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DETERMINING CONDITIONS FOR PROVIDING MAXIMUM TRACTION EFFICIENCY OF TRACTOR AS PART OF A SOIL TILLAGE UNIT

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This study aims to investigate the operation of a tractor as part of the tillage unit on the basis of analysis of its interaction with the supporting surface and the correlation between the mass of the tractor and tool. The classic approach to determining the efficiency factor does not take into account the extensive system of power take-off shafts and the extent of their use in combined tillage units. To solve the related problem, a mathematical apparatus was built in the study, which makes it possible to determine the rational ratio between the traction force of a tractor and the mass of the tillage unit.

Underlying the methodological basis of the work is the generalization and analysis of the study of traction indicators of the tractor as part of the tillage unit. Empirical models of unit operation were constructed by employing the basic principles of the system approach and analysis of technical systems. When improving the methodology of research using the method of partial accelerations and our devised procedures, it was possible to significantly reduce the time without compromising the quality of results. The maximum traction efficiency for John Deere 8R series tractors as part of the tillage unit was determined, $\eta_{T max}=0.719$, as well as the conditions for its provision. The traction efficiency for tractors with wheel formula 4K2, mass $G_{im}=6-10$ t, with power consumption from 60 % to 80 % was determined; it is 0.58–0.64. The results of the study make it possible to obtain a new solution to the scientific problem of ensuring the maximum traction efficiency of the tractor as part of the tillage unit, based on the rational ratio between the traction force of the tractor and the weight of the machine-tractor unit. The proposed system approach could be used to justify the layout of units and recommendations regarding their modes of operation in the case of instability of operating mass and traction force

Keywords: traction efficiency of the tractor, partial acceleration, combined unit, traction force

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1. Introduction

The system approach is an area in the methodology of scientific knowledge, which is based on the study of objects as systems and the conditions of their functioning [1]. Increasing the efficiency of work in the agricultural sector is associated with the need for scientific substantiation of the evaluation of the operational qualities of agricultural tractors when performing various technological operations [2]. To characterize the tractor's potential traction capabilities, the maximum traction force or specific fuel consumption per unit of traction power is used in the English-language scientific literature. This is due to the accepted classification of tractors by engine power. However, a more informative parameter is the very concept of tractor efficiency, which is defined as the share of engine power spent on tractor movement. For more than 100 years, this definition has been the basis for evaluating the traction efficiency of a traction concept tractor and remains relevant for the traction-power concept, as it allows taking into account the power of PTO. To evaluate the qualities of a tractor when performing a certain technological process, a systematic approach based on the analysis of its traction efficiency is proposed [3]. The classic traction calculation does not take into account the specific agricultural tool and assumes the rated load of the engine for each gear, which is almost impossible to achieve under actual operating conditions. The approach to ensuring the maximum traction efficiency needs further development, as it is based on the analysis of the interaction of the tractor with the supporting surface and does not take into account the influence of the mass of the tractor unit and the traction force of the tractor. The efficiency of the unit is determined by the realization of the potential capabilities of the engine and traction power of the tractor, the extent of such realization characterizes the traction efficiency. Therefore, it is a relevant task to determine the maximum traction efficiency of a tractor precisely in the correlation of the mass of the tractor unit and the traction force of the tractor; such a study specifies directions for increasing the traction efficiency, improving the layout of units and, as a result, enhancing work efficiency.

2. Literature review and problem statement

Work [4] reports the results of research into the traction efficiency of a tractor, aimed at ensuring its optimal value, and determines the factors affecting its change. But there remained the problem of determining the degree of influence on the traction efficiency of the instability of the traction force on the hook and the rolling resistance of the wheels of the driving axles. A solution option may be the approach proposed in [5], which takes into account changes in the traction efficiency depending on the speed losses of the plow. However, the lack of a systematic approach to take into account the influence of dynamic parameters does not make it possible to ensure the maximum traction efficiency of the tractor. In [6], the results of the study of the influence of the geometric parameters of the frame of the traction vehicle on its traction and energy indicators are given. The use of the proposed methodology for calculating the redistribution of tractor weight along the axes optimizes the design parameters. However, this technique does not allow taking into account the influence of the mass of the agricultural machine since it is designed for a single tractor.

In work [7], attention is drawn to the fact that an increase in traction efficiency can be achieved due to the use of all-wheel drive and the redistribution of the weight of the tractor along the axles, taking into account the configuration of the tires. In the cited work, along with efficiency, the influence of tractor drives on soil compaction is given a decisive place. In [8], wheel movement with poor traction and high axle load was indicated as the main source of soil compaction along with a decrease in traction efficiency. As a solution, a modern traction wheel was developed, which makes it possible to increase the transmission of engine power with increased efficiency and less damage to the environment. However, this approach does not take into account additional loading of the tractor with the mass of the aggregated agricultural machine, especially when the mass changes during the technological operation. The variable load that causes such an additional load can be simulated using PowerMix tests, as reported in [9], which, together with the optimal selection of the mode, will increase the traction efficiency of the tractor.

It should be noted that modern and promising agricultural machines have a complex structure and, in some cases, a large mass, which reaches the mass of the traction vehicle. This mass can be used as a traction force to create a traction force, which will allow agricultural machines to be aggregated with traction means of a lower traction class and at the same time reduce energy consumption and soil compaction. In work [10] it is stated that the vertical load on the wheel and the pressure in the tires are easily controlled parameters that play an important role in soil cultivation operations. In the cited study, traction was chosen as the determining parameter, but traction efficiency is more appropriate, as it systematically evaluates the efficiency of the tractor. Paper [11] cautions against over-inflating the tire, which leads to increased skidding and can increase fuel consumption by 20 % or more and cause significant compaction. That is, the variation of the vertical load on the wheel, the mass of the agricultural machine, and the change in pressure must be used from the position of an integrated approach to ensure maximum traction efficiency.

In [12], a semi-empirical soil-tire interaction model adapted to simulate traction characteristics of front-wheel drive tractors is considered. This model simulates traction performance, traction efficiency, rolling resistance, wheel load taking into account tire size and pressure. The disadvantage of this model is the need to conduct experimental, field traction studies to obtain empirical coefficients. Such research is a long process that requires the presence of measuring equipment, a device for creating traction resistance, and is costly.

Code 2 of the OECD (Organization for Economic Cooperation and Development) [13] defines the methods of testing tractors when evaluating their operational qualities. The main indicators include power indicators, fuel efficiency of the engine and tractor, its controllability, and braking properties. It should be noted that such tests are energy-intensive and long, so obtaining experimental results is a difficult task. An option to overcome the relevant difficulties can be the use of accelerated tests or non-motorized express tests. This is the approach used in paper [14], in which a systematic approach to the evaluation of traction qualities of a tractor, based on the analysis of accelerations of its movement, is proposed. This method is implemented in SOU 71.2-37-046043090-017:2015 on the determination of traction indicators of a tractor during tests. However, the issue of determining the traction qualities of a tractor in a unit with a variable mass machine remains unresolved. Many non-OECD countries, including Ukraine, partially or fully use OECD codes for tractor testing. The Kharkiv branch of UkrNDIPVT has carried out a number of scientific studies on the evaluation of the functional qualities of tractors and their metrological support during tests [15]. At the same time, by analogy with related fields of technology, the tractor is considered as «a system with many elements, interconnected in a certain way, which form a certain integrity, unity». However, these results are not systematized from the standpoint of solving the problem of ensuring maximum traction efficiency, especially for combined units with variable mass and the use of a power take-off shaft.

Reducing the load on the tractor can be achieved by transferring part of the mass of the aggregated agricultural machines to the driving wheels of the additional traction-technological cart. The peculiarities of the management of these units have not received adequate coverage in the technical literature when evaluating their energy savings and pose new challenges in solving this scientific problem. Work [16] considers a system that can control the weight of the equipment and the intensity of movement in the field thanks to the improved traction characteristics of wheeled tractors. However, incomplete work and the need for additional research are noted.

At the same time, it is indicated in [17, 18] that a systematic approach currently does not exist in the form of a methodological concept for increasing the traction and power qualities of a tractor. This gives grounds for asserting that it is expedient to construct a mathematical apparatus for assessing these qualities.

All this gives reason to assert that it is expedient to conduct a study in order to determine the dependence of the maximum traction efficiency of a tractor as part of a tillage unit on the tractive force and weight of the unit.

3. The aim and objectives of the study

The purpose of our work is to determine the mass of the tractor unit and the traction force on the tractor hook, which ensure the maximum traction efficiency of the tractor.

To achieve the goal, it is necessary to solve the following tasks:

– to formalize the description of the traction efficiency of the tractor as part of the tillage unit;

– to investigate the traction properties of traction-drive, combined agricultural assemblies, taking into account the factors of their layout (use of the front and rear power take-off shafts PTO and the sequence of combining the elements of the assembly).

4. The study materials and methods

The object of our study is the process of performing agricultural work by a wheeled tractor as part of traction and traction-drive (combined) tillage units.

Research hypothesis: the maximum tractive efficiency is determined by the tractive effort and the mass of the unit as the point of intersection of two curves in three-dimensional space (tractive efficiency, tractive effort, mass of the unit).

Accepted assumptions and simplifications:

– the tractor is considered as a completely solid body;

– the forces on the drive wheels and on the hook are determined at constant values of the resistance to rolling and skidding of the pushers (the maximum value for this agrophone is taken);

– unit movement speed during technological operation V=const.

The research methodology is based on the method of partial accelerations [14], underlying which is the reverse transition from the vector sum in the space of forces acting on the tractor to the vector sum in the space of accelerations. The measurement and registration module designed with our participation, which is based on the use of capacitive accelerometers with three working axes, is effective for evaluating the accelerations of the tractor unit on the run (Fig. 1).

The module consists of two or four three-coordinate acceleration sensors MMA 7260 QT, an information device – a laptop for data collection and archiving, equipment for photo-video recording of research.

The movement of the tillage machine-tractor unit (MTU) is executed when the traction force of the tractor and the resistance of the working bodies of assembled agricultural machines are exceeded. Research is carried out on a John Deere 8335R tractor.

Fig. 1. Arrangement of the measuring and registration module in the tractor cab: 1 – acceleration sensors; 2 – a personal computer for data collection and archiving

Technical characteristics of John Deere 8335R tractors:

– rated power of internal combustion engine, N_e, kW – 246;

– traction power, N_T, kW – 212;

– operational mass, m_o, kg – 13820;

– energy saturation, $E=N_e/m_o$, kW/kN – 1.81.

When determining the parameters of the tractor and its traction characteristics, the requirements for different groups of technological operations of the main tillage according to the working speed of the unit are taken into account [2]:

1 – plowing and deep loosening with a rated speed of movement $V_{n1}=2.2\pm0.25$ m/s;

2 – post-harvest no-till combined processing (continuous cultivation), disking and chiseling $V_{n2}=2.7\pm0.3$ m/s;

3 – surface post-harvest treatment (hulling of stubble), pre-sowing treatment and sowing according to zero technology $V_{n3}=3.3\pm0.5$ m/s.

A comparison of the calculated mass-energy parameters of a tractor with different operational mass m_o when performing all three groups of operations allows us to establish its rational specific mass m_{sp}, kg/kW:

$$m_{sp}=\frac{\eta_T\cdot 10^3}{g\cdot\varphi_w V_n},\qquad (1)$$

where η_T is the traction efficiency; g – acceleration of free fall, m/s^2; φ_w – coupling weight utilization factor; V_n is the rated speed of movement of the unit, m/s.

Determining the mass of a tractor, an assembled agricultural machine, and its resistance force is carried out according to the techniques formulated on the basis of the method of partial accelerations [3, 15, 19]:

– the mass of agricultural machines when assembled with a tractor is determined by the advance acceleration (clutch off, neutral gear) on a certain soil background. For example, on a dirt road, to a certain stop of a tractor with and without an agricultural machine at the same start speed;

– the resistance force of an agricultural machine when assembled with a tractor is determined with the known mass of the tractor and the agricultural machine by the difference of the longitudinal accelerations of acceleration on a certain soil background of the tractor with the agricultural machine in the transport and working positions.

Traction efficiency of the tractor is estimated according to the dependence:

$$\eta_T = \frac{\dot{V}_{af} / \left(1 + m_{im} / m_T\right) - \dot{V}_s}{\dot{V}_{af} - \dot{V}_s}, \tag{2}$$

where m_T, m_{im} are, respectively, the mass of the tractor, agricultural attachment, kg; $\dot{V}_{af}$ – partial acceleration during acceleration under the action of only the rolling resistance force of the tractor wheels, m/s^2; $\dot{V}_s$ – partial acceleration during the advance of the tractor, m/s^2.

When $\dot{V}_{af}$ and $\dot{V}_s$ are known, the tangential force on the driving wheels P_k and on the hook of the tractor P_T is determined as a function of:

$$P_k = \left(m_T + m_{im}\right)\left(\dot{V}_{af} - \dot{V}_s\right); \tag{3}$$

$$P_T = m_T\left[\dot{V}_{af} - \left(1 + m_T / m_{im}\right)\dot{V}_s\right]. \tag{4}$$

Analysis of dependences (3) and (4) shows that the traction efficiency of the tractor as part of the tillage unit depends on its mass and traction force.

The traction properties of the combined MTU with active working bodies are evaluated when performing a certain technological process by the ratio of the traction force of the tractor and the active working body. The research methodology involves measuring the weight of the tractor and the weight of the agricultural unit by analogy with tillage units.

5. Results of studying operation of the tractor as part of the tillage unit

5. 1. Formalization of the mathematical apparatus for describing the traction efficiency of a tractor as part of a tillage unit

In the practice of designing and operating tractors, the efficiency of the tractor η_T takes into account energy losses during power transmission in the transmission η_{Tr}, in the running system η_r, on skidding η_δ and on movement resistance η_f [2, 4]:

$$\eta_T = \eta_{Tr}\eta_r\eta_\delta\eta_f. \tag{5}$$

Transmission efficiency η_{Tr} depends mainly on the transmitted power $\eta_{Tr}=f_1(N)$; η_r depends on the transmitted power N, the towing mass of the tractor m, and the support area of the running system S $\eta_r=f_2(N, m, S)$; η_δ, η_f is a function of the speed of movement V, coupling mass m, support area of the running system S, and traction force P η_δ, $\eta_f=f_3$, $f_4(V, m, S, P)$.

Thus, dependence (5) is recorded as follows:

$$\eta_T = f_1(N) f_2(N,m,S) f_3(V,m,S,P) f_4(V,m,S,P). \tag{6}$$

When estimating the extremum η_T is a function of four variables V, m, S, P, which are not independent but are connected by one or more variables, it is possible to determine a relative (or conditional) extremum. For example, when determining the extremum of power loss reduction in the running system $\eta_r=f_2(N, m, S)$, the problem is solved under additional conditions: $\varphi(N, m, S=a)$ and $\psi(N, m, S=b)$, where a and b are constant values. The functional dependence $\eta_r=f_2(N, m, S)$ is written in the form:

$$F(N,m,S) = f(N,m,S) = \lambda\varphi(N,m,S) + \mu\psi(N,m,S),$$

where λ and μ are undefined factors.

The necessary condition for the extremum of the function $f(N, m, S)$ is expressed by the dependences $\varphi=a$; $\psi=b$; $\partial F/\partial N = 0$; $\partial F/\partial m = 0$; $\partial F/\partial S = 0$.

Analysis of the extremum of the function $f(N, m, S)$ was performed under the initial conditions N_0, m_0, S_0, λ_0, μ_0, given by the standards for estimating the extremum of traction efficiency.

If for any increments dN, dm, dS satisfying the equalities $d\varphi=0$ and $d\psi=0$, the sign of the 2nd-order differential of the function $F(N, m, S)$ remains positive, then at the points N_0, m_0, S_0 the functions have a minimum, with a negative – a maximum.

The geometric interpretation of the functions of the variables in this case will represent an n-dimensional space, and the extremum will be located in the n-1st hypersurface.

To determine the parameters of two variables of the MTU mass $m_a=m_T+m_{im}$ and the traction force of the tractor P_T, at which $\eta_{T\max}$ is provided, it is necessary to solve the following equations:

$$\frac{\partial\eta_T}{\partial m_0} = f_1\left(\frac{\partial f_2}{\partial m_0} f_3 f_4 + \frac{\partial f_3}{\partial m_0} f_2 f_4 + \frac{\partial f_4}{\partial m_a} f_2 f_3\right) = 0; \tag{7}$$

$$\frac{\partial\eta_T}{\partial P_T} = f_1\left(\frac{\partial f_2}{\partial P_T} f_3 f_4 + \frac{\partial f_3}{\partial P_T} f_2 f_4 + \frac{\partial f_4}{\partial P_T} f_2 f_3\right) = 0. \tag{8}$$

In this example, the task of a function of two variables is solved, which, when interpreted geometrically, represents a surface in three-dimensional space in the form of an inverted bowl (Fig. 2). The extreme value $\eta_{T\max}$ corresponds to its highest point.

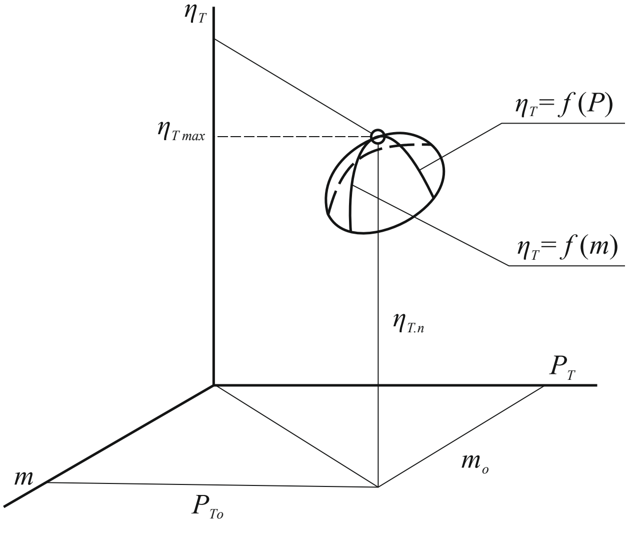


Fig. 2. Dependence of traction efficiency of the tractor η_T on its operational weight m_o and traction force P_T

The estimation $\eta_T=f(m, P_T)$ of the John Deere 8335R tractor by the method of partial accelerations (2) is based on the results of experimental studies during the performance of the most energy-intensive tillage operations in the first (ploughing), second (continuous cultivation), and third (sowing) groups (Table 1).

Table 1

Traction qualities of the John Deere 8335R tractor for the basic groups of tillage operations

Group of operations	Configuration	V, m/s	N_T, kW	P_T, kN	m_o, kg	m_{sp}, kg/kW	η_T
1	1K	2.28	209	65	13820	66.1	0.666
	2K	2.26	213	70	15470	72.6	0.712
2	1K	2.70	214	69	13820	64.5	0.702
	2K	2.65	221	73	14370	65.0	0.719
3	1K	3.61	216	44	11680	54.0	0.673
	2K	3.63	225	47	12950	57.5	0.714

Note: V is the MTU movement speed; N_T – traction power of the tractor; P_T – traction force; m_o, m_{sp} – operational and specific mass; η_T – traction efficiency; 1K, 2K – single and double wheels

An analysis of the traction qualities of the John Deere 8335R tractor with different values of m_o allows us to draw the following conclusions. When performing plowing (operation of the first group) in the traction range, which is limited by towing $0.08 \leq \delta \leq 0.15$, the most efficient is the tractor with the specific mass m_{sp}=66.1 kg/kW and the 1K equipment. The towing range of the tractor δ=0.08–0.15 makes it possible to make maximum use of the capabilities of the 4K4 wheel scheme due to the optimal distribution of specific and, accordingly, operating mass. For other operations of the first group, it is preferable to use MTU with a tractor specific mass of 72.6 kg/kW on double wheels, ensuring an increase in η_T from 0.666 to $\eta_{T\max}$=0.712.

The John Deere 8335R tractor in the 1K configuration is the most effective in soil cultivation operations of the second group with a specific mass of m_{sp}=64.5 kg/kW. Installing double wheels allows one to increase the traction power from 214 to 221 kW at $\eta_{T\max}$=0.719.

In the operations of the third group (Fig. 3, [20]), the maximum energy efficiency of the John Deere 8335R tractor was achieved in sowing at specific mass m_{sp}=57.5 kg/kW and operational m_o=12950 kg at $\eta_{T\max}$=0.714.

John Deere 8R series general-purpose tractors are equipped with front and rear power take-off shafts (PTO), which provide the drive of the working bodies of mounted and trailed agricultural machines and implements as part of a combined agricultural unit. For these units, the efficiency is calculated based on:

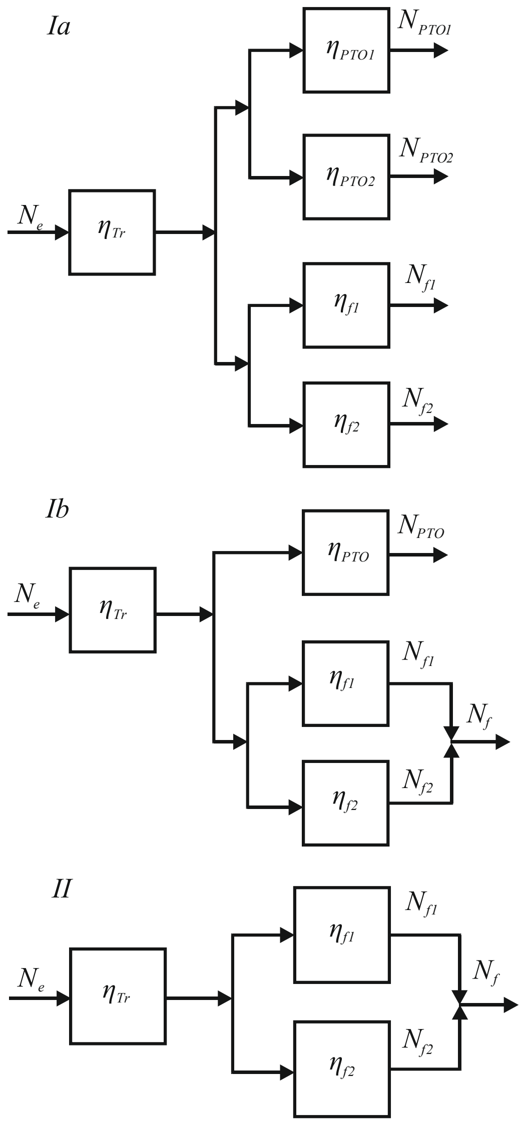
$$\eta_a = \frac{\prod_i^n \eta_T \sum_i^n N_T}{\sum_i^n \left(N_T \Big/ \prod_i^n \eta_y \right)}, \tag{9}$$

where $\prod_i^n \eta_T$ is the product of the efficiency of the power flow distribution links connected in series; $\sum_i^n N_T$ is the sum of usable capacities on the output links of parallel consumers; $\prod_i^n \eta_y$ is the product of the efficiency of serially connected links of parallel consumers.

Using formula (9), the efficiency of combined agricultural units is estimated in Fig. 4.

According to the dependences $h_a=f(N_{PTO}, N_f, \eta_T, \eta_{PTO}, \eta_f)$ rational parameters of weight, traction resistance of agricultural machines, and efficiency of combined units are estimated. Taking into account the range of traction resistances of existing agricultural implements, as well as the tendency to use wide-grip and combined implements, the range of traction resistances of agricultural machines was selected P_r=5–12 kN, agricultural machines G_{im}=5.0–120 kN.

Fig. 3. John Deere 8335R tractor in the field as part of a combined unit



$$\eta_a = \eta_T \cdot \frac{N_{PTO1} + N_{PTO2} + N_{f1} + N_{f2}}{\frac{N_{PTO1}}{\eta_{PTO1}} + \frac{N_{PTO2}}{\eta_{PTO2}} + \frac{N_{f1}}{\eta_{f1}} + \frac{N_{f2}}{\eta_{f2}}}$$

$$\eta_b = \eta_T \cdot \frac{N_{PTO} + N_{f1} + N_{f2}}{\frac{N_{PTO}}{\eta_{PTO}} + \frac{N_{f1}}{\eta_{f1}} + \frac{N_{f2}}{\eta_{f2}}}$$

$$\eta_{II} = \eta_T \cdot \frac{N_{f1} + N_{f2}}{\frac{N_{f1}}{\eta_{f1}} + \frac{N_{f2}}{\eta_{f2}}}$$

Fig. 4. Traction efficiency of combined agricultural units for separate modes of operation: *Ia, Ib* – traction and drive modes of operation when two and one PTO are included, respectively; *II* – traction mode of operation; N_e is the effective power of the engine; η_{Tr} – transmission efficiency; N_f – power for movement (front or rear axle)

5. 2. Investigating traction properties of traction-drive, combined agricultural units

Combined MTUs with a decentralized drive of the supporting wheels of agricultural machines, or an additional driving bridge, are especially effective when working on a field prepared for sowing, in a tractor with a distributed drive system and the efficiency of the drive of agricultural implements η_{PTO}=0.52–0.63. At η_{PTO}=0.7 and η_{PTO}=0.8, the traction efficiency reaches 0.64 and 0.68, respectively. During the selection, it is advisable to realize from 20 % to 60 % of the power of η_{PTO}=0.7 and from 40 % to 80 % at η_{PTO}=0.8 (the mass of agricultural machines m_{im}=6–10 t). Units with a tractor weighing 5 t on a field prepared for sowing are effective at G_{im}=100.0 kN up to P_T=40 kN (η_{PTO}=0.7) and up to P_T=50 kN (η_{PTO}=0.8), and tractors weighing 12 t – starting from P_T=40 kN at m_{im} to 20 t.

Calculations showed that the distributed drive system is competitive on stubble in a unit with a 4K2 tractor at η_{PTO}=0.7. The traction efficiency of the tractor ranges from 0.63 to 0.67, i.e., it is approximately equal to the maximum traction efficiency of the 4K4 tractor under a traction mode. In a 4K2 tractor on a field prepared for sowing, the traction efficiency is η_T=0.58–0.64 (η_{PTO}=0.7). At selection, it is advisable to realize from 60 % to 80 % of capacity (η_{PTO}=6–10 t).

The solution to the problem of reducing the weight of the tractor is aimed at the use of traction-drive MTU, in which the tractor is assembled with an agricultural machine with active working bodies (Fig. 3). In the agricultural sector of Ukraine, the rotary harrow «Zirkon» from the «Lemken» company, which is designed for pre-sowing soil preparation for sowing in one pass, is the most in demand. It performs intensive movement and grinding to a working depth of up to 15 cm. Active working bodies optimally prepare the soil for sowing under almost any soil conditions.

In traction-drive MTUs, the power of the engine is realized through the traction of the tractor and mainly (up to 70 %) to the drive of active working bodies. The power balance of a traction-drive MTU, for example with a rotary tillage machine, is significantly influenced by the «pushing force» P_x from the active working bodies of the agricultural machine. Depending on the ratio of P_x and the traction force on the tractor hook P_T, three possible cases of MTU movement are possible:

– when $P_T>P_x$, the torque (driving) moment $M_к$ and the tangential force P_k acting in the direction of movement of the MTU are applied to the tractor thrusters. At the same time, skidding of tractor engines is possible ($\delta>0$);

– when $P_T=P_x$ the movement of the MTU is carried out without towing the tractor ($\delta=0$);

– when $P_T<P_x$, the tractor engines are loaded with a negative moment M_k, in which the traction force P_T is directed against the tractor's movement, which leads to negative skidding ($\delta<0$).

The difference between the traction power of the tractor N_T and the «pushing force» N_x forms the surplus power $N_{ex}=N_x-N_T$, part of which is spent on towing the thrusters, and the other part is transmitted through the tractor transmission to the drive of the active working bodies of agricultural machines. Excess power circulates in a closed circle from the tractor's engines through the transmission and PTO to the active working bodies of the agricultural machine, from which through the frame of the machine and the attachment to the tractor engine. Under the influence of circulating power, there is intensive wear of the tires, transmission, and drive of the tractor PTO; the traction efficiency of the tractor decreases while the fuel consumption of MTU increases.

This analysis allows us to state the condition for the effective operation of a traction-drive MTU: the optimal traction and energy parameters of MTU with active working bodies are achieved when the pushing force of the active working bodies and the sum of the rolling resistances of the tractor and the machine are equal.

6. Discussion of ensuring the maximum traction efficiency of the tractor as part of the tillage unit

The proposed mathematical apparatus (6) to (8) makes it possible to study the ratio of the traction force of the tractor and the mass of the tillage unit. The research results are aimed at the development of the methodology of a systematic approach to increase the traction efficiency of the tractor as part of the tillage unit, which is based on the analysis of accelerations of its movement on the run. According to the results of the calculations in Table 1 for all three groups of tillage operations, the most rational efficiency value for the John Deere 8335R tractor was found. Thus, in the assembly with various mobile units, the maximum is provided on double wheels for the second group of operations at m_{sp}=65.0 kg/kW (m_o=14370 kg) and the maximum traction efficiency $\eta_{T\max}=0.719$. The ability to take into account the power flows for the John Deere 8R series tractor through the front and rear PTO using equation (9), allows one to estimate the efficiency of the combined units, as shown in Fig. 4. According to the presented schemes and equations, it is advisable to determine the rational parameters of mass, traction resistance of agricultural machines, and efficiency of combined units. It was determined that they have the greatest efficiency when working on a field prepared for sowing. Under the condition of using combined MTU with a decentralized drive of the support wheels of agricultural machines or an additional driving bridge. At the same time, the traction efficiency of the tractor as part of the combined agricultural unit varies within $\eta_T=0.63-0.67$. A further increase in efficiency is possible due to the use of traction-drive MTU, in which the tractor is assembled with an agricultural machine with active working bodies.

In traction-drive MTUs, the power of the engine is realized through the traction of the tractor and mainly (up to 70 %) to the drive of active working bodies. However, there is a scientific problem of justifying the rational redistribution of this power in order to achieve the maximum value of the traction efficiency of the tractor. For this purpose, on the basis of the analysis of the performed calculations, the conditions for the effective operation of the traction-drive MTU were formulated.

Our calculation procedures require data obtained experimentally. To obtain them, tests can be carried out according to the OECD Code 2 procedure, such as in the laboratories of NTTL [21] in the USA and DLG in Germany [22] under Power-Mix cycles. At the same time, the most generalized criteria for the efficiency of tractors are traction efficiency and an indicator close to it in essence – the average specific fuel consumption. The disadvantage of the tractor testing methods at the laboratories of NTTL (USA) and DLG (Germany) is that they involve tests with constant movement of tractor units. Accordingly, it does not make it possible to take into account the cycles of idling with the stability of their mass. This approach does not make it possible to estimate the energy consumption and traction efficiency of the tractor when performing a technological operation and for combined agricultural units. In Ukraine, tractor tests are carried out according to DSTU 7462:2013 and are based on their braking through PTO and the movable braking system, which is also a very energy-consuming and lengthy procedure. The solution to this problem is possible by using the method of partial accelerations [14]. The effectiveness of the method and the measuring and registration module was proven during tests of tractors as part of tillage units [15, 23].

The limitations of our study are the application of the proposed procedures based on the analysis of accelerations for tractors with automatic, stepless transmissions since the experiment must be carried out on a specific transmission. Another limitation is the use of these procedures for tractors with a crawler drive, as currently there are not enough experimental results.

The prospect for the current study is to ensure the maximum traction efficiency of the tractor in the case of instability of its operating weight and traction force by justifying the rational arrangement of units and their modes of operation. At the same time, it should be taken into account that the efficiency of tractors significantly depends on the operating modes of the engine, where there are reserves for increasing efficiency.

7. Conclusions

1. The condition for ensuring the maximum tractive efficiency of the tractor as part of the tillage unit has been formulated as the point of intersection of two curves in three-dimensional space, which ensures the most effective use of it for this type of work. John Deere 8R series general-purpose tractors as part of a tillage unit have a maximum traction efficiency of $\eta_{T\max}=0.719$ when working on double wheels and an operating weight of m_o=14370 kg.

2. The condition for the effective operation of the combined agricultural unit with active working bodies has been formulated. The optimal traction and energy parameters of the unit are achieved when the pushing force of the active working bodies and the sum of the rolling resistances of the tractor and the assembled agricultural machine are equal.

Traction efficiency of a tractor as part of a combined agricultural unit varies within η_T=0.63–0.67, i.e., approximately equal to the maximum traction efficiency of a 4K4 tractor under a traction mode. 4K2 tractors in a unit with an agricultural machine m_{im}=6–10 t with a power take-off of 60 % to 80 % have a traction efficiency of η_T=0.58–0.64.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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