Tractor ballasting in field work

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1. Introduction

Efficiency of work is one of the main tractor rates, i.e. the use of power to carry out useful work. A tractor works economically when no less than 80% of its engine power is used. Seeking to work with greatest economical effectiveness it is necessary to use as great as possible tractor’s traction force. Increasing this force increases slippage of tractor wheels. The slippage can be reduced by using wider and duplicated wheels, tires with better protector or by decreasing air pressure in the tires and by pressing driving wheels to the earth with greater force [1 - 3].

To exploit effectively tractors in field conditions (that its slippage would be optimal) it is necessary often to change ballast weights. There is a few clear information about selection of ballast weights. In exploitation of tractors many farmers ballasting carry out occasionally. The values of ballasting masses they select not using any methodology, and without any reasoning. The same ballasting masses they use in light and heavy transport works. In this occasion frequently increases fuel consumption for driving of unnecessary ballasting masses or for great slippage of driving wheels. Increased energy requirement for pulling after tractors ballasting must be compensated and reduced by less slipperiness of driving wheels. Besides, ballasting of tractor must secure easy control and safe work.

To solve these problems it is necessairy to know wheel grip force and slippage dependencies in various working conditions and its interaction with exploitation properties of the tractor. Physical and mechanical properties of the soil are very different and not steady, therefore grip forces of wheel and soil and the values of slippage often must be measured by experimental way.

Purpose of the work – to estimate interconnection of traction and gravity forces and slippage of the tractor. To make methodology of the tractor ballasting and selection of the ballast masses.

2. Interaction analysis of tractor’s dynamic parameters

Driving wheel load of working tractor will be optimal when driving force will be approximately equal to the force of grip \((F_v \leq F_g)\), and slippage will not exceed allowable border. Prescribed requirements on tractor steady working regime on horizontal surface can be expressed by the equation

\[ P_e \eta_c / v \leq \lambda \ m \ \varphi_g \]

where \(P_e\) is effective power of the engine; \(\eta_c\) is coefficient of transmission efficiency; \(v\) is ground speed; \(\lambda\) is load coefficient of driving wheels (when all driving wheels \(\lambda = 1\)); \(m\) is mass of the tractor; \(\varphi\) is grip coefficient.

In this instance the value of grip coefficient \(\varphi\) must match to the value of weight utilization coefficient \(\varphi_g\) and it must correspond allowable maximal meaning of grip coefficient \(\varphi_{allow}\) in agrotechnical requirements. In operating time physical and mechanical properties of the soil are not the same and not constant and load of driving wheels is not optimal. Therefore the force of the vertical load of driving wheels for grip used only partially. In this instance it is purposeful to connect slippage of the tractor driving wheels \(\delta\) and another dynamic parameters with coefficient \(\varphi_g\) of weight utilization for the grip. Coefficient \(\varphi_g\) can be denominated by the ratio of greatest tangential traction force \(F_v\) and vertical load \(G_v\) \((\varphi_g = F_v / G_v)\), calculating tangential force \(F_v\) from torque of the engine or \(F_v\) from the force of wheel grip with the soil [2, 4, 5].

Features of driving wheel are defined by coefficients of grip \(\varphi_g\), rolling resistance \(f\) and slippage \(\delta\). Rolling resistance coefficient \(f\) evaluate deformation of wheels and soil. Coefficient of wheel efficiency \(\eta_c\) is essential indicator [6].

\[ \eta_c = \left(1 - \frac{f}{\varphi_g \lambda_g}ight)(1 - \delta) \]  \(\text{(2)}\)

where \(\lambda_g\) is load coefficient of driving wheels (for all driving wheels \(\lambda_g = 1\)).

Tractors driving force on horizontal place and constant speed regime is the sum of rolling resistance tractor and traction forces \(F_v = F_r + F_t\). Tractors traction force on horizontal place and constant speed regime is the sum of rolling resistance agricultural machine wheels and technological process resistance forces \(F_t = F_{tm} + F_{tg}\). In Fig. 1 the dependence of driving wheel traction characteristics on the variation of vertical load \([2, 4, 7]\) is presented. By increasing vertical load of the wheel \(G_v\), the coefficient of efficiency varies according curve \(\eta_c\) (Fig. 1). Optimal vertical load of driving wheel \(G_{0v}\) is at the greatest coefficient of efficiency. Driving force \(F_v\) and force \(F_t\) of rolling resistance primarily increases proportionally by increasing vertical load \(G\) but when \(G\) exceeds \(G_{0v}(G > G_{0v})\), growth of force \(F_v\) slows down. The greatest traction force is accessible at given liminary wheel load \(G_{0v}\) [4, 6, 7]. In the work it is purposeful to load driving wheels in the zone while the proportionality between vertical loads and driving force is preserved. Slow down of the growth intensity of wheel driving force depends on load is explained that
the force of friction, pressure and shear acting on contact area of the wheel and soil increases not proportionally to the load or pressure [2, 4, 8].

Dependences of slippage of different mass tractors on traction force in the same soil are different and depend on vertical load $G$ of driving wheels [3, 4, 7]. These loads just determine grip of the driving wheels with the soil and slippage. Therefore to compare different tractors we must use comparative indicators. Such an indicator is weight for wheel grip utilization coefficient $\eta_g$. The dependencies ($\delta = f(\eta_g)$ of the slippage $\delta$ on the weight utilization coefficient $\eta_g$ in the various working conditions (Fig. 2) were obtained. The slippage graphic is one of the most important graphics of the traction characteristics because the other tractor parameters (traction power, economics) depend on slippage [1, 9].

Great (>15 %) slippage deteriorates the structure of soil and increases fuel consumption [4, 10 - 13]. The economy of agricultural aggregates characterizes specific distances, (Fig. 3)

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$$\delta = f(\eta_g)$$

Fig. 1 Dependence of coefficient of efficiency $\eta_v$, driving $F_v$ traction $F_i$ and rolling resistance $F_f$ forces and depth of rut $h$ on the driving wheel load $G$

3. Methodology of tractor ballasting

Wheel slippage there is greater than kinematic speed discrepancy between driving wheels when tractor 4x4 with tight front axle gear is working on the soft soil. Therefore all driving wheels give positive driving force $F_v$

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$$B_{\delta\delta} = P_v \delta \eta_v b_v$$

$$B_{\delta h} = m_v g f_v b_v$$

here $P_v$ is engine power; $\eta_v$ is coefficient of transmission efficiency; $m_v$ is mass of the ballast.

The excessive ballast mass is useless particularly when working at high speed or on swampy soils. Carrying one ton of the ballast mass on soil prepared for sowing with the speed of 8 km/h the tractor uses about 0.8 l/h fuel. So carrying one ton of the ballast mass and increasing the driving speed from 8 km/h to 40 km/h on the subsurface road the fuel consumption increases by 0.6 l/h [3, 7]. However the increased fuel consumption for carrying ballast mass can be compensated by the lower fuel consumption because of the diminished wheel slippage. Therefore for efficient tractor performance under various field conditions it should be properly ballasted.

Driving forces of the front and rear wheels $F_{\delta P}$ and $F_{\delta V}$ will be different and will depend from vertical forces of reactions $R_P$ and $R_V$ on front and rear wheels. Tractors driving forces on horizontal place and constant speed regime when the tractor works with trailing machines is obtained

$$F_{\delta P} = \varphi R_P = \varphi \frac{G_f l + G_s (l + l_1) - M_f - F_f h_i}{L}$$

$$F_{\delta V} = \varphi R_V = \varphi \frac{G_r (L - l) - G_s l_1 + M_f + F_f h_i}{L}$$

here $G_f$ and $G_s$ are forces of weight accordingly: of the tractor and ballast weights; $M_f$ is torque of rolling resistance $\left(M_f = M_y + M_{r'} = F_f r_p + F_f r_v\right)$; $M_y$, $M_{r'}$, $F_f$, $F_{r'}$, $F_{r''}$ are torques and forces of rolling resistance accordingly: of the tractor front and rear wheels; $l, l_1, h_i$, and $L$ is distances, (Fig. 3)

$$F_f + F_{r'} = F_f = f_p R_p + f_v R_v$$

Rolling resistance coefficient $f_r$, $f_v$ of front and rear wheels evaluate deformations of accordingly wheels
and soil. Tractor traction force $F_t$ composes from rolling resistance agricultural machine wheels and resistance of technological process.

Many firms produce 4x4 tractors so that on front wheels would be 40 - 45% of all the tractor mass [14].

### Table

<table>
<thead>
<tr>
<th>Tractors power</th>
<th>Front axle</th>
<th>Rear axle</th>
</tr>
</thead>
<tbody>
<tr>
<td>85-90 kW</td>
<td>kg</td>
<td>%</td>
</tr>
<tr>
<td>Valtra M−120</td>
<td>2320</td>
<td>44</td>
</tr>
<tr>
<td>New Holland TS 115A</td>
<td>2010</td>
<td>40</td>
</tr>
<tr>
<td>John Deere 6520 SE</td>
<td>1930</td>
<td>40</td>
</tr>
<tr>
<td>Fendt Farmer 412 Vario</td>
<td>2175</td>
<td>42</td>
</tr>
<tr>
<td>Case−IH CVX 1135</td>
<td>2610</td>
<td>41</td>
</tr>
</tbody>
</table>

Guskov, V. V. et al. [4], Wong J. [15], Skotnikov, V. A. et al. [6] recommends to calculate all mass $m$ of the tractor as follows

$$m_i = \frac{(1.35−145) F_v}{(\lambda \phi − f) g}$$

Slippage of the tractor not enters into this equation. Here it can be set from the equation of weight utilization coefficient of the tractor for load of driving wheels

$$\varphi_e = \frac{F_v}{G_v} = \frac{F_v}{m} g$$

Evaluating engine power and driving speed the tractor mass can be calculated by the equation

$$m = \frac{3600 P_e \eta_p}{(\lambda \phi − f) v g}$$

Here $P_e$ is engine power in use kW; $\chi_p$ is coefficient of engine over loading; $\eta_p$ is efficiency coefficient of transmission; $v$ is driving speed km/h.

Accepting $\chi_p = 1.15$; $\eta_p = 0.92$; $\lambda = 1$; $\varphi = 0.65$ and $f = 0.05$ (on stubble), get

$$m_i = \frac{640 P}{v}$$

Available equation is analogous to equation [16] proposed by Silsoe research institute (USA) for the selection of the tractor weight

$$m_i = \frac{650 P_{edv}}{v}$$

Here $P_{edv}$ is power of the engine measured through power take off shaft kW.

From Eqs. (2), (3) and (4) it can be seen that at increasing working speed of the tractor its mass must be decreased.

In many of update 4x4 tractors front wheels are loaded 40 – 45% of all the tractor mass. When the tractor works concerning traction force changes the distribution of vertical load on the front and rear axles, and it is difficult to set. USA scientist Frank Zoz [16] calculates the weight transferred from front to rear wheels due to traction force according the simplified equation

$$\Delta G = \xi F_t$$

Here $\xi$ is coefficient of the evaluation of weight transferred from front to rear axle.

F. Zoz set [16] that for mounted agricultural ma-
machines with automatic depth and position regulation \( \xi = 0.65 \); with semimounted machines \( \xi = 0.45 \) and for trailing machines \( \xi = 0.2 \). From Eq. (12) available dependencies of weight transferred from front to rear wheels on traction force are presented in Fig. 4.

![Fig. 4 Dependence of weight force transferred from front to rear wheels on traction force](image)

The value of optimal ballast mass \( m_{\min} \) calculated according Eq. (11) does not ensure greatest efficiency of the tractor work and optimal slippage. The value of optimal ballast mass can be set according the dependence of slippage on total weight of the tractor. To secure tractors safety driving total weight of the tractor can not exceed 30% of tractor mass. So, using experimental data, dependencies \( \phi_g \) and the value of slippage coefficient must be such that coefficient of efficiency \( \eta \) would be

\[
\eta = \left( 1 - \frac{f}{\phi_g \delta} \right) (1 - \delta) \leq \eta_{\max}
\]

(16)

To get optimal value of ballast mass the value of weight utilization coefficient of the tractor \( \phi_g \) and the value of slippage coefficient \( \phi_g \) are put. This dependence was calculated at the middle part of the nomogram. Changings of transferred weight from front to rear wheels on coefficient of weight utilization \( \phi_g \) are presented in Fig. 4.

![Fig. 5 Dependence of wheel slippage and efficiency coefficient of chassis on weight utilization coefficient of tractors](image)

Weight distribution on the wheels constantly changes when the tractor is working with traction force \([16 - 18]\). Force of weight transferred from front to rear wheels is interconnected with coefficient of weight utilization for driving wheel load \( \phi_g \). Under condition \( F_s = F_f + F_r \) and from Eqs. 6 and 10 the equation for the calculation of weight force transferred from front to rear wheels which is right when the tractor works on horizontal field at constant speed is obtained:

\[
\Delta G = m_s g \xi (\phi_g - f)
\]

(17)

Dependencies of transferred weight from front to rear wheels on coefficient of weight utilization \( \phi_g \) for driving wheel load obtained from Eq. (17) presented in Figs. 6, 7 and 8.

4. Results and discussion

For setting interaction of tractor mass \( m_t \) and the slippage \( \delta \) of driving wheels on stubble the nomogram is made (Fig. 6) from three interdependent parts. All parts of the nomogram are connected by common abscise axis, on which the coefficient of utilization of tractor weight for grip of driving wheels \( \phi_g \) is put.

In the bottom part dependencies of wheel slippage on weight utilization coefficient \( \phi_g \) for driving wheel grip adequate for stubble are put. This dependence had been obtained using experimental data \([4, 7, 19 - 21]\). So, using experimental data, dependencies \( m_t = \phi_g \) were located in the middle part of the nomogram. Changing the value of driving wheel grip utilization coefficient \( \phi_g \), the mass of the tractor \( m_t \) was calculated at the
same driving force $F$, and plotted curves $m = f(\phi_g)$ corresponding to $F_v = 2; 4; 7; 10; 13; 16; 20; 25; 30$ and $35$ kN. Eq. (15) for these calculations was used. Dependence $\Delta G = f(\phi_g)$ is placed in the top part (dependencies of the tractor weight force transferred to the rear wheels $\Delta G$ on the weight of driving wheel grip utilization coefficient $\phi_g$). Changing the weight of driving wheel grip utilization coeff- 

Fig. 6 Nomogram for setting transferred force of weight on the tractor rear wheels and ballast mass and its mounting place on the tractor working with mounted machines on the stubble.
ficient \( \phi_g \), the tractor weight force transferred to the rear wheels \( \Delta G \) was calculated at the same mass of tractor \( m_t \) and are plotted curves \( \Delta G = f(\phi_g) \) correspond to \( m_t = 2; 3; 4; 5; 6; 7 \) and 8 tons. Eq. (17) for these calculations was used. Dependencies of transferred weight from front to rear wheels on weight utilization coefficient when tractor works with mounted on machines using force – position depth regulator is presented in Fig. 5. Analogical dependencies are presented in additional figures (Fig. 7 and 8) when the tractor works with semimounted and trailed machines.

By using the nomogram it is possible to set optimal ballast weights of the tractor and the mounting place on the tractor working on the stubble. Working under these conditions at first we must set middle slippage of tractor. Instantaneous wheel slippage is displayed on the instrument cluster of the tractor. After: on the bottom part of the ordinate axis of the nomogram we place wheel slippage \( \delta_0 \) and mass of the tractor \( m_t \) – on the middle part of ordinate axis. From the placed point \( \delta_0 \) horizontal line draws to the right till the slippage curve (point \( \delta_1 \)). Draw a vertical line from the point \( \delta_1 \) to the middle part of ordinate axis a horizontal line to the right to the intersection of these lines (point \( F_{c1} \)). Point \( F_{c1} \) shows traction force \( F_1 \). If the point \( F_{c1} \) is located between the curves, we must draw a proportional intermediary curve. If current slippage is too great, in such case put the desirable value of slippage \( \delta_0 \) on the bottom part of ordinate axis. Draw a horizontal line from that point \( \delta_0 \) to the right till slippage curve (point \( \delta_2 \)). Draw a vertical line from the point \( \delta_2 \) to curve \( F_1 \) (point \( F_{c2} \)). Because \( F_{c1} \) and \( F_{c2} \) are on the same curve so the values of traction force are equal \( (F_{c1} = F_{c2}) \). Draw a horizontal line from the point \( F_{c2} \) to ordinate axis of the middle part. Here we get the required mass of the tractor \( m_2 \) to maintain the required wheel slippage \( \delta_2 \). To decrease the wheel slippage from \( \delta_1 \) to \( \delta_2 \) additional ballast: \( \Delta m = m_2 – m_t \) is necessary.

Knowing the tractor mass \( m_2 \) and slippage transferred force of weight \( \Delta G \) on the rear wheels can be obtained. Draw a vertical line from the point \( \delta_1 \) up in the top part till the tractor mass curve (point \( m_t \)). If the values of tractor mass are located between the curves, we must draw a proportional intermediary curve. Draw a horizontal line from the point \( m_t \) to ordinate axis of the top part (point \( \Delta G \)). Here we get the transferred force of weight of the tractor working with mounted machines. If it is very big, the ballast weights must be fitted in the front of the tractor dismounting it from the rear wheels. In this case, best of all it is to mount the ballast weight on the front three point hitch, as far as possible carried to the front. Transferred force of the weight is very great working with the three point hitch and electronic draft control (Figs. 7 and 8).

Line \( a \)–\( a \) on the upper part of nomogram shows when the load of front wheel becomes less than 20% of common tractor weight of unbalance tractor (static wheel load is 40x60%). This border is over passed when point \( m_2 \) is in the right side of the line \( a \)–\( a \). In this case tractor ballastasting is needed for the work safety. Ballast weights must be mounted as far as possible to the front of the tractor.

When the tractor works with trailing and semimounted machines transferred force of the mass from front to the rear wheels can be set with the additional graphs (Figs. 7 and 8).

From Figs. 6, 7 and 8 it is seen that front wheel load becomes less than 20% of all the mass of the tractor working on the stubble with mounted machine when weight utilization coefficient is more than 0.41; with semimounted machines – more than 0.55; working with trailing machines load on the front wheels does not decline to such degree.
slippage of driving wheels. This methodic enable new shape and is more cleans and more precise, compare with previous methodic [3, 7]. In previous methodic [3, 7] some parameters were connected with weight utilization coefficient of the tractor, and another connected with traction force.

5. Conclusions

1. Tractor weight utilization coefficient for driving wheel grip as indicator of slippage and tractor ballasting can be used.
2. Derived equations of transferred force of weight $AG$ on the rear wheels evaluate its dependence on mass of the tractor and coefficients of weight utilization, evaluate transferred force of weight and rolling resistance of the aggregate.
3. Front wheel load decreases till 20% of all tractor weight when the tractor works an stubble, coefficient of weight utilization is: when working with mounted implements more than 0.4; semimounted machines – more than 0.55 and trailed machines – load of front wheels does not decreases till that level.
4. Required optimal ballast mass for the tractor and its location place can be set by using slippage rate (displaying in the control display) and by created nomogram.
5. To created tractor ballasting methodic adding additional data corresponds all conditions of tractor work it can be used when making various tractor aggregates for field work.

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TRAKTORIAUS BALASTAVIMAS LAUKO DARBAMS

Re z i u m e

Siaprasnyje apžvelgiama, dėl kurių priežasčių reikia balastuoti traktorius. Pateikta traktoriaus traukos ir svaro jėgų bei ratų buksavimo tarpusavio sąveikos analizė. Analizuojamos traktoriaus buksavimo priklausomybės nuo svario jėgos panaudojimo varančiųjų ratų sukibimui koeficiento. Išsitaškinta sąveika tarp traktoriaus balastavimo ir svario jėgos panaudojimo varančiųjų ratų sukibimui koeficiento. Pateikiamas svario jėgos, perkeltamos nuo priekinių ant užpakalinių ratų, priklausomybių nuo traktoriaus masės ir svario jėgos panaudojimo varančiųjų ratų sukibimui, perkeliamas svario vertės ir riedėjimo pasipriešinimo koeficientų lygties. Sudaryta traktoriaus balastavimo bei balastinių masių dydžio nustatymo metodika. Pateikta no-
In the article the necessity of tractor ballasting is over viewed. The analysis of interaction of traction force, forces of weight and slippage of the wheels is presented. A dependency of tractor slippage on coefficient of weight utilization for driving wheel grip is analyzed. An interaction between tractor ballasting and coefficient of weight utilization for driving wheel grip is investigated.

Equations of dependencies of weight force transferred from front to rear wheel on tractor mass and coefficients of: weight utilization for wheel grip value of transferred weight and rolling resistance are presented. Method for tractor ballasting and setting the value of ballast mass is proposing. The nomogram for setting optimal value of ballast mass and its fitting place, when medium instantaneous wheel slippage is known is presented

Methods of nomogram usage and revive of utilization possibilities are presented.

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