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# Effect of tires' pressure on the kinematic mismatch of a four-wheel-drive tractor

**A. Janulevičius*, G. Pupinis**, V. Damanauskas*****
**Aleksandras Stulginskis University, Studentų 15, 53361 Kaunas-Akademija, Lithuania, E-mail: algirdas.janulevicius@asu.lt*
***Aleksandras Stulginskis University, Studentų 15, 53361 Kaunas-Akademija, Lithuania, E-mail: gediminas.pupinis@asu.lt*
****Aleksandras Stulginskis University, Studentų 15, 53361 Kaunas-Akademija, Lithuania, E-mail: damvid@gmail.com*

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## 1. Introduction

In tractors (4×4) all four wheels are driving wheels. Such machines deliver more thrust with less slippage, because all the weight of machine is utilized for its bond with soil or road surface [1-3]. Efficiency is one of the main tractor parameters, i.e. what part of power is utilized for useful work. To work with highest economical effectiveness means to use as much tractor's traction force as possible. But if this force is increased, slippage of tractor wheels increases [4, 5]. The slippage can be reduced by decreasing air pressure in the tires and by pressing driving wheels to the earth with greater force [5-7]. In addition, with reduction of the tire pressure soil compaction also reduces [5, 7].

Many firms design their 4×4 tractors in such a way that front wheels would be loaded by 40-45% of the entire tractor weight [3, 8, 9]. Tractor testers recommend maintaining such proportionality of load distribution in the real work conditions too [1, 3, 8, 10]. When the tractor works, the associated traction force changes the distribution of vertical load onto the front and rear axles, and it is difficult to set the required proportionality of load distribution. USA scientist Frank Zoz [11, 12] calculates the weight transferred from front to rear wheels due to traction force by using in his formula the coefficient ($\xi$), which is used for evaluation of weight transferred from front to rear axle. Research papers [1, 4, 12] indicates that the force of weight transferred from front to rear wheels is related to weight utilization of driving wheels' load by coefficient ($\varphi_g$). If the tractor's work includes pull operations, the vertical load distribution on the front and rear wheels is adjusted by ballast weights [4, 5, 10-12]. However, there are some works for the tractor when the vertical load and its distribution on the front and rear wheels is constantly changing. For example, a work of tractor with mounted front loader. In the work of loading the tractor has to run without load and with loads having different weight. Changes in wheel load change the tire deformations. Soft tires deform more [13-16]. Differently loaded front and rear wheels deform differently. Tire deformation changes radiuses of rolling wheels and theoretical wheel speeds [1, 3, 17, 18].

Disproportional change of front and rear rolling wheel, make the kinematic mismatch of the wheel-drive. The more different front and rear wheel sizes, the larger this mismatch [1, 3, 19]. Theoretical speed of front and rear wheels are not the same, but the tractor (4×4) drive axles, connected to the tractor's chassis, are forced to move at the same speed, which is equal to the total tractor speed. Then, of course, the front and rear wheels are forced to slip unequally, some of them may even slide [3, 8, 19].

Purpose of the work: to investigate for the four-wheel-drive tractor, working with front loader, the dependence of kinematic mismatch and its consequential wheel slippage/sliding on the weight of the load and tire pressure.

## 2. Theoretical anglysis

Theoretical speeds of front and rear wheels are uniform when ratio of their rolling radiuses corresponds to the value of ratios of speed transmission to the front and rear axles. Values of speed transmission to the front and rear axles $i_f$ and $i_r$ are associated with transmission structure and do not change during operation of the tractor, so kinematic mismatch between theoretical speeds of front and rear wheels appears only as a consequence of disproportionate changes in rolling radiuses $r_f$ and $r_r$, i.e. disproportionate distortion of the tires, uneven wear or simply because the wheels are not compatible [1, 3, 8].

The axle with a higher theoretical wheel speed is called "advancing", and that with a lower theoretical wheel speed is called "lagging". Of course, the wheels of advancing axle are slipping more compared to the wheels of lagging axle, which may even slide. The least favorable situation is when lagging wheels slide instead of slipping [3, 19, 20]. Sliding wheels do not create a driving force, but on the contrary – resist to the motion of machine (Fig. 1). In this case, the motor turns the driving wheels through transmission with the torque moment $M_{rd}$ and creates the driving force $F_{rd}$. Sliding wheels create an additional drag force $F_{fs}$ and torque moment $M_{fs}$, which is transferred to the tractor's transmission through the front axle drive and helps driving the rear axle. They create an additional drive torque moment $M_{rd}'$ and additional driving force $F_{rd}'$.

Thus, when the front wheels are sliding, the rear driving wheels of transmission push the front wheels, which create a torque moment again and transfer it back to the transmission; in other words, the result in the so-called power circulation. This circulating power is harmful, because it increases fuel consumption, tire wear, etc. The main drive wheels are much more loaded, because their movement is hindered by the front wheels. For this reason, the main wheels slip much more. While the front wheels return part of the power to the main wheels, a considerable

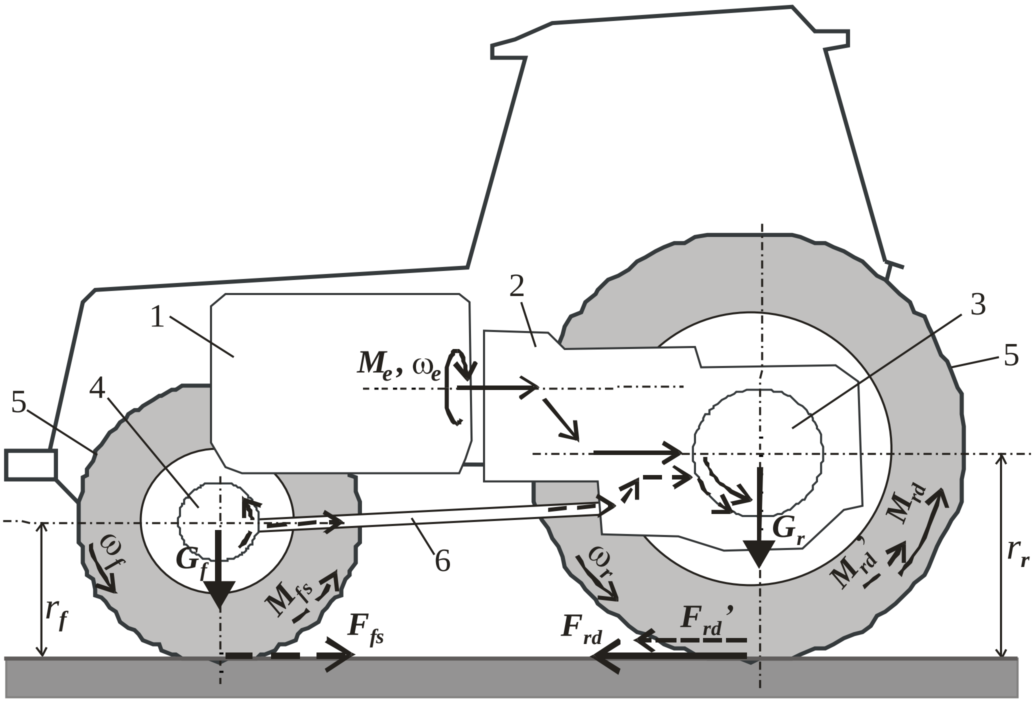


Fig. 1 Kinematic scheme of four-wheel-drive tractor with circulation of power in transmission: *1* – engine; *2* – transmission; *3* – rear driving axle; *4* – front driving axle, *5* – front and rear wheels; *6* – front cardan-shaft

part of it generates the additional load on the transmission and increases its friction losses. The losses in the transmission increase due to circulation of power and increased slippage of the main drive wheels [1, 3, 8, 19].

The circulation of power in longitudinal plan and effecting balance of powers can be investigated by applying the graphs of nodal theory and making the nodal scheme of the tractor, which is shown in Fig. 1.

If losses in the elements of the transmission, expressed in terms of mechanical efficiency, are also taken into consideration, the part of power that arrives to the transmission from the front driving axle has the following expression:

$$P_{fs} = M_{fs}\,\omega_f\,\eta_{tr\,f} = F_{fs}\,r_f\,\omega_f\,\eta_{tr\,f}\,, \tag{1}$$

where $\eta_{tr\,f}$ means the efficiency of power transmission in the tract from the front driven wheels via front driven axle via driven shaft to the rear driven axle through distributive box.

Another flux of power also arrives to the transmission from the part of the driving engine, which can be determined with the following equation:

$$P_m = M_e\,\omega_e\,\eta_{mtr} = P_e\,\eta_{mtr}\,, \tag{2}$$

where $P_e$ means power from the driven shaft of engine (crankshaft); $\eta_{mtr}$ means efficiency of the transmission in the tract from the engine via driven shaft to the rear driven axle through distributive box.

Consequently, on the driven shaft of the transmission's distributive box a total of two powers is acting, expressed by the Eqs. (1) and (2):

$$P_{db} = \left(P_{fs} + P_m\right)\eta_{tr\,r} = F_{fs}\,r_f\,\omega_f\,\eta_{tr\,f} + P_e\,\eta_{mtr}\,, \tag{3}$$

where $\eta_{tr\,r}$ means the efficiency of the transmission in the tract from the wheels of the rear driven axle via driven shaft to the driven axle through the distributive box.

This power is consumed by overcoming resistance to motion from the wheels of rear driven axle, $P_{rd} = F_{rd}\,r_r\,\omega_r$; for $F_{rd} = \varphi G_r$, it has the following expression:

$$P_{rd} = \varphi G_r\,r_r\,\omega_r\,, \tag{4}$$

where $\varphi$ is the coefficient of adherence; $G_r$ is the weight on the wheels of the rear driven axle.

By equalizing the last two equations, we can obtain the balance of powers, which corresponds to the contact area between the ground and the wheels of rear driven axle:

$$\varphi G_r\,r_r\,\omega_r = \left(F_{fs}\,r_f\,\omega_f\,\eta_{tr\,f} + P_e\,\eta_{m\,tr}\right)\eta_{tr\,r}\,. \tag{5}$$

The value in the left side corresponds to the limit of adherence, and the value in the right side represents the flux of power which comes through the transmission to the wheels.

Finally, the force $F_{fs}$ is given by the equation:

$$F_{fs} + \sum R = F_{rd}\,. \tag{6}$$

From this we obtain the following expression:

$$F_{fs} = \varphi G_r - \sum R \tag{7}$$

and introduce this value into Eq. (5). The equation of balance of powers is transferred from the place of contact with the ground to the level of the driven shaft of the distributive box transmission (where the fluxes of power coming from the engine and the circulation power coming from the rear driven axle meet). After separation of two fluxes of power the equation of balance of powers becomes as follows:

$$P_e\,\eta_{mtr}\,\eta_{tr\,r} = \varphi G_r\, r_r\, \omega_r - \left(\varphi G_r - \sum R\right) r_f\, \omega_f\, \eta_{tr\,f}\,\eta_{tr\,r}\,. \quad (8)$$

The convenient grouping of the terms permits separation of different categories of powers in the equation of balance as follows:

$P_e\,\eta_{mtr}\,\eta_{tr\,r}$ - power that comes from the engine;

$\varphi G_r\, r_r\, \omega_r$ - power that corresponds to the limit of adherence;

$\left(\varphi G_r - \sum R\right) r_f\, \omega_f\, \eta_{tr\,f}\,\eta_{tr\,r}$ - circulation power.

From Eq. (8) it is easy to deduce conclusion that if the resistance to the tractor displacement increases, the value of circulation power decreases and may become equal to zero $\left(\sum R = \varphi G_r\right)$; and if the resistance to the tractor displacement decreases, the value of circulation power increases. In order not to have circulation of power between the driving axles it is necessary that the theoretical speeds of wheels of the two driving axles, in rectilinear motion, be equal:

$$\omega_f\, r_f = \omega_r\, r_r\,. \quad (9)$$

The value of circulation power depends on the kinematic mismatch between the theoretical speeds of the front and rear wheels, which is estimated by kinematic mismatch coefficient $k_n$ [1, 19].

When theoretical speeds are different, the actual speeds of front and rear axles may become equal only in that case when their wheel slippage is different. Let us mark theoretical speed of the front axle (regardless of which is advancing) by a symbol $v_f^t$, and that of the rear axle – $v_r^t$; then, respectively, slippage of front and rear drive wheels by symbols $\delta_f$ and $\delta_r$, and actual tractor working speed – by a symbol $v$. We can write the following equation for speed:

$$v = v_f^t\left(1-\delta_f\right) = v_r^t\left(1-\delta_r\right). \quad (10)$$

The wheels' slippage (percentage) is defined by the following equations:

$$\delta_f = \frac{r_f\,\omega_f - v}{r_f\,\omega_f}100\,; \quad \delta_r = \frac{r_r\,\omega_r - v}{r_r\,\omega_r}100\,. \quad (11)$$

To evaluate (from kinematic point of view) the conditions of appearance of longitudinal circulation of power, the notion of kinematic mismatch is introduced. For its study, index of kinematic mismatch in wheel systems of tractors is used, which is given by the following equation:

$$k_n = \frac{v_f^t}{v_r^t} = \frac{r_f\,\omega_f}{r_r\,\omega_r} = \frac{1-\delta_r}{1-\delta_f}\,. \quad (12)$$

This index varies depending on working conditions. Ideally, the kinematic mismatch index $k_n$ should be equal to one, i.e. when theoretical speeds of the wheels on both drive axles are the same. However, this may happen only when tractor's working conditions do not vary. When this index is greater than one, the front axle is advancing, and when less than one – lagging. In specific tractor's working conditions the value of kinematic mismatch can be calculated by separately determining the front and the rear wheel slippage coefficients. It is possible to determine them by tests.

## 3. Materials and method

### 3.1. Equipment, site and layout

Tractor New Holland T 5060 was used for the tests to determine kinematic mismatch of driving wheels. The tractor was fitted with a loader MX 10 in front and 500 kg of ballast mass on the rear hydraulic lift (Fig. 1). Characteristics of tractor and loader are presented in Table, and the diagram of tractor's load – in Fig. 1.

Table

Characteristics of the tractor and loader

| | |
|---|---|
| Mass of the tractor (New Holland T 5060) | 4250 kg |
| Wheelbase of the tractor (L, see Fig. 2) | 2.35 m |
| Front tyres | Contract AC 70 T / 380/70R24 / 125 A8 |
| Rear tyres | Contract AC 70 T / 480/70R34 / 143 A8 |
| Mass of the frontal loader (MX 10) | 1010 kg |
| Total mass of the tractor-loader | 5770 kg |
| Weight share of the tractor front wheels:<br>30.02 kN (when the mass of load - 0 kg)<br>37.75 kN (when the mass of load - 500 kg)<br>47.80 kN (when the mass of load - 1000 kg) | |
| Weight share of the tractor rear wheels:<br>26.44 kN (when the mass of load - 0 kg)<br>23.57 kN (when the mass of load - 500 kg)<br>18.38 kN (when the mass of load - 1000 kg) | |
| Coordinate position of the load ($l_1$, Fig. 2) | 2.06 m |
| Coordinate position of the ballast ($l_2$, Fig. 2) | 1.0 m |

Tests were conducted on a level hard surface, on a straight path. For loading of the tractor via the front loader, hay rolls were used, which were wrapped into film. They were selected by mass, 500±10 kg each. Tests were carried out by making all the combinations of pressure (0.8, 1.2, 1.6, 2.0, 2.5 bar) on the front and rear tires of the tractor. With all of the (twenty five) front-rear tire pressure combinations tests were carried out by travelling without load, transporting 500 kg (one hay roll) and 1000 kg (two rolls) of loading mass. Position of load in respect of the tractor varied in the range of 10 cm. All experiments were performed with enabled and disabled front axle, by travelling the same stretch of road in the same direction. For each combination of tractor load and inflation pressures three runs were performed to ensure repeatability and the reliability of the results obtained.

During the tests, the distances were measured, how far each of the front and rear wheels travelled by making 10 revolutions.

To measure the distance, laser gauge Bosch PLR 50 was used with a measurement error of ± 2 mm. Vertical load of tractor wheels was determined by electronic portal axle weigher WPD-2 with a measurement error of 1 kg.

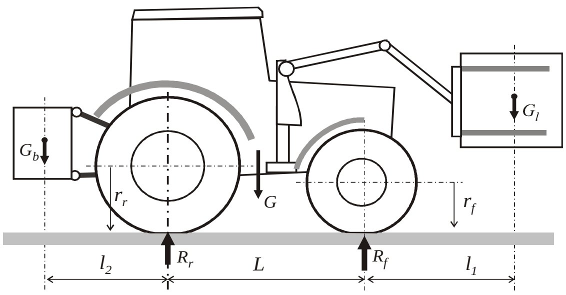


Fig. 2 Load and ballast mounting scheme of test tractor

3.2. Calculations

Slippage (sliding) of front and rear wheels was calculated according to the formula [3]:

$$\delta = \frac{s_d - s_a}{s_d} 100 \text{ , \%,} \tag{13}$$

where $s_d$ and $s_a$ are distance travelled by the wheel, when the front axle is enabled and disabled.

Kinematic mismatch of driving tractor wheels is calculated by formula [3]

$$k_n = \frac{1-\delta_r}{1-\delta_f} \text{ ,} \tag{14}$$

where $\delta_f$ and $\delta_r$ are slippage (sliding) of front and rear wheels.

The coefficient of weight distribution between front and rear axles $k_\omega$ was determined by the following equation:

$$k_w = R_f \big/ \left( R_f + R_r \right), \tag{15}$$

where $R_f$ and $R_r$ are normal forces beneath front and rear tires respectively.

**4. Results and discussion**

The experimental studies of kinematic mismatch of four-wheel-drive tractor have been conducted while running without load, transporting 500 kg and 1000 kg of load. The weight results, including distribution of common weight of tractor with loader on the front and rear wheels, are presented in Fig. 3. The figure shows that while driving without load, front/rear wheel load ratios were respectively 0.53/0.47; while transporting 500 kg of load - 0.62/0.38, and while transporting 1000 kg of load - 0.72/0.28. These results indicate that for a tractor working with front loader, weight distribution between front and rear wheels vary in wide range.

Figs. 4 and 5 shows driving wheels' kinematic mismatch dependence on the front tires' air pressure, while rear tires' air pressures are 0.8, 1.2, 1.6, 2.0 and 2.5 bar. Figs. 6 and 7 show driving wheels' kinematic mismatch dependence on the rear tires' air pressure, while front tires' air pressures are 0.8, 1.2, 1.6, 2.0 and 2.5 bar. Figs. 4 and 6 shows the dependences when tractor's load on the front loader is 0 and 500 kg. Figs. 5 and 7 shows the dependences when the tractor is loaded by 0 and 1000 kg. In addition, in all of the tests the tractor was loaded by 500 kg of ballast on the rear hydraulic lift.

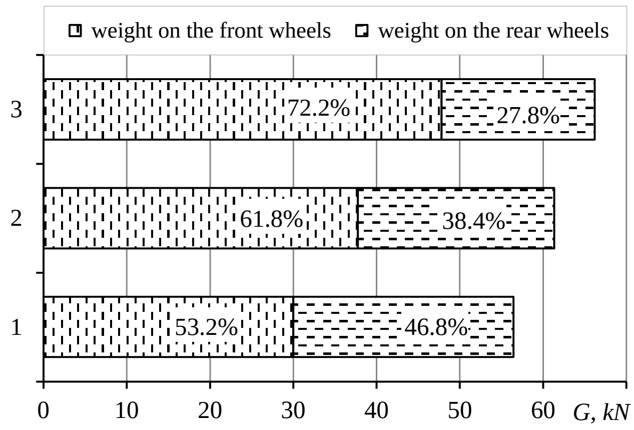


Fig. 3 Weight of the tractor-loader and distribution of weight between front and rear axles: *1* - when the mass of load on front loader is 0 kg; *2* – 500 kg; *3* – 1000 kg

From the dependencies shown in Figs. 4-7 we can see that in most cases kinematic mismatch coefficient was not equal to one $\left(k_n \neq 1\right)$. Not any traction force was added to the tractor, so one set of driving wheels was forced to slip, and the other – to slide. There was circulation of power between tractor driving axles.

From Figs. 4-7 we see that while the tractor is running without load (on the front loader), kinematic mismatch factor $k_n$ is close to one when the rear/front tires are inflated correspondingly as follows: 2.5/1.8 bar; 2.0/1.6 bar; 1.6/1.4 bar of pressure. From Figs. 4 and 6 we see that while the tractor is running with 500 kg of load (on the front loader), kinematic mismatch factor $k_n$ is close to one when the rear/front tires are inflated as follows: 2.5/1.8÷1.9 bar; 2.0/1.6 bar; 1.6/1.3÷1.4 bar; 1.2/1.0 bar; 0.8/0.7÷0.8 bar of pressure. The results presented in Figs. 4 and 6 let us conclude that while the tractor is running without load and with 500 kg of load (on the front loader), kinematic mismatch factor $k_n$ is close to one when the rear/front tires are inflated correspondingly as follows: 2.5/1.8 bar; 2.0/1.6 bar; 1.6/1.4 bar of pressure.

From Figs. 5 and 7 we see that while the tractor is running with 1000 kg load, kinematic mismatch factor $k_n$ is close to one when the rear/front tires are inflated as follows: 2.0/2.5 bar; 1.6/1.5 bar; 1.2/0.8 bar of pressure. The results presented in Figs. 5 and 7 show that while the tractor is running without load and with 1000 kg of load (on the front loader), kinematic mismatch factor $k_n$ is close to one when the rear tires are inflated to 1.6 bar, and the front tires to 1.5 bar.

The results presented in Figs. 4-7 show that when tractor works with a front loader and proper tire pressures are not selected, one set of driving wheels is forced to slip, and the other – to slide. While the tractor runs with load on the front loader, the lagging (rear) drive wheels slide when air pressure is lower in the front tires and higher in the rear tires. While the tractor runs with 500 kg load on the front loader, the lagging (rear) drive wheels begin to slide when air pressure in the front tires is lower than 1.9 bar and higher than 1.2 bar in the rear tires. While the tractor runs with 1000 kg load on the front loader, the lagging (rear) drive wheels begin to slide when air pressure in the rear tires exceeds 1.2 bar.

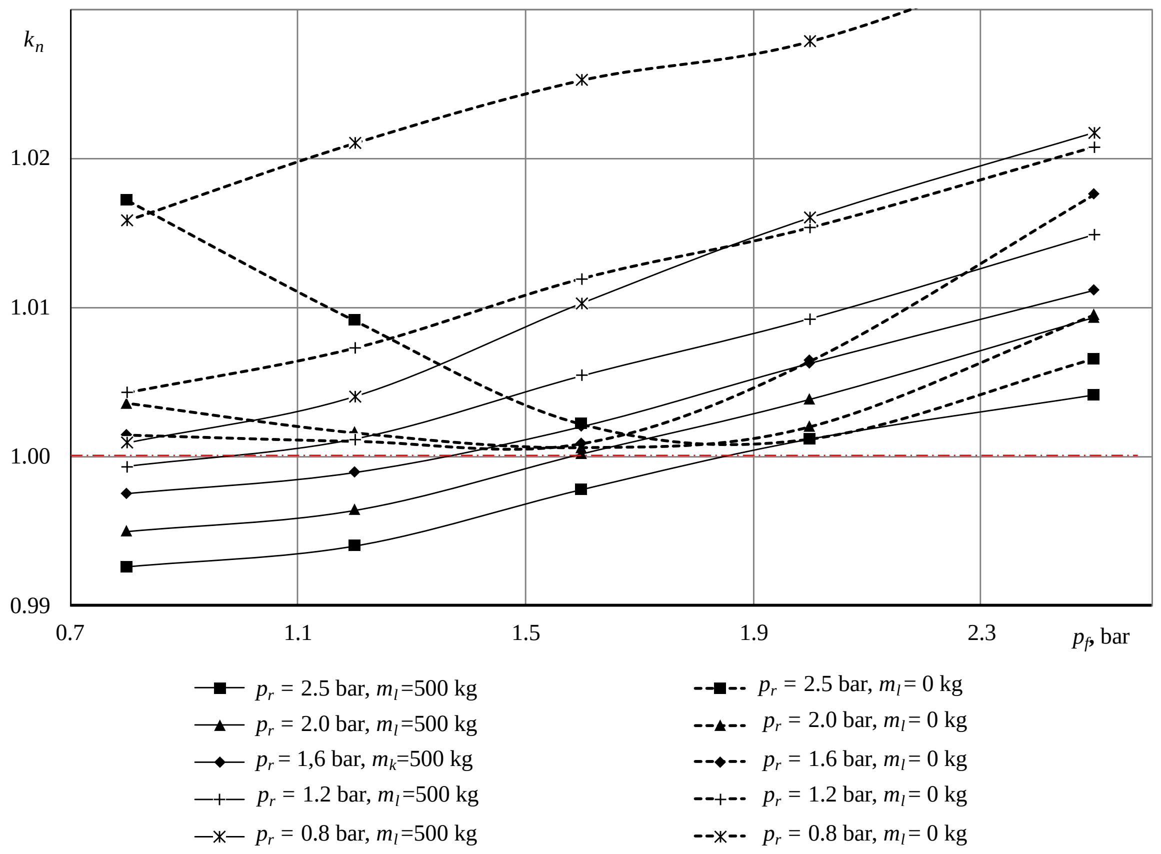


Fig. 4 Tractor driving wheels' kinematic mismatch dependences on front tires' pressure, while driving without load and transporting 500 kg of load, when rear tires' pressure was 0.8, 1.2, 1.6, 2.0 and 2.5 bar

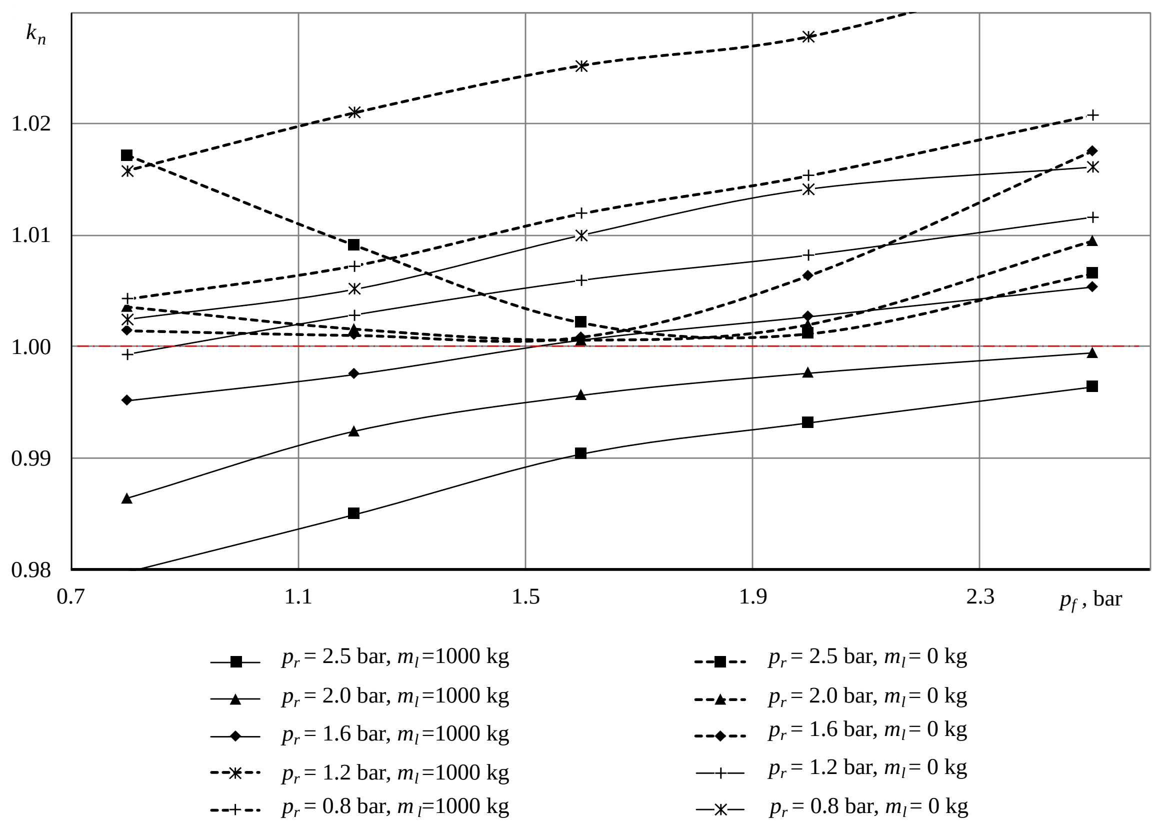


Fig. 5 Tractor driving wheels' kinematic mismatch dependences on front tires' pressure, while driving without load and transporting 1000 kg of load, when rear tires' pressure was 0.8, 1.2, 1.6, 2.0 and 2.5 bar

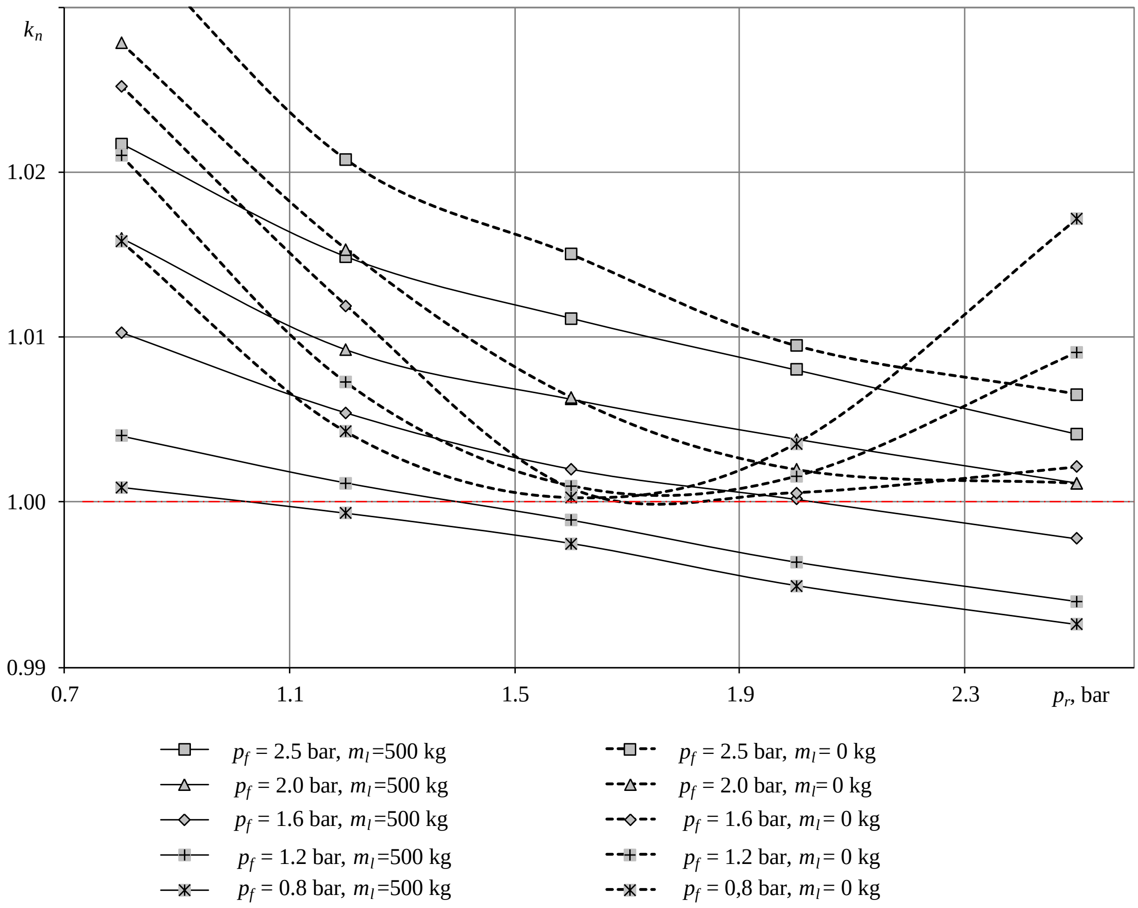


Fig. 6 Tractor driving wheels' kinematic mismatch dependences on rear tires' pressure, while driving without load and transporting 500 kg of load, when front tires' pressure was 0.8, 1.2, 1.6, 2.0 and 2.5 bar

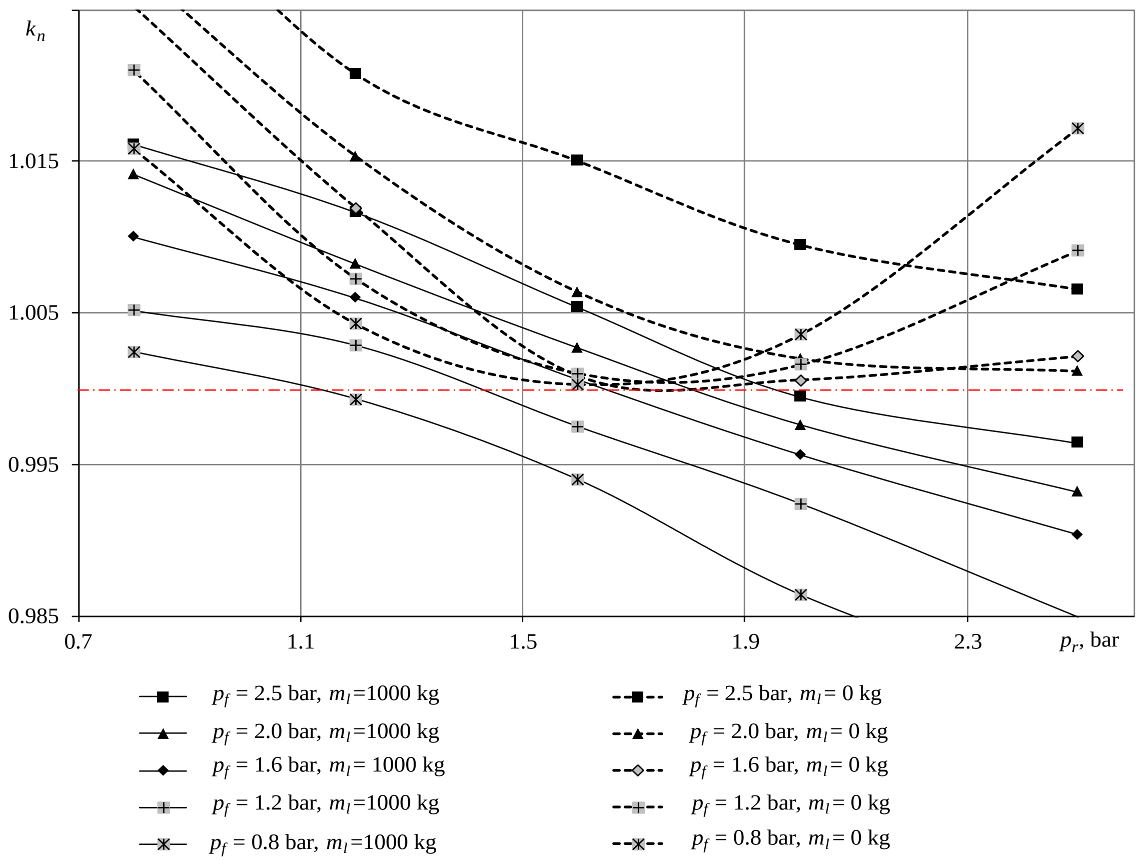


Fig. 7 Tractor driving wheels' kinematic mismatch dependences on rear tires' pressure, while driving without load and transporting 1000 kg of load, when front tires' pressure was 0.8, 1.2, 1.6, 2.0 and 2.5 bar

## 5. Conclusions

1. When the tractor works with front loader, weight distribution between front and rear wheels vary in wide range. While driving without load, front/rear wheel load ratios were 0.53/0.47 respectively; while transporting 500 kg of load - 0.62/0.38, and while transporting 1000 kg of load - 0.72/0.28 respectively.

2. When the tractor works with front loader and proper air pressures are not selected in rear and front tires, kinematic mismatch $(k_n \neq 1)$ appears in most cases, forcing one set of drive wheels to slip, and the other – to slide.

3. When the tractor works with front loader without load, also when it transports 500 or 1000 kg of load (on the front loader), the most suitable air pressure is 1.6 bar in the rear tires, and 1.4÷1.5 bar in the front tires.

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A. Janulevičius, G. Pupinis, V. Damanauskas

TRAKTORIŲ SU KETURIAIS VARANČIAISIAIS RATAIS PADANGŲ ORO SLĖGIO POVEIKIS RATŲ KINEMETINIAM NESUTAPIMUI

R e z i u m ė

Straipsnyje analizuojamos traktorių su keturiais varančiaisiais ratais varančiųjų ratų kinematinio nesutapimo priežastys. Vienas iš svarbiausių eksploatacinių veiksnių yra ryšys tarp priekinių ir užpakalinių ratų padangų oro slėgio bei ratų vertikaliųjų apkrovų. Kintant padangų oro slėgiui ir ratų apkrovoms, kinta priekinių ir užpakalinių ratų riedėjimo spinduliai, todėl traktoriaus transmisijoje gali atsirasti galios cirkuliacija. Ji priklauso nuo priekinių ir užpakalinių ratų teorinių greičių skirtumo.

Straipsnyje išanalizuota keturių ratų varomo traktoriaus tiesiaeigio judesio dinamika. Galios cirkuliacija tarp priekinio ir užpakalinio varančiųjų tiltų yra sąlygojama ratų slydimo. Tuomet dinamikos teorinis tyrimas atliekamas nagrinėjant traktoriaus galios balansą ir pagrindžiama galios cirkuliacija išilginiame plane.

Bandymais siekiama nustatyti ryšį tarp padangų oro slėgio, ratų vertikaliųjų apkrovų ir varančiųjų ratų teorinių greičių kinematinio nesutapimo. Darbo tikslas buvo nustatyti keturių ratų varomo, traukos jėga neapkrauto traktoriaus ratų slydimo pasireiškimą ir dydį. Pateiktos ratų buksavimo, slydimo ir kinematinio tarpusavio nesutapimo teorinių greičių priklausomybės.

A. Janulevičius, G. Pupinis, V. Damanauskas

EFFECT OF TIRES' PRESSURE ON THE KINEMATIC MISMATCH OF A FOUR-WHEEL-DRIVE TRACTOR

S u m m a r y

In the article causes of kinematic mismatch of four-wheel-drive tractor were reviewed. One of the most important operating characteristics is the relationship between tire inflation and vertical load of the wheels. Due to changes in inflation pressure and tire load, variations in rolling radiuses of the front and rear wheels can cause power circulation in the tractor transmission. This power circulation is dependent on the difference between theoretical speeds of front and rear wheels.

In the paper, dynamics of a four-wheel-drive tractor performing a rectilinear motion is analyzed. Power circulation between the front and rear driving axles is determined, tacking into account slipping of the wheels. Then dynamic study is conducted to achieve power balance of tractor and put in evidence power circulation in longitudinal plan.

Experiments were carried out to establish relationship between tires' inflation, vertical load and kinematic mismatch with theoretical speeds of driving wheels. The purpose was to determine the effect of additional slip on four-wheel-drive tractors operated without drawbar pull. Dependences of wheels' slippage and kinematic mismatch with theoretical speeds are presented.

**Keywords:** tires' pressure, kinematic mismatch, four-wheel-drive tractor.

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