MATHEMATICAL MODELING OF WORKING OPERATIONS FOR THE ROAD-BUILDING MACHINES BASED ON PERFORMANCE FACTORS

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ABSTRACT

The introduction of many production operations using road-building machines is characterized by a high level of exposure to the operator by unfavorable factors of the production environment. Performance in difficult operating conditions is determined by the costs of processing, operation and maintenance of machines. The structural features of construction and road machines allow working on non-standard technological schemes. The conditions for the working may be incompatible with the standards of psychophysical stress of operators. Using the technology of remote control of road-building machines leads to functional changes in the performance indicators for the interaction of the machine and the operator.

Keywords: construction, road-building machines, work equipment, performance, remote control.

1. INTRODUCTION

Possibilities of construction of road-building machines allow their use outside standard technological schemes. Road construction machines are used for their intended purpose in the construction and road industries, and for solving non-trivial production tasks. At the same time, operating conditions may not be comparable with the norms of psychophysical loads for operators and require the operator to be removed from the local work area. Using the technology of remote control of construction road machines functionally leads to a change in the performance indicators and high-quality interaction in the "environment-machine-operator" system. Expansion of the scope of road construction machines requires the addition of forms to ensure safe working conditions for the operator, combined with a high level of performance of technological operations.

2. MATERIALS AND METHODS

Any machine which was manufactured in conformity with the requirements of normative and technical documentation has a nominal functional performance. This means the machine's ability to produce a designed quantity of products in time. In general, the usage efficiency means the ratio of the actual performance of the machine to its nominal performance.

The nominal performance of the machine in physical meters for a given time interval is determined by the formula (Karakulev *et al.*, 1991):

$$P_n = g_n t_n; \qquad (1)$$

g_n is the nominal (designed) performance of the machine, volume of production/hour;

t_n is the nominal duration of use of the machine, hours.

However, in the practical usage of the machine there are some conditions that limit the performance of the technological operation and it is not possible to fully realize the designed performance thereby achieve effective usage of the machine (Karakulev *et al.*, 1991).

During the calculation of the operational efficiency of road-building machines, many scientists are limited to general technical characteristics. While the concretization of possible states the "machine-operator" system and is not taken into account (Drozdova *et al.*, 2007; Dobronravov, 1991; Beletsky & Bulgakova, 2005).

Due to the negative influence of various factors on the machine, actual performance output P_E is less than the nominal:

$$P_E = g_n P(g) t_n F(t); \qquad (2)$$

$P(g)$ is the statistical estimation (probability) of a fraction of the nominal performance of the machine; $0 \le P(g) \le 1,0$;

F(t) is the statistical estimation of a fraction of machine usage during a certain time interval; $0 \le F(t) \le 1,0$(Karakulev *et al.*, 1991).

The main task of machines operation is the applying to the machine such of technical and organizational actions which maximize the practical actual performance (2). However, maximization of the actual performance can be accompanied by a significant increase of economic costs. Therefore, when choosing the control actions that effect on the variables $P(g);F(t)$, it is necessary to take into account each of the performance components which are regarded as quantities which depend on controlled and uncontrolled factors(Pavlov, 2007):

A. Environment ***[1→0]: $P_1(g)$; $F_1(t)$.***

The conditions determine the physical and chemical properties of the environment (climate, acidity, radiation), processing material (mass, strength), the spatial feasibility of work (urban or open construction sites). These conditions impose restrictions on the machine usage and maximizing of its performance. For example, severe frosts, winds and the prevalent frozen soils in the North regions of Russia reduce the performance of machines by 30% or more in comparison with the work of the same machines in the middle regions (Sevrugina & Prohorova, 2013). Natural and climatic conditions are not a controlled element of the organization of the technological process, but they are a reason for its adaptation.

B. Technical state*[1→0]: P2(g); F2(t).*

The technical condition of any technical system is constantly changing and deteriorating during operation time. The changes of structural elements caused by destruction process lead to proportional increase in load, decrease in operating speeds, and, as a result, a decrease in productivity. The main instrument of reduce the negative impact of the machine`s performance is the maintenance and repair system which is able to support and restore the efficiency of machines.

C. Machine assignment factor ***[const]: $P_3(g)$; $F_3(t)$.***

This factor is determined by the range of variation of the machine usage. The set of machines is carried out in relation to the volume and technology of work. The change in the destination factor depends on the type of technological scheme; type of working equipment; features of using the functionality of the machine.

D. «Machine-operator» factor ***[1→0]: $P_4(g)$; $F_4(t)$.***

The useful effect of using «machine-operator» system will be determined by the sphere of its functional features. That is to say, the existing possibilities for the functioning of the machine and the choice of technological methods for performing operations will be limited by the psychophysical features of the operator. Experience shows that in the first two hours of work the efficiency of operator`s labor reaches 100%, at the end of the day it falls down up to 70% or even more (Taketsugu, 2006). Therefore, in places where high accuracy quality of work is required, semi-automatic and automatic control of the machine should be used. That will provide stabilization of modes and safety of industrial operations performance.

E. Technology of work execution ***[const]: P5(g); F5(t).***

The loss of time due to the violation of the technology of work, disruptions with the supply of machinery materials, violations of labor discipline or illness of the operators. However, these factors might be controlled by qualified management and forecasting the operation of each individual machine.

3. INFORMATIVE PART

Therefore, it is necessary to take into account each of the performance components, which are considered as quantities that depend on controlled and random factors *P (g); F (t)*. Consequently, in accordance with formula (2), in order to maximize the specific production of machines, it is necessary to know the causal factors of increasing or decreasing the values of the variables *F(t)* and *P(g)* and it is necessary to follow technical and organizational ways of influencing on the factors in question:

$$P_E = g_n\,[P_1(g)P_2(g)P_3(g)P_4(g)]\;t_n\,[F_1(t)F_2(t)F_3(t)F_4(t)F_5(t)]; \quad (3)$$

The lack of constant monitoring of performing factors leads to premature decommissioning of expensive machines.

The scheme of operation of the machine as a functionally controlled system makes it possible to analyze the interaction of factors (Nguyen, 2000). In this case, the possibilities of control actions are considered for remote control (Table-1).

Table-1. Control actions are considered for remote control.

No.	Performance factors		Determination of the factor for the Remote Control Systems (RCS)
1	Environment	RCS	- change in the quality of transmission of control signals; - change in the influence of external conditions; - non-occurrence in the affected area
2	Technical state		-
3	Machine assignment factor		-
4	"Machine-operator" factor	RCS	- change the position of the viewpoint; - exclude the influence of negative effects (vibration, temperature, noise, etc.).
5	Technology of work execution		- use of the operational capabilities of the machine, which cannot be used when the operator is in the cab.

Consider the modernized graphic scheme of the machine operation with the logical sequence of performance factors and control devices for excavating equipment (Kudryavtsev, 2010). The graphic scheme shows the necessary actions to perform the specified process.

The interaction of factors set and actuating mechanisms occurs when a certain set of events is

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performed. It displayed on the graphic scheme (the conditions for remote control are indicated by dashed lines) (Figure-1):

- Circle-Performance factors: E - Environment; TS - Technical state; MAF - Machine assignment factor; M - Machine; O - Operator.
- Square- actuating mechanisms of the machine equipment: 1 - controlling devices for working equipment; 2- electronic control unit; 3- electromagnetic proportional mechanism; 4- hydraulic equipment; 5- working equipment; 6- remote control device.

Arrows are arranged in an order to show the logic of the actions of actuating mechanisms and performing factors (Kudryavtsev, 2010). An event is final if it has no subsequent interactions.

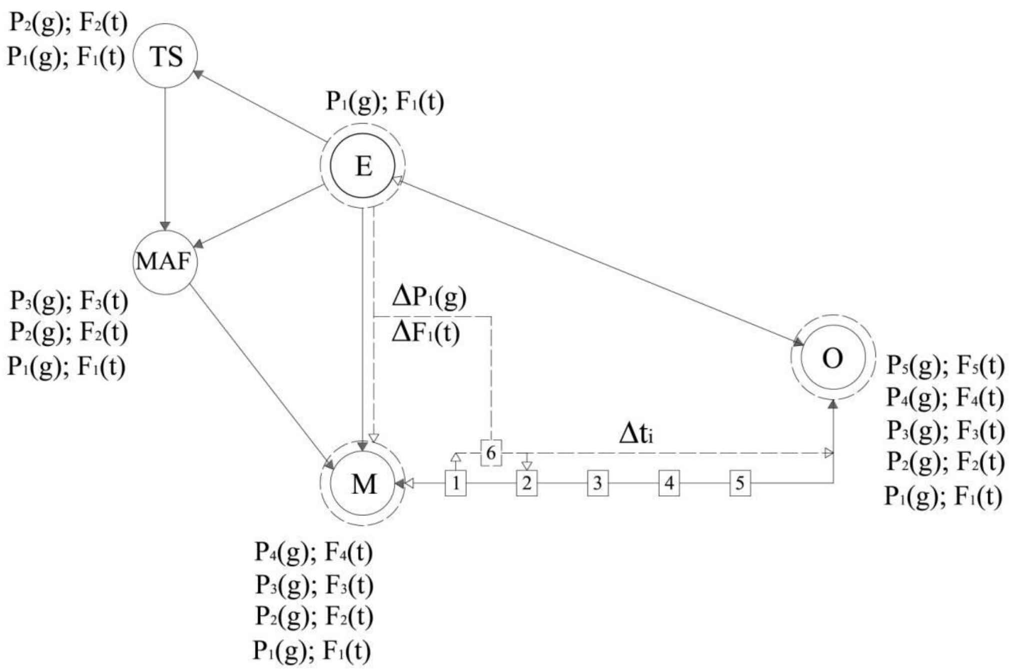

Figure-1. Graphic scheme of remote control system for working equipment (road-building machine).

Performance depends on the number of factors. The probability that the performance will be less than g, under the action of the factors $P_i(g)$. Therefore, $F_i(t)$is not less than a given value of *t*. Algorithm of calculating the graphic scheme for the given conditions?

- Production conditions determine the general primary parameters of the system's operation environment (favorable conditions);
- The current technical condition of machine equipment is determined by the current operating time;
- The destination factor is the choice of machines in relation to the type, volume and technology of work;
- Operation mode, useful work of the "machine-operator" system;

Analysis of this graphic scheme allows determining the order and magnitude of the factors impact on the operation of the machine as well as their influence between them. The proposed graphic scheme demonstrates the work of the machine control system in conjunction with performance factors. The usage of remote control increases the transmission time of operating commands for the machine.

Thus, the systematization and estimation of dynamic and stationary (limiting) probabilities for all possible states of the "machine-operator" system, it makes possible to obtain the formula of the performance of the basic machine taking into account the variation of the qualitative interaction of the "man-machine" system, which is determined by a mode of operation "man-machine", $К_{rf}$:

$$К_{rf} = (S_i)dt = k_{pf.c}k_{ct.f}k_{dn.f}, \quad (4)$$

where $k_{pf.c}$is psychophysical state of the operator. During operating process the operability of the operator can change randomly from stage to stage

$$k_{pf.c} = \frac{PS_{act.}}{PS_{nom.}} = \frac{PS_{act.}}{1}, (0<k_{pf.c}<1); \quad (5)$$

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$$k_{pf.c} = \frac{\prod_{i=1}^{m} PS_{act.}}{PS_{nom.}} = \frac{\prod_{i=1}^{m} PS_{act.}}{1}.$$

$k_{ct.f}$ are static factors of operation of the machine-operator mode (visibility, temperature, humidity, illumination, etc.):

$$k_{ct.f} = \frac{SF_{act.}}{SF_{nom.}} = \frac{SF_{act.}}{1}, (0<k_{ct.f}<1); \quad (6)$$

$$k_{ct.f} = \frac{\prod_{i=1}^{m} SF_{act.}}{SF_{nom.}} = \frac{\prod_{i=1}^{m} SF_{act.}}{1}.$$

$k_{dn.f}$ are dynamic factors of operation of the machine-operator mode (noise, vibration, etc.):

$$k_{dn.f} = \frac{DF_{act.}}{DF_{nom.}} = \frac{DF_{act.}}{1}; (0<k_{dn.f}<1); \quad (7)$$

$$k_{dn.f} = \frac{\prod_{i=1}^{m} DF_{act.}}{DF_{nom.}} = \frac{\prod_{i=1}^{m} DF_{act.}}{1}.$$

The current conditions allow us to consider the new mode of machine-operator system operation as a system that takes the states of S_i from competed set ($i=0..1$) with given intensities $\tau i(t)$ and υ_i. These conditions (Figure-2) form a variant of operator's state (Naumenko, 2013).

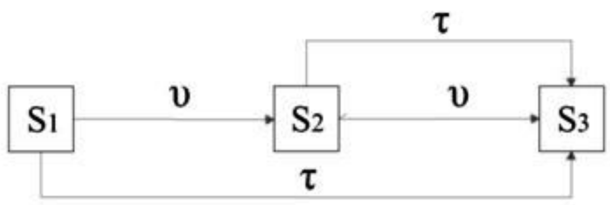

Figure-2. Operator's working capacity status.

They can be constant and functionally dependent. The sequence of states with the beginning S_1 (the nominal state of the object) can have a branch in each S_i. S_1- active and able to work; S_2 - able to work; S_3– unable to work (Figure-3).

$$S_1 = \tau/(\tau + \upsilon_1);$$
$$S_2 = \tau\upsilon_3/(\tau + \upsilon_2)(\tau + \upsilon_3); \quad (7)$$
$$S_3 = \frac{\tau\upsilon_1\upsilon_2}{(\tau + \upsilon_1)(\tau + \upsilon_2)(\tau + \upsilon_3)}.$$

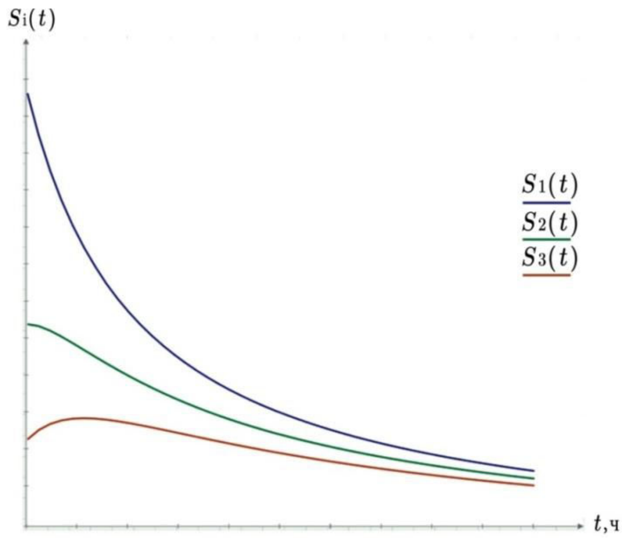

Figure-3. An analysis of the operability of the operator by states, S_1- S_2- S_3.

It is logical to conclude that for machine equipment the operating capacity during operating in the changing conditions of the "machine-operator" system will take the form:

$$P_E = (g_n[P_1(g)P_2(g)P_3(g)]\ t_n\ [F_1(t)F_2(t)F_3(t)])K_{rf} = P_n K_{rf}. \quad (8)$$

The proposed model demonstrates the functioning of machine control system with performance factors. Thus, the use of the remote control system provides a change in the values of the performing factors. These factors determine the operator`s state. It assumes machine operation by the way of particular removing the restriction from performance factors. It influences so much on machine's actual performance in time.

4. DISCUSSIONS

Back in the 70s, Australian researchers found that the usage of the remote control for the construction machine increases productivity by 10-30%, depending on the type of production operations (Astafurov *et al.*, 2011; RMT, 2017).

World experience in the use of remote control technologies for road construction machines has made it possible to identify the main companies for developing the direction of remote control of special equipment. These are world-famous companies (Volvo, CAT, Komatsu, Brokk, XCMG), as well as engineering offices (Hetronic, Brodrene Gjermundshaug Anlegg AS, Armofer Cinerari Luigi S.r.l.).

In modern production, there are examples of successful use of remote control systems for machines (Table-2).

Table-2. Enterprises using technologies of remote control for construction machines.

BrodreneGjermundshaug Anlegg AS 2010	**Company BrodreneGjermundshaugAnlegg AS. The company was engaged in the restoration of land in the former military training zone in what is now the Dovre National Park (Norway). The danger was in the numerous unexploded ordnance contained in the ground (BrødreneGjermundshaugAnlegg, 2017).**
ArmoferCinerari Luigi S.r.l. 2011	Using the specialized equipment for dismantling and radio-controlled equipment, the Italian company Armofer dismantled the concrete bridge structures on the E45 highway in the Emilia-Romagna region (Armofer, 2017).

5. CONCLUSIONS

The carried out analytical researches allow defining a model of functioning of the "environment-machine-operator" system, which describes the information-energy processes of each element of the system. The established interrelations demonstrate the relationship between the functioning of the control system and the performance factors. This allows us to conclude that reducing the influence of limiting parameters on the operator from the environment and the machine leads to a change in the efficiency of the technological task due to a more complete use of the operational capabilities of the machine.

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