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# Theoretical research into the frictional slipping of wheel-type undercarriage taking into account the limitation of their impact on the soil

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**Abstract.** The frictional slipping of the tractor's wheels causes great damage to the soil fertility. To ensure the minimal disturbance of its structure, it has been proposed to determine the maximum slippage of driving wheels taking into account the value of their permissible pressure on the soil in the horizontal plane. As a result, it has been established that for the substantial reduction of the soil structural damage during the spring agricultural field operations the maximum permissible frictional sliding $\delta_{max}$ of the wheel-type undercarriage of tractors classified into drawbar pull categories 5, 3 and 1.4 (drawbar pull based classification approach is used in Ukraine and some other countries) has to be equal to 15%, 12% and 9% respectively. In the summer/autumn period, the values $\delta_{max}$ can be greater and, accordingly, be equal to 20%, 16% and 13%. Wheeled tractors in drawbar pull category 5 equipped with single standard tyres can be used for field operations only in the summer/autumn period. For their operation in spring they must certainly be equipped with twin tyres. The implementation of this design solution is appropriate for all wheeled tractors.

**Key words:** agricultural engineering, tractor, undercarriage, driving wheel, tyre, drawbar pull category, slipping.

## INTRODUCTION

The slipping of the driving wheels of a wheeled tractor and power unit is known not only to cause the increased fuel consumption (Abraham et al., 2014) and tyre wear, but also to destroy substantially the structure of soil (Lang & Huder, 1985; Molari et al., 2012). This process is associated with the crushing and shearing deformations caused by the pressure on the soil of the sidewall of the currently rearmost ground lug on the wheel contacting the soil (Chyba et al., 2013; Chyba et al., 2014; Kutkov, 2014).

It should be noted that the crushing deformation of soil renders the active organic matter (or humus) inactive. In this process, the former is partially released in the form of separate thin films and partially remains on the separate mechanical elements of the destroyed clump of soil (Gudehus, 1981). The said thin films pass into the category of inactive humus, and no methods of reviving its properties are currently known to agrarian scientists. Moreover, soil shearing is accompanied by the sliding of ground lugs on the bearing surface, which results in the pulverisation of the soil medium up to erosion hazardous condition. Eventually, all these processes to a significant extent inhibit the process of development of various cultivated agricultural plants (Braunack et al., 2006; Kuht et al, 2012; Arvidsson & Hakansson, 2014).

Overall, the greater is the slipping of the undercarriage of the tractor and power unit, the more intensive is the process of soil structure destruction (Komandi, 2006; Schreiber & Kutzbach, 2008). At the same time, the smaller slipping rate translates into the smaller value of the tangential tractive force delivered by the wheel. According to the studies, the maximum value of this force is reached, when the undercarriage of the tractor operate with a frictional sliding rate of 22…24% (Guskov et al., 1988). Which, we believe, significantly exceeds the level that could be admissible in terms of the impact produced by the wheel on the soil structure.

This indicates the need to find the following compromise: the slipping rate limit for the wheel-type undercarriage must be set at such a level that at the minimum permissible degradation of soil structure the maximum possible tangential tractive force is delivered.

## MATERIALS AND METHODS

The problem with solving this task lies in the fact that at the moment any limitations of the pressure applied by the propelling units of tractor and power units to the soil in the horizontal plane stipulated by the agronomical requirements are absent.

At the same time, such limitations exist for the deformation of cultivated land by the undercarriage of tractor and mobile power units in the vertical plane. Namely, at the moment, for example, the following standard is in effect in Ukraine: DSTU 4521:2006 ‘Mobile agricultural machinery. Standard rates of impact on soil by undercarriage’. This standard stipulates the rates of permissible maximum pressure applied by the undercarriage of tractor and power units to the soil $[Q_{max}]$ depending on the latter’s particle-size distribution and humidity as well as the timing of agricultural work in various edaphic-climatic zones.

If we assume a priori that the process of inhibition of the growth of plants does not depend on the choice of the plane, in which the soil structure is destroyed – be it the vertical or horizontal one – then the above-mentioned compromise can be reached by applying the following formula:

$$[Q_{max}] \geq Q_{eff}, \qquad (1)$$

where $Q_{eff}$ – pressure applied by the driving wheel’s ground lug to the soil in the horizontal plane (kPa).

To determine the value $Q_{eff}$, we take the following approach. The tangential tractive force $F_{tg}$ of a single wheel-type undercarriage is decomposed into two forces $P_{tg}$ (Fig. 1), each being equal to a half of force $F_{tg}$ and concentrated in its respective plane located at a distance of a quarter width of the tyre $b_t$ from the wheel’s centre plane.

The generation of each of these forces can be the result of the action of one or several ground lugs. Their number $n_g$ is determined by the following formula:

$$n_g = \mathrm{int}\frac{L}{t_g}, \tag{2}$$

where: $L$ – length of the contact area between the driving wheel tyre and the soil; $t_g$ – pitch of the ground lugs on the tyre.

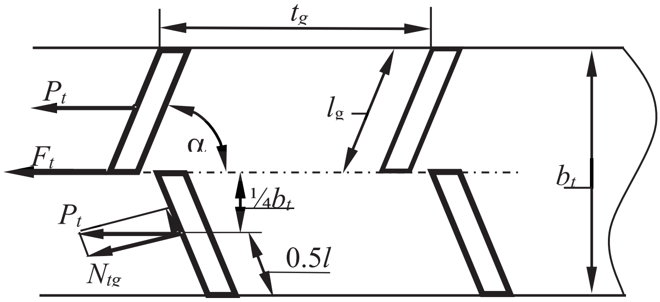


**Figure 1.** Analytical model of the forces acting on the soil via the tyre.

Each of the ground lugs in contact with the soil generates a tractive force $P_{tg}$ (Fig. 1), which, taking into account dependency (2), is equal to:

$$P_{tg} = \frac{F_{tg}}{2\,\mathrm{int}\frac{L}{t_g}}. \tag{3}$$

We assume a priori that the shift and shear deformations of the soil by a ground lug are produced mainly by the action of force $N_{tg}$ (Fig. 1), which, with the substitution of formula (3), can be found from the formula:

$$N_{tg} = P_{tg} \cdot \sin\alpha = \frac{F_{tg}\sin\alpha}{2\,\mathrm{int}\frac{L}{t_g}}, \tag{4}$$

where $\alpha$ – the angle between the centre planes of the ground lug and the wheel.

This force generates the following pressure in the horizontal plane:

$$Q_{eff} = \frac{N_{tg}}{l_g h_g}, \tag{5}$$

where $l_g$, $h_g$ – the length and height of the ground lug, respectively.

It can be concluded from Fig. 1 that:

$$l_g = b_t/(2\sin\alpha).$$

Taking into account this conclusion as well as formulae (4) and (5), requirement (1) assumes the following representation:

$$Q_{max} \geq \frac{F_{tg} \sin^2 \alpha}{2 \operatorname{int} \frac{L}{t_g} b_t h_g}. \quad (6)$$

In obtained limitation (6), the wheel-type undercarriage tangential tractive force $F_{tg}$ is an unknown quantity. To determine it's value, it is most appropriate to use the function proposed by Guskov et al. (1988):

$$F_{tg} = \frac{f_{cl} k_\tau G}{\delta L} \left[ \ln \operatorname{ch} \frac{\delta L}{k_\tau} - f_{sup} \left( \frac{1}{\operatorname{ch} \frac{\delta L}{k_\tau}} - 1 \right) \right] + 2\tau_{sh} \frac{h_g L}{t_g}, \quad (7)$$

where: $f_{sl}$ – the coefficient of sliding friction; $k_\tau$, $\tau_{sh}$ – the coefficient of deformation and rigidity modulus of the soil, respectively; $G$, $\delta$ – the vertical load on the wheel-type undercarriage and its slipping; $f_{sup}$ – the superficial friction factor.

Substituting expression of force $F_{tg}$ (7) into formula (6), we obtain a formula that provides the correlation between the slippage of the wheel-type undercarriage and the pressure exerted by it in the horizontal plane, but not in the vertical one:

$$[Q_{max}] \geq \left\{ \frac{f_{sl} k_\tau G}{\delta L} \cdot \left[ \ln \operatorname{ch} \frac{\delta L}{k_\tau} - f_{sup} \left( \frac{1}{\operatorname{ch} \frac{\delta L}{k_r}} - 1 \right) \right] + 2\tau_{sh} \frac{h_g L}{t_g} \right\} \frac{\sin^2 \alpha}{\operatorname{int} \frac{L}{t_g} b_t h_g}. \quad (8)$$

Now we will analyse the components of obtained formula (8). According to Guskov et al. (1988), coefficient of soil deformation $k_\tau$ can be found with practically adequate accuracy from the formula:

$$k_\tau = 0.4 t_g. \quad (9)$$

The value of force $G$ is assumed equal to the maximum load specified for the respective tyre by standard GOST 7463-2003 'Inflated tyres for tractors and agricultural machines. Standard specifications'.

For the assessment of the length of the contact area between the tyre and the bearing surface Guskov et al. (1988) proposed the following relation:

$$L = R_w \cdot \operatorname{arctg}[(2 \cdot R_w \cdot h - h^2)^{0.5} / (R_w - h)] + (2 \cdot R_w \cdot h)^{0.5},$$

where: $R_w$ – the static radius of the wheel; $h$ – the depth of the track produced by the wheel-type propelling unit.

According to the data in (Kiss, 2003), the value of $h$ can be represented with a practically sufficient accuracy as follows:

$$h = 2 \cdot f_{roll}^2 \cdot R_w \cdot,$$

where $f_{roll}$ – coefficient of rolling resistance.

Taking this into account, after the transformations we finally obtain:

$$L = R_w \cdot \{\mathrm{arctg}[f_{roll} \cdot (1 - f_{roll}^2)^{0.5} / (0.5 - f_{roll}^2)] + 2f_{roll}^2\}. \quad (10)$$

The superficial friction factor can be found from the following function (Opeiko, 1960):

$$f_{sup} = 2.55 \cdot [(f_{st} - f_{sl}) / f_{sl}]^{0.825}, \quad (11)$$

where $f_{st}$, $f_{sl}$ – coefficients of static and sliding friction, respectively.

To calculate the values of coefficients $f_{st}$ and $f_{sl}$ we suggest using the relations obtained by means of approximating the experimental data presented in publication (Guskov et al., 1988):

$$f_{st} = 5.95 + 27.83q - 23.9\sqrt{q} \quad (12)$$

$$f_{sl} = 2.25 + 7.25q - 6.69\sqrt{q} \quad (13)$$

where

$$q = \frac{G}{b_t L} 10^{-6}. \quad (14)$$

Finally, the limiting value for the slipping rate $\delta_{max}$ of a wheel-type undercarriage taking into account that the limitation of its pressure on the soil can be obtained from the following set of equations (9), (10), (11), (12), (13), (14) and (8).

In this set of equations, the terms $G$, $t_g$, $h_g$, $b_t$, $R_w$ and $\alpha$ – design parameters of various wheel-type undercarriage. Their values are known for all tractors in any drawbar pull category. Further in our considerations we will concentrate on the following three categories: 5, 3 and 1.4[1].

Wheeled tractors and power units in lower drawbar pull categories (0.2, 0.6 and 0.9) are seldom used as parts of machine and tractor units. In the past they were considered non-system equipment, for which reason there even was no arrays of machines/implements designed for them.

Tractors in drawbar pull categories 6 and 8 achieve more or less acceptable traction and power ratings usually during the primary soil cultivation operations. But at this stage the resistance of the soil to shift and horizontal shear is significantly higher than that of the cultivated land prepared for seeding. At the same time, in work on soft soil the optimal loading of tractors of drawbar pull categories 6 and especially 8 is rather problematic. The working width of the machine and tractor unit in this case is limited not so much by the traction and power capacities of these propulsion and power units, as by the large overall widths of the applied machines/implements.

[1] For tractors in this traction category only the rear propelling units are taken into consideration

The values of the design parameters: vertical load on the wheel-type undercarriage $G$, pitch of the ground lugs on the tyre $t_g$, height of the ground lug $h_g$, width of the tyre $b_t$, static radius of the driving wheel $R_w$ and angle between the centre planes of the ground lug and the wheel $\alpha$ for the undercarriage of wheeled tractors of drawbar pull categories 5, 3 and 1.4 are assumed according to their technical specifications (Table 1).

**Table 1.** Design parameters of the undercarriage of the compared tractors and power units

| Drawbar pull category of tractor, series | Nominal size of tyre | Design parameter of undercarriage and its value | | | | | |
|---|---|---|---|---|---|---|---|
| | | $G$ (N) | $t_g$ (m) | $h_g$ (m) | $b_t$ (m) | $R_w$ (m) | $\alpha$ (deg) |
| 1.4 (MTZ-82) | 16.9R38 | 25,261 | 0.23 | 0.038 | 0.43 | 0.770 | 43 |
| 3 (KhTZ-170) | 23.1R26 | 35,807 | 0.23 | 0.045 | 0.59 | 0.715 | 47 |
| 5 (K-744) | 28.1R26 | 40,466 | 0.23 | 0.045 | 0.72 | 0.720 | 47 |

Terms $f_{roll}$ and $\tau_{sh}$ in set of equations (9, 10, 11, 12, 13, 14 and 8) represent the soil medium. The selection of their values will be based on the following considerations. According to the data in Guskov, et al. (1988), the $\tau_{sh}$ for clay loams varies within 1,260÷1,940 N m$^{-1}$, for sand loams within 1,500÷2,600 N m$^{-1}$. The estimation shows that the variation of $\tau_{sh}$ even within a range of 1,260÷2,600 N m$^{-1}$ has an effect only on the tenths in the value of the wheel-type propelling unit slipping rate. Therefore, for the further calculation we assume $\tau_{sh}$ to be equal to the mean of the range that is common for clay and sand loams: (1,500 + 1,940)/2 = 1,720 N m$^{-1}$.

As we already stressed above, the greatest shift and shear deformation occurs in soil prepared for planting, which features $f_{roll}$ = 0.16÷0.20 (Kutkov, 2014). At the same time, another sufficiently widespread type of cultivated land is broken stubble field, where the coefficient of rolling resistance varies within 0.12…0.16 (Kutkov, 2014). In light of that, for the following analysis we assume the value $f_{roll}$ = 0.16, which is common for both types of cultivated land – broken stubble field and field prepared for planting.

Finally, we have to decide on the value of $Q_{max}$. The above-mentioned DSTU 4521:2006 specifies two periods of field cultivation operations: spring and summer/autumn. We assume the first of them, when the soil is most vulnerable with regard to the deformations of shift and shear, as the basis for the following calculations. In the said period, when the structure of the cultivated land is moderately dense (0.9…1.0 g cm$^{-3}$) and its humidity is 0.4…0.5 times the minimum moisture-holding capacity, the level of permissible maximum pressure on soil of the tractor's driving gear may not exceed 160 kPa. This value of $Q_{max}$ we are going to use as the reference one.

## RESULTS AND DISCUSSION

As a result of solving set of equations (9, 10, 11, 12, 13, 14 and 8), it has been found that taking into account the limitation of the pressure on soil by a level of 160 kPa, tractors in drawbar pull categories 1.4, 3 and 5 have to comply with a slipping limit of 9%, 12% and 15%, respectively. Conceptually, this can be expressed as follows: the lower the drawbar pull category of the tractor is, the smaller the value of $\delta_{max}$ has to be.

To analyse the reached result, we will examine the relation between the slipping rate of a wheel-type undercarriage $\delta_{max}$ and those design parameters, which are used in set of equations (9), i.e. $G, t_g, h_g, b_t, R_w$ and $\alpha$. The undercarriage of the tractor of drawbar pull category 5 (series K-744) will be taken as an example.

The study of set of equations (9, 10, 11, 12, 13, 14 and 8) shows that the value of the slipping limit of the undercarriage very little depends on its radius ($R_w$, Fig. 2). Such a conclusion is due to the fact that the change of this parameter has effect only on the length of the contact area between the tyre and the bearing surface $L$. While this area, as the calculation proves, changes inessentially with the variation of wheel radius $R_w$ within the assumed range of 0.72 ± 0.04 m.

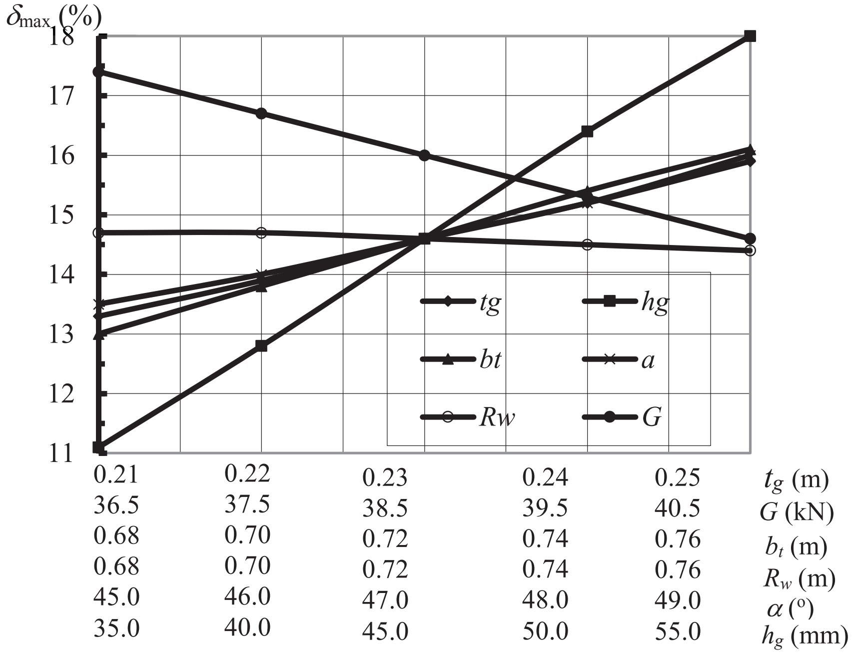


**Figure 2.** Relation between the maximum permissible frictional slipping $\delta_{max}$ of the undercarriage of a drawbar pull category 5 tractor and the wheel parameters ($G$, $t_g$, $h_g$, $b_t$, $\alpha$, $R_w$).

Increase of the undercarriages design parameters $t_g$, $b_t$ and $\alpha$ allows to set the level of its slippage limit higher (Fig. 2). At the same time, the intensity of their effect on value $\delta_{max}$ is insignificant and virtually the same.

The growth of the vertical loading $G$ of the tyre induces the reduction of the value of the undercarriages slippage limit. In principle, this effect is also fully consistent, because pursuant to relation (7) the increase of value $G$ is accompanied by the corresponding growth of the value of tangential force $F_{tg}$. Which, as formula (4) implies, results in the increase of force $N_{tg}$ and growth of the pressure applied by the ground lug's side surface to the soil (formula (5)).

The most significant influence on the value of the undercarriages slippage limit has the height of ground lug $h_g$ (Fig. 2). The greater it is, the greater $\delta_{max}$ can be and this is quite logical, since the said variation of parameter $h_g$ entails increase of the bearing surface area of the ground lug, which helps to reduce its pressure on the soil.

There is no need to consider separately how the undercarriage design parameters influence value $\delta_{max}$ in tractors of drawbar pull categories 1.4 and 3, because in essence they are similar to what has been described above.

The analysis of the values of the undercarriage design parameters of the compared propulsion and power units reveals that most significantly they differ only in two of them – the tyre width $b_t$ and the permissible vertical loading $G$ (see the Table 1). In our case at different values of the maximum vertical loading $G$ on the tyre each undercarriage exerts approximately the same pressure $q$ on the soil. For example, for tractors in drawbar pull category 5 $q$ = 210 kPa, drawbar pull category 3–230 kPa and drawbar pull category 1.4–210 kPa. Thus, there is virtually no difference between the values of $\delta_{max}$ for these tractor and power units as regards parameter $G$.

While the width $b_t$ of the undercarriage has essentially different and measurable influence on $\delta_{max}$. When it becomes smaller, the permissible slipping rate $\delta_{max}$ must also be set lower and vice versa (Fig. 3).

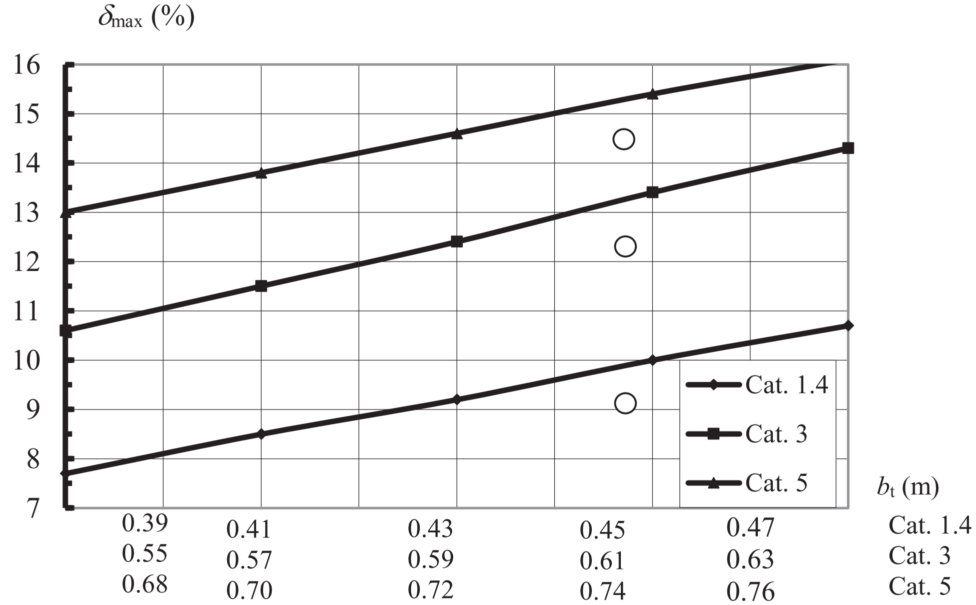


**Figure 3.** Dependence of the maximum permissible slipping $\delta_{max}$ rates of undercarriage of wheeled tractors in different drawbar pull categories on their tyre widths $b_t$.

Such a result can be explained as follows. The narrower the tyre is, the shorter its ground lug length $l_g$ is. As this, according to formula (5), results in the increase of pressure $Q_{eff}$, the undesirable probability of infringing requirement (6) increases.

The sizable difference between the tractors in drawbar pull categories 1.4; 3 and 5 as regards their undercarriage tyre widths $b_t$ is exactly what defines the result obtained above with respect to their ranking on the maximum permissible slipping rate (Fig. 3): 9%, 12% and 15%, respectively.

It should be stressed that the stated values of $\delta_{max}$ are defined at the maximum pressure $q$ of undercarriage on the soil in the vertical plane. The effective values $q_{eff}$ of this pressure are slightly lower. According to the calculations, for tractors in drawbar pull category 5 (series K-744) $q_{eff} \approx 200$ kPa, in drawbar pull category 3 (series HTZ-170) $q_{eff} \approx 160$ kPa and in drawbar pull category 1.4 (series MTZ-82) $q_{eff} \approx 100$ kPa.

From this we can conclude that with regard to the correlation between $q_{eff}$ and $Q_{max} = 160$ kPa the recommended maximum values for the undercarriage slippage hold true for tractors in drawbar pull categories 1.4 and 3.

For tractors and power units in drawbar pull category 5 $q_{eff} \approx 200$ kPa > $Q_{max} = 160$ kPa, therefore, with single standard tyres (see the Table 1) they can be used only in the summer/autumn period of field operations with the steady-state soil density of 1.2…1.3 g cm$^{-3}$ and the soil humidity at 0.4…0.5 of the minimum moisture-holding capacity. Pursuant to the requirements of DSTU 4521:2006, value $Q_{max}$ in this case may not exceed 210 kPa, while $\delta_{max}$, as our calculations show, may not exceed 20%. For tractors in drawbar pull categories 3 and 1.4 working in the summer/autumn period the maximum permissible propelling unit slipping rates are 16% and 13%, respectively.

In the spring period of field operations, tractors of drawbar pull category 5 can be used only with twin tyres installed. In this configuration their pressure on the soil is reduced almost twice. This implies that the coefficients $f_{st}$ and $f_{sl}$ increase and the superficial friction factor $f_{sup}$ decreases. This results, as follows from the analysis of formula (7), in the corresponding reduction of the undercarriage slippage.

In practice, it can occur that the effective values of the undercarriage slipping rates of tractors in drawbar pull categories 3 and 1.4 during their operation in the spring period exceed levels of 15% and 12%, respectively. In that case, the situation can be corrected by the installation of twin tyres on their wheels. At the same time, on tractors of drawbar pull category 1.4 the implementation of this design solution can be limited by the tyres of the rear axle only.

It should be emphasized that with twin tyres on the undercarriage the infringement of requirement (6) becomes possible at a considerably higher level of slippage. According to the calculations, under such conditions the value of $\delta_{max}$ for tractors in drawbar pull categories 5 and 3 is equal to 23%, while for tractors in drawbar pull category 1.4–16%.

Moreover, with the implementation of twin tyres a potential arises to increase the tractive force of the tractor and power unit by its ballasting. Nevertheless, this solution should be employed only with due consideration of the 'eco-friendliness' of the tyres, the technique of estimating that feature is rather comprehensively presented in study (Nadykto, 2013).

## CONCLUSIONS

In order to reduce considerably the destruction of soil structure in the spring period of field operations, the maximum permissible slipping rates $\delta_{max}$ of the wheel-type undercarriages of tractors in drawbar pull categories 5, 3 and 1.4 have to be 15%, 12% and 9%, respectively. In the summer/autumn period $\delta_{max}$ can have greater values and, respectively, be equal to 20%, 16% and 13%.

Wheeled tractors in drawbar pull category 5 equipped with single standard tyres can be used in field operations only in the summer/autumn period. For operation in spring they have to be equipped without fail with twin tyres. The implementation of this design solution is advisable for all wheeled tractors and power units.

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