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To cite this article: A I Pavlov *et al* 2020 *J. Phys.: Conf. Ser.* **1515** 042065

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Method for determining the optimal operating time before replacement of high-pressure hoses of hydraulic drives of transport and technological machines

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Abstract. This article is devoted to the development of a method for determining the optimal operating time before replacing hydraulic drives of transport and technological machines using the obtained diagnostic data, which allows you to make a decision about the need to replace the elements of the hydraulic drive. The method is based on the use of the Markov chain theory, which allows us to determine the probability of transitions of hydraulic drive elements from a serviceable to a faulty state based on the results of previous inspections of machines. In this case, a simple homogeneous discrete Markov chain is used, described by a transition matrix, in which the transition probabilities allow us to identify the state in which the replacement of the hydraulic drive element is required, in particular – the high-pressure hose. With timely detection and prevention of defects associated with failures, it becomes obvious to reduce material losses, but premature replacement of expensive hydraulic drive elements will be accompanied by unreasonable costs due to underutilization of their resource. In this regard, the application of the developed method for determining the optimal operating time allows you to ensure maximum efficiency of the machine and minimum operating costs. The maximum total economic effect was used as a criterion for evaluating the efficiency of transport and technological machines.

1. Introduction

Currently, in Russia and abroad, forestry, road-building and other transport-technological machines that have hydraulic drives for technological equipment have found widespread use, with 78 % of the machines being operated in areas with a cold climate [1, 2].

As the experience of operation of hydraulic drives of machines working in areas with a cold climate shows, the resource and reliability of their elements are at a low level.

Technical diagnostics is a means of improving the reliability, quality and efficiency of the hydraulic drive. It increases the culture of technical operation, provides reliable forecasting of the residual resource [3].

However, the availability of diagnostic data can only characterize the possibility of determining the presence or origin of malfunctions leading to failures. In this regard, the next step to improving the efficiency of the functioning of machines is to develop a method for determining the optimal operating time of hydraulic drive elements before replacement, based on indicators of economic effect.



The relevance of the work in this direction is confirmed by the work in the field of justification of increasing the economic efficiency of transport and technological machines during the full life cycle [4-13].

2. Materials and methods

Purpose of research: improving the efficiency of transport and technological machines by reducing the cost of their operation.

Method of research: methods of mathematical modeling, basic provisions of hydrodynamics and theoretical hydromechanics, test methods of hydraulic drive elements according to GOST 25452-90.

Failures of hydraulic drive elements during operation lead to a significant decrease in the efficiency of transport and technological machines [1, 3].

In addition to the losses associated with machine downtime, significant material damage is caused by leaks of the working fluid when seals fail or high-pressure hoses break.

On the one hand, with the timely detection and prevention of defects, material losses can be significantly reduced. On the other hand, premature replacement of hydraulic drive elements will also be accompanied by unreasonable expenses due to underutilization of their resource. Thus, there is a contradiction and its resolution is possible through the development of a method for determining the optimal operating time of a high-pressure hose before replacement, which ensures maximum machine performance and minimum operating costs associated with failures of high-pressure hoses of hydraulic machines. Variants of the statement of such a problem are written as follows:

$$\text{a) } C \rightarrow \max C \text{ by } P \leq P_{\text{permissible}} ;$$

$$\text{b) } P \rightarrow \min P \text{ by } C \rightarrow C_{\text{permissible}} ,$$

where C , P - accordingly, the values of performance indicators (for example, productivity) and material costs; $C_{\text{permissible}}$, $P_{\text{permissible}}$ - permissible value.

The optimal strategy will be considered to provide $\min P$ (option b). The efficiency limitation in this case will appear implicitly according to the condition of equal time uptime of the compared options.

Let there be a hydraulic drive element (for example, a high-pressure hose), the state of which is controlled after a certain period of time Δt .

Let's assume that this element can fail only during this interval, that is at the interval Δt , two random events can occur with the pipeline:

A - the pipeline is out of order (probability P);

B - the pipeline remained intact (probability $1 - P$).

As a result of these events, the system either remains in good condition A_2 , either go into malfunctioning A_1 .

Since the conclusion about the degree of deterioration of the high pressure hose is made only at each inspection, it can be assumed that the probability A and B of events will depend only on the results of the previous inspection.

Thus, the sequence of tests consisting in the operation of a high-pressure hose during time intervals Δt forms a discrete Markov chain [14, 15]. It has been accepted that the probabilities of transitions depend only on the results of each previous inspection, so the chain is simple. If we assume further that the laws of distribution of uptime for all pipelines are the same, then this Markov chain has the property of homogeneity.

Therefore, in this case there is a simple homogeneous Markov chain described by a transition matrix of the form [16]:

$$P_2 = \begin{pmatrix} 1 & 0 \\ P & 1 - P \end{pmatrix}. \tag{1}$$

Transition probability $P(A_1 / A_1) = P_{11} = 1$, $P_{12} = 0$, that is the state A_1 it is absorbing, since it requires replacement of the pipeline if it gets into it.

The average number of times you get into this state can be determined by the formula:

$$N = (I - Q)^{-1}, \tag{2}$$

where I - identity matrix.

Of greater interest is the determination of the optimal strategy for preventive measures using the received diagnostic data solutions.

In this case, under K – strategy, it is understood that the decision to replace the high-pressure hoses or leave it in the hydraulic drive for a further period of operation Δt . Obviously, each decision will be associated either with certain revenues (due to the normal operation of the machine), or with costs (downtime, loss of fluid, the cost of the pipeline, etc.). Since in case of unsatisfactory condition of the pipeline (according to the diagnostic parameter), the only decision is made to replace it, then the initial state A_2 (serviceable) is taken in the future. Let's make a table of possible states, strategies and income (table 1).

Table 1. Possible pipeline conditions and the economic effect of the optimal replacement.

Condition i	Strategy K	Transition probability		Economical effect	
		P_{i1}^k	P_{i2}^k	u_{i1}^k	u_{i2}^k
A_2	Pipeline Replacement	$P_{21}^{(1)}$	$P_{22}^{(1)}$	$u_{21}^{(1)}$	$u_{22}^{(1)}$
	Do not change the pipeline	$P_{21}^{(2)}$	$P_{22}^{(2)}$	$u_{21}^{(2)}$	$u_{22}^{(2)}$

The average value of income for the time t (operating time of the machine) can be represented as a sum:

$$u_i(n) = q_i + \bar{u}_i(n-1), \tag{3}$$

where $q_i = \sum_{j=1}^n P_{ij} \cdot u_j$ – immediate expected economic effect (revenue at one step Δt);

$\bar{u}_i(n-1) = \sum P_{ij} \cdot u_j(n-1)$ – total average income during $n-1$ process step.

Dependence (1) takes into account the probability of occurrence of any of the considered events at each step (stage) of the process and the associated income or expenses.

Obviously, the optimal operating time of the high-pressure hose corresponds to - $\max u_i(n)$.

This case can occur if the result is taken into account not only the expected income directly, but also all subsequent decisions, that is, if the Bellman optimality principle is applied [16, 17], according to which optimal management in a multi-step process must be optimal for the whole process at each step. Since we consider a random process, this problem belongs to the class of stochastic dynamic programming problems. Specific input data is needed to solve this problem.

In the future, as an example, we will consider the high-pressure sleeves of the felling-packing machine of the LP-19V type and its operating time before the next maintenance (250 hours).

Transition probability (P_{ij}^k) pipeline out of working order A_2 in faulty A_1 it was determined for the summer and winter periods of operation (figure 1).

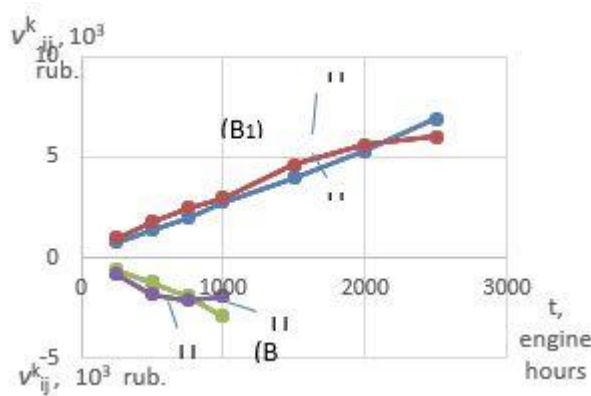


Figure 1. Total amount of income operating high pressure hoses in winter (B_2) and summer (B_1).

Economic effect u_{ij}^k accepted as follows:

$$u_{21}^{(1)} = u - (u_{downt.} + u_{f.r.} + u_{c.p.r.}), \tag{4}$$

where u - income due to the smooth operation of the machine during $\Delta t = 250$ hours; $u_{downt.}$ - the cost of machine downtime in the presence of a fault; $u_{f.r.}$ - flow rate due to loss of working fluid in case of pipeline breakage; $u_{c.p.r.}$ - the cost of the pipeline including its replacement.

$$u_{c.p.r.} = K_{l.c.} \cdot T_{h.r.} \cdot K_{r.c.}, \tag{5}$$

where $K_{l.c.}$ - labor costs for elimination of failure; $T_{h.r.}$ - hourly rate of repair workers; $K_{r.c.}$ - regional coefficient.

$$u_{c.p.r.} = C_{hose.cost} + t \cdot T_{h.r.} \cdot K_{l.c.}, \tag{6}$$

where $C_{hose.cost}$ - high pressure hose cost; t - time of elimination of failure.

$$u = P_{r.p.} \cdot \Delta t \cdot C_{h.wood}, \tag{7}$$

where $P_{r.p.}$ - replaceable performance forest harvester machine; $C_{h.wood}$ - cost 1 m³ harvested wood.

$$u_{22}^1 = u - (u_{c.p.r.} + u_{red.out.}), \tag{8}$$

where $u_{red.out.}$ - losses when reducing the output of the machine due to downtime.

$$u_{21}^2 = u - (u_{f.r.} + u_{downt.}); \quad u_{22}^2 = u \tag{9}$$

Thus, the following matrix of economic effects was obtained

$$R = \begin{vmatrix} u_{21}^1 & u_{22}^1 \\ u_{21}^2 & u_{22}^2 \end{vmatrix} \tag{10}$$

Knowing the probability of transitions for the summer $P_{ij}^k = P(A/B_1)$ and winter $P_{ij}^k = P(A/B_2)$ periods of operation, you can determine the expected revenue:

$$P_{ij}^k = \begin{vmatrix} 1 & 0 \\ 0,02 & 0,98 \end{vmatrix} \tag{11}$$

$$q_1^1 = P_{21}^1 \cdot u_{21}^1 + P_{22}^1 \cdot u_{22}^1; \quad q_2^2 = P_{21}^2 \cdot u_{21}^2 + P_{22}^2 \cdot u_{22}^2. \tag{12}$$

Calculate the average expected income during $n - 1$ the steps process start with the last stage. It is obvious that in the last stage of the process

$$\bar{u}_i(0) = u_2(0) = 0$$

So one step before the end of the process the value of the total expected economic effect will be equal to the directly expected income:

$$\bar{v}_1(1) = q_1^1; \quad \bar{v}_2(1) = q_2^2.$$

Two steps before the end of the process $\bar{v}_1(2) = P_{21}^1 \cdot \bar{v}_1(1) + P_{22}^1 \cdot \bar{v}_2(1),$

$$\bar{v}_2(2) = P_{21}^2 \cdot \bar{v}_1(1) + P_{22}^2 \cdot \bar{v}_2(1). \tag{13}$$

Then the full total economic effect for two steps before changing the model will be equal to:

$$v_1(1) = q_1^1 + \bar{v}_1(2), \quad v_2(2) = q_2^2 + \bar{v}_2(2). \tag{14}$$

3. Results and discussion

In table 2 as an example, the calculation of the total amount economic effect in the operation of the high-pressure hose installed on the feller buncher machine LP-19 (VPM LP-19), in the winter and summer periods of operation, expressed in Russian rubles.

Table 2. Total amount of income from pipeline operations.

Δt_i	250	500	750	1000	1250	1500	2000	2500
$P(A/B_1)$	0,02	0,0438	0,103	0,199	0,34	0,49	0,752	1
$v_1^{B_1}$	693	1393	2079	2772	3465	4158	5544	6930
$v_2^{B_2}$	762	1523	2272	2996	3682	4485	5660	6237
$P(A/B_2)$	0,08	0,334	0,75	1	–	–	–	–

$v_1^{B_2}$	693	1392	2079	2772	–	–	–	–
$v_2^{B_2}$	759	1496	2177	2079	–	–	–	–

On figure 1 shows graphs of the total amount economic effect in the operation of high-pressure hoses in summer and winter.

4. Conclusion

To determine the optimal operating time before the replacement of hydraulic drive elements, you can use the Markov chain theory, which allows you to determine the probability of transitions of hydraulic drive elements from a serviceable to a faulty state based on the results of previous inspections of machines.

During the summer operation of the feller buncher machine LP-19, the optimal operating time before replacement of high-pressure hoses is 2300 hours, during the winter operation-800 hours, which corresponds to the maximum economic effects during operation.

The developed method for determining the optimal operating time before replacing the high-pressure hoses of transport and technological machines can be used for other elements of the hydraulic drive (hydraulic valves, hydraulic cylinders, and others).

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