrical, pneumatic, drilling, and transmission. The transmission diagram of the drilling

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machine was constructed to obtain the reliability of the fleet of drilling machines by considering the constant failure rates. Moreover, a preventive maintenance schedule was proposed for each system of drilling machines. Similar studies have been done for LHD machines (Samanta et al., 2004), drilling operations (Ugurlu and Kumral, 2020), Dozer (Bhushan et al., 2022), and tunnel boring machine (Agrawal et al., 2019).

Choudhary and Murthy (2018) studied the failure rate and reliability of the hydraulic excavator. In the mentioned study, the statistical approach was applied to estimate the reliability function of a hydraulic shovel in a surface limestone mine in India. Moreover, the reliability-based time intervals for preventive maintenance were computed and suggested. Kumar et al. (2020) applied the basic statistical approach for the RAM (reliability, availability, and maintainability) analysis of shovels and dumpers in a surface coal mine in India. In the reviewed study, shovel and dumper were decomposed to their main subsystems, and then the Weibull distribution was selected as the best-fit distribution for analysis. Moreover, the preventive maintenance time intervals were proposed to keep the studied vehicles at the desirable reliability level. The basic statistical approach has been applied to the reliability analysis of mining equipment and machinery such as conveyors systems (Kumar, 2016), LHD (Jakkula et al., 2020), draglines (Kumar et al., 2020), drilling machines (Rahimdel et al., 2016), and shovel (Roy et al., 2001, Czaplicki and Temeng, 2022).

Rahimdel and Ghodrati (2022) applied the proportional hazard model (PHM) to the reliability assessment and remaining lifetime estimation of a mining railcar of a Swedish Railway Company. In the mentioned paper, the operational condition that affected the reliability performance were identified, and then, the conditional reliability in the presence of adequate operational condition were estimated. Moreover, the preventive maintenance plan was proposed regarding the desired failure rate, and then, its effect on the reliability level of the railcar is studied and discussed. The PHM approach has been applied in similar studies on the reliability performance of LHD (Ghodrati and Kumar, 2005), haul truck wheel motors (Jardine et al., 2001), spare parts estimation for wheel loaders (Ghodrati et al., 2012), maintainability of loader and dump truck (Nouri Qarahasanlou et al., 2017), and remaining lifetime estimation of mining truck tires (Rahimdel, 2022),

This paper aims to investigate the failure behavior and, accordingly reliability of the fleet of mining trucks as a case study: Songun Copper Mine, Iran. For this purpose, the reliability of each truck and then the fleet of trucks were modeled and analyzed using the statistical method. Moreover, the reliability-based preventive maintenance time intervals were obtained and proposed to keep the fleet reliability at a desirable level.

This paper is organized into three sections. In section 2, the statistical method of the reliability analysis is presented as a research methodology. In section 3, the reliability of the mining trucks in the Songun copper mine is analyzed and discussed.

II. RESEARCH METHODOLOGY

This section is devoted to introducing the basic methodology for statistical reliability modeling. First, the reliability analysis process based on the statistical approach is introduced, and then, the failure rate analysis is presented and discussed.

A. RELIABILITY ANALYSIS

The basic methodology for the reliability modeling of repairable systems is shown in Fig. 1. Regarding Fig. 1, three methods are generally used for reliability analysis: Renewal Process (RP), Homogeneous Poisson Process (HPP), and Non-Homogeneous Poisson Process (NHPP) (Rahimdel, 2022). The time between failures (TBFs) is the main parameter in reliability modeling. If the failure data are statistically independent and identically distributed (iid), classical statistical methods are used. If the data do not have this condition, non-statistical techniques will be used. In order to validate the iid assumption for the failure data, the trend and serial correlation tests are used. The trend refers to the failure pattern, which can be uniform or non-uniform. In a simple graphic test, the number of failures is plotted against the cumulative time of failures. If there is any trend in the data, a heterogeneous Poisson process such as the Power Law Process is used, and otherwise, the correlation of the data is investigated. In addition, the analytical method is also used to determine the trend between the failure data. To investigate the presence of a trend using analytical methods, the statistical index U can be used regarding the MIL-HDBK-189 test as follows (Rahimdel et al., 2016):

$$U = 2\sum_{i=1}^{n-1} \ln (T_n / T_i) \tag{1}$$

Where n is the total number of failures, T_n is the time of the nth failure, and T_i is the time of the ith failure.

Under the null hypothesis of HPP, the test statistic U is Chi-square distributed with a $2(n\text{-}1)$ degree of freedom. In the serial correlation test, the independence or correlation of the failure data is investigated. In the graphical test, nth TBFs are plotted against the $(n\text{-}1)$th TBFs. If the existing points are randomly scattered without any specific trend, the TBF data does not correlate, and the data is independent. If there is a correlation in the data, the homogeneous Poisson process, such as Branching Poisson Process, is used. IF the TBFs are free of trend and correlation, the classical statistics are used for modeling (Ascher and Feingold, 1984; Esmaeili et al., 2011).

In this paper, the Kolmogorov–Smirnov (K-S) test (Hassani and Silva 2015) is used for the validation and selection of the best-fit distribution.

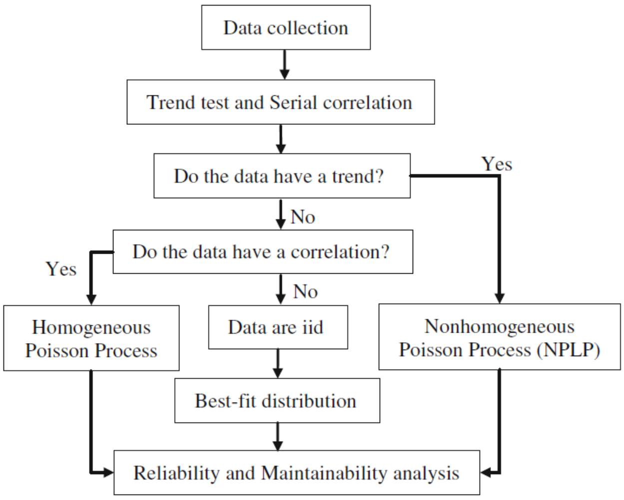

Fig. 1. Process flowchart used for reliability modeling

B. FAILURE RATE ANALYSIS

The failure rate is one of the most essential reliability measures used in maintenance management and risk analysis. In the reliability analysis, it is usually assumed that the hazard or time-dependent failure rate of items follows the shape of a bathtub curve shown in Fig. 2.

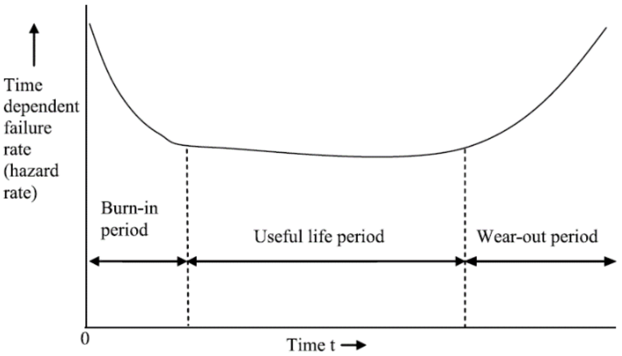

Fig. 2. The bathtub hazard rate curve (Dhillon 2008)

As can be seen in Fig. 2, the diagram is divided into three parts: the first period, or the burn-in period; the second period, or the useful life period; and the third period, or the wear-out period. In the burn-in period, the failure rate decreases with increasing time t. The reasons for this period can be low-quality control, non-standard materials and insufficient skill, poor manufacturing, insufficient debugging, poor processing, and human errors. During the useful life period, the failure rate remains constant. The main reasons for this period are the low safety factors, undetectable defects, natural and inherent failures, abuse, higher-than-expected random stress, and human errors. In the third period, the failure rate increases with time. The causes of failures during this period are friction, poor maintenance, corrosion, improper disassembly for the repair operation, and short life design of the parts and components (Dhillon, 2008).

The failure rate at time t can be obtained according to the following equations:

$$\lambda(t) = \frac{f(t)}{R(t)} = -\frac{1}{R(t)}.\frac{dR(t)}{dt} \qquad (2)$$

Where, $f(t)$ is the probability distribution function of the failures at time t and $R(t)$ in the reliability at time t.

III. RESULTS

This section is devoted to modeling the reliability of a fleet of dump trucks in Sungun Copper Mine, Iran. First, the case study is described and then the reliability analysis is performed using the statistical approach.

A. CASE STUDY

Songun Copper Mine is located in Azarbaijan-e-Sharghi Province in the northwest of Iran. This mine is 130 kilometers north of Tabriz city. Regarding the exploration activities, the mine's geological resource is about 740 million tons of copper with a grade of 0.66%, and molybdenum with a grade of 240 ppm. The probable reserve of mine was estimated about 1.7 billion tons (MOBIN, 2016). The mining activities and mineral extraction are done by employing a fleet of Komatsu 30, 60 and 100-ton trucks, Komatsu and Caterpillar loaders, Liebherr shovels, Komatsu excavators, and Tamrock drilling rigs.

B. FAILURE DATA COLLECTION AND ANALYSIS

In this paper seven rucks, named T1 to T7, were considered for the data collection and analysis. The failure data was obtained from the operation and maintenance unit of mine for six months. In the first step, the time between failures (TBF) of all studied trucks was calculated, and then, the iid assumption was checked using the MIL-HDBK-189 test. The computed value of the statistic U and Chi-squared test for the TBFs data set are given in Table 2. Regarding Table 2, the failure data of all the trucks except T2, T3, and T4 have no trend and are free of correlation. Therefore, the iid assumption is valid for trucks T1, T5, T6, and T7, and the renewal process method can be used for reliability modeling.

To check the iid assumption analytically for trucks T2, T3, and T4, the scaled failure number is plotted against the scaled cumulative TBFs. The trend and serial correlation plots for the failure data of trucks T2 and T3 are shown in Figs. 3 and 4, respectively. Regarding both analytical and graphical methods, the iid assumption is not valid. Therefore, regarding the reliability modeling approach, the non-homogenous passion process (NHPP) is used. In this paper, the power low process (PLP) is applied as a particular form of the NHPP for reliability modeling of trucks T2, T3, and T4. In the next step, the parameters of reliability functions are estimated. In this study, the Easy*fit* software (Schittkowski, 2002) was used for data analysis and finding the best-fit distributions for the reliability analysis of trucks T1, T5, T6, and T7. To achieve this, the Kolmogorov-Smirnov (K-S) test was used to select the best distribution function. Moreover, the parameters of the PLP model for trucks T2, T3, and T4 were estimated using the RGA software (ReliaSoft, 2020). The best-fitted distributions and estimated parameters for all failure data sets are given in Table 3.

Table 1. The test statistic *U* at a 95% confidence level

Truck	No. of failure	Degree of freedom	*U* statistic	Lower Chi^2 value	Upper Chi^2 value	Null-hypothesis	Decision on trend	Modelling method
T1	110	218	203.19	184.83	253.44	not rejected	no trend	PR
T2	71	140	169.70	113.66	168.61	rejected	decreasing trend	NHPP
T3	82	162	120.90	133.57	192.70	rejected	increasing trend	NHPP
T4	41	80	109.20	60.39	101.88	rejected	decreasing trend	NHPP
T5	115	228	233.90	194.05	264.22	not rejected	no trend	PR
T6	68	134	133.60	108.26	162.02	not rejected	no trend	PR
T7	82	162	155.31	133.57	192.70	not rejected	no trend	PR

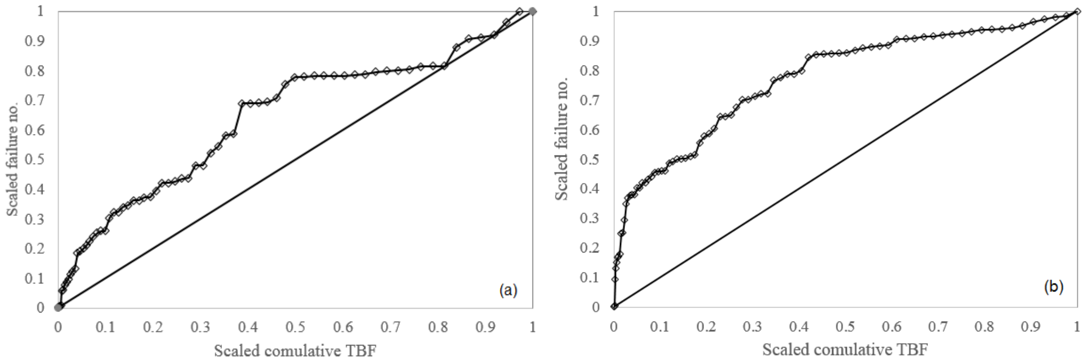

Fig. 3. The trend plots for TBF of (a) truck T2 and (b) truck T3

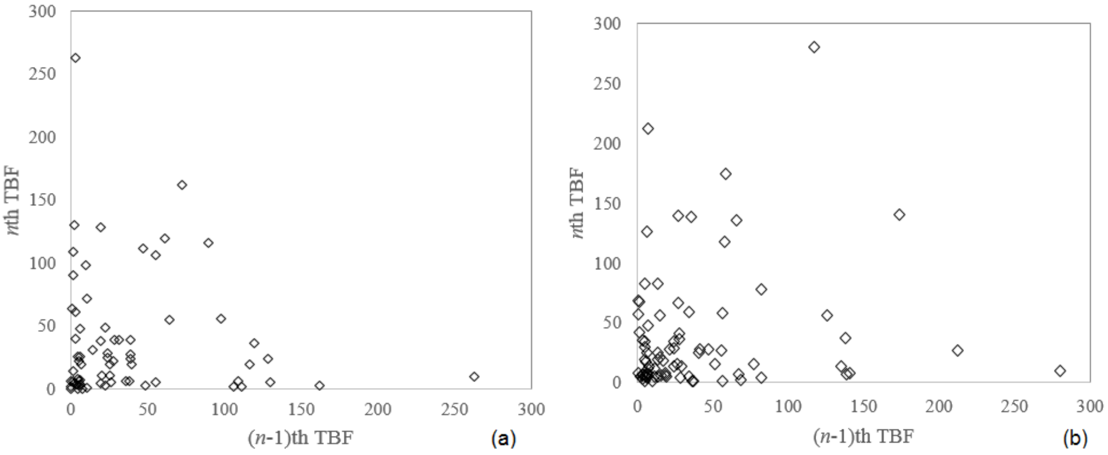

Fig. 4. The serial correlation plots for TBF of (a) truck T2 and (b) truck T3

Table 2. The results of data analysis and best-fit distributions

Truck	Best-fit distribution	Estimated parameter
T1	Gamma	$\alpha = 0.65$, $\beta =38.97$
T2	PLP	$\alpha = 0.76$, $\beta = 28.25$
T3	PLP	$\alpha = 0.85$, $\beta = 31.80$
T4	PLP	$\alpha = 0.90$, $\beta = 22.92$
T5	Weibull	$\alpha = 0.86$, $\beta = 21.58$
T6	Weibull	$\alpha = 0.76$, $\beta = 27.21$
T7	Weibull	$\alpha = 0.80$, $\beta = 34.33$

Regarding the best-fit distributions, the reliability and hazard rate for all trucks were plotted and shown in Fig.s 5 and 6, respectively. Reliability of trucks T3 and T7 reached about 51% in time 20 h. However, after 20 h operation, the reliability of trucks T6 and T2 decreased to approximately 46%, and the reliability of trucks T1, T4, and T5 reached 40%.

The failure rate of all trucks increased rapidly at the start of their life. After 12 h operation, the failure rate of trucks T1, T2, T3, T4, T5, T6, and T7 increased to 0.04, 0.03, 0.032, 0.043, 0.044, 0.036, and 0.030, respectively. From this time forward, the failure rate of all trucks decreased at a constant rate.

As mentioned earlier, the failure of each truck results in the reduction of the mineral transportation capacity. However, at least one truck must operate generally for the successful operation of the mineral transportation system. Therefore, the parallel network was assumed for the reliability estimation of the fleet of mining trucks. In this approach, the reliability of the fleet of mining trucks (Rf) can be calculated as follows (Dhillon, 2008):

$$R_f = 1 - \prod_{i=1}^{7} (1 - R_i) \qquad (3)$$

Where, R_i is the reliability of the *i*th truck.

The reliability of the fleet of mining trucks was calculated and given in Table 3. Regarding Table 3, the reliability of the fleet of trucks decreased to 50% in 78 h. This means that, after 78 hours of continuous operation of a fleet of trucks, the failure probability increased to 22%. The reliability of the mineral transportation reaches zero in about 345 h. These results indicate that to keep the reliability of the fleet of mining trucks at a level of 80%, the maintenance tasks must be carried out before 48 hours.

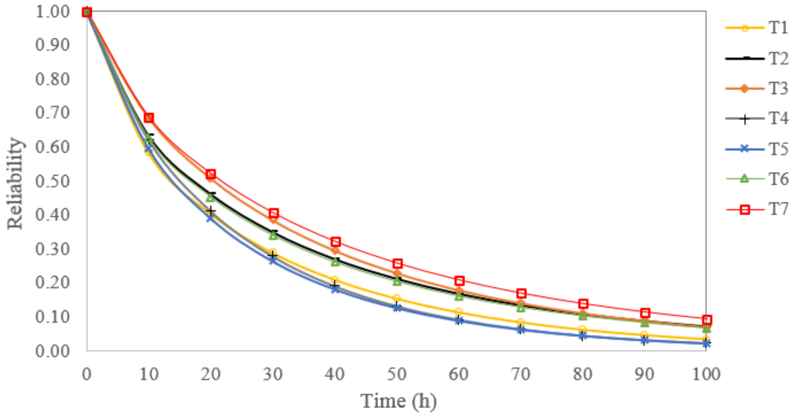

Fig. 5. Reliability plot for the studied trucks

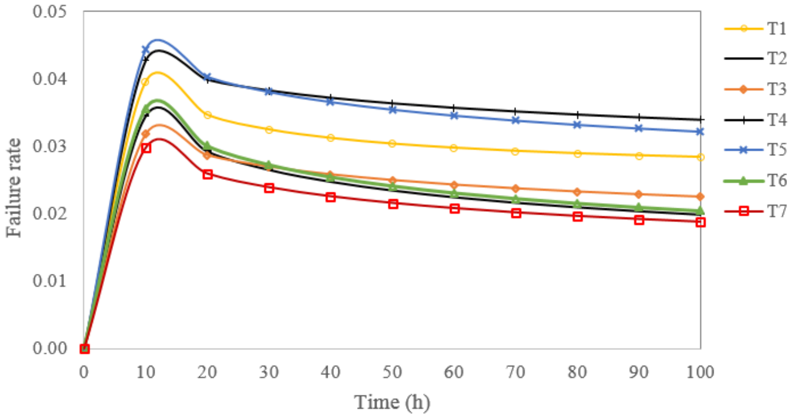

Fig. 6. Hazard rate plot for the studied trucks

Table 3. Reliability of the fleet of mining trucks at different times

Time (h)	Failure probability	Reliability	Time (h)	Failure probability	Reliability	Time (h)	Failure probability	Reliability
10	0.0008	0.9992	60	0.3299	0.6701	110	0.7251	0.2749
20	0.0146	0.9854	70	0.4289	0.5711	120	0.773	0.2270
30	0.0585	0.9415	80	0.5195	0.4805	130	0.8127	0.1873
40	0.1334	0.8666	90	0.5993	0.4007	140	0.8453	0.1547
50	0.2281	0.7719	100	0.6676	0.3324	150	0.8721	0.1279

IV. DISCUSSION

In the previous section, the reliability and failure rate of a fleet of mining trucks were analyzed. Regarding the results, reliability of trucks T7 and T3 is at a higher level of all time in comparison to other trucks. It takes approximately 150 h for the reliability of all trucks to reduce to zero. Failure rate analysis shows that all trucks have the same failure behavior. By comparing the failure rate curves with the bathtub hazard rate curve, it can be seen that the trucks have passed their burn-in period and entered their useful life period.

As the trucks are critical for mining companies, an appropriate maintenance policy is necessary to ensure excellent haulage operation. Maintenance has a direct impact on the equipment availability and reliability and, accordingly the economical aspect of a mining operation. The reliability approach is one of the well-known ways to schedule maintenance operations. Regarding this approach, the preventive maintenance (PM) intervals can be estimated. In this paper, the reliability-based PM time intervals for each truck were calculated and shown in Fig. 8. In many cases, the reliability level of 80% is proposed as the best practical value for efficiency and performance evaluation. Therefore, in this paper, 80% is selected as the desired reliability level for scheduling the PM intervals. Fig. 7 shows that all trucks should be inspected and serviced in 4 hours or the middle of each working cycle to have a reliable mineral transportation operation.

These results are helpful for the mine contractors to schedule an optimal maintenance program. It is a guideline for managers to provide adequate production scheduling.

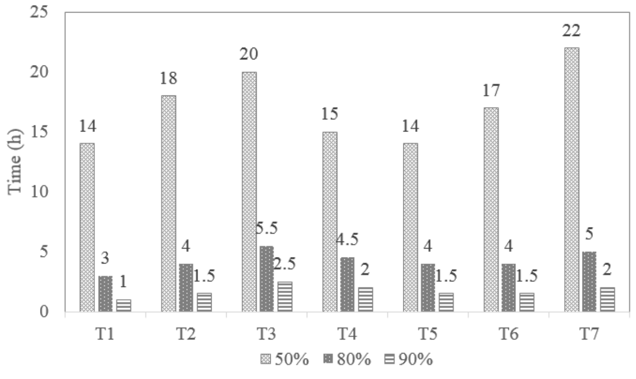

Fig. 7. Reliability-based maintenance intervals for different reliability levels

V. CONCLUSIONS

Mining equipment is vital in increasing the production rate and safety of mining operations. Dump trucks are the well-known and most conventional haulage system in mines, and any failure of this system, results in the production stoppage. In this paper, the reliability of a fleet of mining trucks is modeled and discussed. To this end, failures of seven dump trucks in Songun Copper Mine of Iran were collected for reliability analysis using the statistical reliability modeling approach. Regarding the results of this study, the reliability of trucks reaches zero in 150 h operation. The failure rate of trucks showed that they passed their burn-in period and entered their useful life period. The failure probability of the fleet of trucks increased to 20% in 48 hours. Moreover, to have excellent and reliable mineral transportation, it is suggested that the trucks should be checked and serviced every 4 hours.

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