METHODS TO DETERMINE MEASURES PROVIDING A MOTOR-GRADER ROAD-HOLDING ABILITY

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Abstract: *Performance of work operations by a motor-grader is accompanied by action of asymmetrically applied external loading. As dissipative forces act between the wheels and the support surface, this force action leads to the grader deviation from the set trajectory of movement. The experimentally developed model of the vehicle behavior at performing work operations allows estimating indexes of road-holding ability depending on soil characteristics, geometric and kinematic parameters of the machine.*

Keywords: MOTOR-GRADER, LOADING, INDEXES OF ROAD-HOLDING ABILITY, ASYMMETRIC LOADING, LATERAL DISPLACEMENT, TURNING ANGLE WITH REGARD TO THE MACHINE CENTER LINE

1. Introduction

The main working operations of a motor-grader are blading and grading of the road bed, handling and distribution of soil and construction materials. When performing the mentioned operations, depending on working conditions, it is recommended to position the main blade of the grader at the working angle of 90º – 45º (at digging drain ditches of about 40º – 20º) and the angle of obliquity in the vertical plane of 0º – 18º (at slope levelling — up to 60º) [1].

Such positioning of the blade with respect to the main path of the machine motion results in formation of a complex spatial scheme of its loading. In particular, except for the longitudinal horizontal component of digging resistance there arise additional lateral and vertical forces. Influence of the latter results in the motor-grader deviation from the straight-line trajectory in the course of the working operation implementation.

In practice, to ensure the road-holding ability the operator should continually adjust the machine position. Nevertheless, loss of the road-holding ability results in decreasing the performance indexes of the working operations, the need to make additional trips. Ultimately, this leads to a drop in productivity, increase in cost of the work performed and the specific fuel consumption.

2. Analysis of publications

A whole series of developments has been devoted to the problem of road holding ability of earth-moving machines. Their distinctive feature is analysis of the machine path of motion under the impact of lateral loadings such as centrifugal force, arising in the process of the machine movement at making a turn; gravitational component, arising at movement on the support surface with a transverse gradient; the lateral component of the resistance resultant on the working attachment.

The problem of road holding ability was considered more thoroughly in respect of the machine movement at making a turn[2-5].

In agricultural mechanical engineering mainly operation of the machine on a slope has been studied [6-8]. Basically, all the indexes of the road-holding ability depend on the machine weight, the angle between the horizontal plane and the plane of the slope where the machine is located.

A number of scientific researches are devoted to theoretical analysis of the wheel motion under the impact of lateral force [9, 10, 14].

A number of authors [11] believe that at describing a machine with a steering frame, parameters characterizing the road-holding ability are insignificant.

Researches conducted in the field of earth-moving equipment allow stating that coefficients characterizing the road-holding ability directly depend on ultimate loads acting on the blade cutting edge at loss of stability [12, 1].

For tracked vehicles this coefficient is characterized by the ratio of the moment of keeping the machine from turning to the moment of its turning. [13].

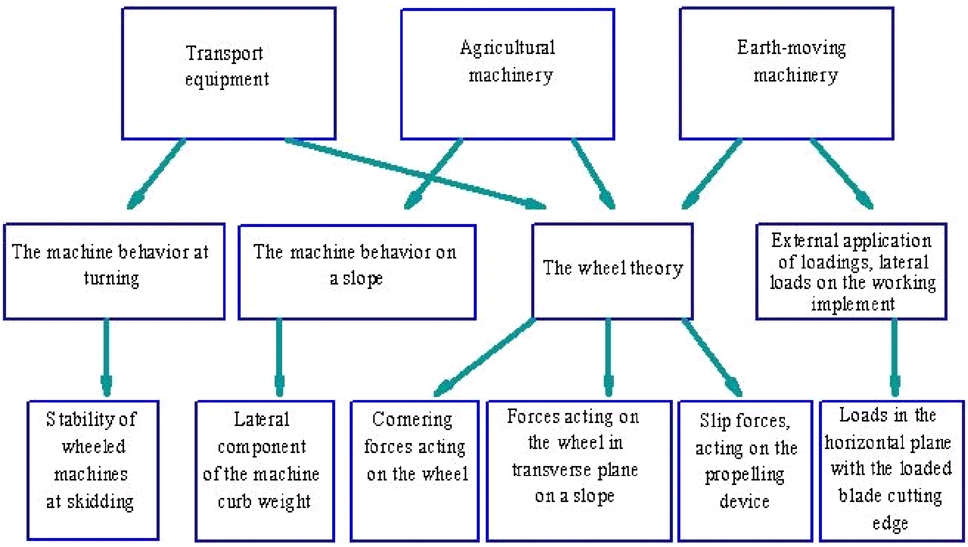

Figure 1: *Area of analizing the road-holding ability parameter*

Summing up the result, it is possible to determine three main areas of mechanical engineering, where much attention is paid to research of the machine road-holding ability: transport equipment, agricultural and earth-moving machinery, which in their turn have own specifics in approaches to estimation of the road-holding ability parameters (see Fig.1).

Purpose and tasks of the research

The research purpose is experimental estimation of impact of the motor-grader working process parameters on the road-holding ability parameters**.**

Research of the motor-grader road-holdng ability parameters

To achieve the set purpose in conditions of the Testing ground of Kharkiv National Automobile and Highway University there were prepared and conducted field researches with the motor-grader ДЗК – 251. At carrying out the tests the process of cutting soil of category II with the main blade end in the form of cross-section cut layer. The relative degree of the soil humidity was about 19 – 25%. In order to obtain more information on the impact of various factors on the parameters of the grader road-holding ability it was decided to carry out the experiment in two stages. At the first stage the test was conducted according to the classic scheme. The initial speed of the motor-grader and the blade angular displacement in the plane were chosen as variable parameters (Table 1).

The parameters of the factors were set on the basis of the values recommended for main working modes of the motor-grader. In the course of the experiments it was noticed that loss of the motor-grader road-holding ability results from the rear axle slipping (Fig. 2). At this the machine path of motion consists of straightways and the section where the motor-grader turning takes place.

Table 1. *Levels of the factors variation.*

Variable values	Sym bol	Unit of measure ment	Levels of the factor variation
The angle of the blade positioning in the plane	α	gr.	45º
			90º
			135º
The machine velocity	V	m/sec	1.01
			1.4
			1.57

Fig.2 The motion trajectory of one of the grader leading side.

Measuring the lateral displacement and turning angle with respect to the machine's longitudinal axis were made according to the scheme (Fig. 3.)

Point A designates the blade edge, by which the soil cutting is performed. The data of measurements corresponding to the coordinate system are presented in Table 2.

The experimental data analysis shows that on the face length of 20 m limiting lateral displacements of the front axle make 3.5 m and of the rear axle – 2.6 m. The angle of turning of the machine’s longitudinal axis correspondingly equals 20º–65º. Cutting with the leading blade end results in the machine displacement and turning to the side of the applied load. In the case when cutting is performed with the back blade end, results in the machine displacement and turning to the opposite direction.

Table 2: *Parameters characterizing the motor-grader road-holding ability*

Experimental		Displacement, m		β –angle of the machine
α, gr.	V,	h_1 – front	h_1 – rear	
45	1.01	3.471	2.575	47°44'
	1.4	0.339	0.764	22°26'
	1.57	0.160	0.228	3°57'
90	1.01	0.339	0.299	2°17'
	1.4	1.454	1.352	6°4'
	1.57	2.411	2.306	6°5'
135	1.01	1.427	1.329	5°50'
	1.4	0.937	0.674	17°6'
	1.57	0.287	1.567	65°31'

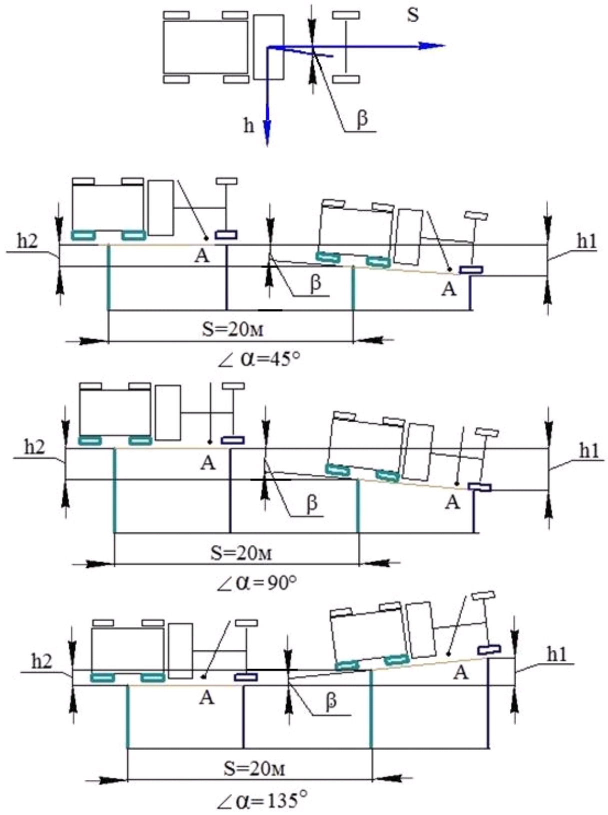

Fig. 3 The scheme of measuring the parameters characterizing the motor-grader road-holding ability

Processing of the obtained data with the help of MATLAB software allowed receiving a number of regressional relationships presented in Table 3.

Graphic interpretation of the obtained results is presented in Figures 4–6 in the form of the machine path of motion at changeable factors.

The analysis of the results showed that the second-degree regression equation gives the most accurate description of the machine motion. Thus, at increasing the speed from 1.01 to 1.57 m/sec the lateral displacement had a random character, in some cases there was observed its growth proportionally to the speed, in other cases at low rates of speed the value of displacement rose. There were not observed any strict regularities of changes in the motor-grader road holding ability in relation to changes in the machine speed. High values of the experimental data can be explained by high humidity of the surface layer of soil, low coefficient of adhesion of the propelling device with the ground, high slip coefficient.

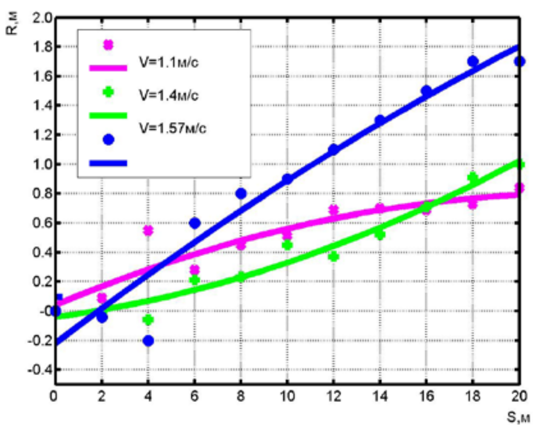

Fig.4 *The curve of regression equation at the working angle of α=45°*

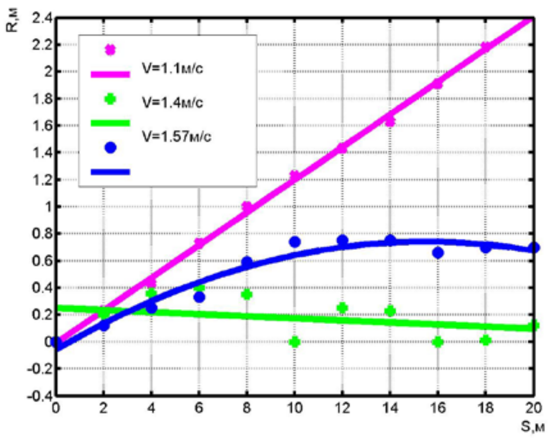

Fig.5 *The curve of regression equation at the working angle of α=90°*

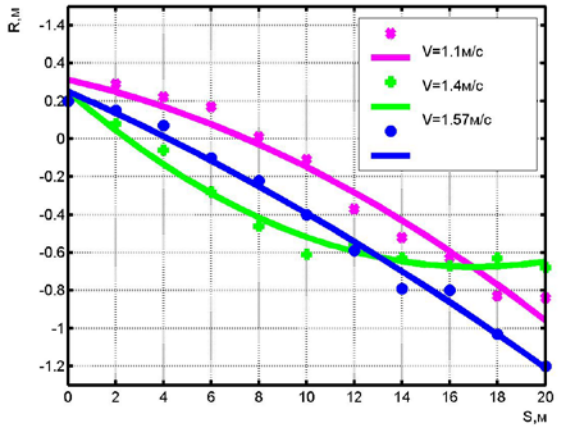

Fig.6. *The curve of regression equation at the working angle of α=135°*

At the second stage of the field research on the basis of methods of planning a series of tests, which allowed estimating the degree of influence on the road-holding ability of the whole group of additional factors that characterize the conditions of performance of working operations by the grader was conducted.

The experimental data demonstrated that at the first stage of the research, the greatest influence on the formation of road-holding ability parameters have the numerical value and coordinates of application of the resultant vector of external resistance to the working attachment. At a less degree there was studied a complex impact on the grader road-holding ability of such factors as the transverse grade of the working site, the ratio of the longitudinal and lateral grip of the propelling devices with the supporting surface, the angle of rotation of the front steering wheels in the vertical and horizontal planes. To determine the regularities we are concerned in, it was decided to carry out the second stage of the field research based on the realization of the factorial experiment in conditions of the Testing ground of Kharkiv National Automobile and Highway University with the ДЗК-251 motor-grader.

Table 3: *Parameters characterizing the motor-grader path of motion*

Angle of the blade adjustment	Velocity, m/sec	Displacement value, m										
		0	2	4	6	8	10	12	14	16	18	20
90°	1.01	0	0.09	0.55	0.28	0.45	0.51	0.69	0.7	0.69	0.73	0.84
	1.4	0	0	-0.06	0.21	0.23	0.45	0.37	0.52	0.71	0.91	1
	1.57	0	-0.4	-0,2	0.6	0.8	0.9	1.1	1.3	15	1.7	1.7
45°	1.01	0	0.23	0.43	0.73	1	1.23	1.43	1.63	1.91	2.18	2.43
	1.4	0	0.2	0,36	0.4	0.35	0.2	0.25	0.23	0	0.01	0.12
	1.57	0	0.12	0.25	0.33	0.59	0.74	0.75	0.75	0.66	0.7	0.7
135°	1.01	0	0.09	0.02	-0.03	-0.19	-0.31	-0.57	-0.72	-0.83	-1.03	-1.04
	1.4	0	-0.12	-0,26	-0.48	-0.66	-0.81	-0.76	-0.83	-0.87	-0.83	-0.88
	1.57	0	-0.05	-0,13	-0.3	-0.42	-0.6	-0.79	-0.99	-1	-1.23	-1.4

Table 3 *(continuation) Parameters characterizing the motor-grader path of motion*

Angle of the blade adjustment	Velocity, m/sec	Regression equation
90°	1.01	$R = -0.0014 + 0.0664S + 0.0406S^2$
	1.4	$R = 0.0016 + 0.0210S - 0.0410S^2$
	1.57	$R = -0.0010 + 0.1206S - 0.2193S^2$
45°	1.01	$R = 0.1210 - 0.0100S$
	1.4	$R = -0.0076 + 0.2509S$
	1.57	$R = -0.0033 + 0.1032S - 0.0576S^2$
135°	1.01	$R = -0.0017 - 0.0287S + 0.1121S^2$
	1.4	$R = 0.0032 - 0.1088S + 0.0495S^2$
	1.57	$R = -0.0009 - 0.0561S + 0.0517S^2$

The full factorial experiment was designed as a plan-matrix of the 2^4 type [15, 16]. To neutralize the impact of the application of the coordinates and the resultant vector of resistance on the working attachment in the process of conducting the experiment the position of the main grader blade in each test remained the same. Cutting the soil of category II was made from the pit with the digging face of 20 meters. In the process of conducting the experiment the physical and mechanical parameters of the soil did not change.

At compiling the table of levels and varying intervals the standard techniques of experimental design were used (see Table 4). The factorial experiment is designed to use three levels - the upper (+1), the basic (0) and lower (-1) presented in a coded form:

$x_1 = \varphi$, deg., — transverse gradient of the surface;

$x_2 = k$ — coefficient of traction on the sides;

$x_3 = \gamma$, deg., — angle of the front wheels rotation in the horizontal plane;

$x_4 = \rho$, deg., — angle of the front wheels tilt in the vertical plane.

By the well-known formulas the regression coefficients were determined. To calculate the reproducibility, adequacy and significance of the coefficients of regression equations standard techniques were used [15, 16]

After analyzing the coefficients of the regression equations for adequacy and significance, the following regression equations were obtained:

Table 4. *Values and coding of the factors levels*

Variability interval	Independent factors			
	x_1, deg.	x_2	x_3, deg.	x_4, deg.
Lower (-1)	0	0.4	0	0
Medium (0)	4	0.6	5	7.5
Upper (+1)	8	0.8	10	15
Variability interval (δ_i)	4	0,2	5	7,5

— for the grader lateral displacement:

$$H(x_1,x_2,x_3,x_4) = -1,0375 - 0,27x_1 - 0,126x_2 - 2,011x_3 - 0,835x_4 + \\ +0,6813x_1x_3 + 0,5225x_1x_4 + 0,2475x_2x_3 - 0,5738x_2x_4 - \\ -0,3563x_3x_4 - 0,2325x_1x_2x_3 + 0,19625x_1x_2x_4 - 0,15375x_1x_3x_4 - \\ -0,3975x_2x_3x_4 - 0,3725x_1x_2x_3x_4.$$

— angle of rotation in relation to the longitudinal axle:

$$\beta(x_1,x_2,x_3,x_4) = -4,6875 - 6,75x_3 - 2,375x_4 - 0,5625x_1x_2 + \\ +2,9375x_1x_3 + 0,9375x_1x_4 - 0,6875x_2x_4 - 1,6875x_3x_4 - 1,375x_1x_2x_3 + \\ +1,25x_1x_2x_4 + 0,75x_1x_3x_4 - 2,125x_2x_3x_4 - 1,8125x_1x_2x_3x_4.$$

In the process of generating the regression equations the significance of the factors on Student criterion was analyzed (Table 5).

To describe the grader road-holding ability in the process of digging the soil two indicators should be used: the lateral displacement of the machine in relation to the planned straight path of motion and rotation angle in relation to the longitudinal axis of the machine with respect to the same path. It is for these indicators that on the basis of the conducted experiments the regression equations were generated. At that a linear model was considered. In the process of calculations evaluation of the significance of influence of each factor and their complex on values of the above indicators was made.

The evaluation is performed with the help of Student criterion:

$$|b_i| \geq \Delta b_i = t(0.05; f_y)\frac{S_y}{\sqrt{n}} \tag{1}$$

where $|b_i|$ – the regression coefficient at the process reproducibility;

Δb_i – Student criterion

$t(0.05; f_y)$ – table value of Student criterion at 5% point of distribution with f_y degrees of freedom;

S_y – experimental error,

which value for the given experiment made up: 0.126 for the lateral displacement $(\Delta b_i(H))$ and 0.558 for the rotation angle in relation to the path of motion $(\Delta b_i(\beta))$.

In Table 5 the significant factors are marked with the sign «+», and not significant with the sign «-».

The machine lateral displacement is mostly influenced by:

– the angle of the front wheels rotation in the horizontal plane $|b_3|(\gamma) = 2,011$, which displacement value made up – 3.1 m, the motion path in this case was displaced to the left from the planned straight path of motion;

– angle of the front wheels tilt in the vertical plane $|b_4|(\rho) = 0,835$ with the displacement value of 2.2 m, the motion path was displaced to the right from the planned straight path of motion;

– the complex impact of coefficients of traction of the driving wheels with the support surface under the right and left sides of the machine ant the angle of the front wheels tilt in the horizontal plane $|b_6|(\varphi,\gamma) = 0,6813$ with the displacement value of 3.14 м, the path of motion was displaced to the left from the planned straight path of motion;

The machine lateral displacement is not influenced by the complex impact of the surface gradient and the coefficient of traction on the sides $|b_5|(\varphi,k) = 0,0013$.

The greatest impact on changing the rotation angle of the longitudinal axis in relation to the planned path of motion is made by:

– the rotation angle of the front wheels in the horizontal plane $|b_3|(\gamma) = 6,75$, which value accounted for 12°, the motion path was displaced to the left from the planned math of motion;

– the complex impact of the gradient of the machine surface and the rotation angle of the front wheels in the horizontal plane $|b_6|(\varphi,\gamma) = 2,9375$ with the angle of 7° and the motion path displaced to the left from the planned motion path;

– the tilt angle of the front wheels in the vertical plane $|b_4|(\rho) = 2,375$ with the displacement value of 6.5°, the motion path was displaced to the right from the planned path of motion;

Changing of the rotation angle of the machine longitudinal axle is not influenced by the surface gradient $|b_1|(\varphi) = 0,125$, the traction coefficient under the machine sides $|b_2|(k) = 0,25$, as well as the complex impact of the coefficient of traction under the machine sides and the wheels rotation in the horizontal plane $|b_8|(k,\gamma) = 0,4375$.

Table 5. *The signification coefficients for addends in the regression equations.*

Parameter	The machine lateral displacement - H		The rotation angle of the machine longitudinal axle in relation to the planned motion path - ρ	
	The signification coefficient value	Signification	The signification coefficient value	Signification
$\|b_1\|(\varphi)$	0,27	+	0,125	-
$\|b_2\|(k)$	0,126	+	0,25	-
$\|b_3\|(\gamma)$	2,011	+	6,75	+
$\|b_4\|(\rho)$	0,835	+	2,375	+
$\|b_5\|(\varphi,k)$	0,0013	-	0,5625	+
$\|b_6\|(\varphi,\gamma)$	0,6813	+	2,9375	+
$\|b_7\|(\varphi,\rho)$	0,5225	+	0,9375	+
$\|b_8\|(k,\gamma)$	0,2475	+	0,4375	-
$\|b_9\|(k,\rho)$	0,5738	+	0,6875	+
$\|b_{10}\|(\gamma,\rho)$	0,3563	+	1,6875	+
$\|b_{11}\|(\varphi,k,\gamma)$	0,2325	+	1,375	+
$\|b_{12}\|(\varphi,k,\rho)$	0,19625	+	1,25	+
$\|b_{13}\|(\varphi,\gamma,\rho)$	0,15375	+	0,75	+
$\|b_{14}\|(k,\gamma,\rho)$	0,3975	+	2,125	+
$\|b_{15}\|(\varphi,k,\gamma,\rho)$	0,3725	+	1,8125	+
$\|b_0\|$	1,0375	+	4,6875	+

The regression equation in its ordinary look after the code conversion and consideration of the signification is as follows:

$$H(\varphi,k,\gamma,\rho) = 2{,}6589 - 0{,}1538\varphi + 0{,}7015k - 0{,}80095\gamma +$$
$$+0{,}1441\rho - 0{,}4219\varphi k + 0{,}0208\varphi\gamma - 0{,}0343\varphi\rho + 0{,}505k\gamma -$$
$$-0{,}4967k\rho - 0{,}0343\gamma\rho + 0{,}035\varphi k\gamma + 0{,}0948\varphi k\rho +$$
$$+0{,}0064\varphi\gamma\rho - 0{,}0033k\gamma\rho - 0{,}0124\varphi k\gamma\rho.$$

$$\beta(\varphi,k,\gamma,\rho) = 3{,}6875 + 0{,}875\varphi + 5k - 2{,}2\gamma + 0{,}5333\rho -$$
$$-2{,}8125\varphi k + 0{,}04375\varphi\gamma + 0{,}3\varphi\rho + 1{,}25k\gamma - 1{,}0833k\rho -$$
$$-0{,}04\gamma\rho + 0{,}1094\varphi k\gamma + 0{,}5104\varphi k\rho + 0{,}0413\varphi\gamma\rho -$$
$$-0{,}0417k\gamma\rho - 0{,}0604\varphi k\gamma\rho.$$

Conclusions

On the basis of the review we can argue that main reasons for the machine loss of its road-holding ability and deviation from the specified path of motion are lateral forces arising at performing working operations: centrifugal forces and gravitational components applied to the machine mass center, as well as impact of an eccentrically applied resistance resultant on the working implement.

On the basis of the field research we can conclude that for the most accurate description of road-holding ability parameters of earth-moving machinery, namely a motor-grader, it is expedient to use two parameters: lateral displacement and angle of the machine turning with respect to the longitudinal axis.

The motor-grader speed has insignificant influence on formation of its course stability. During the experiment there were not observed any strict regularities of changing in the road-holding ability parameters in relation to changing in the machine speed.

The most considerable influence on the motor-grader parameters of road-holding ability has the coordinate of application of the resultant vector of external resistance, which is determined by the angle of the blade position in the plane. Cutting with the leading or back ends of the blade results in changing the direction of lateral displacement, which are within the limits: at cutting with the leading end 0.12 – 2.43 m; at cutting with the back end 0.8 – 1.4 m; at the working angle 90º the eccentric application of the rolling resistance causes the lateral displacement of 0.8 – 1.7 m at the face length of 20 m.

All the determined additional factors also influence the parameters of the grader road-holding ability, the rotation angle of the front wheels in the horizontal plane most, the tilt angle of the front wheels in the vertical plane less and the surface gradient and the traction coefficient on the sides least of all. Besides, the considerable effect is made by the complex impact of the factors of coefficients of traction of the driving wheels with the support surface under the right and left side of the machine, the rotation angle of the front wheels in the horizontal plane, the effect of the machine surface gradient and the rotation angle of the front wheels in the horizontal plane.

The conducted field research allows determining the characteristics of the mathematical model describing the motion of the grader at performing work operations.

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