ESTIMATION OF TRACTOR WHEEL SLIPPAGE WITH DIFFERENT TIRE PRESSURES FOR 4WD AND 2WD DRIVING SYSTEMS

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Abstract. The wheel slippage of agricultural tractors is a critical parameter for fuel consumption and field performance. Optimally it should be in the range of 8-12 % and should not exceed 15 %. Therefore, during assembling agricultural units, it is not enough to consider the traction characteristics, but also the recommended value of the slippage must be followed. Of the available solutions to decrease the tractor driving wheel slippage is to decrease the air pressure in the tires and increase the additional mass (ballast weight) of the tractor, avoid tilling soil that is too wet or too dry and choose the right implement, tillage speed and depth. The wheels' slippage could be reduced with a traction control and other relevant tractor systems. Agricultural/field applications require tractors with 4WD or 2WD driving systems. Engaging the four-wheel drive, when using the tractor for tillage operations, also can decrease the wheel slippage. In any case, the fuel consumption must be taken into consideration. For the theoretical calculation of the optimal tractor wheel slippage it is important to know the attraction factor dependence on the size of the traction force and the vertical load on the tires and the tire pressure indicators as well. However, literature analysis shows that known tractor wheel slippage determination mathematical modules do not take into consideration the tire inflation pressure. The goal of this study is to investigate the tire air pressure influence on the driving wheel slippage, tractive force and the traction coefficient for 4WD and 2WD driving systems of the tractor. With help of mathematical equations the traction force and wheel slippage coefficient dependencies on the air pressure in tractor tires are calculated. As well, according to the research result data, the wheel slippage forecasting methodology based on the numerical evaluation of the tire inflation pressure for 4WD and 2WD driving systems of the tractor is provided.

Keywords: tractor, tire, pressure, slippage, force.

Introduction

Tractors are known as the main energy source for various field applications in combination with different agricultural machinery and implements. During field operations, fuel consumption, work performance and negative environmental impacts are the most important tractor performance indicators [1-3]. Fuel consumption at various field operations depends on many factors, such as soil texture and structure, tractor size and its configuration, relationship of the tractor and implement, tillage speed, etc. [4;5]. Previous research shows that less than 60-70 % of the tractor energy that the engine develops is used to pull the agricultural implement through the soil, also it may be even drop to 50 % on soft soils. Also, the research shows that about 20-55 % of the available tractor power is wasted at the tire-topsoil interface, i.e. because of tire and soil deformation and drive wheel slippage [6-8]. The wheeled tractors operate at peak efficiency, if their drive wheel slippage is maintained in a certain optimum range. Analysis of the research materials shows that optimal tractor wheel slippage in topsoil should be in the range of 8-12 % [9-12]. Excessive slippage of the tractor wheels (greater than 15 %), when the tire turns on the soil, may cause excess deformation of the upper layer of the soil and energy losses, and this is not productive. When selecting tractors and tillage equipment, it is necessary to predict the pulling and economic characteristics of the assembly. The traction performance of an agricultural tractor is the result of adhesion-slip interaction between the tractor wheels and the topsoil. This interaction is affected by several factors, including the physical mechanical properties of the soil, power and geometry (wheelbase, hitch type and drawbar height) of the tractor, wheel slip, number of drive axles, wheel vertical load, tire width and diameter, tire inflation pressure and stiffness, all of which exert a significant influence. While most of the above factors have a more or less limited possibility to change the values, the wheel load and tire inflation pressure can be varied within wide ranges, allowing easy management of the traction performance of the tractor. Consequently, these factors are very useful for practical applications. Many researchers in their research works solve the problem of tractor drive wheel slippage normalization by reducing the tire inflation pressure and adding ballast masses [11-13]. The influence of the wheel vertical load and tyre inflation pressure on the tractor traction performance is investigated using both the theoretical and the experimental approach. There are many methods to decrease tractor slippage during tillage. Primary of them is the tire inflation pressure reduction to the minimum [13-14].

The purpose of mathematical modeling is to predict the traction properties of a tractor by estimating various factors. At the moment, there are tractor traction models that describe various agricultural and field work. Usually, mathematical models evaluate soil hardness, traction force, tractor and wheel geometric parameters. Agricultural/field applications require tractors with 4WD or 2WD driving system. Engaging the four-wheel drive, when using the tractor for tillage operations, also can decrease the wheel slippage. However, in any case, the fuel consumption must be taken into consideration. For the theoretical calculation of the optimal tractor wheel slippage it is important to know the attraction factor dependence on the size of the traction force and the vertical load on the tires and the tire pressure indicators as well. However, literature analysis [13-19] has shown that known tractor wheel slippage determination mathematical modules do not take into consideration the tire inflation pressure. The researchers Hinsburg, Parfenov and Swede have proposed an empirical model for prediction of the tractor slippage [18]:

$$s = s_{\lim}\left[1-\left(1-\frac{F_t}{F_t^{\lim}}\right)\right]^b, \tag{1}$$

where F_t – traction force developed by the tractor, N;
F_t^{lim} – traction force, when it almost does not increase, the slip becomes complete, N;
s_{lim} – limit factor of slippage (0.4-0.5), at which it develops into full slippage at almost no increase of the traction force;
b – function degree indicator.

The aim of this paper is to find a theoretical method of calculating (forecasting) slippage of the tractor's driving wheels by estimating the air pressure in the tires. Also, to provide a mathematical equation describing the drive wheel slippage under developed traction and different tire inflation pressure.

Materials and methods

In order to link the tractor slippage prediction formula (1) with the tire inflation pressure values, the experimental studies of slippage dependence on traction power and its data analysis at various tire pressure were performed.

For slippage dependence, during drawbar pull tests, on different tire inflation pressures, the tractor "Case Farmall 115U" was used. Tractor drawbar pull was performed by pulling tractors "Zetor 10540" and "MTZ 82", which were connected on rigid link. There was fitted a drawbar pull measurement sensor PCE-FB50K Force Gauge, measuring the range up to 50,000 N, resolution – 0.01 N, max. 0.1 % fault tolerance of the measuring range. The main technical data of the tractor used in the experiments are shown in Table 1

Table 1

Technical data of the tractor (Case Farmall 115U)

Characteristics	Value	Unit of measure
Engine	FPT 3.4L, 4 cylinder, in-line, liquid-cooled, turbocharged intercooled diesel	-
Crankshaft nominal rotary speed	2300	min^{-1}
Nominal power	85.83	kW
Transmission	Power shuttle, 12 forward and reverse, four synchronized gears in three non-synchronized ranges	-
Drive type	MFWD	-
Standard tires (ag)	Front: 14.9 R 24; Rear: 18.4 R 34	-
Weight	4250	kg
Weight of the front axle	1990	kg
Weight of the rear axle	2260	kg
Wheel base	2.34	m

Dry stubble was selected (hardness in 5 cm depth was 0.54 MPa, soil moisture in 5 cm depth was 16.4 %) for investigations. The wheel slippage drive test was performed at the tractor's 4WD drive mode (front axle drive switched on) and at 2WD drive mode (front axle drive switched off). During the test, the differential of the driving axle was blocked. The tests were carried out with the same air pressures in the front and rear tires, accordingly with 80, 120, 160, 200 and 240 kPa tire pressures.

Results and discussion

Figure 1 shows the experimental and theoretical tractor slippage dependences in stubble on the traction force, at 4WD and 2WD modes and at 240, 200, 160, 120 and 80, kPa of the air pressure in tires. Experimental wheel slippage dependencies at the 2WD mode presented in "+" (without lines as well) and 4WD mode are presented in "×" (without lines). Theoretical curves are presented in continuous lines. For its calculation, the formula 1 was used. The function degree indicator (b) was chosen, so that the difference between the experimental and calculated results would not exceed 5 %.

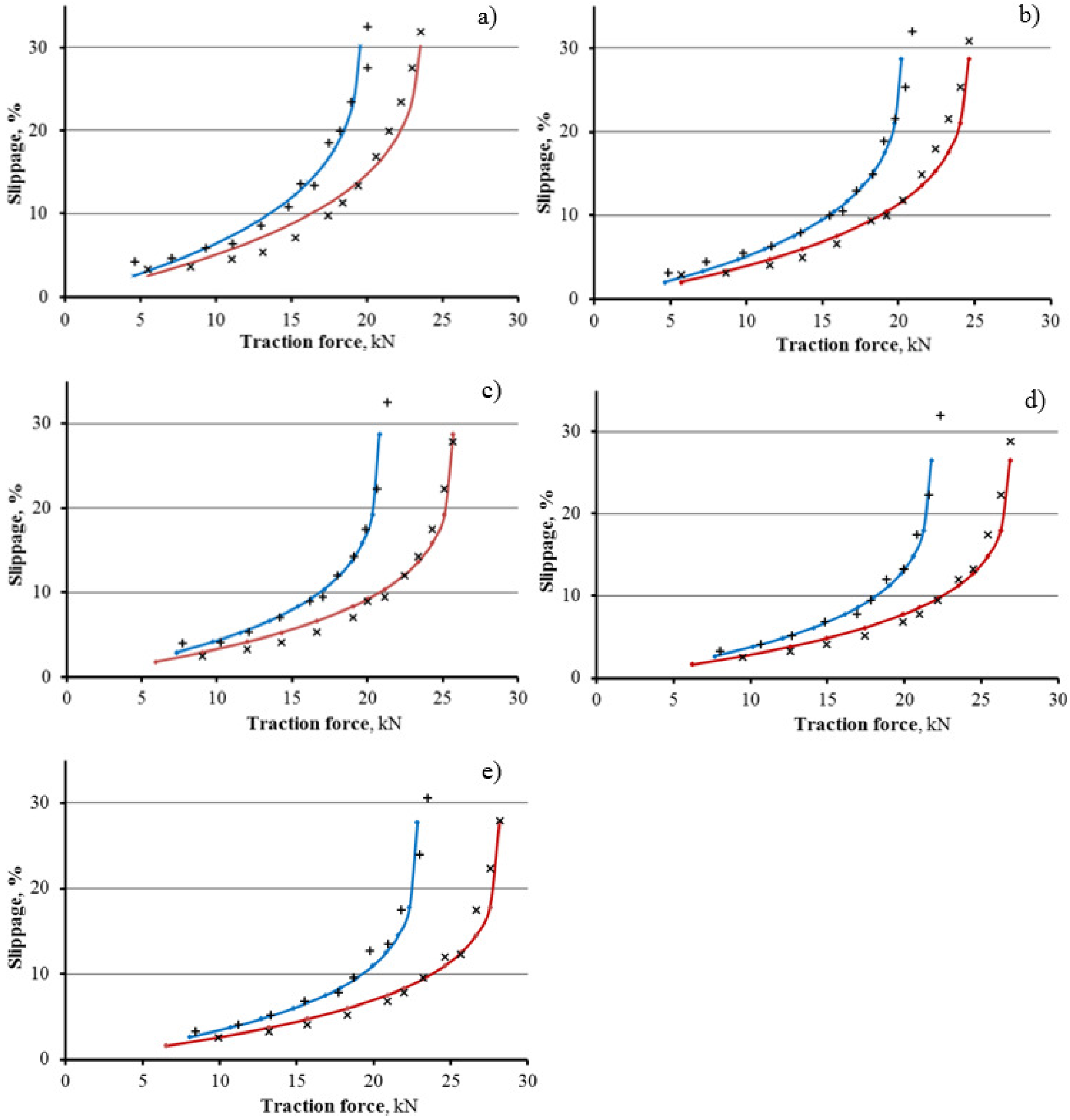

Fig. 1. **Experimental and theoretical dependences of tractor slippage on traction force and air pressure in tires:** a – air pressure 240 kPa; b – 200 kPa; c – 160 kPa; d – 120 kPa and e – 80 kPa; + is an experimental dependency in 2WD mode; × is an experimental dependency in 4WD mode; theoretical dependencies presented by continuous lines, respectively

Tractor Case Farmall 115U at 4WD and 2WD mode and at the air pressure in the tire 240, 200, 160, 120 and 80 kPa the formula (1) function degree (b) values: 0245, 0204, 0178, 0165 and 0157 were identified. As seen from Figure 1, the tractor's slippage has been reduced by reducing air pressure in the tires. With a traction force less than 15 kN, slippage of the tractor in stubble under various tire inflation pressures did not exceed 10 %. In case of bigger tractor traction loads, tire pressures had a significantly higher impact on slippage. At 20 kN traction force, in 4WD mode and at 240 kPa air pressure in the tires, the tractor slippage was about 18 % and about 7 % slippage was, when the tire pressure was 80 kPa. In the 2WD mode and with 17 kN traction force and 240 kPa air pressure in the tires the tractor slippage was about 19 % and about 10 % of slippage was at the tire pressure of 80 kPa. In addition, Figure 1 shows that the traction force developed by the tractor in the 4WD mode was 20-25 % higher than the traction force in the 2WD mode. Similar results are seen in previous publications by us and other researchers [6;9;20-22].

Many scientists argue that tractor slippage, during field work, should not be beyond the 15 % limit. Traction force dependence on the tire inflation pressure at the maximal and 15 % of the wheel slippage are given in Figure 2. The figure shows the linear dependence on the traction force at different air pressure in the tire at maximum and 15 % wheel slippage. By reducing the tire inflation pressure from 240 kPa to 80 kPa, the tractor traction force increased by 5-6 kN in 4WD mode and about 4-5 kN in 2WD mode. Similar results were obtained in previous studies and are seen in the publications of other researchers [5;12;20;23].

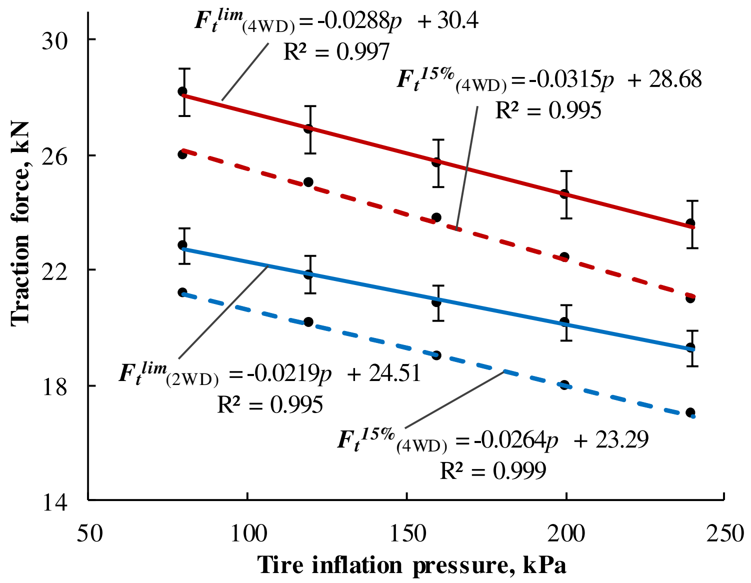

Fig. 2. **Traction force F_t^{lim} and $F_t^{15\,\%}$ dependence on tire inflation pressure at maximum and 15 % of slippage limit:** continuous lines in 4WD mode, dotted lines in 2WD mode

Based on the results of the tests (Fig. 2), the tractor's maximum traction force values in the 4WD or 2WD modes at any permissible air pressure in the tires, when the nominal figures of these values are known, a mathematical equation (2) was formed.

$$F_t^{\lim} = F_v^{\lim} + a\ p_v - a\ p\,, \tag{2}$$

where p_v – nominal tire inflation pressure, kPa;
F_v^{lim} – maximum traction force of the tractor at the nominal tire inflation pressure, N;
a – function coefficient.

The value of the function coefficient a, under real-life conditions of the tested tractor, in the 4WD mode is 0.0288 and in 2WD - 0.0219.

According to the experimental and calculation data presented in Figure 1, the dependence of the index (b) of the mathematical formula (1) on the inflation pressure of the tires was formed (Fig. 3). The dependence shown in Figure 3 is suitable for setting the indicator (b) when calculating the tractor slippage in 4WD and 2WD modes.

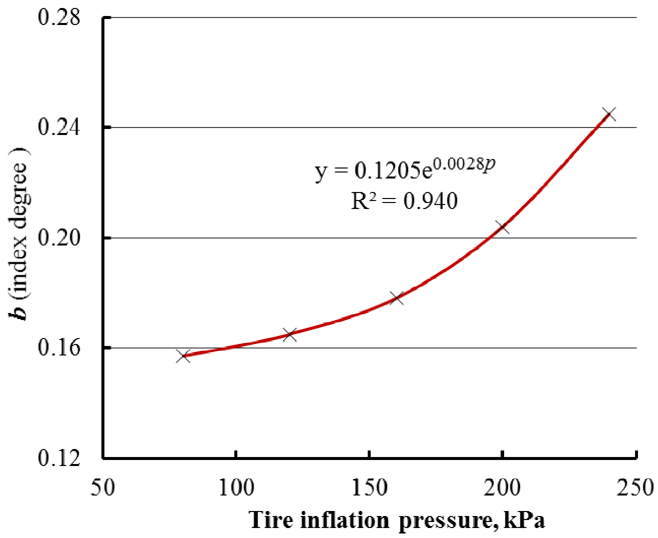

Fig. 3. **Index degree *b* from formula (1) dependence on tire inflation pressure**

The regression analysis of dependency (Fig. 3) showed that the values of the degree indicator b and tire inflation pressure p well correlate ($R^2 = 0.94$) according to exponential dependence. Based on the results shown in Figure 1 and dependence (Fig. 3) for the slippage calculation a mathematical equation (3) for calculating the degree indicator b of the formula (1) was made.

$$b = b_v \ e^{(j\,p - j\,p_v)}, \tag{3}$$

where b_v – degree indicator value for nominal air pressure in tires;
j – function coefficient.

The function factor j of the tested tractor, with tire inflation pressures from 80 kPa to 240 kPa, is equal to 0.0028. Summarizing the results, an empirical model is provided to calculate the tractor slippage with regard to the tire inflation pressures.

$$s = s_{\lim}\left[1-\left(1-\frac{F_t}{F_v^{\lim} + a\ p_v - a\ p}\right)\right]^{(b_v e^{(j\,p - j\,p_v)})}, \tag{4}$$

Conclusions

1. The analysis of the literature has shown that at present the theoretical prediction of the tractor's drive wheel slippage is problematic, because the known theoretical methods of tractor slippage prediction do not assess the tire inflation pressure.
2. Based on the slippage on stubble the experimental research results of the Case Farmall 115U tractor the use of empirical formula 1 was expanded. Including the tire inflation pressures, mathematical model (formula 1) variables, the formula for calculating the traction force F_t^{lim} and the degree indicator b calculation formula were formed. Taking into account tire inflation pressures, the extended calculation method (formula 4) makes it possible to theoretically calculate the slippage values of the tractor's driving wheels in 4WD and 2WD modes.
3. For further studies, it is appropriate to test this method under other conditions with other tractors and extend it based on the tractor traction factor to accommodate theoretical tractor slippage prediction.

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