

# DETERMINING THE MAGNITUDE OF TRACTION FORCE ON THE AXES OF DRIVE WHEELS OF SELF-PROPELLED MACHINES

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*Наведено принципи утворення тягової сили тракторів та автомобілів. Точка прикладання тягової сили знаходиться на осі приводного колеса. Причому, величина тягової сили приблизно у два рази перевищує реактивну силу, що передається від дороги на приводне колесо. Визначення принципів утворення тягової сили дозволяє інтенсифікувати дослідження технічних та енергетичних засобів загалом та обґрунтувати принципи зменшення негативного впливу рушіїв на родючий шар ґрунту, зокрема*

*Ключові слова: тягова сила, приводне колесо, самохідні машини, енергетичний засіб, трансмісія*

*Приведены принципы образования тяговой силы тракторов и автомобилей. Точка приложения тяговой силы находится на оси ведущего колеса. Причем, величина тяговой силы примерно в два раза превышает реактивную силу, что передается от дороги на приводное колесо. Определение принципов образования тяговой силы позволяет интенсифицировать исследования технических и энергетических средств в общем и обосновать принципы уменьшения негативного влияния движителей на плодородный слой почвы, в частности*

*Ключевые слова: тяговая сила, приводное колесо, самоходные машины, энергетическое средство, трансмиссия*

## 1. Introduction

A clear understanding of the application processes that are means for the purpose of their further improvement. It also concerns the issues of formalization of the process of creating traction force on the drive wheel of tractors and vehicles. This is especially important for the agricultural machine-tractor units that cause a number of problems related to the interaction between running systems and the surface of fertile layer of soil. Solving the problems aimed at bringing

down negative impact of engines on the fertile layer of soil is a relevant task today.

## 2. Literature review and problem statement

The occurrence of traction force on the drive wheel is often explained by the fact that at the point of contact between the wheel and road surface the torque (Fig. 1–3) causes tangent force  $F_O$ . The counteraction of road to this tangent force

is expressed by a reactive force transferred from the road to the drive wheel. This force is directed in the direction of motion of the vehicle and it is called the traction force  $F_{TC}$ . Traction force from the wheels is transferred to the drive axle and further on the frame forcing the vehicle to move [1]. This explanation of the origin of traction force gives rise to considerable doubts since the forces of reaction characterize only the stress that is created by a drive wheel while interacting with the road. Reaction forces are not the active ones. Traction force from the road surface by no means can be passed on to the frame of a vehicle and it cannot set it in motion. There is another explanation. The torque from the vehicle engine is passed on to the driving wheels. It then causes friction force at the point of contact between the wheel and the road (a force of road counteraction to the rotation of drive wheel). This force is also called tangent or tangential reaction. The friction force as the sum of tangential reactions of the drive wheels is equal to the traction force, which is transferred to the frame of the vehicle. Traction force sets the vehicle into a forward motion. Thus, the traction force is represented as the sum of stresses in a horizontal direction, which arise as a result of soil counteraction to the rotation of the wheel [2]. Such explanation is also false, because friction force is the passive force and it cannot move a vehicle.

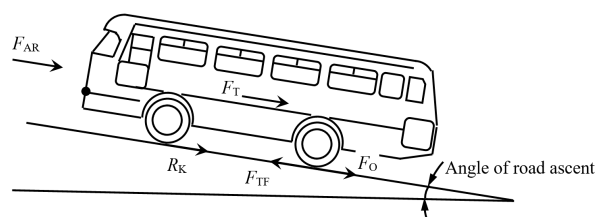


Fig. 1. Diagram of forces and interaction between the wheels and the road during ascending motion of a bus

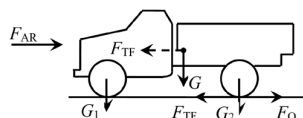


Fig. 2. Diagram of forces and interaction between the wheels and the road during horizontal motion of a freight vehicle

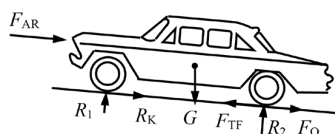


Fig. 3. Diagram of forces and interaction between the wheels and the road during ascending motion of a car

One more variant of a false explanation, which is in principle similar to the previous ones, is as follows. The torque of the engine, applied through the mechanisms of transmission to the drive wheels of a vehicle, causes rotation of the wheels. In the place of contact between the wheel and the road, the torque gives rise to the tangent force  $F_O$  while the tangent reaction  $F_{TF}$  is created by the road and it is equal by magnitude to the transitional force but directed in the opposite direction. Total tangent reaction of the drive wheels is transmitted to the rear axle and causes the motion of the whole vehicle, which is why it is called the traction force [3].

Another explanation for physical essence of the occurrence of traction force on the drive wheels is given in [4]. It is argued, by analogy to the described above, that the force on the radius of a wheel, which acts from the torque, is called the tangent force of the wheel thrust. This force, applied to the wheel, due to the friction and adhesion in contact with supporting surface is balanced by the resultant reaction of soil, equal to it by magnitude but oppositely directed. Given this, the driving force is the force applied in the center of the wheel and directed in the direction of motion of the machine. In order to explain how the force got there, the force of soil reaction is called an external force while the tangent force – internal. And since the internal force cannot lead to displacement, then the machine has to move under the action of the external force – the reaction of soil. Fallibility of this explanation is predetermined by the arbitrary choice of terminology and by the absence of clear explanation of the physical essence of the process of formation of the traction force of the drive wheel.

Paper [5] presented a torque on the drive wheel as a pair of forces. One of the forces is applied in the center of the wheel. This is a mistake as the torque does not create a force applied in the center of the wheel. By analogy, the force passing through the center of rotation does not create rotational moment.

Examining a diagram of forces and moments acting on the tractor, article [6] also states that the force that pushes the tractor occurs in the contact spot between the drive wheel and the ground. It should be noted that the author presents the diagram of forces and moments acting on the tractor, which lacks a vector of the traction force, since power analysis does not make it possible to apply traction force to the axis of the wheel.

In paper [7], authors explore optimal methods of control over traction force depending on the driving torque and consider driving force as the difference between the horizontal soil reaction and internal rolling resistance of the wheel (deformation of the tire). The reaction of soil and the internal rolling resistance are caused by the action of the driving torque. It is stressed that the force of motion resistance of a vehicle is applied to the axis of wheel rotation, which is certainly true. Driving force, which has to compensate for the force of motion resistance, should also be applied to the axis of wheel rotation and directed in the opposite direction. However, the authors do not give the explanation for the transformation of torque of the drive wheel into a driving force.

Articles [8, 9] give expressions for determining the traction effort of tractor, which is derived as the difference between horizontal action of the ground force on the wheel and resistance force to the motion of the wheel. Physical essence of the occurrence of traction force is also missing.

Author of [10] examines distribution of torque and traction effort on the drive wheel of a wheeled tractor. He determines driving force as the difference between the horizontal component of soil reaction on the wheel rotation and the resistance force to the wheel rolling. Numerically, the force is equal to the sum of torque applied to wheel and the rotational moment of wheel inertia divided by the dynamic radius of wheel rotation.

Traction force of a tractor is determined by authors of paper [11] based on the balance of forces applied to the drive wheel. Driving torque applied to the wheel is divided into rotational moment of wheel inertia and the driving torque.

Driving torque of the wheel creates traction force of the wheel forces to overcome the resistance to wheel rolling. It should be noted that the wheel traction force and the rolling resistance force are located in the point of contact between the wheel and the ground and directed in such a way that they counteract to the driving torque of the wheel.

When examining motion of the drive wheel with active tread, traction force is represented as the sum of horizontal efforts, operating on the wheel rim and the tread. In this case, direction and the point of traction force application is not specified [12].

Traction force is also determined as the difference between horizontal action of the traction force applied to the wheel axis and the wheel motion resistance force, applied in the point of contact between the wheel and the ground [13]. Horizontal resultant force of soil resistance is also considered as a traction effort that leads to the forward motion. Such force is considered as a function of soil and wheel parameters located in the place of contact between the wheel and the ground, pointed in the direction of motion [14].

All of the above explanations of physical essence of the occurrence of traction forces on the drive wheels are the most common and mostly false. It should be noted that a lot of respectable monographs and textbooks represent traction force as the ratio of torque on the drive wheel to its radius. Moreover, they consider traction force to be the reaction of road on the wheel rotational force. In many monographs and scientific articles authors generally avoided the need to introduce a vector of traction force. They realize that traction force is applied on the axis of the wheel, but cannot explain how the force got there.

Most authors, considering ground resistance in the point of interaction between the wheel and the ground to be the driving traction force, transfer this resistance to the axis of the wheel. However, such a transfer is not substantiated. That is why a well-reasoned formalization is required of the phenomenon of the formation of traction force on the axis of the drive wheel in self-propelled transportation vehicles and tractors.

### 3. Research goal and objectives

The goal of present research is to substantiate the formation of traction force on the drive wheel axis of self-propelled transportation vehicles, tractors, etc. and determining the magnitude of traction effort.

To accomplish the goal, the following tasks have been set:

- to establish the mechanism of formation of traction force on the drive wheel axis;
- to receive an expression for determining the magnitude of traction effort of tractors and to compare it with experimental data.

### 4. Materials and methods for examining interaction between the drive wheel and the surface

To conduct research into interaction between the drive wheel and the surface we employed mathematical modelling based on the laws of mechanics.

In order to check the dependences derived, we modeled a change in the traction force on the hook depending on a change in the transmission gear ratio of a tractor. When

performing theoretical calculations we accepted values of tractor performance indicators, in line with the parameters obtained when conducting experimental studies on a change in the traction force of tractor MTZ-80 (Belarus). In the course of research, we conducted several experiments in the relevant gears under nominal modes of engine operation at maximal fuel feed. Fuel consumption, engine rotation, indicators of skidding and traction force on the hook were registered (Table 1) [15].

Table 1  
Basic traction indicators of tractor MTZ-80

Gear	Fuel consumption, kg/hours	Engine rotations, rpm	Speed, km/hours	Skidding, rel. units	Traction force on the hook, N
4	13.48	2200	7.05	0.19	15000
5	14.16	2190	8.74	0.12	13500
7 (reducing)	13.9	2183	9.56	0.1	12400
6	13.5	2143	10.56	0.099	11250
8 (reducing)	13.37	2140	11.6	0.098	10100
7	13.37	2133	13.5	0.08	8600
8	13.6	2100	16.9	0.05	6750

During studies, weight of the tractor was 3808 kg, wheel rolling friction coefficient 0.8, radius of the wheel drive rolling 0.725 m, area of the tractor frontal surface 4.5 m<sup>2</sup>, and the frontal tractor drag coefficient of drag 0.75 N c<sup>2</sup>/m<sup>4</sup>. Coefficient of transmission efficiency was accepted, according to studies [16], at the level of 0.96. Low heat generating capacity of the diesel fuel was accepted at the level of 42.5 MJ/kg. Effective efficiency coefficient of the engine for the respective modes was obtained based on a regulatory characteristic of the D-240 engine operation of tractor MTZ-80 [15]. Stubble of wheat served as agricultural background when conducting the studies.

### 5. Results of examining interaction between the drive wheel and the surface

When the drive wheel contacts the surface, there will occur a brake moment due to the forces of surface reaction, which counteracts to the wheel rotation (Fig. 4). The magnitude of the brake moment in this case is:

$$M_B = R_{SR}r_{DT}, \quad (1)$$

where  $M_B$  is the brake moment on the drive wheel due to the occurrence of surface reaction force, which counteracts to the wheel rotation, N·m;  $R_{SR}$  is the surface reaction force that counteracts to the wheel rotation, N;  $r_{DT}$  is the radius of the drive wheel taking into account deformation of the tyre, m.

During formation of the instantaneous center of rotation, the force with which the wheel acts on surface  $F_{WS}$  compensates for the force of surface reaction, that is,  $R_{SR}=F_{WS}$ . In this case, the force that compensates for the force of surface reaction in recalculation for the shaft of the wheel is derived from ratio:

$$F_{SS}r_s = F_{WS}r_{DT}, \quad (2)$$

and it will equal to:

$$F_{SS} = F_{WS} \frac{r_{DT}}{r_s}, \quad (3)$$

where  $F_{WS}$  is the force on the wheel, which compensates for the force of surface reaction, N;  $F_{SS}$  is the force that compensates for the force of surface reaction in recalculation for the shaft of the wheel, N;  $r_s$  is the radius of the drive shaft, m.

Because the driving torque on the shaft of the wheel can be represented by a pair of forces  $F_{SS}$  and  $F_{DS}$ , and identical by magnitude and pointed in the opposite directions (Fig. 5), and the magnitude of torque can be determined as the sum of the product of forces magnitudes by the shaft radius, it is possible to write:

$$M = F_{SS}r_s + F_{DS}r_s = r_s(F_{SS} + F_{DS}), \quad (4)$$

where  $M$  is the torque on the drive shaft, N·m; where  $F_{DS}=F_{SS}$  is the driving force in the point of intersection of the line that passes through the center of shaft rotation and the instantaneous rotation center of the wheel and the circle produced by the shaft diameter, N.

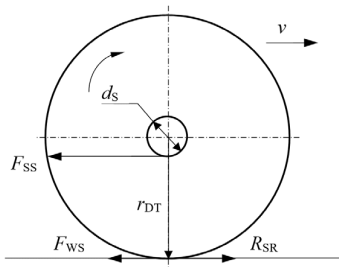


Fig. 4. Calculation diagram of the force that compensates for the force of surface reaction in recalculation for the wheel shaft

Since a pair of forces does not have the resultant force, that is, the action of a pair of forces on a body cannot be mechanically equivalent to the action of any one force, then, respectively, a pair of forces cannot be balanced by one force.

During grip in the point of contact between the shaft and the surface, there occurs a compensation of one force of the shaft torque by the force of grip with the surface, that is,  $F_{SS} = R_{SR}^S$ . In this case, an instantaneous center of rotation is created in the point of contact. Force  $F_{pB}$  creates a torque relative to the instantaneous center of rotation, which is numerically equal to the moment on the engine shaft:

$$M = F_{DS}d_s. \quad (5)$$

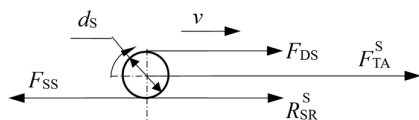


Fig. 5. Calculation diagram of traction force on the shaft without a drive wheel

Thus, if the wheel is removed while the shaft is mounted on the supporting surface, then traction force on the shaft axis would equal to:

$$F_{TA}^S r_s = 2F_{DS}r_s = F_{DS}d_s$$

or

$$F_{TA}^S = F_{DS} \frac{d_s}{r_s} = 2F_{DS} = 2F_{SS} = \frac{M}{r_s}, \quad (6)$$

where  $F_{TA}^S$  is the traction force on the rotation axis of the drive shaft if the shaft is positioned on the supporting surface, N.

Because

$$F_{DS} = F_{SS} = F_{WS} \frac{r_{DT}}{r_s}, \quad (7)$$

then traction force on the shaft axis considering (6) will have a value:

$$F_{TA}^S = 2F_{WS} \frac{r_{DT}}{r_s}. \quad (8)$$

With regard to the equality of moments of the traction force relative to the force action shoulder, in particular, radius of the shaft and traction force relative to the force action shoulder, in particular radius of the deformed wheel, it is possible to write (Fig. 6):

$$F_{TA}^S r_s = F_{TA}^W r_{DT}, \quad (9)$$

where  $F_{TA}^W$  is the traction force on the rotation axis of the drive shaft when the wheel is positioned on the supporting surface, N.

In this case, traction force on the shaft axis in recalculation for the wheel will have a value:

$$F_{TA}^W = F_{TA}^S \frac{r_s}{r_{DT}} = 2F_{WS} \frac{r_{DT}}{r_s} \frac{r_s}{r_{DT}} = 2F_{WS}. \quad (10)$$

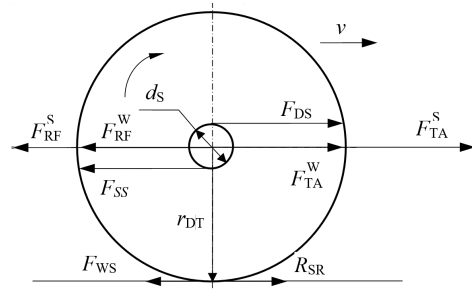


Fig. 6. General diagram for the calculation of traction force of the drive wheel

That is, radius of the wheel does not affect the calculation of traction force on the wheel axis, and the traction force itself is equal to the doubled force, which compensates for the force of surface reaction in the interaction between the wheel and the surface, that is:

$$F_{TA}^W = F_{RF}^W = 2F_{WS}, \quad (11)$$

where  $F_{TA}^W$  is the traction force on the rotation axis of the drive shaft, N;  $F_{RF}^W$  is the resistance force, which is directed opposite to the traction force, N.

The presence of resistance forces to the working tools, inertia forces (at acceleration and deceleration), forces to

overcome the ascent, as well as the rolling forces leads to the existence of resistance forces  $F_{RF}^W$  on the drive wheels axes wheels, which are directed against the motion and which need to be overcome at displacement:

$$F_{RF}^W = F_{FR} + F_{AR} + F_{WM} = mgf \cos \alpha + k_{AR} S_F v^2 + f' m_{WM} g + kab + \theta abv^2, \quad (12)$$

where  $F_{FR}$  is the force to overcome the friction of rolling, N;  $F_{AR}$  is the air resistance force, N;  $F_{WM}$  is the force of traction resistance of the working machine, N;  $m$  is the mass of a tractor or a vehicle, kg;  $g$  is the acceleration of the Earth's gravity force, m/s<sup>2</sup>;  $f$  is the rolling friction coefficient, rel. units;  $\alpha$  is the inclination angle of the surface, rad.;  $k_{AR}$  is the coefficient of air resistance, N s<sup>2</sup>/m<sup>4</sup>;  $S_F$  is the area of frontal drag of a tractor or a vehicle, m<sup>2</sup>;  $v$  is the motion speed, m/s;  $f'$  is the total friction coefficient of the working machine, rel. units;  $m_{WM}$  is the mass of the working machine, kg;  $k$  is the specific soil deformation resistance, N/m<sup>2</sup>;  $a$  is the width of the processed layer, m;  $b$  is the depth of the processed layer, m;  $\theta$  is the speed coefficient of the working machine, N s<sup>2</sup>/m<sup>4</sup>.

Overcoming resistance forces is ensured by the traction force  $F_{TA}^W$  applied to the axis of the drive shaft, which is pointed in the direction of motion of the wheel.

The total magnitude of the pair of forces on the drive wheel requires a torque on the shaft of the drive wheel of magnitude:

$$M = 2F_{WS} r_{DT} + M_B = F_{TA}^W r_{DT} + M_B, \quad (13)$$

where  $M_B$  is the brake moment on the drive wheel due to the losses on friction, deformation of soil and wheels and other brake moments that occur on the wheel, N m.

It is possible to determine from the given expression the maximal traction force on the drive wheel (at two drive wheels):

$$M_{MAX} - 2M_B = F_{TAMAX}^W r_{DT}, \quad (14)$$

$$F_{TAMAX}^W = \frac{1}{r_{DT}} (M_{MAX} - 2M_B), \quad (15)$$

$$F_{TAMAX}^W = \frac{1}{r_{DT}} \left( \frac{N_{EMAX}}{\omega_{DS}} \eta_{TR} - 2M_B \right), \quad (16)$$

where  $M_{MAX}$  is the maximal torque on the drive shafts, n m;  $F_{TAMAX}^W$  is the maximal traction force on the drive wheels, N;  $N_{EMAX}$  is the maximal engine power, W;  $\omega_{DS}$  is the angular velocity of the drive shaft of a wheel 1/s;  $\eta_{TR}$  is the transmission efficiency, rel. units.

Thus, the maximal traction force that occurs on the drive wheels is directly proportional to the engine power and decreases in proportion to the growth of brake torque on the drive wheels due to the losses on friction, deformation of soil and wheels and other brake moments that occur on wheels.

The largest problems in determining the maximal traction force arise in determining a brake moment on the drive wheel due to the losses on soil and wheels deformation. This power losses can be taken into account through the introduction of skid coefficient, then the total traction force will have a value:

$$F_{TAMAX}^W = \frac{1 - \delta_s}{r_{DK}} \frac{N_{EMAX}}{\omega_{DS}} \eta_{TR}, \quad (17)$$

where  $\delta_s$  is the skid coefficient, rel. units.

It is more appropriate to express the given formula not through the shaft rotations of the drive wheel but via engine rotations because it is possible to control this magnitude:

$$F_{TAMAX}^W = \frac{1 - \delta_s}{r_{DT}} q_{FMAX} Q_F \frac{i_{TR}}{\omega_E} \eta_E \eta_{TR}, \quad (18)$$

where  $q_{FMAX}$  is the maximal fuel supply, kg/s;  $Q_F$  is the lower heat generating fuel capacity, kJ/kg;  $\omega_E$  is the angular velocity of the engine crankshaft, 1/s;  $i_{TR}$  is the transmission gear ratio, rel. units;  $\eta_E$  is the effective engine efficiency, rel. units.

It is advisable to take also into account the dependence of effective engine efficiency on the engine crankshaft angular velocity:

$$\eta_E = \alpha \omega_E^2 + \beta \omega_E + \gamma, \quad (19)$$

where  $\alpha$ ,  $\beta$ ,  $\gamma$  are the coefficients of approximation.

It is advisable to also take into account the dependence of fuel supply on the engine rotations:

$$q_{FMAX} = \frac{S_{PL} l_{PL} \rho_F k_{PL} \omega_E}{2\pi}, \quad (20)$$

where  $S_{PL}$  is the area of the plunger pair, m<sup>2</sup>;  $l_{PL}$  is the active run of the plunger, m;  $\rho_F$  is the fuel density, kg/m<sup>3</sup>;  $k_{PL}$  is the coefficient of fuel supply by the plunger of fuel pump;  $i$  is the number of fuel sprays per one engine rotation, rev<sup>-1</sup>.

The driving force of machine-tractor unit is the energy of fuel, which an internal combustion engine of energy means converts into rotations and torque that are transmitted to the drive wheels. The torque of the engine is spent on the drive of the working machine through the power take-off shaft and the creation of traction force. The traction force of the machine-tractor unit drive wheels can be determined from the following expression [17]:

$$F_T = \frac{1 - \delta_s}{r_{DT}} \left( \frac{S_{PL} l_{PL} \rho_F k_{PL}}{2\pi} Q_F \eta_E - \frac{H_{WM} Q_{WM}}{\eta_{WM} \omega_{WM} i_{TRPTO} \eta_{TRPTO}} \right) i_{TR} \eta_{TR}, \quad (21)$$

where  $i_{TRPTO}$  is the gear ratio of transmission from the engine to power take-off shaft, units;  $\eta_{TRPTO}$  is the efficiency coefficient of transmission of the power take-off shaft, rel. units;  $H_{WM}$  is the pressure generated by the fan of the working machine, Pa;  $Q_{WM}$  is the volumetric air consumption by the fan of the working machine, m<sup>3</sup>/s;  $\eta_{WM}$  is the efficiency coefficient of the fan of the working machine, rel. units;  $\omega_{WM}$  is the angular speed of rotating parts of the working machine, rad/s.

It follows from expression (21) that the traction force on the hook, which can be achieved by a mobile energy means, for example, tractor, will take the form:

$$F_{TH} = \frac{1 - \delta_s}{r_{DT}} \left( \frac{S_{PL} l_{PL} \rho_F k_{PL}}{2\pi} Q_F \eta_E - \frac{H_{WM} Q_{WM}}{\eta_{WM} \omega_{WM} i_{TRPTO} \eta_{TRPTO}} \right) \times i_{TR} \eta_{TR} - f m_T g - k_{AR} S_F v^2, \quad (22)$$

where  $k_{AR}$  is the coefficient of air resistance, N s<sup>2</sup>/m<sup>4</sup>;  $S_F$  is the area of machine-tractor unit frontal drag, m<sup>2</sup>.

Fig. 7 shows charts of experimental and estimated data on a change in the traction force of energy means depending on the transmission gear ratio. Experimental dependence of change in the traction effort is constructed according to the conducted studies on the tractor MTZ-80 performance [15]. Theoretical dependence is calculated using expression (22), based on the values of relevant parameters, which were reported in article [15] when carrying out experimental research into a change in the traction resistance of tractor MTZ-80 and which are outlined in chapter "Materials and methods for examining interaction between the drive wheel and the surface" of the present paper.

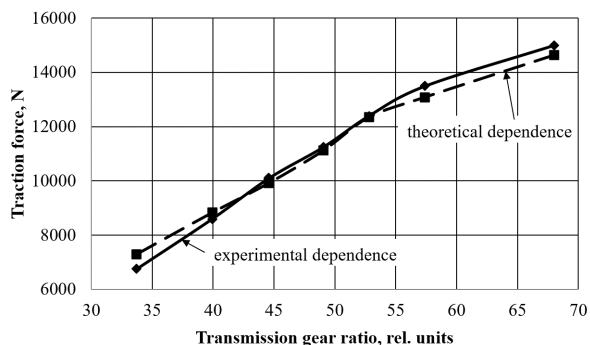


Fig. 7. Dependence of traction force of energy means on the transmission gear ratio

The determination index of values of experimental and theoretical dependences of a change in the traction force on the change of transmission gear ratio, calculated according to procedure [18], is  $\eta^2=0.986$  (Table 2).

Because determination index is 0.986, it is possible to argue about the adequacy of the derived theoretical dependence (22) to model a change in the the traction force at a change in the transmission gear ratio.

## 6. Discussion of results of examining interaction between the drive wheel and the surface

As a result of the research conducted, we substantiated principles of the occurrence of traction force on the axis of the drive wheel of tractors and vehicles. Determining the principles of formation of traction force makes it possible to intensify studying engineering and energy means in general, and to substantiate the principles of reducing negative impact of the engines, in particular, on the fertile soil layer.

Improving effectiveness of scientific research will contribute to the improvement of technical and energy means. Such studies are relevant for agricultural machine-tractor units. This is linked to the fact that the work of agricultural machine-tractor units is associated with problems concerning the interaction between running systems and the surface of fertile layer of soil.

Present article questioned the position on that the total tangent soil reaction under the action of the drive wheels on it is the traction force, which is transferred to the rear axle and thus sets the whole vehicle or tractor into motion.

Regarding the motion of wheeled energy means and vehicles, then the driving force for them is the fuel energy. Internal combustion engine of energy means converts fuel energy into rotations and torque, which are transferred through transmission to the drive wheels. In the machine-tractor units, the torque of the engine is also spent on the drive of the working machine through the power take-off shaft and creation of the force of traction.

The point of application of traction force is on the axis of the drive wheel. Moreover, the magnitude of traction force is about two times greater than the reactive force transferred from the road to the drive wheel. In this case, the surface reaction is transmitted from the road to the drive wheel and counteracts to the wheel rotation.

Table 2

Calculation of determination index of experimental and theoretical values of traction force dependences on the transmission gear ratio

Gear ratio of transmission, rel. units	Experimental value of traction force, N	Estimated value of traction force, N	The square of deviation of experimental values from the general arithmetic mean	The square of deviation of experimental data from theoretical	Determination index
68.01	15000	14641.47	15321632.65	128541.74	0.986
57.43	13500	13094.08	5828775.51	164768.65	
52.81	12400	12352.26	1727346.94	2278.93	
49.07	11250	11124.25	26989.80	15812.35	
44.59	10100	9924.17	971632.65	30914.65	
39.94	8600	8832.33	6178775.51	53978.82	
33.73	6750	7297.59	18798418.37	299853.62	
Sum of values	77600.00	77266.17	48853571.43	696148.76	

Further studies are planned for determining a degree of compaction of the soil medium under the wheels of agricultural machine-tractor units. The research is also required to clarify the nature of skidding. This will help establish energy losses at wheels rolling taking into account inter-deformation between the wheel and the surface of the rolling.

## 7. Conclusions

1. We substantiated and formalized creation of traction force in the form of expression for the calculation of the traction force on the axis of the drive wheel. Traction force is about two times larger than the reactive force transferred from the road to the drive wheel. The maximal traction force that occurs on the drive wheels is directly proportional to the engine power and decreases in proportion to the growth of the brake torque on the drive wheels due to friction losses,

the deformation of soil and wheels and other braking moments that occur on wheels.

2. The driving force of tractors and vehicles is fuel energy, which is converted by internal combustion engine of an energy means into rotations and torque, which are transferred using the transmission to the drive wheels. In the machine-tractor units, torque of the engine is also spent on the drive of the working machine through the power take-off shaft and creation of the force of traction. The adequacy of the derived theoretical dependence of traction force on the hook, which can be attained by a mobile energy means, is confirmed on the basis of comparison of experimental and calculated data on a change in the traction force of an energy means. Determination index of the values of experimental and theoretical dependences of traction force at a change in the transmission gear ratio is  $\eta_0=0.986$ , indicating the possibility to apply the theoretical dependence received for simulating the traction force of energy means.

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