Mathematical models of truck failures in the North

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Abstract. The article studies the failures of 50 KAMAZ trucks operated in the Republic of Sakha (Yakutia). The statistical analysis results of failures of KAMAZ truck parts and assembly units groups which limit its reliability in adverse climatic and road conditions of the North are given. Autocorrelation of the failure time series of the observed groups revealed the presence of a linear trend for every series, and the statistical significance of the linear regression equation parameters was confirmed for all groups, except for the steering. The wear rate in harsh natural and climatic conditions can be estimated in terms of the value of the regression slope. The groups of parts and assembly units were ranked by the values of the regression slope. After the failure time series have been centred, the harmonic analysis was carried out. The significant harmonic components were allocated from the Fourier series to describe the regular change in the failure series. Mathematical models, consisting of equations of linear trend and significant harmonics, approximate the failure time series with an acceptable confidence level, which makes it possible to determine the rhythmological features of vehicle operability changes in extreme conditions of permafrost zone.

1 Introduction

The operability of machinery, especially in the North, is a complex problem, since technical objects are complex systems consisting of a large number of parts and assembly units made of different materials. The properties of structural and operational materials significantly depend on the operating conditions, which in the North are characterized by a variety of variable factors and their combinations [1]. The climate of Yakutia is one of the harshest on our planet: its distinctive feature is extremely low air temperatures in winter (below – 60 °C), rather high temperatures in summer (above 30 °C), sharp diurnal temperature variations (25-30 °). The duration of winter is from 7 to 9 months. The adverse road conditions in Yakutia are due to the fact that most of its territory belongs to the areas of continuous permafrost. In such conditions, the machinery operability is reduced [2].

The study of the influence of natural and climatic factors of the cryolithozone on the operability and safety of vehicle elements was carried out on the basis of statistical data of truck failures, since this type of vehicle is operated in Yakutia almost year round. The
KAMAZ trucks produced in Russia are the most popular trucks in the country with a weight carrying capacity from 10 to 40 tons. They have been in operation in the Arctic and northern regions for more than 40 years. During this time, they have shown their reliability at low climatic temperatures and in difficult road conditions of the cryolithozone. Information on the operability of 250 trucks of this brand in Yakutia has been collected and structured in the KAMAZ database. A total of 50 vehicles were selected for analysis, for which there are failure records for four full years from the start of their operation after delivery from the factory. During this period, 13913 failures of the selected vehicles were recorded. Seven out of 34 groups of parts and assembly units according to the catalog of the KAMAZ truck have the highest number of failures: brake system (2146 failures), electrical equipment (1874), engine (1344), suspension (1327), engine cooling system (1023), fuel-feed system (891), steering (836). These seven groups account for 67.9% of all failures, which suggests that they limit the operability of KAMAZ vehicles in cryolithozone conditions.

Since the service life of a new KAMAZ truck exceeds four years, the sample of its failures during this time can be considered as a response to the action of some factors. Therefore, the analysis of the time series of failures with the determination of their structure can be useful to identify the causes of these failures. Calculations were carried out in PTC MathCad, which provides great opportunities for mathematical analysis.

2 Materials and Methods

Using information from the KAMAZ database, time series of monthly numbers of failures for 48 months of the observation period were constructed for the reliability-critical groups of parts and assembly units of the vehicles. In the software package STATISTICA 10, the distributions of these time series were fitted with the check of the correspondence between observed and expected data using chi-square ($\chi^2$) goodness of fit test [3]. The normal distribution of the failure numbers was confirmed for the brake system, electrical equipment, suspension, engine cooling system and fuel-feed system. The normal distribution is typical for gradual failures (deterioration due to wear, fatigue, corrosion, etc.) and indicates the influence of many factors, as well as the possibility of sudden failures at any time. The steering and engine failures have the lognormal distribution. In reliability engineering, the lognormal distribution is used to describe recovery processes and wear-out failures (wear, fatigue, corrosion). The accuracy of trend estimation largely depends on how accurately the original time series is close to the normal distribution and on its length.

To determine the structure of the time series, autocorrelation analysis was carried out. For all the groups, except for the steering, the maximum values of the autocorrelation function were noted at the time lag equal to 1. The coefficient of first-order autocorrelation characterizes the tightness of the linear relationship between the current and previous levels of the series. Thus, the failure time series of reliability-critical groups, except for the steering, have linear trends. The highest values of the first-order autocorrelation coefficient were determined for the suspension (0.704) and electrical equipment (0.644). Figure 1 shows the time series of suspension failures ($a$) and its autocorrelation function ($b$).
For the studied series of failures, with the exception of the steering, trend analysis was performed. The adequacy of the obtained trend models was assessed based on the Fisher criterion. The regression coefficient $p$, which characterizes the slope of the trend line, can serve as a measure of the influence of the time variable $t$ on the variable of the monthly numbers of failures. Therefore, the regression slope $p$ of the trend equation can be interpreted as a parameter of the degree of the influence of car element wear in the specific operating conditions on the increase in the failure numbers over time. All the obtained trend equations have positive regression coefficients; their statistical significance was verified using the Student's criterion with a confidence level of 0.95.

Determination coefficients were calculated for the trend models. The determination coefficient of the data series characterizes the proportion of variance of the dependent variable explained by regression. The parameters of the linear trend equations of the data series under consideration and the coefficients of determination of trend models are given in Table 1. The reliability-critical groups of parts and assembly units of the KAMAZ truck in the table were arranged in descending order of the failure numbers.

Table 1. Parameters of linear trend of failure time series of KAMAZ trucks.

<table>
<thead>
<tr>
<th>Group of parts and assembly units</th>
<th>Average number of failures per month</th>
<th>Constant term $m$</th>
<th>Regression slope $p$</th>
<th>Coefficient of determination of trend model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brake system</td>
<td>44.7</td>
<td>33.44</td>
<td>0.46</td>
<td>0.146</td>
</tr>
<tr>
<td>Electric equipment</td>
<td>39</td>
<td>17.829</td>
<td>0.866</td>
<td>0.404</td>
</tr>
<tr>
<td>Engine</td>
<td>28</td>
<td>17.606</td>
<td>0.424</td>
<td>0.198</td>
</tr>
<tr>
<td>Suspension</td>
<td>27.6</td>
<td>13.312</td>
<td>0.585</td>
<td>0.402</td>
</tr>
<tr>
<td>Engine cooling system</td>
<td>21.3</td>
<td>11.399</td>
<td>0.405</td>
<td>0.294</td>
</tr>
<tr>
<td>Fuel-feed system</td>
<td>18.6</td>
<td>9.489</td>
<td>0.37</td>
<td>0.29</td>
</tr>
<tr>
<td>Steering</td>
<td>17.4</td>
<td>17.597</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
According to the values of the regression slope, it can be concluded that the wear in the harsh natural and climatic conditions of the North occurs more intensively for the elements of the electrical equipment and suspension \((p = 0.866\) and \(p = 0.585\), respectively). At the same time, the coefficients of determination of their trend models also have the highest values \((0.404\) and \(0.402\), respectively). The next descending regression slope \((p = 0.46)\) is for the brake system, but it has the lowest determination coefficient of \(0.146\).

Thus, the regression slope \(p\) can be considered as an indicator of sensitivity to the duration of operation in specific operating conditions and the groups of parts and assembly units can be ranked according to its value: electrical equipment (0.866), suspension (0.585), brake system (0.46), engine (0.424), cooling engine system (0.405), fuel-feed system (0.37).

It should be noted that the resulting ranking order is slightly different from the ranking by the failure number, which is traced in Table 1. The time series of the steering failures does not have the linear trend; this indicates a greater influence of the periodic factors compared to the wear during the four years of observation.

In connection with the above, in order to identify the hidden periodicities, the centering of the time series of the steering failures was performed relative to the average value of the failure numbers, and the time series of other groups – relative to their linear trends. After centering the time series, their decomposition into a Fourier series was performed according to the formula [4]:

\[
 f(t) = \sum_{i=1}^{N/2-1} \left( a_i \cos \frac{2\pi}{N} it + b_i \sin \frac{2\pi}{N} it \right) + a_{N/2} \cos \pi t, \tag{1}
\]

where \(t\) is the ordinal number of the observation month; \(i\) is the harmonic number; \(a_i, b_i\) are the Fourier coefficients; \(N\) is the length of the time series.

Since the data series are equidistant, the Fourier coefficients are calculated using the formulas:

\[
a_i = \frac{2}{N} \sum_{t=1}^{N} Y_t \cos \frac{2\pi}{N} it, \quad a_{N/2} = \frac{1}{N} \sum_{t=1}^{N} (Y_t \cos \pi t), \quad b_i = \frac{2}{N} \sum_{t=1}^{N} Y_t \sin \frac{2\pi}{N} it, \tag{2}
\]

where \(Y_t\) is the quantity of failures in the month with number \(t\).

For all the studied groups of parts and assembly units of the KAMAZ truck, additive functions containing 24 harmonics and the linear trend were defined. They accurately approximate the time series of failures. But the purpose of the analysis was to identify and then evaluate the regular change in the studied time series, so it was necessary to find significant harmonics. To highlight significant harmonics, it is convenient to use the representations of the Fourier series in amplitude-phase form:

\[
 f(t) = \sum_{i=1}^{N/2} A_i \cos \left( \frac{2\pi}{N} it - \varphi_i \right), \tag{3}
\]

where \(A_i\) is the amplitude of the \(i\)-th harmonic and \(\varphi_i\) is its initial phase. They are calculated using Fourier coefficients according to the formulas:
\[ A_i = \sqrt{a_i^2 + b_i^2}, \phi_i = \begin{cases} \arctg \frac{b_i}{a_i}, & \text{if } a_i \geq 0 \\ \pi + \arctg \frac{b_i}{a_i}, & \text{if } a_i < 0 \end{cases} \] (4)

3 Results and discussions

The representation of the Fourier series in the form (3) makes it possible to construct amplitude spectra, from which the significant harmonics can be determined. The significant harmonics were identified by spectra for all the studied series of failures. On the amplitude spectrum of the Fourier series of the engine cooling system failures, one amplitude is noticeable, corresponding to the harmonic with the period of 12 months (Fig. 1, a). For the electrical equipment failures, four harmonics are significant (Fig. 1, b).

![Fig. 2. Autocorrelation functions of time series of suspension (a) and electrical equipment (b) failures.](image)

Chronogram is a time domain graph that shows how the failure quantity fluctuates over time. The additive function approximating the chronogram consists of the linear trend and significant harmonics. The additive functions of all the data series have the coefficient of determination greater than 0.5, indicating that the models are acceptable. The additive function for the engine cooling system contains the linear trend and annual harmonic, and its coefficient of determination is 0.577. The coefficient of determination of the additive function for the electrical equipment is 0.76. Fig. 3 shows the chronograms and graphs of the additive functions of the failure time series for the engine cooling system (a) and electrical equipment (b).

![Fig. 3. Chronograms and graphs of additive functions of failure time series for engine cooling system (a) and electrical equipment (b).](image)
The number of significant harmonics of the failure time series of the KAMAZ truck does not exceed four: only one harmonic is significant for the engine cooling system, two for the engine and steering, three for the brake system, electrical equipment and fuel-feed system, four for the suspension. Only for the failure time series of the brake system, the first significant harmonic has the period equal to the length of the series of 48 months. Such a long-period harmonic, together with the trend, can be taken as the main tendency in the data.

Three groups (brake system, electrical equipment, suspension) have the harmonics with the period of 16 months. According to this harmonic, the maximum failures of the brake system are observed in February, May and September. For the electrical equipment and suspension, the maxima of this harmonic coincide and occur in March, July and November. In the town of Mirny (Yakutia), near which the KAMAZ trucks were operated, the slipperiness of snowy roads increases in February and November, and seasonal deterioration of the dirt road quality is observed in April-May and August-September. Frequent heavy braking under such conditions causes the increase in failures.

For all the groups of parts and assembly units of the KAMAZ truck, except for the brake system, the harmonic with the period of 12 months is significant. This annual harmonic has the largest amplitude among the other significant harmonics. Thus, the seasonal harmonics characterizing the effect of climatic temperatures are more significant.

The harmonics with the period of 9.6 months are significant for the electrical equipment, engine, engine cooling system and steering system. Probably, this periodicity is affected by the resources of the elements of the specified groups of parts and assembly units, such as friction units. Probably, this periodicity is affected by the resources of the elements of the specified groups of parts and assembly units, such as the friction units. Shorter periods of the significant harmonics (8 months or less) are defined for the suspension, brake system, engine and fuel-feed system. It can be assumed that they are related to the road operating conditions and vehicle maintenance frequency.

4 Conclusion

Based on the analysis of the failure time series of the critical reliability groups of parts and assembly units of the KAMAZ truck, we can conclude the following. The autocorrelation functions of these series have a maximum at lag 1, which indicates the presence of the linear trend. After performing the regression, the statistical significance of the parameters of the linear trend equations was confirmed for all the groups, except for the steering. The linear trend models the increase in the failures over time, which allows us to consider the regression slope as the indicator reflecting the effect of the vehicle element wear on the increase in the failure number in the specific operating conditions. Based on the value of this coefficient, the groups of parts and assembly units of the KAMAZ truck were ranked according to the wear rate: electrical equipment, suspension, brake system, engine, engine cooling system, fuel-feed system.

After Fourier analysis of the centered data series, the significant harmonic components were determined from their amplitude spectra. The obtained additive functions from the equations of the linear trend and significant harmonics are mathematical models that describe the regular change in the operability indicators of the KAMAZ truck in harsh natural and climatic conditions in the North. They make it possible to evaluate the rhythmological features of the failure time series associated with the natural-climatic and operational factors.
References


