Mathematical model of increase in durability of road machines taking into account operating conditions

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Abstract. In this article results of researches and development of a mathematical model of extension of a resource and increase in durability of the road machines functioning in tropical conditions of Vietnam taking into account operating conditions are considered. By means of the software of Matlab the original rated program of determination of optimum parameters of frequency of maintenance and repair is developed; the number of repairs and categories of maintenance which need to be carried out throughout all life cycle of the road machine for ensuring best values of indicators of durability of machines taking into account operating conditions.

1. Introduction

It is known that the organization of effective use and quality of functioning of road machines (are defined by the level of their reliability) play an important role in ensuring quality of construction of roads and minimization of damage to the national economy \cite{1, 2, 13-15}.

Increase in a resource and increase in durability of road machines requires carrying out the complex of actions covering spheres of design, production and operation. The efficiency of actions for increase in durability of road machines is estimated by the sum of costs of production and operation of the machine throughout all life cycle taking into account operating conditions \cite{7, 9, 10, 12, 13}.

2. Methods

As criterion of optimization at a solution of an objective it is selected a minimum of specific total costs of $C(t)$ of technical maintenance, repair of the machine and compensation of losses because of decline in production and increase in a consumption of fuels and lubricants owing to deterioration in technical condition of the machine.

Vasilyev V.O. and Dombrovsky K.P. were the first who conducted researches of models of optimization of resources of machines. In work \cite{12} Vasilyev V.O. offered a method of definition of optimum operating time of engines with use of criterion of the smallest average cost value of maintenance of machines. Dombrovsky K.P. \cite{7} suggested to set best value of a resource of operation...
of the machine equal to number of years through which increase in average repair cost becomes comparable or exceeds the value of annual norm of depreciation.

The method of definition of an operation life of cars offered Tokareva E.G. deserves attention [11] and Selivanov A.I. [8]. In these works, optimum is understood as service life which provides the minimum value of costs of run unit for the entire period of operation.

In the field of operation of the road-building equipment the greatest distribution was gained by the optimization models described in works [9, 10]. Target function is the cornerstone of these models:

$$C(t) = \frac{n_c(t)}{M} C_{dep} + \frac{C_{los}}{t_{r1}} + \sum_{i} \frac{C_{tm}}{t_{m1}} \rightarrow min.$$  (1)

where

- $n_c(t)$ - number of repair cycles for service life of the road machine before write-off;
- $C_{dep}$ - the average value of depreciation charges is over one repair cycle of the road machine;
- $C_r$ - costs of elimination of failures and faults of the road machine in the course of repairs for one repair cycle;
- $C_{los}$ - costs of compensation of losses owing to decline in production and increase in a consumption of lubricants at wear of details of the road machine during one repair cycle;
- $C_{tm}$ - costs of technical maintenance of one road machine;
- $t_{r1}$ - resource before the first major repair;
- $C_{tm}$ - costs of technical maintenance of road machines;
- $t_{m1}$ - frequency of technical maintenance;
- $M$ - coefficient, is defined as follows: $M = 1 + k_r [n_c(t) - 1]$.

Here $k_r$ - the coefficient equal to the resource relation after major repair to a resource of the new road machine:

$$k_r = \frac{t_{r1}}{t_{r1}}.$$  (2)

According to provisions of Technical regulations of TPTC 010/2011 "About safety of machines and the equipment" [6], the machine which underwent major repair on the technical condition should conform to regulatory requirements.

Provided that machine resources after the major repairs first, second, etc. are equal among themselves, it is possible to define depreciation charges for one repair cycle as follows:

$$C_{dep} = \frac{[C_{ma} + C_{mr}(n_c(t) - 1)]}{n_c(t)}.$$  (2)

where

- $C_{ma}$ - the cost of the road machine;
- $C_{mr}$ - the cost of major repair.

Meanwhile costs of compensation of losses $C_{los}$ declines in production and increases in a consumption of lubricants are function which depends on technical condition of the machine (I) and is reflected degree dependence (taking into account operating conditions):

$$C_{los} = c . I^\beta = K_s . c_0 . I^\beta = K_s^\beta . c_0 . b^\beta . t_{tm}^{(a-1)\beta} . t_{r1}^{\beta}.$$  (3)

where

- $\beta$ - exponent caused by construction and functional purpose of interface;
- $c$ - the coefficient depending on an operation mode and operating conditions of the road machine;
- $c_0$ - the coefficient defined under operating conditions the road machine, which is not depending on climatic conditions;
- $K_s$ - the coefficient determined by technical rigidity of climate [16].

On the other hand, total costs of elimination of failures and faults in the course of repairs $C_r$ are the function depending on operating time $t_{r1}$, accounting of operating conditions it is possible to define as follows:

$$C_r = f_0^{t_{r1}} e . t^\gamma = e . t_{r1}^{\gamma+1}.$$  (4)

After the conversions made by means of expressions (2), (3) and (4), expression (1) will take a form:
\[ C(t) = \frac{c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta}{t_r} + \frac{n_e(t)e^r}{(y + 1)M^{y+1}} + \sum\frac{c_{tm}i}{t_{tm}} \rightarrow \text{min.} \] (5)

Here \( t_r \) - a full average resource; \( t = M \cdot t_r \);

\( I_{lim} \) – an indicator of a limit status; \( I_{lim} = K_s \cdot b \cdot t_{r,1}^\beta 

3. Result

Let’s take derivative \( C(t) \) on the variable \( x = t_r \) and having equated it to zero. Then from expression (5) we will receive:

\[ \frac{\partial C(t)}{\partial t_r} = -\frac{c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta}{t_r^2} + \frac{n_e(t)e^r}{(y + 1)M^{y+1}} = 0. \] (6)

or

\[ (y + 1)M^{y+1}\left[c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta\right] - n_e(t)e^r = 0. \] (7)

From here, the optimal value of a resource of the road machine is defined with operating conditions by the following expression:

\[ t_{r,\text{opt}} = \left(\frac{M^{y+1}(y + 1)\left[c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta\right]}{n_e(t)e^r}\right)^{\frac{1}{y+1}}. \] (8)

If to accept that during operation of the machine before the first technical maintenance of expense for elimination of failures and faults of the machine are equal to zero \((C_r = 0)\), then the equation (5) corresponds in a look:

\[ C(t) = \frac{K_s^b\left[c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta\right]}{M\cdot I_{lim}}\cdot t_{tm}^\alpha - \frac{c_{tm}I_{lim}}{t_{tm}} \rightarrow \text{min.} \] (9)

Having taken derivative \( C(t) \) on the variable \( x = I_{lim} \) and having equated it to zero, from expression (9) we will receive:

\[ \frac{\partial C(t)}{\partial I_{lim}} = K_s^b t_{tm}^\alpha \frac{(\beta - 1)K_c\sigma_{allim}^\beta - \left[c_{ma} + c_{mr}(n_e(t) - 1)\right]}{M I_{lim}} = 0. \] (10)

From here, best value of an indicator of a limit status of the machine:

\[ I_{lim,\text{opt}} = \left[\frac{c_{ma} + c_{mr}(n_e(t) - 1)}{(\beta - 1)K_c\sigma_{allim}^\beta}\right]^\frac{1}{\beta}. \] (11)

Then, if best value of an indicator of a limit status is more than corresponding value set by criterion of impossibility of further operation \((I_{lim,\text{opt}} > I_{lim})\), in calculations we accept value \( I_{lim} \).

Further, we will take derivative \( C(t) \) on the variable \( x = t_{tm} \) and having equated it to zero, from expression (9) we will receive:

\[ \frac{\partial C(t)}{\partial t_{tm}} = K_s^b t_{tm}^\alpha \left[c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta\right] + \frac{c_{tm}}{t_{tm}} - t_{tm}^\alpha - \frac{c_{tm}}{t_{tm}} = 0. \] (12)

From here, optimum maintenance rate taking into account operating conditions:

\[ t_{tm,\text{opt}} = \left[\frac{M I_{lim} c_{tm}}{K_s^b (\alpha - 1)\left[c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta\right]}\right]^\frac{\alpha}{2}. \] (13)

If set the number of services for optimal resource equal to \( N_{tm} \):

\[ N_{tm} = \frac{K_s^b (\alpha - 1)\left[c_{ma} + c_{mr}(n_e(t) - 1) + n_e(t)K_c\sigma_{allim}^\beta\right]}{M c_{tm}}, \] (14)

then expression (13) can be rewritten in a look:

\[ t_{tm,\text{opt}} = \left(\frac{I_{lim}}{N_{tm}}\right)^\frac{1}{\beta}. \] (15)

Therefore (14), (15) and (8) we can create a mathematical model for determination of optimum parameters of durability of the road machine taking into account operating conditions from the equations as follows:
\[
N_{tm} = \frac{K_s(a-1)[C_{ma}+C_{mr}(n_c(t)-1)+n_c(t)K_xc_0^{\beta I_{lim}}]}{MC_{tm}}
\]
\[
t_{tm,\text{opt}} = \left( \frac{I_{lim}}{bN_{tm}} \right)^{\frac{1}{\alpha}}, \quad (16)
\]
\[
t_{r,\text{opt}} = \left( \frac{M^{Y+1}(Y+1)[C_{ma}+C_{mr}(n_c(t)-1)+n_c(t)K_xc_0^{\beta I_{lim}}]}{n_c(t)\gamma Y} \right)^{\frac{1}{Y+1}}
\]

If best value of an indicator of a limit status is less or to equally corresponding value set by criterion of impossibility of further operation \((I_{lim,\text{opt}} \leq I_{lim})\) when calculating the value \(I_{lim,\text{opt}}\) is accepted. Having made corresponding changes to expression (11), we will receive a mathematical model (16) in the following look:

\[
N_{tm} = \frac{K_s(a-1)\beta[C_{ma}+C_{mr}(n_c(t)-1)]}{MC_{tm}(\beta-1)}
\]
\[
t_{tm,\text{opt}} = \left( \frac{I_{lim,\text{opt}}}{bN_{tm}} \right)^{\frac{1}{\alpha}}
\]
\[
t_{r,\text{opt}} = \left( \frac{M^{Y+1}(Y+1)\beta[C_{ma}+C_{mr}(n_c(t)-1)]}{n_c(t)\gamma Y(\beta-1)} \right)^{\frac{1}{Y+1}}
\]

On the basis of mathematical models (16) and (17) we build algorithms of determination of optimum parameters of durability of the road machines functioning in tropical conditions (on the example of Vietnam):

- Step 1: Define coefficient of \(K_s\) which characterizes severity of tropical climate of Vietnam in comparison with a temperate climate;
- Step 2: Determination of the optimum parameters connected with durability of the road machine.
BEGAN THE STEP 1

Input of basic data about climatic conditions

\[ t_{max.w}, t_{max.aw}, \sigma_w, Q_s, v_{sw}, n_r, \varphi_w, \tau_{az} \]

Define technical rigidity of climate

\[ S_{c.tr} = (0.55 \cdot t_{max.w} + 0.20 \cdot t_{max.aw})(1 + 0.01 \cdot Q_s)(1 + 0.0075 \cdot \sigma_w) \\
\quad \cdot (1 - 0.03 \cdot v_{sw})(1 + 0.026 \cdot \varphi_w)(1 + 0.009 \cdot n_r)(1 + 0.012 \cdot \tau_{az}) \]

Define coefficient \( K_s \)

\[ K_s = f(S_{c.tr}) = 0.0017 + 0.0034S_{c.tr} + 0.0011S_{c.tr}^2 \]

Output data \( K_s \)

END OF STEP 1
Input of basic data

Define best value of an indicator of a limit status

\[ I_{\text{lim,opt}} = \left( \frac{C_{ma} + C_{mr}(n_c(t) - 1)}{(\beta - 1)K_0c_0n_c(t)} \right)^{\frac{1}{\beta}} \]

Determine optimum parameters:

\[
N_{tm} = \frac{K_s(\alpha - 1)\left[ C_{ma} + C_{mr}(n_c(t) - 1) + n_c(t)K_0c_0I_{\text{lim}}^\beta \right]}{MC_{tm}} \\
t_{tm,opt} = \left( \frac{I_{\text{lim}}}{bN_{tm}} \right)^{\frac{1}{\beta}} \\
t_{r,opt} = \left( \frac{M^{r+1}(\gamma + 1)\left[ C_{ma} + C_{mr}(n_c(t) - 1) + n_c(t)K_0c_0I_{\text{lim}}^\beta \right]}{n_c(t)e^\gamma} \right)^{\frac{1}{r+1}}
\]

Output data

\[ N_{tm}, t_{tm,opt}, t_{r,opt} \]
On the basis of an algorithm by means of the software of Matlab, we build the graphic program of calculation of parameters. In Figure 1 the example of start of the program is given.

![Figure 1](image.png)

**Figure 1.** An example of calculation of optimum parameters of the excavators working in Hanoi

4. Conclusion

Taking note of operating conditions on reliability and efficiency of use will allow to prove the choice of models of road machines when forming parks of means of mechanization of construction, more precisely to plan terms of carrying out construction works, to make the reasonable diagram maintenance and repair of machines during construction works, to calculate need of the park for spare parts and operational materials. The most important direction of reliability augmentation, extension of a resource and increase in durability of road machines in the conditions of aggressive influence of the corrosion environment is use of polymeric composition materials at technical maintenance and repair [2-5].

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