

METHODOLOGY FOR ASSESSING TRACTION PROPERTIES OF A TRACTOR WITH A VARIABLE WEIGHT COUPLING

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Abstract - The aim of the study is to improve the efficiency of wheel tractor traction weight utilization by reducing the uneven distribution of vertical reactions between wheels.

The work further develops the theory of tractor traction properties by substantiating a methodology for assessing the impact of traction weight instability and center of mass position on the distribution of vertical reactions and the traction weight utilization coefficient.

The results obtained can be used during testing, operation, and adjustment of all-wheel-drive tractors and machine-tractor units in order to increase their traction efficiency, in particular in plowing operations with asymmetric loads.

The methodological basis of the study is the analysis and generalization of known scientific results on the theory of tractors in traction mode, the application of analytical methods, comparative analysis, and probability theory in the construction of empirical models.

The main provisions of the methodology for assessing the traction properties of a tractor under unstable traction weight conditions have been formulated. A method for determining vertical reactions on tractor wheels based on measuring the reaction on only one of the four wheels is justified. It is shown that the highest probability of uniform distribution of vertical reactions between the wheels of one axle is achieved when the center of mass is shifted to the front or rear axles, and the lowest probability is achieved when it is located in the middle between the axles. It has been theoretically substantiated and experimentally confirmed that during plowing with uneven lateral loads, the maximum traction efficiency of the tractor is ensured by locking the front and rear axle drives.

Keywords: tractor, traction properties, coupling weight, center of mass, vertical reactions, driving bridges, blocking.

1. Introduction

The classical approach to a tractor as an object of design and control is to consider it as a traction machine with one connection to the external environment (running system) [1]. Such a view leads to the formulation of tasks for optimizing tractor properties: tractive effort and efficiency (EFC), rolling resistance, axle load, etc. These parameters of tractors are determined during their testing in laboratories in the United States of America and Germany [2].

A number of works are devoted to the study of tractor traction properties, in particular [3–6]. These works analyze methods and means of assessing tractor traction properties. It is substantiated that the most promising method for assessing tractor traction and speed properties is a method based on measuring its accelerations when moving at a gallop.

During tractor operation in traction mode, its connection with the soil is carried out through two channels (running system, working tool), which lead to instability of the tractor's traction force and the resistance of the aggregated agricultural machine [7, 8]. In this case, it is assumed that the reactions

between the wheels of the front and rear axles are distributed evenly. Although, due to different rolling resistance of the wheels, for example, when the tractor performs some work, the reactions between the wheels are distributed unevenly [9]. The movement of the tractor during the technological process leads to the occurrence of longitudinal, lateral and vertical vibrations of sprung and unsprung masses and tractor wheels.

Longitudinal and lateral vibrations of the tractor lead to an increase in the dynamic tension of the soil due to skidding, wear of the engines, reducing its traction force, and vertical vibrations are the main cause of dynamic soil compaction [10]. At the same time, there is an uneven distribution of vertical reactions between the tractor wheels, which affects the efficiency of using its coupling weight in traction mode [11]. An essential feature of the tractor's movement in traction mode has not received proper coverage in the technical literature when assessing its support and coupling properties [12].

The solution to the problem of studying the dynamics of a tractor and the influence of the center of mass of a mobile machine is reflected in a number of works in foreign publications [13–19], which note the promising nature of research in the direction of machine operation in traction mode. It is proposed to determine the energy parameters of the machine by differentiating its mass.

2. Setting Tasks

Practice poses the need for science to solve the problem of developing a methodology for assessing the uneven distribution of vertical reactions between the wheels of a tractor in traction mode. The purpose of the study is to increase the efficiency of using the tractor's coupling weight in traction mode by reducing the uneven distribution of vertical reactions between the wheels. To achieve this goal, it is necessary to solve the following research tasks:

- to substantiate the dependence of the tractor's traction properties on the use of the coupling weight of the driving axles;
- to assess the distribution of vertical reactions between the wheels of one driving axle of a tractor;
- to substantiate the zone of the most probable reduction in the use of the coupling weight of an all-wheel drive tractor.

3. Methods and Materials

The methodological basis of the work is the generalization and analysis of known scientific results regarding the theory of a tractor in traction mode. To formulate a scientific problem, determine the goal and set the objectives of the study, an analytical method and comparative analysis were used. When creating empirical models of the tractor, the basic principles of probability theory were used. Experimental studies were

performed using the method of partial accelerations [20, 21].

As input data, we assume that the tractor is on a flat horizontal surface and moves at a constant speed with the power take-off shaft (PTO) turned off (Fig. 1). The traction efficiency of the tractor can be expressed by the equation [1]:

$$\eta_t = \frac{N_t}{N_e} = \frac{P_h v_d}{M_d n_d} \frac{716,2}{270} = 2,65 \frac{P_h v_d}{M_d n_d} \quad (1)$$

where N_t – tractor traction power, kW; N_e – effective engine power, kW; P_h – hook traction force, kN; v_d – actual speed, km/h; M_d – engine torque, kN·m; n_d – engine crankshaft speed, min⁻¹.

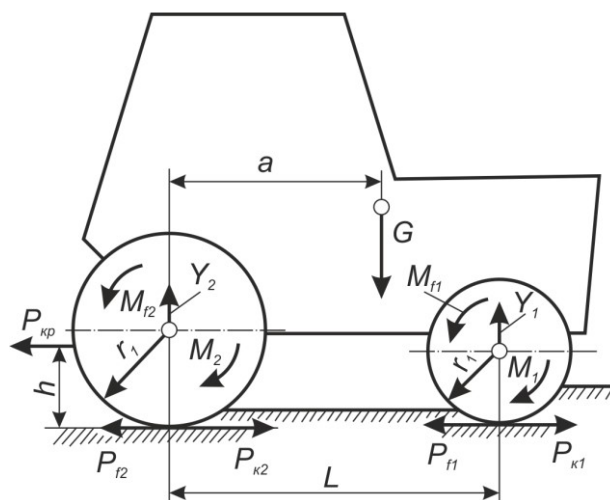


Figure 1: Diagram of forces acting on the tractor

Let us express the traction forces on the hook and the actual speed of movement, which are included in expression (1) for the traction coefficient of the tractor's useful action, as functions of the dimensionless coefficients of use of the coupling weight of the driving axles:

$$\phi_{1,2} = \frac{P_{k1,2}}{Y_{1,2}} \quad (2)$$

where $P_{k1,2}$ is the tangential traction force of the driving axle; $Y_{1,2}$ is the soil reaction, which is numerically equal to the tractor's coupling weight, which falls on the driving axle ($Y_{1,2}=G_{1,2}$).

In expression (2) and further, the index "1" refers to the front, and the index "2" to the rear axle.

To obtain the dependence $P_{kp}=f(\phi_1, \phi_2)$ we express

$$P_h = P_{h1} + P_{h2} - P_{f1} - P_{f2}$$

$$P_{k1,2} = G_{1,2} \phi_{1,2}$$

$$P_{f1,2} = G_{1,2} f_{1,2}$$

where $P_{fl,2}$ – driving axle rolling resistance force;
 $f_{l,2}$ – driving axle rolling resistance coefficient.

Taking into account the redistribution of the coupling weight depending on the traction force, we obtain:

$$P_h = \frac{G[A_1(\phi_1 - f_1) + A_2(\phi_2 - f_2)]}{A_3 + h(\phi_1 - \phi_2)} \quad (3)$$

where $A_1 = a - f_2 r_2$; $A_2 = L - a - f_1 r_1$;
 $A_3 = L - h(\phi_1 - f_2) + f_1 r_1 - f_2 r_2$; G – tractor weight, N; L – tractor longitudinal base, mm; h – trailer point height, mm; r_1, r_2 – wheel rolling radii.

4. Research Results

The supporting and coupling properties of a tractor depend mainly on its operating weight G_e , the conversion of which into traction force P_h is estimated by the coefficient of use of the coupling weight $\phi_h = P_h / G_e$. When a wheeled tractor moves on an equal agrobground with the coefficient of adhesion of the driving wheels to the soil ϕ_c , rolling resistance f and the share of weight borne by the driving wheels λ_k , the supporting and coupling properties of a tractor with one driving axle are estimated by the dependence $\phi_h = \phi_c \lambda_k - f$, for all-wheel drive tractors – $\phi_h = \phi_c - f$. Analysis of tractors with one driving axle and all-wheel drive shows that the greater the coefficient of adhesion compared to the coefficient of rolling resistance, the greater the reserve of traction force the tractor has.

Under operating conditions, the tractor's tractive effort varies from zero to the maximum value $P_h = P_{h \max}$, which is determined by the coupling properties by $G_e = \text{const}$.

Therefore, the coefficient ϕ_h changes from zero to $\phi_{h \max}$. The nominal tractive effort corresponds to a certain value $\phi_{h n}$. If the tractive resistance line is parallel to the road surface, then the change in loads y_n and y_s occurs as a result of the redistribution of the tractor's weight between the front and rear wheels. A decrease in the load on the front wheels causes the same increase in the load on the rear wheels and vice versa. The sum $y_n + y_s$ is equal to the tractor's weight G_t . The instability of y_n and y_s leads to an uneven distribution of vertical reactions between the tractor wheels, a decrease in the efficiency of using its coupling weight in the traction mode. In this case, even if the tractor's center of mass is located strictly in the longitudinal plane of symmetry, there may be uneven vertical reactions on the left and right wheels of the same axis. This is due to the static uncertainty of a four-wheeled tractor as a spatial structure that has four supports (links) and, accordingly, four vertical link reactions. The methodology for solving

this problem is based on the relationship between dimensionless (specific) forces on the tractor wheels:

$$\begin{aligned} \gamma_{z1} &= R_{z1} / G; \quad \gamma_{z2} = b / L - \gamma_{z1}; \\ \gamma_{z3} &= 0,5 - \gamma_{z1}; \quad \gamma_{z4} = \frac{a}{L} - 0,5 + \gamma_{z1} \end{aligned} \quad (4)$$

where R_{z1} – vertical reaction on the front wheel; G – tractor weight; $\gamma_{z1}, \gamma_{z2}, \gamma_{z3}, \gamma_{z4}$ – fractions of weight borne by the driving wheels; a, b, L – distances from the projection of the center of mass on the horizontal plane to the front and rear axles, respectively, the longitudinal wheelbase of the tractor.

By measuring the vertical reaction on one of the four wheels of the tractor, it is possible to accurately determine the vertical reactions on the last three. At the stage of designing the tractor, it is advisable to specify the vertical reaction on one of the wheels as a random variable, the distribution of which obeys the normal law. Let us assume that such an independent random variable will be γ_{z2} , the changes of which are theoretically possible within $[0, b/L]$. With a decrease in γ_{z1} , there is a decrease in and γ_{z4} , which cannot acquire negative values, since this leads to a violation of the equilibrium of the system.

Thus, for $\gamma_{z1} = 0$ the following condition must be satisfied:

$$\gamma_{z4 \min} = \frac{a}{L - 0,5} \geq 0 \text{ or } b/L \leq 0,5 \quad (5)$$

Therefore, for $b/L \leq 0$ the value of γ_{z1} can vary within the limits:

$$\frac{b}{L} - 0,5 \leq \gamma_{z1} \leq 0,5 \quad (6)$$

According to the normal law of distribution of vertical reactions on the tractor wheels, the density of distribution of the specific load on one front wheel is estimated by the equation:

$$f(\gamma_{z1}) = \begin{cases} \frac{2,394}{b/L} \mu_\sigma \exp \left[-\frac{1}{2} \left(\frac{6}{b/L} \gamma_{z1} - 3 \right)^2 \right] \text{ при } \frac{b}{L} \leq 0,5; \\ \frac{2,394}{1-b/L} \mu_\sigma \exp \left[-\frac{1}{2} \left(\frac{6}{1-b/L} \gamma_{z1} - \frac{3b/L}{1-b/L} \right)^2 \right] \text{ при } \frac{b}{L} > 0,5 \end{cases} \quad (7)$$

where μ_σ – the selected scale of the standard deviation, i.e. the value conditionally taken as a unit when conducting the analysis.

Fig. 2 shows graphs of functions (7) for different positions of the tractor's center of mass (parameter b/L) taking into account the possible range of change γ_{z1} .

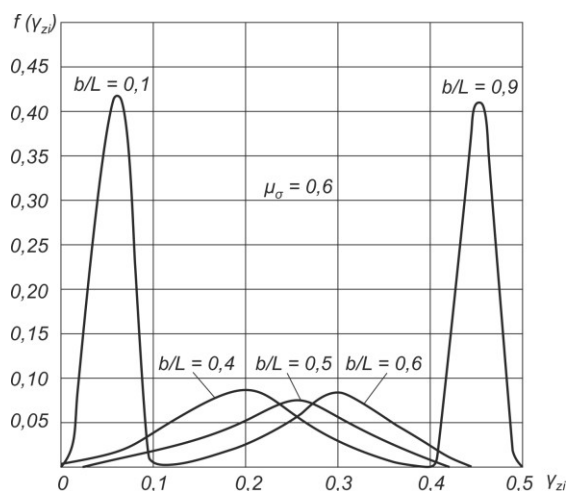


Figure 2: Density of distribution of specific load on one front wheel at different positions of the tractor's center of mass

Analysis of the calculation results shows that the greatest probability of equal distribution of vertical reactions between the wheels of one axle is for tractors with a center of mass offset to the front or rear axles. The least probability of equal distribution of vertical reactions is for tractors with a center of mass located in the middle between the axles $b/L = 0.5$, and the greatest probability is for $b/L = 0.9$ and $b/L = 0.1$.

If for $b/L = 0.1$ this probability is 0.4, then for $b/L = 0.5$ it is 0.1.

During tractor operation in traction mode, the uneven distribution of vertical reactions leads to a deterioration of its traction-speed characteristics, since the total tangential traction force is determined by the wheel that is in the worst grip conditions. If we consider the specific vertical reactions on the wheels (the ratio of the corresponding reaction on the j -th wheel to the total weight of the tractor) taking into account their possible changes within the standard deviation, then the dependences for their calculation are written in the form:

$$\begin{aligned} \gamma_{z1} &= m_{\gamma1} + \sigma_{\gamma1}, \quad \gamma_{z2} = m_{\gamma2} - \sigma_{\gamma2}, \\ \gamma_{z3} &= m_{\gamma3} - \sigma_{\gamma3}, \quad \gamma_{z4} = m_{\gamma4} + \sigma_{\gamma4} \end{aligned} \quad (8)$$

where $m_{\gamma1}, m_{\gamma2}, m_{\gamma3}, m_{\gamma4}$ – mathematical expectation of specific vertical reactions on the corresponding wheels (1, 2 – front wheels; 3, 4 – rear wheels; 1, 3 – left side wheels; 2, 4 – right side wheels); $\sigma_{\gamma1}, \sigma_{\gamma2}, \sigma_{\gamma3}, \sigma_{\gamma4}$ – root mean square deviations of specific vertical reactions on the specified wheels.

Obviously, that

$$m_{\gamma1} = m_{\gamma1} = \frac{1}{2} \frac{b}{L}; \quad m_{\gamma3} = m_{\gamma4} = \frac{1}{2} \left(1 - \frac{b}{L}\right) \quad (9)$$

For $b/L \leq 0.5$ we have

$$\sigma_{\gamma} = \sigma_{\gamma1} = \sigma_{\gamma2} = \sigma_{\gamma3} = \sigma_{\gamma4} = \frac{1}{6} \frac{b}{L} \quad (10)$$

For $b/L > 0.5$ it is defined

$$\sigma_{\gamma} = \sigma_{\gamma1} = \sigma_{\gamma2} = \sigma_{\gamma3} = \sigma_{\gamma4} = \frac{1}{6} \left(1 - \frac{b}{L}\right) \quad (11)$$

The accelerations that occur during tractor acceleration in the absence of wheel slippage are determined by the wheel that is in the worst grip conditions, i.e. the one that has the lowest vertical load

$$a = g \phi \phi_h \quad (12)$$

where g – acceleration of free fall, $g = 9.81 \text{ m/s}^2$; ϕ – coefficient of adhesion of wheels to the road; ϕ_h – coefficient of use of coupling weight in traction mode for an all-wheel drive tractor

$$\phi_h = 2(\gamma_{z2} + \gamma_{z3}) = 2(m_{\gamma2} + m_{\gamma3} - 2\sigma_{\gamma}) = \begin{cases} 1 - \frac{2b}{3L} \text{ at } \frac{b}{L} \leq 0.5 \\ \frac{1}{3} - \frac{2b}{3L} \text{ at } \frac{b}{L} > 0.5 \end{cases} \quad (13)$$

Fig. 3 shows a graph illustrating the dependence of ϕ_h on the parameter b/L .

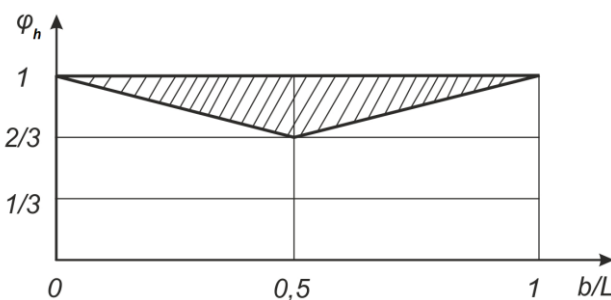


Figure 3. Zone of most probable values of reduction in the coupling weight utilization factor of a two-axe all-wheel drive tractor in traction mode (shaded)

With an asymmetric application of traction force on the tractor hook, for example, the resistance force of a plow, characterized by the distance α from the tractor axis to the point of application P_{pl} and different rolling resistance P_{fi} of the wheels, due to their different rolling conditions, the traction force required to overcome P_{fi} will be different for each wheel P_{ki} (Fig. 4).

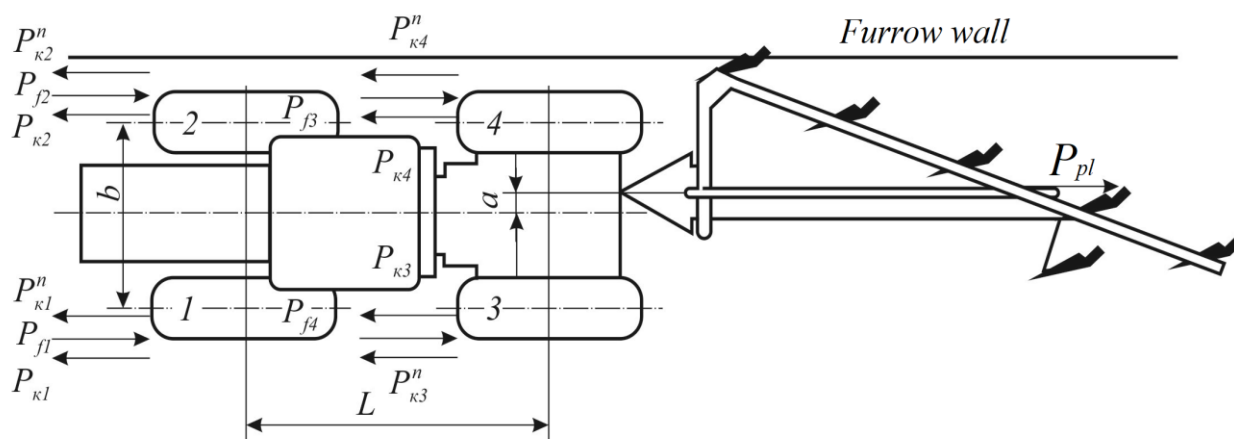


Figure 4: Diagram of the action of forces on the tractor wheels during plowing operations

To ensure uniform rectilinear movement of the tractor, it is necessary to fulfill the condition $P_{ki} = P_{fi} + P_{ki}^n$, where P_{ki}^n is the traction force necessary to overcome the resistance force of the plow.

For this case, the tangential traction force of the wheels is written in the form:

$$\left. \begin{aligned} P_{k1} &= P_{nn} \frac{(b/2-a)}{b} + P_{\kappa 3} + \sum (P_{f1,3} + P_{\kappa 1,3}^n) \\ P_{k2} &= P_{nn} \frac{(b/2-a)}{b} + P_{\kappa 4} + \sum (P_{f2,4} + P_{\kappa 2,4}^n) \\ P_{k3} &= P_{nn} \frac{(b/2-a)}{b} + P_{k1} + \sum (P_{f1,3} + P_{\kappa 1,3}^n) \\ P_{k4} &= P_{nn} \frac{(b/2-a)}{b} + P_{k2} + \sum (P_{f2,4} + P_{\kappa 2,4}^n) \end{aligned} \right\} \quad (14)$$

Analysis of this system of equations shows that for $P_{f1,3} \neq P_{f2,4}$ due to different rolling conditions of the wheels during the tractor performing plowing work ($P_{f2} > P_{f4}$, $P_{f1} > P_{f3}$, $P_{f2} > P_{f1}$, $P_{f4} > P_{f3}$) has $P_{k2} > P_{k4}$, $P_{k1} > P_{k3}$, $P_{k2} > P_{k1}$, $P_{k4} > P_{k3}$.

In order to evaluate the dependence of the tractor's traction force on the coupling weight with an uneven distribution of reactions between the axles, experimental studies of the KhTZ-17021 tractor aggregated with a PLN-5.35 plow were conducted. The results of the experimental studies are given in Table 1.

Table 1: Torques (M_h) on the sun gears of the wheel reducers of the tractor KhTZ-17021 with the plow PLN-5-35 (plowing winter wheat stubble to a depth of 25-27 cm)

y, m	a, m	M_h, Hm			
		M_{h1}	M_{h2}	M_{h3}	M_{h4}
0,150	0,36	947	2222	875	2150

y – distance from the edge of the groove to the outer edge of the wheel;
 a – asymmetry of the application of the traction load;
 $M_{h1}, M_{h2}, M_{h3}, M_{h4}$ – torques on the sun gears of the front left and right, rear left and right wheels, respectively

Analysis of this table shows that during plowing work on the KhTZ tractor, the front right wheel is the most loaded, the rear left wheel is the least loaded. Behind the sides of the tractor, the front wheels are loaded by 3 - 5% more than the rear wheels. Let us assume $P_{k1}^n = P_{k3}^n$ and $P_{k2}^n = P_{k4}^n$ for simplification. In this case, the load on the wheels of the right P_f^n and left P_r^n sides of the tractor, which is necessary to overcome the resistance of the plow, is written from the system of equations (14) in the form:

$$\left. \begin{aligned} P_f^n &= P_{pl} \left(\frac{1}{2} + \frac{a}{b} \right) \\ P_r^n &= P_{pl} \left(\frac{1}{2} - \frac{a}{b} \right) \end{aligned} \right\} \quad (15)$$

The asymmetry of the plow attachment, characterized by the parameter a , leads to a greater load on the right side of the tractor compared to the left. For a tractor of the KhTZ type in plowing operations with a PLN-5-35 plow, this excess is 50 - 60%. In this case, to ensure stable rectilinear movement of the plowing unit, it is necessary to fulfill the condition $M_2 \approx 1.5M_1$, $\omega_1 \approx 1.5\omega_2$.

For example, Fig. 5 shows a universal characteristic of the traction efficiency of the KhTZ-170 tractor during plowing work with a PLN-5-35 plow of winter wheat stubble to a depth of 25-27 cm (tractor operating weight 8.0 t, engine power 121.1 kW, travel speed 2.37 m/s).

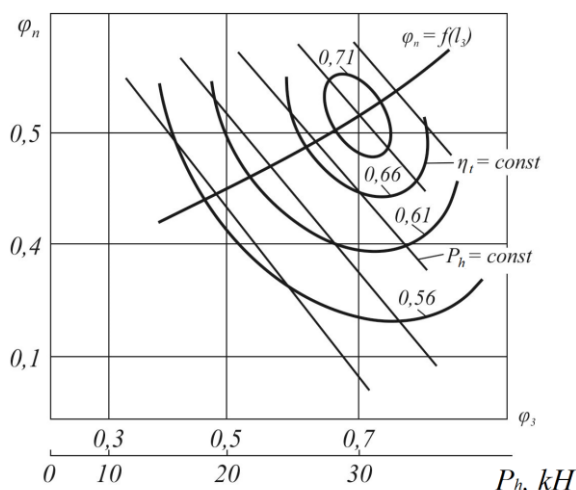


Figure 5: Universal characteristic of traction efficiency of the KhTZ-170 tractor for plowing

The universal characteristic shows the tractor's traction range as a series of straight lines $P_h=const$, on which the function $\varphi_n=f(\varphi_3)$ is plotted for η_{tmax} , i.e. the optimal combination of coupling weight utilization coefficients of the driving axles, which lead to the tractor operating with maximum traction efficiency.

Analysis of the universal characteristic shows that $\eta_{tmax}=0.71$ of the tractor KhTZ-17021 on plowing will be with the front and rear drive axles locked. When the front drive axle is turned off, all η_t points are located on the abscissa axis (since $\varphi_n=0$). At the same time, η_t on the universal characteristic will be located below η_{tmax} .

According to this characteristic, it is possible to estimate η_t when the differentials are unlocked, the front and rear axles are simultaneously turned on.

The tractor as part of the tillage unit operates in a cyclic mode (working stroke, turning at the end of the run), the work performed which can be estimated by the dependence:

$$A = \frac{N_{tp}}{1 + \left(\frac{1}{v_{idling} + \frac{T_{on}}{S_r}} \right) v_r} \quad (16)$$

where N_{tp} – tractor traction power; v_{idling} , v_r – working and idling speeds; T_{on} – stopping time in the cycle and turning at the end of the run; S_r – working stroke length (run length).

Dependence (16) allows to determine the optimal values of tractor traction power N_{tp} and working speed v_r to ensure maximum useful work of the unit. This statement was confirmed experimentally when aggregating the KhTZ-17221 tractor with a GRU-2.5 (Frank-2.5) deep cultivator (Fig. 6).



Figure 6: Soil tillage unit KhTZ-17221+deep cultivator GRU-2.5 in operation

The useful work A of the unit is estimated by its traction and speed characteristics (Fig. 7).

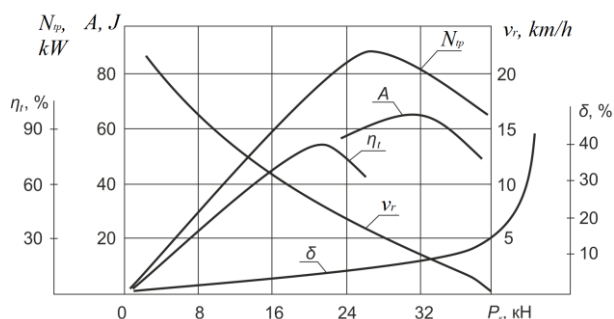


Figure 7: Traction-speed characteristics of the soil tillage unit KhTZ-17221 + deep cultivator GRU-2.5 (Frank-2.5): N_{tp} – traction power; A – useful work; η_t – traction efficiency; v_r – speed; δ – slippage

Analysis of this characteristic shows that the maximum N_{tp} , A and η_t do not coincide. To ensure maximum useful work of this unit, it is necessary to operate it at increased traction and reduced speed.

When aggregating a tractor with an agricultural machine, energy is spent on performing a technological operation and on dynamic processes that occur in the "tractor - agricultural implement" system. The traction properties of a tractor are determined by the ratio of driving (traction) forces and resistance forces during unsteady movement (acceleration, gear shifting, instability of the traction resistance of the agricultural machine, etc.) [25-30].

5. Discussion

The results of the research are mainly aimed at solving the scientific problem of increasing the efficiency of using the tractor's coupling weight in traction mode by reducing the uneven distribution of vertical reactions between the wheels. New dependences of the tractor's traction properties on the use of its coupling weight and a method for evaluating the vertical reactions on the tractor

wheels from its coupling weight are proposed. It is proven that the greatest efficiency of using the coupling weight of an all-wheel drive tractor in traction mode is achieved when its center of mass is located between the axes of the driving axles. At the same time, during plowing work (the most energy-intensive technological process), its operation with maximum traction efficiency is ensured with the driving axles blocked. To ensure maximum useful work of the tillage unit, its operation is necessary at increased traction force and reduced speed.

Domestic and foreign scientists draw attention to the fact that the efficiency of tractors significantly depends on the position of its center of mass and the distribution of vertical reactions between the wheels. However, both domestic regulatory documents and tractor testing methods according to the OECD Code 2 procedure in NTTL laboratories [22-24, 30] in the United States of America and in Germany do not provide for the assessment of the efficiency of tractors from the position of its center of mass during the execution of the technological process. This is mainly due to the lack of methods and instrumentation for assessing the traction properties of a tractor during its unsteady movement.

6. Conclusions

A methodology for assessing the traction properties of a tractor under conditions of instability of vertical reactions on the wheels has been developed. It has been shown that even with the location of the center of mass in the longitudinal plane of symmetry, the deviation of the vertical reactions between the left and right wheels of one axle is possible within the mean square deviation, which reduces the coefficient of use of the coupling weight.

A method for determining the vertical reactions on the wheels of a tractor based on the results of measuring the reaction on only one wheel has been substantiated, which allows unambiguously determining the reactions on the other three wheels under conditions of static equilibrium of the system.

It has been established that the highest probability of uniform distribution of vertical reactions between the wheels of one axle is achieved by shifting the center of mass of the tractor to the front or rear axles ($\lambda = 0,1$ or $\lambda = 0,9$) and is about 0,4, while with the location of the center of mass in the middle between the axles ($\lambda = 0,5$) it decreases to 0,1, which corresponds to the worst conditions for using the coupling weight. It was determined that for a two-axle all-wheel drive tractor, the greatest decrease in the coupling weight utilization factor in the traction mode is observed at $\lambda = 0,5$ and can reach 33%.

Experimental studies of the KhTZ-17021 tractor with the PLN-5-35 plow showed that during plowing

operations, the load on the right side exceeds the left by 50–60%, with the front right wheel being the most loaded, and the rear left wheel the least. It was theoretically and experimentally confirmed that the maximum traction efficiency of the KhTZ-17021 tractor ($\eta_{r\max} = 0,71$) is achieved when the front and rear axle drives are blocked; when the front axle is turned off, the traction efficiency decreases. It was shown that the maximum useful work of the unit is provided with increased traction force and reduced speed.

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