Rationale and frequency of the diagnosis of component parts of tractors Belarus in the development of technology maintenance

V I Karagodin and R A Khapugin
Moscow automobile and road state technical University (MADI), 64, Leningradsky Ave., Moscow, 125319, Russia
E-mail: bik250248@yandex.ru

Abstract. The article presents the solution of a new scientific and technical problem of substantiating the frequency of diagnosis and the composition of control and diagnostic operations performed during maintenance of machines based on Belarus-82.1. The methodology of justification of the specified parameters of technological processes of maintenance service takes into account the probability of failures in control periods and provides for increased reliability of cars. It is proved that manufacturers in some cases unreasonably increase the frequency of maintenance for advertising purposes. Experimentally determined parameters of the distribution laws of time between failures of component parts of machinery on the basis of the Belarus-82.1. The new dependence of the probability of the failure of the operating time of machines on existing and recommended strategies ensures their efficiency at all the intervals of achievements. The composition of control and maintenance operations for different types of maintenance is justified not only for warranty period and for the entire service life of the machine. The practical use of the research results presented in the article can significantly improve the reliability of equipment with a slight increase in the cost of maintenance.

1. Introduction
The system of preventive maintenance of machines, originally created as a system of standards that strictly determine the frequency and scope of work in maintenance and repair, with the development of technical diagnosis, has become more flexible and provides for a given frequency of control and diagnostic works and subsequent performance of technical effects on the needs identified as a result of diagnosis.

Issues concerning maintenance intervals are quite deeply explored, but issues concerning frequency and composition of the control and diagnostic operations for maintenance need such a deep study. The reliability of components and machines as a whole depends on the results of solving this problem, which determines the relevance of the tasks, the solution of which is reflected in this article.

2. Collection of information on the reliability of components of machines based on tractors Belarus-82.1
Collection of information on reliability of components of Belarus-82.1 tractors and machines on their basis was carried out at the operational enterprise "Resurs Trans". The information is given in the form of table 1.
Table 1. Source data (fragment)

| Names of components | Time between failures, machine-hour for vehicles with number |
|---------------------|------------------------------------------------------------|
|                     | 1               | 2               | 3               | 4               | 5               | 6               |
| Clutch              | 2869            | 4369            | 4387            | 3867            | 6925            | 8952            |
| Front tyre          | 6219            | 5160            | 5961            | 7856            |                 |                 |
| Rear tyre           | 3566            | 6219            | 5129            | 5160            | 5961            | 7856            |

Based on actual production capabilities, a test plan \([N, M, T]\) was selected. The first letter in the designation of the plan (N) indicates that the test delivered N products, the second (M) that failed during the test machine was restored. The tests shall be terminated at the end of the test time T.

Termination of data collection at the end of the test time T causes a difference in the periods of observations of the reliability of the controlled products [1]. In this case, the resulting samples are considered as censored or repeatedly censored. Censorship is an event that leads to the termination of tests or operational observations of the object before the failure (limit state) of the studied nature. The reasons for censoring are the different times of the beginning and (or) the end of the tests, as well as the need to assess the reliability before the failure of all tested products. In a repeatedly censored sample, the values of developments before censoring are not equal.

Table 1 shows that the front tyres of vehicles 1 and 3 were not replaced during the observation period. They have been modified not to failure and to censorship. Time to the reduction of the first machine is 3566 machine-hours, and the 3rd machine – 5129 machine-hours as it is known that during these developments on the machines rear tires were replaced.

It was hypothesized that the distribution of time to failure of the components of tractors is subject to the distribution of Weibull. This distribution describes the time to failure and failure of non-recoverable and recoverable products, which failure occurs due to fatigue failure. This law is often used in reliability theory to describe uptime and manifests itself in the so-called "weak link" model.

The most important issue in assessing reliability is to determine the volume of tests, which depends on the law of distribution of time to failure. The minimum allowable number of recorded failures in the Weibull distribution for the evaluation of developments for failure with a given limit relative error and confidence probability are presented in [25]. With minimum requirements for accuracy and reliability of the results, the number of recorded failures in the sample should be at least five.

A specially developed program was used to calculate the required parameters. For clutches where the number of failures was 9, the obtained values of the parameters of Weibull distribution \(a = 7828\), \(b = 2.2\), and mean time to failure \(t_{avg} = 6933\), standard deviation MTBF \(\sigma = 3336\), coefficient of variation \(v = 0.48\) and \(\gamma\)-percent time to failure (at \(\gamma = 90\%\) \(t_{90} = 2806\).

The relatively small number of reported failures affected the accuracy and reliability of the estimates. With a confidence probability of 0.8, the relative error of the obtained parameters is 0.2. For most of the components of tractors, where the number of failures is even smaller, satisfactory accuracy and reliability estimates of reliability could not be obtained.

This led to the need to collect additional information about the reliability that was produced at another enterprise. As a result, other samples of the studied parameters were obtained. To combine them with previously obtained samples, it was necessary to make sure that these samples belong to the same population.

To test the hypothesis that two samples belong to the same population, it is necessary to assess the randomness of the discrepancy between the two sample means and the two sample variances. In the case when the initial data is not enough to construct the distribution law of the studied quantity, the series criterion can be used to verify the belonging of two samples to one General population. Let there be two samples of volumes \(N_1\) and \(N_2\):

\[
X_1, X_2, ..., X_{N1};
Y_1, Y_2, ..., Y_{N2}.
\]
Placing all the values of both samples in ascending order, marking the elements from the first sample with a “+” sign and the elements from the second sample with a “−” sign, we get the sequence:

\[ X_1 \leq X_2 \leq Y_1 \leq Y_2 \leq X_3 \leq X_4 \leq Y_4 \leq Y_5 \leq \ldots \]  

(1)

Let’s call the sequences “+” and “−” series. The number of series is two when the samples are very different from each other. With a slight difference in their number of series will be large. It is known [6] that if both samples X and Y belong to the same population, the probability of obtaining m series in sequence (1) is expressed as a function \( h(m) \):

\[ \sum_{m=2}^{d} h(m) \leq \beta, \]  

(2)

where \( \beta \) is the significance level, the difference between samples is considered significant. Otherwise, the difference between the samples is insignificant, and they can be considered as belonging to the same population. Usually we take the level of significance \( \beta = 0.05 \).

We tested a hypothesis about belonging of one general set of time between failures of clutches, tractor Belarus-82.1. Variational series of clutch operating time of the first sample:

\[ N_1 = 1438; 2869; 3867; 4369; 4387; 6925; 7029; 7561; 8952. \]

The statistics of the time between failures of couplings of the second sample:

\[ N_2 = 3025; 3639; 4356; 4573; 4963; 5783; 5835; 5843; 5896; 6254; 6632; 6973; 7253; 7533; 7583; 7647; 7987; 8034; 8422; 8753; 8785; 9457. \]

Placing all the values of both samples in ascending order, marking the elements from the first sample with a “+” sign and the elements from the second sample with a “−” sign, we get the sequence:

\[ 1438; 2869; 3025; 3639; 3867; 4356; 4369; 4387; 4573; 4963; 5783; 5835; 5843; 5896; 6254; 6632; 6973; 7253; 7533; 7583; 7647; 7987; 8034; 8422; 8753; 8785; 8952; 9457 \]

The number of received series \( m = 14 \). With this number of series, the left part of the condition (2) is 0.298. Since 0.298 \( \geq \beta = 0.05 \), the differences between the two samples are insignificant, and they can be considered as samples from the same universe. Therefore, the samples can be combined.

In the combined sample for couplings where the number of failures was 31, and the resulting values of the parameters of Weibull distribution \( a = 7939, b = 3.6 \), mean time between failure \( t_{\text{avg}} = 7157 \), the standard deviation of the MTBF \( \sigma = 2195 \), the coefficient of variation \( v = 0.31 \), \( \gamma \)-percent time to failure (at \( \gamma = 90 \% \)) \( t_{\gamma 90} = 4267 \).

The increase in the number of observations has significantly improved the accuracy and reliability of the estimates. With a confidence probability of 0.9, the relative error of the obtained indicators will not exceed 0.1. For most of the components of tractors, for which previously, due to the small number of failures, satisfactory accuracy and reliability estimates of reliability were not obtained at all, the union of samples allowed this to be done.
Failure times of tractor components in machine-hour are shown in table 2. Relative errors were determined at a confidence probability of 0.8 and 0.9 depending on the number of failures of the component under consideration and on the obtained coefficient of variation of its MTBF.

From the data table 2 it follows that for most of the components obtained acceptable accuracy and reliability of the results that can be practically used. The most accurate and reliable results were obtained for the clutch with the highest number of failures. The relative error in determining the parameters of the Weibull distribution of the clutch failure time is 0.1 at a confidence probability of 0.8 and 0.1 at a confidence probability of 0.9. Close to this accuracy of determining the parameters of the distribution of Weibull’s workings on failure is achieved only for the front and rear tires, which also recorded a large number of failures.

The limiting case, when the result still obtained can be considered satisfactory in accuracy, is observed for the generator and the front spar. With a confidence probability of 0.9, the relative error exceeds 0.20, and with a confidence probability of 0.8, it is within 0.20.

| Name of the failed component | Weibull distribution parameters | Statistical estimates of time-to-failure | Relative error at 90 % operating time | Confidence probability |
|------------------------------|---------------------------------|----------------------------------------|--------------------------------------|------------------------|
|                              | a, b                            | average MTBF                           | standard deviation                   | co-efficient of variation | 0.80 | 0.90 |
| Elements of governance mechanisms |                                 |                                        |                                      |                         |
| Tie rod end                  | 1074, 4.18                      | 9762                                   | 2633                                 | 0.27                    | 6269 | 0.15 | 0.2  |
| Steering column              | 14307, 3.09                     | 12792                                  | 4530                                 | 0.35                    | 6904 | 0.15 | 0.9  |
| Steering booster             | 14307, 3.09                     | 12792                                  | 4530                                 | 0.35                    | 6904 | 0.15 | 0.9  |
| Front spar                   | 14590, 3.17                     | 13062                                  | 4518                                 | 0.35                    | 7175 | 0.2   |
| Front tyre                   | 8579, 3.4                       | 7708                                   | 2499                                 | 0.32                    | 4432 | 0.1  | 0.15 |
| Rear tyre                    | 8598, 3.7                       | 7756                                   | 2350                                 | 0.3                     | 4660 | 0.1 | 0.15 |
| Clutch                       | 7939, 3.6                       | 7157                                   | 2195                                 | 0.31                    | 4267 | 0.1 | 0.1  |
| Transmission                 | 11679, 4.2                      | 10619                                  | 2839                                 | 0.27                    | 6851 | 0.15 | 0.2  |
| Transfer case                | 12278, 4.3                      | 11169                                  | 2960                                 | 0.27                    | 7239 | 0.15 | 0.2  |
| Outboard bearing             | 11553, 4.09                     | 10485                                  | 2881                                 | 0.27                    | 6666 | 0.15 | 0.2  |
| Elements of the transmission |                                 |                                        |                                      |                         |
| Starter                      | 12622, 2.8                      | 11233                                  | 4399                                 | 0.39                    | 5585 | 0.15 | 0.2  |
| Generator                    | 14966, 2.3                      | 13257                                  | 6146                                 | 0.46                    | 5592 | 0.2 | 0.2  |
| Accumulator                  | 13446, 3.1                      | 12031                                  | 4206                                 | 0.35                    | 6556 | 0.15 | 0.2  |
| Fuel injection pump          | 12651, 3.5                      | 11387                                  | 3581                                 | 0.31                    | 6681 | 0.15 | 0.2  |
| Radiator cooling system      | 12121, 4.2                      | 11017                                  | 2957                                 | 0.27                    | 7094 | 0.15 | 0.2  |
| Elements of hydraulic drive and attachments | | | | | | |
| Rubber products hydraulic systems | 10811, 3.5            | 9729                                   | 3069                                 | 0.32                    | 5697 | 0.15 | 0.2  |
| High pressure hoses          | 14458, 2.8                      | 12871                                  | 5003                                 | 0.39                    | 6441 | 0.15 | 0.2  |
| Support arms for attachments | 12123, 3.9                      | 10968                                  | 3169                                 | 0.29                    | 6779 | 0.15 | 0.2  |
| Rear suspension arms for attachments | 10684, 3.6            | 9628                                   | 2968                                 | 0.31                    | 5721 | 0.15 | 0.2  |
The values of the mean time between failures of the components of the machine vary from 7157 machine hours for the clutch to 13257 machine hours for the generator, i.e. almost twice. The minimum value of the coefficient of variation is 0.27 for the transmission, the maximum is 0.46 for the generator, i.e. the variation of the operating time for failure of the components differs almost twice. This shows that at close mean time between failures, different components can have a significantly different nature of the increase in the probability of failure with increasing time between failures.

This is illustrated by the 90 percent failure times of the various components. So, a starter with an average time to failure 11233 machine hours has a 90 percent operating only 5585 machine hours, while the radiator of the cooling system with an average time to failure 11017 machine hours (lower than the starter) has a 90 percent operating time 7094 machine hours (nearly one and a half times higher than the starter). Similar conclusions follow, for example, from the comparison of the developments of the generator and the front spar, the tip of the tie rod and the support arms of the attachments. This requires an analysis of the dynamics of failure probabilities of components with increasing operating time. To this end, the failure probabilities were calculated for operating time up to 10 thousand machine hours of individual elements and systems.

3. Study of the dynamics of failure probabilities of components and machines in general

The probability of failure of the system element was determined by the formula:

$$ F(t) = 1 - e^{-(t/a)^b}, $$

where $t$ is operating time, machine-hour;

$a$ and $b$ are the parameters of the Weibull distribution (table 2).

The probability of failure of the k-th system was determined based on the probability of failure of its elements by the formula [34]:

$$ P_k(t_i) = 1 - \prod_{j=1}^{J_k} [1 - P_{j}(t_i)] $$

where $P_{k}(t_i)$ – the probability of failure of the k-th system when $t_i$ is running;

$j$ – index of the component part;

$J_k$ – set of components included in the k-th system;

$P_{j}(t_i)$ – the probability of failure of the j-th component of the operating time $t_i$.

The probability of failure of the parts of the machine, the previous routine diagnosis in miscontrolling period is defined as the quotient of the number of failures by the total number of cars that passed the routine maintenance and diagnosis to the beginning of the reporting period miscontrolling and worked until the end of this period:

$$ P_j(l_i) = \frac{n(l_i)}{A(l_i)} $$

where $n(l_i)$ – the number of failures of the considered component parts of the machine in miscontrolling period $l_i$;

$A(l_i)$ – the total number of machines that underwent scheduled maintenance and diagnostics at the beginning of the miscontrolling period $l_i$ and operated until the end of this period.

The probability of failure of the machine as a whole is determined by the probabilities of failure of components that do not pass diagnosis, and the probabilities of failure of diagnosed components. The first probabilities on the i-th operating time interval $P_l(t_i)$ are determined by the formula (2). The probabilities of failure of the diagnosed components are determined by the formula (3), and the probability $P_{m}(t_i)$ failure of the machine as a whole-by the formula:

$$ P_m(t_i) = 1 - \prod_{j=H} [1 - P_{j}(t_i)] \prod_{j=D} [1 - P_{j}(l_i)] $$

where $j$ – the index of the component;

$H$ – a subset of undiagnosed constituents;

$D$ – a subset of the components to be diagnosed.
Schedule routine maintenance of tractors Belarus-82.1 recommended by the manufacturer, provides routine adjustments, a forced substitution of certain elements and fluids, as well as routine checks when servicing the various elements and systems of the tractor, which include the above elements, limiting the reliability and elements of the testing are necessary due to requirements of safety and performance. A fragment of the schedule of planned maintenance, reflecting the control and diagnostic operations to check the technical condition of the elements that limit the reliability of the tractor, is presented in table 3.

| Controlled systems and elements | Operating time, machine-hour |
|--------------------------------|-----------------------------|
|                                | 125 | 250 | 375 | 500 | 625 | 750 | 875 |
| Steering                       | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
| Carrier system                 |     |     |     |     |     |     |     |
| Clutch                         |     |     |     |     |     |     |     |
| Transmission                   | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
| Engine                         |     |     |     |     |     |     |     |
| Electrics                      |     |     |     |     |     |     |     |
| Hydraulic equipment            |     |     |     |     |     |     |     |

Preliminary analysis of the reliability of tractors showed that due to the large inter-control period of diagnosis of the transmission, electrical equipment and hydraulic drive, the probability of failure of equipment, although less than in the absence of diagnosis, is still very high. Therefore, an option was worked out, providing for a reduction in the frequency of monitoring of these systems to 250 machine-hours. A fragment of the recommended schedule of planned maintenance is presented in table 4.

| Controlled systems and elements | Operating time, machine-hour |
|--------------------------------|-----------------------------|
|                                | 125 | 250 | 375 | 500 | 625 | 750 | 875 |
| Steering                       | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
| Carrier system                 |     |     |     |     |     |     |     |
| Clutch                         | 1   | 1   | 1   | 1   | 1   | 1   | 1   |
| Transmission                   |     |     |     |     |     |     |     |
| Engine                         |     |     |     |     |     |     |     |
| Electrics                      |     |     |     |     |     |     |     |
| Hydraulic equipment            | 1   | 1   | 1   | 1   | 1   | 1   | 1   |

Figure 1 shows the probability of failure of equipment at intervals of operation for the three options under consideration: in the absence of diagnosis, with the frequency of diagnosis established by the manufacturer and with the recommended frequency of diagnosis. From the presented data it can be seen that the timely replacement of the diagnosis of elements with low reliability in the maintenance schedule, recommended by the manufacturer, leads to a significant increase in the reliability of equipment. However, this is not the best option. The transition to the recommended frequency of diagnosis can reduce the probability of failure of equipment by more than one and a half time.

Thus, the customer of technical service is offered a choice of two options: either to carry out diagnostics and maintenance according to the operational documentation of the manufacturer, or to follow our recommendations and, increasing their costs for maintenance by about 5 %, to achieve an increase in the reliability of machines 1.5 times.

4. Conclusion
1. The study experimentally determined parameters of the distribution laws of time between failures of component parts of machines on base tractor Belarus-82.1.
2. The result of simulation based on the new probability of the failure of the achievements of the machines recommended by the manufacturer and we offer the periodicity of the diagnosis and composition of the control and diagnostic operations on all intervals of the developments.

3. Reducing the frequency of diagnosis of some systems reduces the probability of failure of the machine in half, which can be recommended to customers of technical service and operating companies to reduce downtime.

Figure 1. Probability of failure at operating intervals: 1 – in the absence of diagnosis; 2 – at the frequency of diagnosis established by the manufacturer; 3 – at the recommended frequency of diagnosis

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