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THE SLIPPAGE OF THE DRIVING WHEELS OF A TRACTOR IN A CULTIVATED SOIL AND STUBBLE

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Abstract. The article analyses the relation between the slippage of driving wheels and the traction characteristics of a tractor. The indicators for estimating wheel slippage are a coefficient of tractor weight force utilization for driving wheel grip and a coefficient of the ratio of trailer and tractor mass. The dependencies of wheel slippage on the weight utilization coefficient of tractors and the ratio of trailer and tractor mass are overviewed. The presented and carried out analysis of the equations of weight utilization coefficient φ_g determined its dependencies on rolling resistance coefficients f of a means of transport, working speed v and acceleration a on the mass ratio of a trailer and tractor m_p/m_t. The results of experimental research on acceleration and constant speed regimes in a cultivated soil and stubble are presented. The dependencies of slippage on the ratio of trailer and tractor mass and the weight utilisation coefficient of a tractor and trailer are viewed.

Keywords: tractor, trailer, driving wheel, slippage, grip, weight utilization coefficient, ratio of mass, traction force.

1. Introduction

Work of a tractor and trailer in a cultivated soil and stubble is always affected by the slippage of a driving wheel. The slippage of driving wheels is inherently connected with traction force. The dependencies of the slippage of tractors having different mass on traction force in the same soil are different and depend on the vertical load (G) of driving wheels, see Skotnikov *et al.* (Скотников и др. 1986); Giedra and Janulevicius (2005). These loads only determine the grip of driving wheels with the soil and slippage. Therefore, to compare different tractors, we must use comparative indicators. One of these is weight utilization coefficient φ_g, see Guskov *et al.* (Гуськов и др. 1988); Janulevičius and Juostas (2007). For evaluating the slippage of a tractor and trailer, we propose the coefficient of the ratio of trailer and tractor mass m_p/m_t see Giedra and Janulevicius (2005); Janulevicius and Giedra (2007).

The weight utilization coefficient as a comparative indicator to evaluate the slippage of the tractor is widely used in various origins of literature. It is used to evaluate slippage on the settled speed regimes. With reference to the dynamic theory of operating a tractor, we can see that the greatest traction resistance and slippage exist on acceleration and run up, see Guskov *et al.* (Гуськов и др. 1988); Skotnikov *et al.* (Скотников и др. 1986) and Guskov (Гуськов 2007). However, no exhaustive results of similar investigations are available.

Work speed is one of the main indicators of working on a tractor as a means of transport. To obtain proper work speed, a means of transport must accelerate as quickly as possible. Run-out is not the only way of accelerating a tractor and trailer. Work speed constantly changes within the process of work. If a tractor and trailer can not quickly accelerate (reach proper speed), its productivity decreases and runs into difficulties of controlling it. The great slippage of driving wheels is a frequent obstacle to fast acceleration.

The purpose of work is to investigate the dependencies of the slippage of driving wheels and the weight utilization coefficient of a tractor and trailer on acceleration and constant speed regimes. The dependencies of the slippage of driving wheels and the ratio of trailer and tractor mass are also researched.

2. Theoretical Analysis

The slippage and characteristics of the traction of tractors greatly depend on the exploitation parameters of driving wheels and the physical and mechanical properties of the soil. Slippage and traction force also depends on the interaction between driving wheels and the soil. The above mentioned tractor parameters also depend on the

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conditions of the interaction between driving wheels and soil. The notable studies include Ivanov, Rusev and Ilchev (2006); Jun *et al.* (1998); Neunaber (1997); Lober and Neunaber (1998); Prentkovskis and Bogdevičius (2002); Upadhyaya *et al.* (1997); Giedra and Janulevičius (2005). The coefficients of the grip and rolling resistance of driving wheels define the interaction between the soil and driving wheels. Rolling resistance coefficient f varies when wheel vertical load and developed torque M_v change. On hard surface roads, when vertical wheel load varies in the range of 80–110% of nominal load limit, rolling resistance coefficient f varies insignificantly. Overloading motoring wheels by 20%, rolling resistance coefficient f increases by around 5%. The vertical load of the wheel has a significant influence on rolling resistance coefficient f for low pressure tyres (tractors) and on the roads distorted by wheels, see Air pressure… (2005) and Skotnikov *et al.* (Скотников и др. 1986). For calculating rolling resistance coefficient f and estimating driving torque and vertical wheel load value, we could use Litvinov and Farobin (Литвинов и Фаробин 1989) formula:

$$f = \frac{a_p}{r_d} + \frac{M_v\left(r_{rv} - r_r\right)}{R_z r_d r_{rv}}, \tag{1}$$

where: a_p – the distance between wheel vertical axis and an attached point of vertical reaction force; r_d – a dynamic radius of the wheel; r_r – wheel rolling radius; r_{rv} – a rolling radius of the wheel in driven regime; R_z – the force of wheel vertical reaction; M_v – the torque of a driving wheel.

The grip coefficient of driving wheels depends on slippage and is estimated in the theory of the interaction between the soil and driving wheels. The dependence of the grip coefficient of slippage was investigated: Guskov (Гуськов 2007); Guskov (Гуськов 1966); Guskov *et al.* (Гуськов и др. 1988); Janulevičius and Giedra (2004, 2007). The grip coefficient φ can be denominated by the ratio of the greatest tangential traction force F_v and vertical load G_v($\varphi = F_{v\,max}/G_v$ or $\varphi = F_\varphi/G_v$) calculating tangential force F_v from the torque of the engine or F_φ – from the force of wheel grip with the soil, see Guskov *et al.* (Гуськов и др. 1988); Wong (Вонг 1989); Juostas and Janulevičius (2008). When a driving wheel interacts with the soil, two different tangential forces are generated: one of those is the force of friction between the tire and the soil and another is the force originated by tire spurs that cut and press the soil. For calculating a summary of tangential force, an equation by Guskov *et al.* (Гуськов и др. 1988); Guskov (Гуськов 2007) could be applied:

$$F_v = \int_0^L b f_f q_x \left(1 + \frac{f_{fp}}{ch\dfrac{\delta x}{k_\tau}}\right) th\frac{\delta x}{k_\tau}dx + 2\tau_k \frac{h_p L}{t}, \tag{2}$$

where: L, b and τ_k – the length and width of wheel tread and section module; h_p and t – spur height and tread; f_f – slip friction coefficient; f_{fs} – static friction coefficient; $f_{fs} = f(f_f, f_{fs})$ – a reduced coefficient of friction; k_τ – deformation coefficient.

By setting up optimal vertical load on driving wheels, we recommend accepting maximal tangential traction force $F_{v\,\max}$ not exceeding maximal admissible wheel slippage. The physical and mechanical properties of the soil are not equal and not constant, and therefore it is difficult to count maximal tangential traction force due to the difficulties in counting what force can give tire spurs pressed in to the soil. Therefore, the maximal horizontal reaction greatly affecting the wheel is set by an experimental test. This force is named the grip force ($R_{x\,\max} = F_\varphi$). According to the value of this force, the grip coefficient of the tyre φ is counted. The theory of the interaction between tractor wheels and the soil propose that the grip coefficient of a driving wheel is connected with the slip, see Guskov *et al.* (Гуськов и др. 1988); Nagaoka *et al.* (2001).

To decrease traction force, a great vertical load of the wheel is partially used, for example, if the traction force of tractor F_{tr} = 5 kN, and its mass m_t = 5000 kg therefore $\varphi_g = F_{tr}/m_g$ = 5000/(5000×9.81) = 0.101, where φ_g – weight utilization coefficient. If F_{tr} = 20 kN and the mass of a tractor m_t = 5000 kg, φ_g = 0.408. In this case, when the grip coefficient in the field ready for sowing is about φ = 0.5 at wheel slip δ > 50%, the coefficient of wheel grip utilization φ_g becomes the coefficient of grip φ, see Guskov *et al.* (Гуськов и др. 1988), Gonsharenko *et al.* (Гончаренко и др. 2007).

A driving wheel load of a working tractor will be optimal when driving force will be near to grip force ($F_\varphi \geq F_v$) and slippage will not exceed the allowable border. The prescribed requirements for a tractor working in a steady regime on the horizontal surface can be expressed by the equation:

$$\frac{P_e \eta_{tr}}{v} \leq \lambda m_t \varphi g, \tag{3}$$

where: P_e – an effective power of the engine; η_{tr} – the coefficient of transmission efficiency; v – ground speed; λ – the load coefficient of driving wheels (when all driving wheels λ = 1); m_t – the mass of a tractor.

In this case, the value of the grip coefficient φ will be close to the value of weight utilization coefficient φ_g and will correspond to agro technical requirements allowable for a maximal meaning of the grip coefficient φ_{leist}. On operating time, soil physical and mechanical properties differ and are not fixed and the load of driving wheels is not optimal. Therefore, vertical load force for the grip of driving wheels is only partially used. Thus, the slippage of tractor driving wheels δ and other dynamic parameters is purposeful to relate to the coefficient of weight utilization for grip φ_g.

The driving force of tractors on the horizontal surface and under conditions of constant speed regime is a sum of rolling resistance and traction forces ($F_v = F_f + F_{tr}$). However, on the horizontal place and under conditions of tractor acceleration, the sum of forces acting the tractor consists of rolling resistance F_f, traction F_{tr} and inertia F_a forces ($F_v = F_f + F_{tr} + F_a$) that can be expressed by the equations presented by Litvinov and Farobin (Литвинов *и* Фаробин 1989); Guskov *et al.* (Гуськов и др. 1988); Skotnikov *et al.* (Скотников и др. 1986):

$$\varphi_g \lambda m_t g = f_t m_t g + F_{tr}, \tag{4}$$

$$\varphi_g \lambda m_t g = f_t m_t g + F_{tr} + a\left(\delta_{st} m_t + \delta_{sp} m_p\right), \tag{5}$$

where: m_p – the mass of a trailer; δ_{st} and δ_{sp} – the coefficient of the inertia of the revolving mass of a tractor and trailer; f_t – the coefficient of the rolling resistance of a tractor; F_{tr} – traction force; a – acceleration.

The equations of the dependencies of weight utilization coefficient φ_g on tractor traction force follow from equations 4 and 5:

$$\varphi_g = \frac{1}{\lambda}\left(f_t + \frac{F_{tr}}{m_t g}\right), \tag{6}$$

$$\varphi_g = \frac{1}{\lambda}\left(f_t + \frac{F_{tr}}{m_t g} + \frac{a}{g}\left(\delta_{st} + \delta_{sp}\frac{m_p}{m_t}\right)\right). \tag{7}$$

The traction resistance of a trailer has similar properties. The traction force of a tractor and trailer in a working order on the horizontal surface and constant speed regime equal to the force of trailer rolling resistance: $F_{tr} = f_p m_p g$; where: f_p and m_p – the coefficient of rolling resistance and the mass of a trailer. Considering a possibility of writing the coefficient of weight utilization φ_g and the ratio of trailer and tractor masses m_p/m_t, the interaction equation is as follows:

$$\varphi_g = \frac{1}{\lambda}\left(f_t + f_p\frac{m_p}{m_t}\right), \tag{8}$$

$$\varphi_g = \frac{1}{\lambda}\left(f_t + f_p\frac{m_p}{m_t} + \frac{a}{g}\left(\delta_{st} + \delta_{sp}\frac{m_p}{m_t}\right)\right). \tag{9}$$

The main indicators that define machine racing are acceleration, time and driven off distance. From the equation of acceleration ($a = dv/dt$), it is possible to calculate acceleration time which is $dt = dv/a$. To calculate acceleration time (t_i) from the beginning of racing up to the point when a means of transport gains the required speed v, we must integrate the presented equation:

$$t_i = \int_0^v dv/a. \tag{10}$$

From equation 9 it is possible to get the dependencies of weight utilization coefficient φ_g on working speed v, acceleration time t_{it} and the ratio of trailer and tractor masses m_p/m_t on the regime of acceleration:

$$\varphi_g = \frac{1}{\lambda}\left(f_t + f_p\frac{m_p}{m_t} + \frac{1}{g}\left(\delta_{st} + \delta_{sp}\frac{m_p}{m_t}\right)\int_0^v \frac{dv}{t_i}\right), \tag{11}$$

A value of acceleration given in equation 5 inserted into equation 10 makes possible to receive an equation having the shortest acceleration time:

$$t_i = \frac{1}{g}\int_0^v \left(\frac{\delta_{st} m_t + \delta_{sp} m_p}{\varphi \lambda m_t - f_t m_t - f_p m_p}\right) dv\,. \tag{12}$$

Taking into account that the coefficient of the rolling resistance of a tractor and trailer is similar and marking it by the symbol f, we will write the interaction equation of the coefficient of weight utilization φ_g and the ratio of trailer and tractor masses m_p / m_t:

$$\varphi_g = \frac{f}{\lambda}\left(1 + \frac{m_p}{m_t}\right). \tag{13}$$

In consideration that the coefficient of the rolling resistance of a tractor and trailer is the same ($f = \frac{F_{fp}}{m_p g} = \frac{F_{ft}}{m_t g}$), we will write the interaction equation of the ratio of trailer and tractor masses m_p/m_t, the forces of the rolling resistance of trailer F_{fp} and tractor F_{ft} and traction force F_{tr}:

$$\frac{m_p}{m_t} = \frac{F_{fp}}{F_{ft}} = \frac{F_{tr}}{F_{ft}}. \tag{14}$$

The interaction equation between the coefficient of weight utilization φ_g, the ratio of trailer and tractor masses m_p/m_t of a tractor and trailer working on the horizontal surface and acceleration regime is:

$$\varphi_g = \frac{1}{\lambda}\left(1 + \frac{m_p}{m_t}\right)\left(f + \frac{a}{g\delta_s}\right), \tag{15}$$

where: δ_s – the coefficient of the inertia revolving masses of a means of transport. Following equation 15, it can be accepted that: $\delta_s = \delta_{st} = \delta_{sp}$; δ_{st} – the coefficient of the inertia of the revolving masses of a tractor; δ_{sp} – the coefficient of the inertia of the revolving masses of a trailer.

The experiments show that the acceleration of a tractor and trailer increased from zero to 6÷8 km/h during 2÷4 seconds. The average acceleration of the vehicle is:

$$a_v = \frac{v - v_0}{t_i}. \tag{16}$$

Accepting that the initial speed v_0 of the vehicle equals 0 km/h and working speed v is expressed by theoretical speed v_t, the following equation of medium acceleration is obtained:

$$a_v = \frac{v}{t_i} = \frac{v_t\left(1 - \delta\right)}{t_i}, \tag{17}$$

where: t_i – an acceleration period of a vehicle.

3. Testing Equipment and Methods

All test measurements were carried out using tractor MTZ–82.1 (60 kW) and trailer GKB–8323. The scheme of the load and measurement of an experimental tractor – trailer is presented in Figure 1.

The tractor scaled 3950 kg not including extra weights with 31% (1225 kg) load on the front axle. The tractor was equipped with 15.5 R38 rear and 11.2 R 20 front tires. The mass of a trailer is 2600 kg and it has 2 axles. During the experiments, the differential of the rear axle was locked and the front axle was engaged.

All test measurements were carried out in a cultivated soil and stubble. The 6th slow gear was tested maintaining 2000 min^{-1} engine speed. The trailer was loaded with bags full of sand.

The measurements included engine speed, driving speed, acceleration time and distance, wheel slippage and traction force. Traction power was calculated using traction force and drive speed. The traction force of the tractor was measured using a spring dynamometer. The measurement borders of the dynamometer were 0–20 kN, graduation value – 200 N. The slippages of tractor driving wheels were measured by calculating the wheel revolutions and measurement of a driven distance. The measurements were performed on the move off, acceleration and constant speed regimes.

4. Results and Discussion

The results of the investigation into move off, acceleration and constant speed regimes are presented in Figures 2 and 3.

As shown in Fig. 2, the allowable 15% slippage in a cultivated soil driving the trailer loaded with 7.7 tons of weight on constant speed was achieved. Slippage was about 10% in stubble loading the trailer with the same weight. 15% of the slippage border have not been achieved

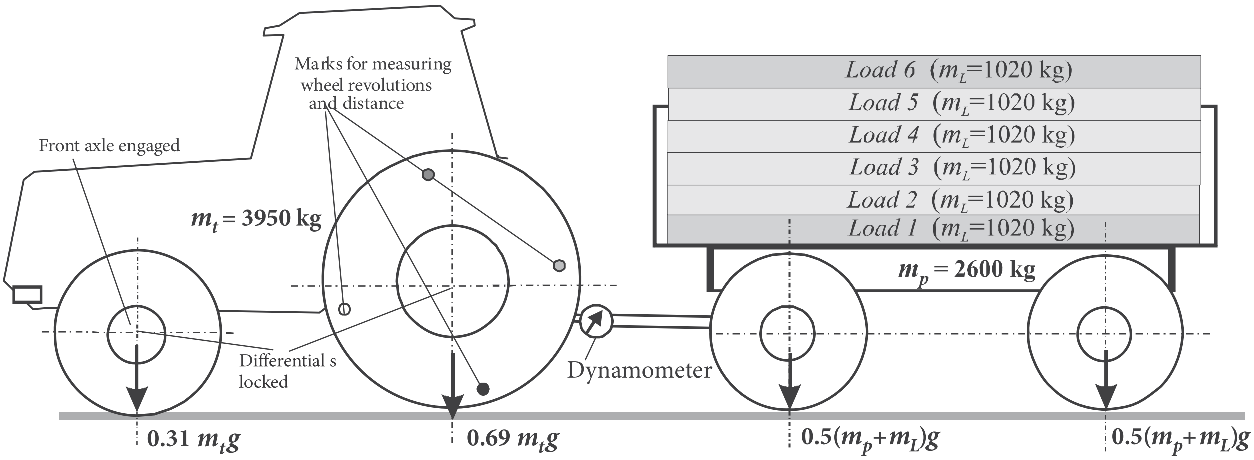

Fig. 1. The scheme of the load and measurement of an experimental tractor – trailer

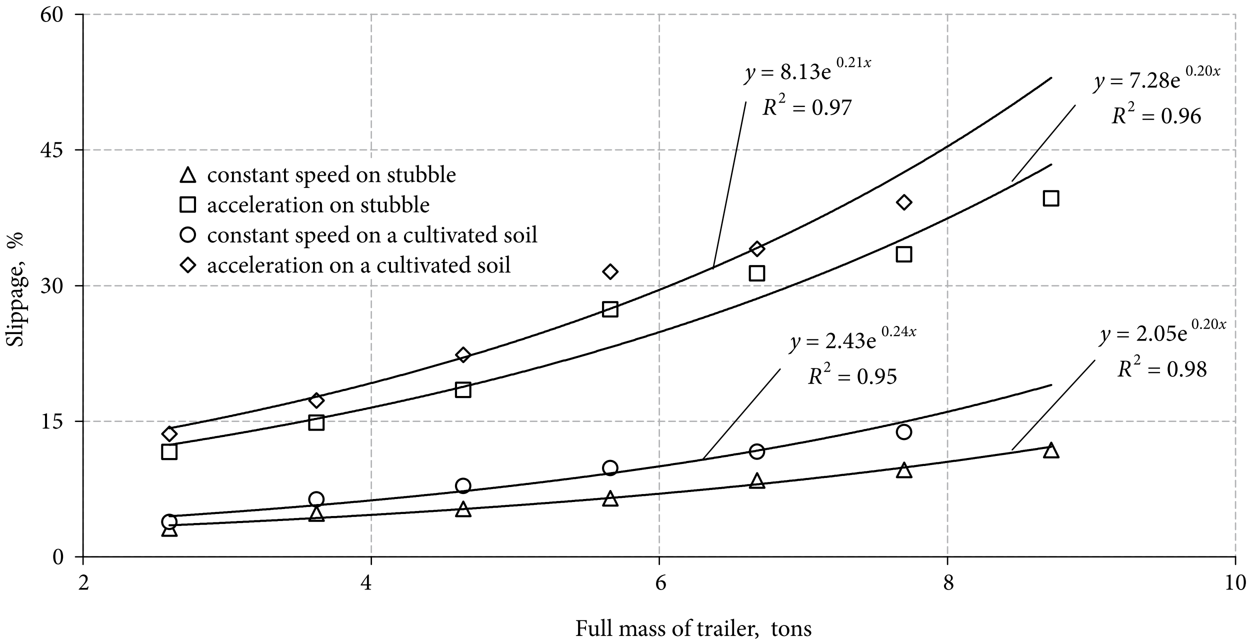

Fig. 2. The dependence of wheel slippage on the full mass of the trailer

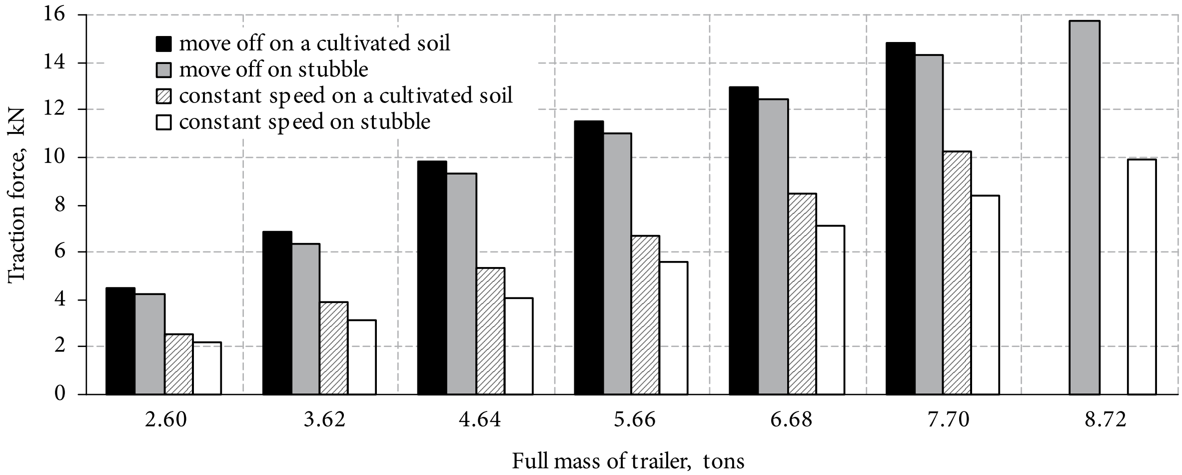

Fig. 3. The dependence of traction force on the fully loaded trailer

in stubble with the trailer loaded with the weight of 8.72 tons. Traction force in a cultivated soil was about 10 kN, whereas in stubble it made about 8.5 kN with the trailer full of 7.7 tons of weight.

Traction force in stubble was about 10 kN with the trailer loaded with the weight of 8.72 tons. Traction force and acceleration time was 30–50% greater on moving off while slippage exceeded from 1 to several times.

Considering the results of traction forces and characteristics of the investigated transport, the values of the coefficients of trailer and tractor mass ratio, weight utilisation and rolling resistance can be calculated.

The dependence of the rate of traction features (the ratio of the mass of a trailer and tractor and grip and rolling resistance coefficients) on the indicated weight of the trailer is presented in Figure 3.

The received coefficients of rolling resistance fall in the borders presented by other researchers. Crop stubble makes 0.08÷0.10 and the field prepared for sowing – 0.15÷0.18, see Litvinov and Farobin (Литвинов и Фаробин 1989); Guskov *et al.* (Гуськов и др. 1988), and Skotnikov *et al.* (Скотников и др. 1986). The value of the coefficient of the weight utilisation approach to the value of the grip coefficient is shown in the articles of scientific literature (the grip coefficient of stubble is 0.6÷0.8 and in the field prepared for sowing – 0.4÷0.6, see Litvinov and Farobin (Литвинов и Фаробин 1989) Guskov *et al.* (Гуськов и др. 1988), and Skotnikov *et al.* (Скотников и др. 1986).

The tests show that the value of the coefficient of weight utilisation approaches the value of grip coefficient when the tractor pulls a fully loaded trailer carrying the weight of 8÷8.72 tons. In stubble, under the tested conditions, the value of the coefficient of weight utilisation has not received the value of the grip coefficient.

When a means of transport is in the mode of acceleration, the coefficient of weight utilisation for wheel grip already reaches the value of 0.4 under conditions of the trailer fully loaded with 4.0 tons of weight. Figures 4 and 5 show that the values of weight utilization coefficient φ_g and the coefficient of φ are approximately the same when the vehicle accelerates or when the tractor pulls an 8 (or more) tons weight trailer. Pulling the trailer weighting less then 8

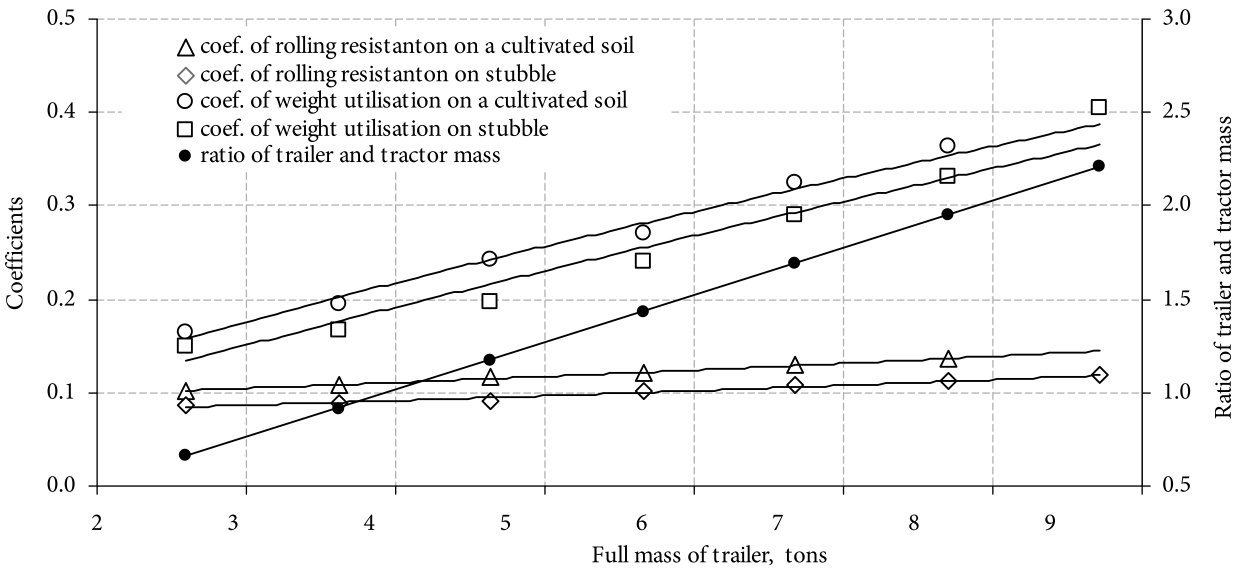

Fig. 4. The dependence of the rate of traction features on the fully loaded trailer at a constant speed of the vehicle

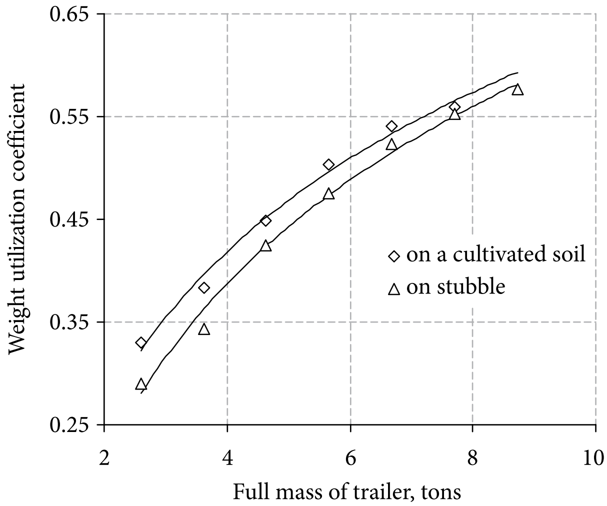

Fig. 5. The dependence of the coefficient of weight utilization on the fully loaded trailer at the time of accelerating the vehicle

tons and using decreased traction force, the weight of the tractor for the grip of driving wheels is partially used.

It is clear that the slippage of tractor driving wheels can be compared with comparative indicators. A common comparative indicator of slippage is weight utilization coefficient (φ_g) for driving wheel grip.

For evaluating the slippage of the means of transport consisting of a tractor and trailer, we can propose the coefficient of the ratio of trailer and tractor mass m_p/m_t. The dependencies of the slippage of driving wheels on the ratio of trailer and tractor mass (m_p/m_t) presented in Figure 6.

Figure 6 indicates the allowable 15% slippage in a cultivated soil driving a constant speed when the ratio of trailer and tractor mass ($m_p/m_t \geq 2$) was achieved.

Slippage was about 10% in stubble loading the trailer the same weight. A slippage border of 15% was not achieved in stubble with the ratio of trailer and tractor mass ($m_p/m_t = 2.2$).

Figure 6 shows that the slippage of the driving wheels of the vehicles was 2÷3 times greater in the mode of acceleration. A slippage border of 15% was achieved in the mode of acceleration with the ratio of trailer and tractor mass $m_p/m_t \geq 1$. The dependencies of the slippage of driving wheels on weight utilization coefficient φ_g for driving wheels grip are presented in Fig. 7.

Figure 7 discloses that the means of transport correspond to the same coefficient of weight utilization φ_g for driving wheel grip on a similar soil and slippage is approximately the same in the modes of constant speed and acceleration.

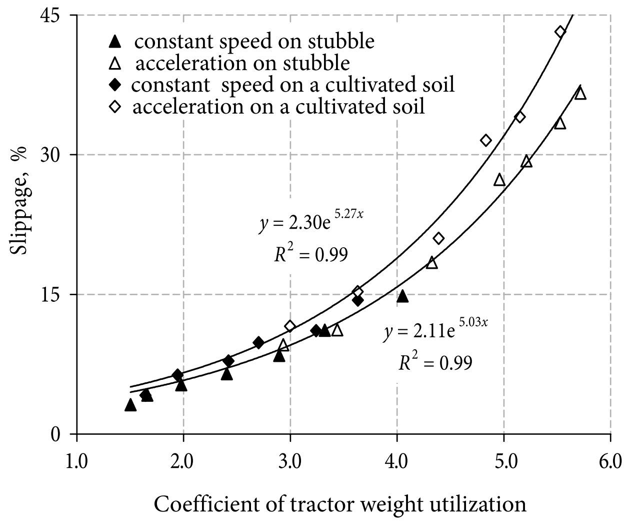

Fig. 7. The dependence of wheel slippage on the coefficient of weight utilization

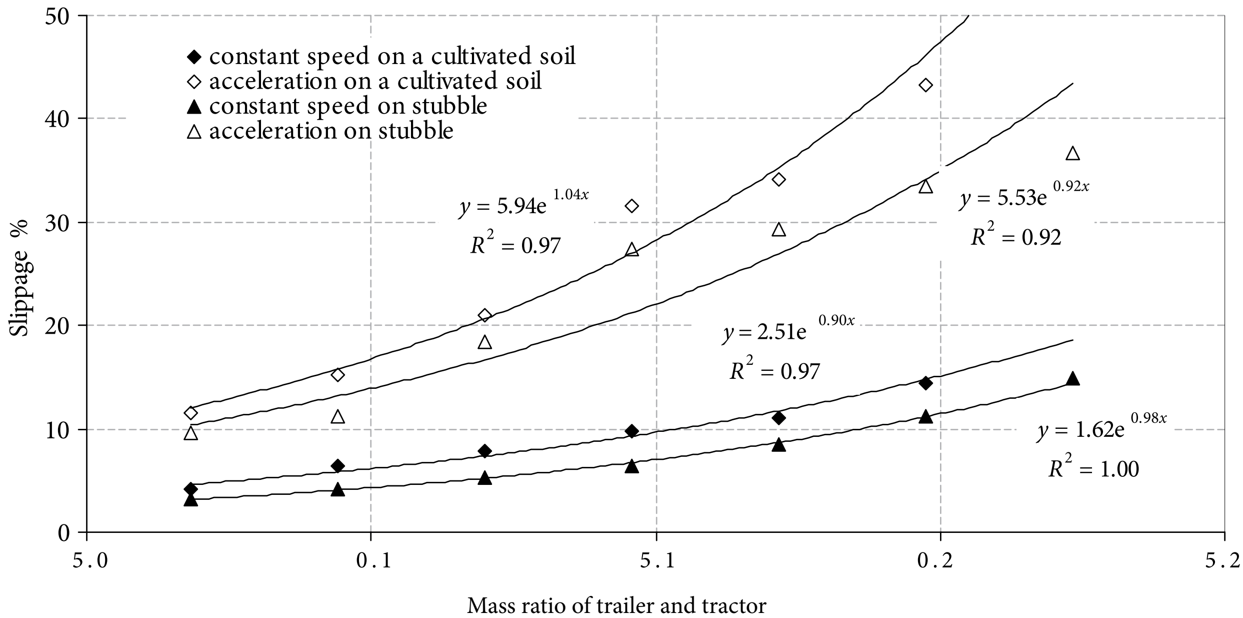

Fig. 6. The dependence of wheel slippage on the mass ratio of a trailer and tractor

5. Conclusions

1. Tractor weight utilization coefficient for driving wheel grip and the ratio of trailer and tractor mass for slippage indications can be used.
2. The worked out equations of weight utilization coefficient φ_g evaluate its dependence on the ratio of trailer and tractor masses m_p/m, the coefficient of rolling resistance f of a vehicle, working speed v, acceleration time t_i, acceleration a and the coefficient of the inertia of the turning masses δ_s of a means of transport.
3. Weight utilization coefficient φ_g of a tractor and trailer can be calculated on the horizontal surface within the mode of constant speed when working conditions are known and include the coefficient of rolling resistance and the masses of trailer m_p and tractor m_t. In addition, within the mode of acceleration, working speed v, acceleration time t_i and the coefficient of the inertia of turning masses δ_s of a means of transport must be considered.
4. The carried out investigations showed that the transport means corresponding to the same weight utilization coefficient φ_g under similar soil conditions, had approximately the same wheel slippage as driving a constant speed or under the acceleration regime.
5. The slippage of the driving wheels of a tractor – trailer is 2÷3 times greater in the mode of acceleration in comparison with wheel slippage on constant speed regime.

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