Estimation of the resistance to movement of a wheeled tractor train in field tests

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Abstract.- The purpose of the studio was to determine the movement resistance of a wheeled tractor train taking into consideration the random nature of changes in external operational factors. The research was based on the example of the unit MTZ-80+2PTS-M in the Mariinsky district of the Kemerovo (Russia) in 2021. The method of control dynamometry was used to determine the probabilistic characteristics of the traction resistance of an agricultural trailer and its dependence on the load-speed mode. The studies were carried out on various backgrounds (unsurfaced road, grain stubble and sowing field) with a trailer load from minimum to maximum. Authors have studied the energy assessment of a tractor transport unit in relation to specific natural-production conditions of its operation. Based on the results authors have revealed the influence of high-speed and load operating modes of a tractor train and determined the operating weight rational values.

Keywords: Dynamometery; Traction Resistance; Slipping; Trailer.

Estimación de la resistencia al movimiento de un tren tractor de ruedas en ensayos de campo

Resumen.- El propósito del estudio fue determinar la resistencia al movimiento de un tren tractor de ruedas teniendo en cuenta la naturaleza aleatoria de los cambios en los factores operativos externos. La investigación se basó en el ejemplo de la unidad MTZ-80+2PTS-M en el distrito Mariinsky de Kemerovo (Rusia) en 2021. Se utilizó el método de dinamometría de control para determinar las características probabilísticas de la resistencia a la tracción de un remolque agrícola y su dependencia del modo carga-velocidad. Los estudios se realizaron en varios fondos (carretera sin asfaltar, rastrojo de cereales y campo de siembra) con una carga de remolque de mínima a máxima. Los autores han estudiado la evaluación energética de una unidad tractora de transporte en relación con las condiciones específicas de producción natural de su funcionamiento. Con base en los resultados, los autores revelaron la influencia de los modos de operación de alta velocidad y carga de un tren tractor y determinaron los valores racionales del peso operativo.

Palabras clave:Dinamómetro; Resistencia a la Tracción; Corrimiento; Remolque.

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1. Introduction

Transport operation in agriculture has a number of distinctive features associated with the variety of loads, different transportation distances and the complexity of road conditions. Therefore, it is impossible to use effective mode of transport, a certain complex of vehicles is needed that meets the operating conditions, taking into account the specific features of production [1, 2, 3].

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A significant volume of technological transport (up to 40 %) in agriculture is carried out by tractor transport units, as well as transport and technological means that combine the functions of transport and technological machines. As a rule, wheeled tractors are used for transportation, since they are more versatile than tracked ones, have lower initial and operating costs, and higher transport speeds.

However, as studies have shown, the productivity and fuel-economic efficiency of wheeled train exports are often limited not by the power of the tractor engine, but by its insufficient traction and coupling properties, as well as by its high energy consumption for movement, due to incorrectly selected operating modes jurisdiction to the specific conditions of the transport operation [4, 5, 6, 7].

Improving the efficiency of using a tractor train due to a reasonable choice of traction and speed parameters of the tractor, depending on the working loads and the conditions of the unit movement, can be considered relevant [8, 9, 10, 11].

The purpose of the study is the energy assessment of a tractor transport unit in relation to specific natural-production conditions of its operation, taking into account the random nature of changes in external operating factors [12, 13, 14].

To achieve this goal, the following tasks were solved:

- to carry out control dynamometry of the tractor trailer and to determine statistical estimates for the main traction- energy indicators of the MTA and the tractor;
- to reveal the influence of high-speed and load operating modes of a tractor train on the change in resistance to its movement using the basic theoretical provisions formulated on the basis of a mathematical model of the MTA functioning as the system "soil - agricultural machine - propeller - transmission - engine" ("S-Am-P-T-E");
- to determine the operating weight rational values and to estimate the required power range of the tractor engine for use as part of a transport unit, in relation to the conditions of the experiment.

2. Materials and methods

Field tests of the unit were carried out on the fields of the farm “N.N. Nepochatoi” in the Mariinsky district of the Kemerovo region in 2021 (Figure 1).

The experimental research program was developed in accordance with the requirements of the current regulatory documents (GOST 28307-2013, GOST R 52777-2007, GOST 7057-2001) and included the control dynamometry of the tractor trailer as part of the MTA to determine the effect of working loads and driving conditions on the resistance to movement tractor train and the dynamics of its change, assessing the compliance of the propeller slipping with the established requirements, as well as determining the statistical characteristics of the studied indicators [13], [15, 16, 17].

The unit energy assessment was carried out using the control, measuring and recording equipment manufactured by the Novokuban branch of the Federal State Budgetary Scientific Institution “RosIinformAgroTech”, which included the measuring information system SI-302 and a set of primary signal converters (sensors) (Figure 2)

The sensors installed on the unit are shown in Figure 2.

In the process of testing the unit, the following performance indicators were recorded and measured: traction resistance of the trailer (force on the tractor hook) (P, kN), working speed (Vp, m/s), slipping of the tractor driving wheels (δ,‰).

For installing of tools and sensors on the MTA, special devices were developed and manufactured to allow their reliable fixation during the experiment, as well as performing an ability to change their position quickly depending on the design features and layout of a particular operating tool as part of the MTA [18].

The unit test conditions were as follows:

- agrophone - unsurfaced road, grain stubble and sowing field;
- prior processing: unsurfaced road, grain stubble – no cultivation, sowing field - continuous cultivation (10 cm);
- soil type and structure - dark gray forest medium loamy;
- average absolute moisture and density of soil composition in the horizon of 0...15 cm: grain stubble - 37,48 ‰ or 1,18 g/cm^3, sowing field - 35.86 ‰ or 1,05 g/cm^3, respectively.

Energy poverty assessment of the honest transport preparatory unit justice was carried out at the time limit of three minimum levels of the equator of the useful chip loading of the trailer

(a)

(b)

(c)

Figure 1: Tractor transport unit MTZ-80 + 2PTS-4M in field tests

building, in the entrance limits of its poverty of the established finances of the nominal coniferous (maximum) land use load capacity. The weight of the coniferous trailer is at least in accordance with the minimum level of its loading justice with a minimum of outpost dynamometry, the chemical is given in smooth Table 1.

The trailer dynamometry was carried out when the unit was moving within the range of recommended operating speeds (up to 20 km/h) [19]. Measurements were made when the unit was moving within the test plot.

The energy assessment of the transport unit was carried out at three levels of the trailer's payload, within its specified nominal (maximum) carrying capacity. The trailer weight in accordance with the level of its load during dynamometry is given in Table 1.

The number of experiments and the average duration of the implementation of those, depending on the type of agricultural background in the range of change in the trailer payload $G(min)$ - $G(max)$, are presented in Table 2.

The measurement results for calculating such statistical evaluative characteristics as mathematical expectation $M(x)$, maximum xmax and minimum xmin values, standard deviation $\sigma(x)$ and variation $v(x)$ were processed by the method of analysis of variance [20] (Table 3).

Table 1: Values of the trailer 2PTS-4M weight during field tests

Indicator	Trailer payload levels		
	G_{min}	G_{mid}	G_{max}
Payload of the trailer, kN	0	17,8	35,5
Trailer weight, kN			
- structural	17,2		
- operational	17,2	34,95	52,7

3. Results

According to the test results of the transport unit and depending on the trailer payload, the average

(a) general view of the unit MTZ-80 + 2PTS-4M equipped with sensors

(b) strain gauge sensor for measuring tractive effort K-R-20G-20-C1

(c) sensors of driving wheel revolutions on the tractor IP-268

(d) distance traveled sensor IP-266

Figure 2: General view of the sensors installed on the unit

Table 2: Parameters of the experiments

Agricultural background	Sample size, N	Duration of the experiment		Average length of the test plot, m
		Time, s	Distance, m	
Unsurfaced road	33	29,91	70,25	1159,1
Grain stubble	38	29,75	76,81	1429,9
Sowing field	27	30,03	59,77	806,7

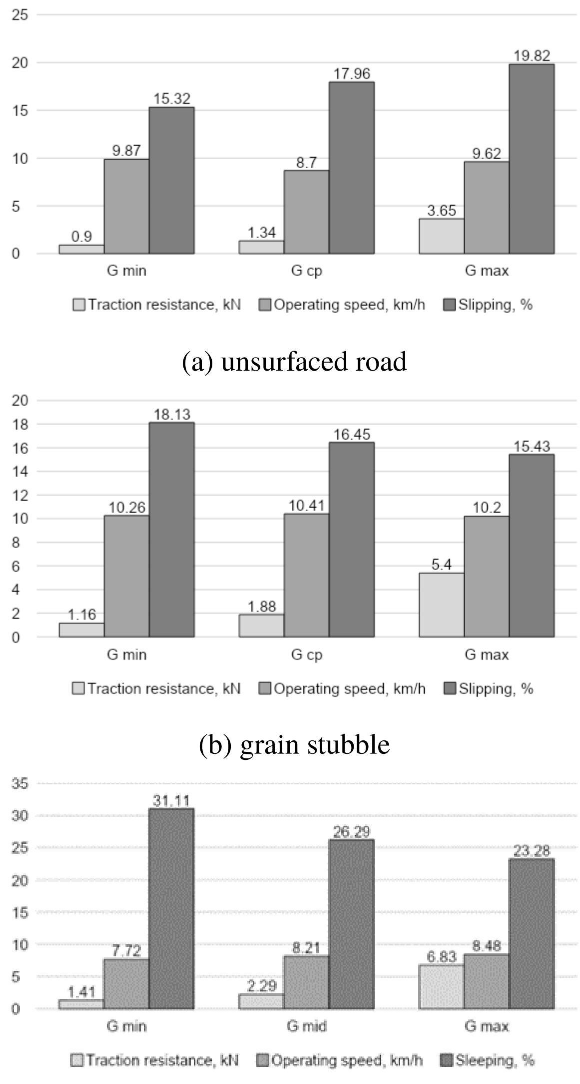
Table 3: Descriptive statistics of the unit performance, determined during dynamometry

Indicator	$M(x)$	x_{max}	x_{min}	$\sigma(x)$	v, %
Agricultural background: unsurfaced road					
P, kN	2,10	4,21	0,85	1,22	57,95
Vp, m/s	9,45	11,91	7,60	0,92	9,73
Agricultural background: grain stubble					
P, kN	2,90	6,41	1,08	1,75	60,45
Vp, m/s	10,29	11,93	5,52	0,95	9,20
Agricultural background: sowing field					
P, kN	3,71	9,01	1,26	2,31	62,3
Vp, m/s	8,16	9,62	6,81	0,69	8,41

values of the main energy indicators varied within the following limits (Figure 3).

Driving on agricultural backgrounds (stubble, cultivated soil) led to an increase in the trailer moving cost in comparison with the unsurfaced road, on average it was: on stubble - by 32,4 %, on the sowing field - by 46,6 %.

When driving on the unsurfaced road and stubble background, the tractor MTZ-80 ensured the fulfillment of the established agrotechnical requirements (18 %) for the slipping of the propellers, when the operating weight of the trailer changed from the structural weight to the one corresponding to the nominal load. When driving



(a) unsurfaced road

(b) grain stubble

(c) sowing field

Figure 3: Dependence of the average indicators of the tractor train dynamometry on the agricultural background and the trailer load

across the field for sowing, the propeller slipping exceeded the established requirements within the entire range of changes in the transport load, on average it varied within 23,3–31,1 %.

The processing of the experimental data (Table 3) made it possible to obtain graphical dependencies (Figure 4), as well as equations for the relationship of the average tractive effort on the tractor hook (tractive resistance of the trailer) (P, kN) with the working speed (Vp, m/s) and slipping of the tractor driving wheels (δ,%) on: - unsurfaced road (equations (1) and (2)):

$$P = 2.83 + 0.262 \cdot V_p^2, \quad R = 0.741; \tag{1}$$

$$\delta = 11.82 + 0.77 \cdot P, \quad R = 0.582. \tag{2}$$

- grain stubble (equations (3) and (4)):

$$P = 1.82 + 0.27 \cdot V_p^2, \quad R = 0.775; \tag{3}$$

$$\delta = 16.64 + 0.46 \cdot P, \quad R = 0.672. \tag{4}$$

- sowing field (equations (5) and (6)):

$$P = 2.95 + 0.07 \cdot V_p^2, \quad R = 0.589; \tag{5}$$

$$\delta = 21.46 + 0.42 \cdot P, \quad R = 0.383. \tag{6}$$

The processing of teat data obtained on various agricultural backgrounds made it possible to form equations for the relationship between the resistance force to the tractor trailer movement (tractive effort on the tractor hook) ($P_f = P, kN$) and the resistance to the unit movement ($P_a = P_f + P, kN$) with the payload of the trailer (G, kN) taking into account the state of the agrophone (f) (Figure 5):

- resistance to the trailer movement $P_f = P$ (equation (7)):

$$P = 4.608 + 0.349 \cdot G + 1.916 \cdot G \cdot f, \quad R = 0.885; \tag{7}$$

- resistance to the unit movement $P_a = P_f + P$ (equation (8)):

$$P_a = 4.781 + 0.349 \cdot G + 23.59 \cdot f + 1.916 \cdot G \cdot f, \quad R = 0.817; \tag{8}$$

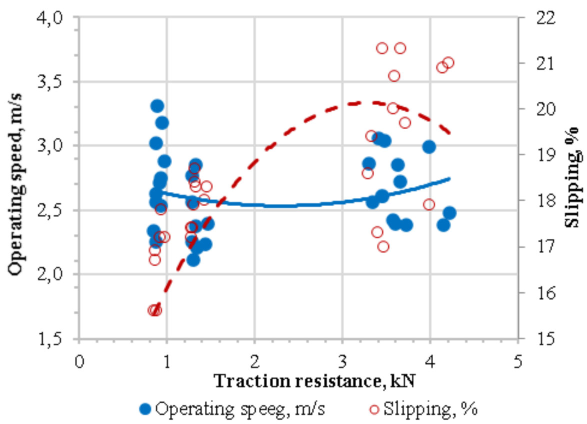
The resistance coefficient of the unit's running systems characterized the state of the agrophone and was determined on the basis of the data obtained during the unit dynamometry (Table 4) with the equation (9).

$$f = \frac{P}{G}, \tag{9}$$

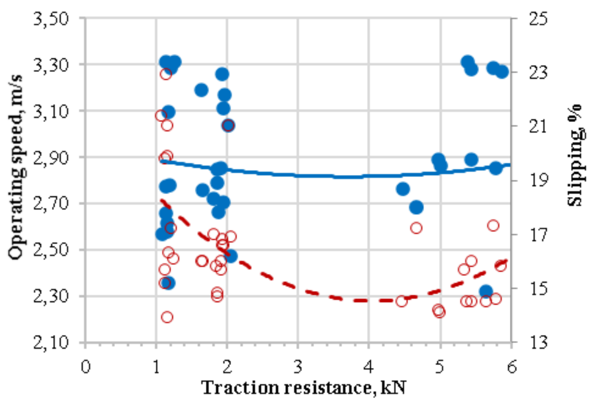
where P is the traction resistance of the unit, G is the weight of the trailer. The average energy

Table 4: Average energy performance values of the trailer 2PTS-4M

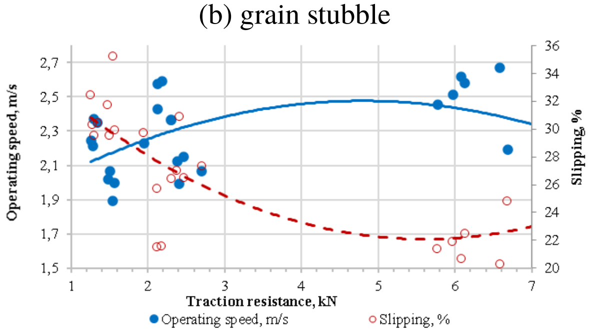
Agricultural background	Sample size N	$M(P)$, kN	$\sigma(P)$, kN	$\nu(P)$, %	f
Unsurfaced road	33	2,10	1,219	57,9	0,055
Grain stubble	38	2,90	1,754	60,5	0,075
Sowing field	27	3,71	2,311	62,3	0,094



(a) unsurfaced road

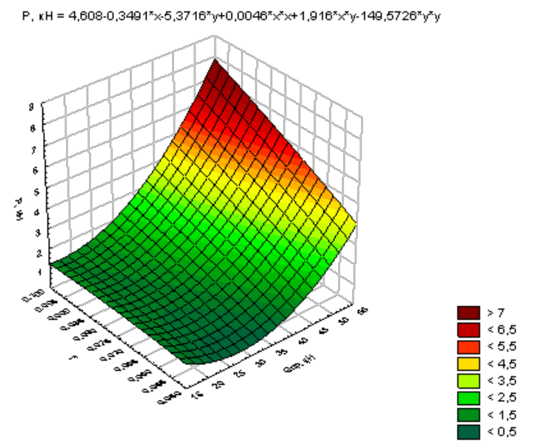


(b) grain stubble

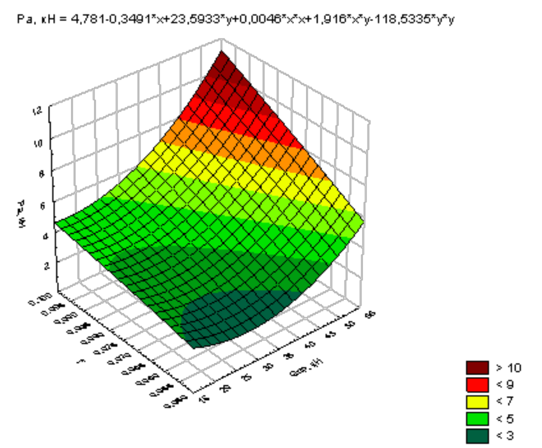


(c) sowing field

Figure 4: Dependence of the average operating speed and slipping of the tractor propellers on the 2PTS-4M traction resistance



(a) resistance force to the trailer movement (tractive effort on the tractor hook)



(b) resistance force to the tractor train movement

Figure 5: Dependence of the resistance force components to the movement of the tractor train MTZ-80+2PTS-4M on the trailer payload and the state of the agricultural background

performance values of the trailer 2PTS-4M are shown in Table 4.

The obtained generalized data on the unit power indicators made it possible to use the developed probabilistic model of the MTA functioning as the system “soil - agricultural machine - propeller - transmission - engine” (“S-Am-P-T-E”) [13, 21] with the calculated probability to predict the values of the parameters and output performance indicators of the tractor for a particular soil climatic zone in conditions of unsteady external influences.

Operating weight of the tractor required to ensure the fulfillment of agrotechnical requirements for propeller slipping, kN:

$$G'_{tr} = \frac{P_{max}}{\lambda\left(\varphi_{max} - Ae^{-B[\delta]_{max}}\right)}, \quad (10)$$

where P_{max} is the maximum value of the tractor average tractive effort (traction resistance of the unit) obtained under the test conditions, $[\delta]_{max}$ is the maximum allowable amount of the tractor driving wheels' slipping according to agrotechnical requirements, λ is the redistribution coefficient of the tractor operating weight the between its axles; A, B, ϕ_{max} are the function coefficients that approximate the propeller slip curve during traction tests of the tractor.

According to the equation (10), the average value of the tractor operating weight G'_{tr} was calculated, which is necessary to fulfill the established agrotechnical requirements for slipping of its propellers (Table 5).

When working within the entire range of transport load and under various driving conditions, the minimum value of the tractor operating weight should be 38,8 kN, which is by 13,1 % less than the weight of the tractor MTZ-80 (33,7 kN).

According to the literature data [13, 21], to determine the values of the unit traction power, there was used the equation (11), kN:

$$N_{\text{kp}} = N_{\text{H}}\lambda_N\eta_{\text{T}}, \quad (11)$$

where N_{H} is the rated power of the tractor engine, kW; λ_N – is the coefficient of using the rated power of the tractor engine.

The coefficient λ_N (equation (12))that depends on the tractor technical characteristics, the conditions for the unit testing and the statistical characteristics of the draft resistance of the working agricultural. Machine; thus, it can be determined using a highly significant regression dependence obtained by scientists of the Altai State Agrarian University, according to the test results [13]:

$$\begin{aligned}\lambda_N = &114 - 13,85q + 8,43\varepsilon_0 \\ &+ 157.3v\left(P_0\right) - 161.3qv\left(P_0\right) \\ &- 162.7v\left(P_0\right)^2,\end{aligned} \quad (12)$$

where q is the average denominator value of the geometric series of the tractor main transmission range; ε_0 is the proportionality coefficient, s^2/m^2; $v\left(P_0\right)$ is the variation coefficient of the average reduced traction resistance of the unit.

Traction efficiency of the tractor is calculated by equation (13)

$$\eta_{\text{T}} = \eta_{\text{Tp}}\eta_f\eta_\delta, \quad (13)$$

where η_{Tp}, η_f, η_δ – time-pressure efficiency mechanical losses in the tractor transmission, losses for the tractor rolling and slipping of its propellers, respectively.

- time-pressure losses for the tractor rolling (equation (14))

$$\eta_f = 1 - \frac{P_f}{P_f + P}. \quad (14)$$

- chipped losses for the slipping of the tractor propellers (equation (15))

$$\eta_\delta = 1 - \delta, \quad (15)$$

where δ (equation (16)) is the slipping of the tractor driving wheels. The calculated value of the tractor propellers' slipping with an operating weight G'_{tr} was obtained by expressing it from the equation (10)

$$\delta = B^{-1}\ln\left(\frac{A}{\varphi_{max} - \dfrac{P}{\lambda[G'_{tr} + \Delta G_{tr}]}}\right). \quad (16)$$

Tractor rolling resistance force was calculated with the equation (17)

$$P_f = f \cdot G'_{tr}. \quad (17)$$

The traction power of the unit, according to the results of control dynamometry, can also be calculated using the equation (18):

$$N_{\text{kp}} = PV_p.(18) \quad (18)$$

Table 5: The results of calculating the value of the tractor operating weight when aggregated with the trailer 2PTS-4M

Agricultural background	V_{pmax}, km/h (m/s)	P_{max}, kN	coefficients			λ	$[\delta]_{max}$, %	G'_{tr}, kN
			A	B	C			
unsurfaced road	11,91(3,31)	4,21	0,756	8,82	0,7	0,6	18	18,13
grain stubble	11,93(3,31)	6,41	0,75	8,81	0,6	0,6	18	27,6
sowing field	9,62(2,67)	9,01	0,65	7,35	0,55	0,6	18	38,8

Table 6: The results of calculating the average value range of the rated power of the of a power unit engine when aggregated with 2PTS-4M

Agricultural background	G, kN	P, kN	P_f, kN	η_f	δ, %	η_δ	η_T	N_{kp}, kBt	λ_N	G'_H, kW
unsurfaced road	17.2	0.85	1.0	0.46	3.9	0.96	0.41	2.83	0.93	7.39
	34.95	2.10		0.68	6.3	0.94	0.60	7.00		12.47
	52.7	4.21		0.81	10.2	0.90	0.71	14.03		21.24
grain stubble	17.2	1.08	2.07	0.34	9.0	0.91	0.30	3.60	0.93	12.78
	34.95	2.90		0.58	11.4	0.89	0.51	9.67		20.34
	52.7	6.41		0.76	16.5	0.84	0.65	21.37		35.35
sowing field	17.2	1.26	3.65	0.26	10.6	0.89	0.23	4.20	0.93	19.9
	34.95	3.71		0.50	13.4	0.87	0.44	12.37		30.13
	52.7	9.01		0.71	17.8	0.82	0.61	30.03		53.19

By substituting the expression (18) into the equation (11) and solving it, taking into account equations (12)... (17) with respect to N_H, the calculated range of average values of the rated engine power N'_H was determined to be used as part of the unit during operation within changing the payload of the tractor trailer $G_{min} - G_{max}$ without violating the established requirements for operating speed and slipping of propellers [13, 22, 23, 24, 25] (Table 6).

When operating within the established range and under various driving conditions, the required value of the rated engine power should be 21,2–53,2 kW, which is on average by 11,4 % lower than the tractor MTZ-80 used in the unit (60 kW).

The average values of the tractor operating weight and the rated engine power, depending on the driving conditions of the transport unit, are shown in Figure 6.

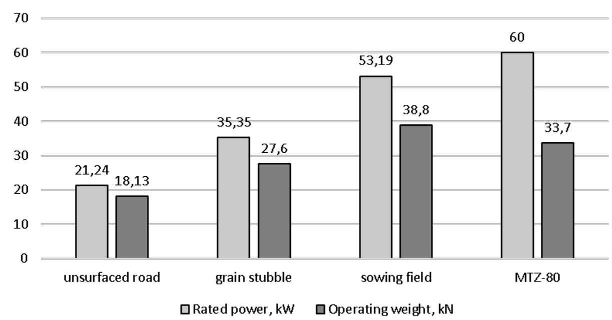


Figure 6: Average required values of the operating weight and the rated power of the power unit engine

4. Conclusions

On the basis of the tractor transport unit energy assessment, it was found that the movement on agricultural backgrounds (stubble, cultivated soil) within the studied range of operating speeds of 5,52–11,93 km/h (1,53–3,31 m/s) led to an increase in the cost of the trailer moving in comparison with the field road, on average it was on stubble - by 32,4 %, in the field for sowing - by 46,6 %. The increase in the tractor moving cost was on average: on stubble - by 51,7 %, in the field for sowing - by 72,6 %. In general, the resistance to movement of the tractor train increases by 37,8 % when driving on the stubble background and by 55,6 % when driving on the cultivated soil.

When driving on the unsurfaced road and the stubble background ($f = 0.055 - -0.074$), the tractor MTZ-80 ensured the fulfillment of the established agrotechnical requirements (18 %) for the propellers' slipping, when the operating weight of the trailer changes from the structural weight to the one corresponding to the nominal load (17,2–52,7 kN). When driving on cultivated soil ($f = 0.093$), the slipping of the propellers exceeded the established requirements within the entire range of changes in the transport load, on average it varyed within 23,3–31,1 %.

The calculated average values of the operating weight of the power unit required to fulfill the agrotechnical requirements for slipping of its driving wheels when aggregated with the trailer 2PTS-4M, depending on the driving conditions of the unit, were 18,1–38,8 kN. The calculated average values of the required rated power of the power unit engine, depending on the movement conditions were 21,2–53,2 kW (28,8–72,35 hp).

Based on the calculated values of operational indicators, the tractor MTZ-80 aggregated with the trailer 2PTS-4M has sufficient indicators of the rated engine power within the entire range of changes in driving conditions ($f = 0,055--0,093$) and working loads (17,2–52,7 kN); however, it has insufficient operating weight (lower than the calculated one by 13,1 %), when driving on cultivated soil. To ensure the required traction and coupling performance, it is necessary to provide additional ballasting of a tractor weighing 0.51 kN or the use of a wheel arrangement modification 4K4a - MTZ-82 with an operating weight of 40 kN.

To develop specific zonal recommendations for the aggregation of the trailer train, it is necessary to conduct additional field tests with a wider range of variation of their conditions, parameters and operating modes of the unit.

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