PREDICTING CHANGES IN TRACTOR TRAVEL SPEED AT DIFFERENT INFLATION PRESSURES ON DRIVE TIRES

Algirdas Janulevicius[1], Vidas Damanauskas[2]
[1]Vytautas Magnus University, Lithuania;
[2]Lithuanian Research Centre for Agriculture and Forestry, Lithuania
algirdas.janulevicius@vdu.lt, vidas.damanauskas@lammc.lt

Abstract. The traction efficiency of the tractor is determined by the energy used for the work and the energy loss. The use of tractor power depends on the drawbar pull and travel speed. Narrow working speed ranges are recommended for tractors performing specific agricultural operations. Deviations from the work speed degrade the quality of work and increase energy consumption. The main options for balancing the tractor traction efficiency and performance are drawbar traction prediction and drive wheel slippage control. According to research conducted by many scientists, the slippage should not exceed 15-17%, otherwise the engine power is used inefficiently, more soil damage occurs. Agricultural tractors use several measures to reduce slippage to a rational level, including the use of ballast weights and the use of low-pressure tires, and correct tire inflation pressures. In general, reducing the inflation pressure of tires reduces not only their slippage but also their rolling radius. Both of these factors affect the tractor travel speed in their own way. The purpose of this study is to find a method for predicting the change in the travel speed of a tractor depending on the inflation pressure of a tire, which includes the change in the speed due to the slippage and rolling radius of the drive wheel. Based on the results of experimental studies of Case Farmall 115U MFWD tractor equipped with radial-ply tires, on wheat stubble on loam soil, a method was investigated to predict the change in the travel speed of a tractor based on the tire inflation pressure. The investigated method allows to theoretically predict the change of the tractor travel speed according to the inflation pressure of the tire, which includes the change of the speed due to the slippage and rolling radius of the drive wheel.

Keywords: tractor; drive wheel; tire inflation pressure; tire slippage; wheel rolling radius.

Introduction

In agriculture, tractors are the main source of traction for pulling a variety of agricultural implements during a variety of field work. The traction and economic characteristics of the tillage aggregate must be taken into account when combining the tractor and the implement. The traction properties of an agricultural tractor are the result of an interaction between the tractor wheels and the topsoil [1-3]. Tractor traction is affected by a number of factors, including soil properties, tractor power and setup (wheelbase, hook type and drawbar height), wheel slippage, number of drive axles, vertical wheel load, tire parameters, tire stiffness and inflation pressure, all of which make a big impact [4-6]. The influence of the wheel vertical load and tire inflation pressure on tractor traction properties has been studied by a number of scientists using both theoretical and experimental methods [7-9]. When a wheeled tractor acts as a traction machine, slipping of its drive wheels is a natural phenomenon. In medium-hard soils (cone index 500-1000 kPa) tillage is considered rational when the slippage of the tractor-drive wheels is between 10 and 17 percent [10; 11]. Agricultural tractors use several measures to reduce slippage to a rational level, including the use of ballast weights and the use of low-pressure tires, and correct tire inflation pressures. In general, reducing the inflation pressure of tires reduces not only their slippage but also their rolling radius [1; 5; 9]. Both of these factors affect the tractor travel speed in their own way. The purpose of this study is to find a method for predicting the change in the travel speed of a tractor depending on the inflation pressure of a tire, which includes the change in speed due to the slippage and rolling radius of the drive wheel. Predicting a change in the tractor travel speed due to two factors (driving wheel slippage and rolling radius change) is a new solution to the problem addressed in this study.

Theoretical considerations

A tractor is a machine that, according to its operating parameters, supplies the energy required to carry out the work. In agricultural technology, it is important that tractors, especially medium-power ones, perform proper traction operations. When a tractor acts as a traction machine, slipping of its drive tires is a natural phenomenon. In soils of medium hardness (cone index 500-1000 kPa), tractor operation is considered to be economical when the slippage of the driven tires is between 10 and 17% [10; 11]. Modern tractor control technologies use tractor traction control in conjunction with the use of ballast weights and selection of the inflation pressure of low-pressure tires to rationally reduce slippage of the drive tires. Adjusting the inflation pressure of the drive tires changes not only their slippage, but also their dynamic radius. Both of these factors affect the change in the actual tractor speed from the theoretical speed. The actual speed of the tractor is calculated from the equation [5]:

$$v = v_t (1 - s) = \omega_r \, r_d (1 - s), \tag{1}$$

where v_t – theoretical speed of the tractor, m·s^{-1};
s – slippage coefficient of the drive tire;
ω_r – angular speed of the drive tire, s^{-1};
r_d – tyre dynamic rolling radius, m.

Many researchers recommend that the problem of normalizing the slippage of a tractor's drive tires be addressed by reducing the tire inflation pressure. In this case, in order to theoretically calculate the slippage κ of the tractor drive tires, it is important to know its dependence not only on the traction force and the vertical force acting on the drive tires, but also on the inflation pressure of the tires. The slippage of the tractor drive tires is calculated from the equation by calculating the traction coefficient and the inflation pressure of the tires [12]:

$$s = s_{lim} \left[1 - \left(1 - \frac{k}{k_n^{lim} + ap_n - ap} \right)^{b_n e^{(cp - cp_n)}} \right], \tag{2}$$

where s_{lim} – value of the slippage coefficient of the tire, after which the slippage increases very intensively;
k – traction coefficient;
k_{lim} – value of the traction coefficient, after which the slippage increases very intensively;
p and p_n – actual and nominal tire inflation pressure, kPa;
a and c – constant.

The dynamic rolling radius of the drive tire is calculated from the equation [5]:

$$r_d = r_0 - \Delta h \,, \tag{3}$$

where r_0 – radius of the unloaded tire, m;
Δh – tire deflection, m. It is common to estimate from what is on the surface of the hard surface.

Typically, r_d depends nonlinearly on the wheel vertical load, and the nonlinearity is due to the material and construction of the tire [1; 13; 14]. Guskov et al. (1988, p. 40) [14] use an empirical formula to calculate the deflection of a tire on a rigid surface as follows:

$$\Delta h = \frac{F_z}{2\pi 10^5 \, p_t \sqrt{b_t / 2 r_0}} \,, \tag{4}$$

where F_z – wheel vertical load, N;
p_t – tire inflation pressure in bar;
b_t – tire section width, m.

Materials and methods

In order to relate the actual tractor speed prediction formula (1), the drive wheel slippage formula (2) and the tire deflection formula (4) to the values of the tire inflation pressure, experimental studies of the dependence of the above parameters on the traction force were performed. For actual speed, slippage and tire deflection dependences, during drawbar pull tests, on different tire inflation pressures, the tractor "Case Farmall 115U" was used. Tractor drawbar pull tests were performed by towing the towed tractor Zetor 10540, connected via a flexible towbar. The test tractor towed the Zetor 10540 with a manual transmission, so the towed tractor applied traction force to the test tractor. The traction force sensor PCE-FB50K was installed in the flexible towbar, measuring range up to 50 000 N, resolution – 0.01 N, max. 0.1% fault tolerance of measuring range. The most important data of the tractor used in the experiments are given in Table 1.

Table 1

Technical data of the tractor (Case Farmall 115U)

Characteristics	Value	Unit
Engine	FPT 3.4L, 4 cylinder, in-line, liquid-cooled, turbocharged intercooled diesel	–
Rated speed	2300	min^{-1}
Rated 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: 14.9R24 Rear: 18.4R34	–
Weight	4250	kg
Weight of the front axle	1990	kg
Weight of the rear axle	2260	kg
Wheel base	2.34	m

The method of calculating the actual tractor speed, tire deflection and slippage was to calculate the rear tire revolutions of the test tractor and to measure the distance traveled during the relevant period. The parameters analyzed in the study were calculated according to the American Society of Agricultural Engineers (ASAE) standard S296.5 (ASAE, 2018) [15]. A field of wheat stubble of medium humidity (about 17%) and hardness (about 0.75 MPa) was selected for experimental studies. All test measurements were performed with the tractor running in 4WD mode (front axle engaged) and the differential locked.

Results and discussion

Figure 1 shows the experimental and theoretical (calculated according to equation 2) dependences of the tractor drive wheels on the traction coefficient of the tractor drive tires at 190, 130 and 70 kPa inflation pressures.

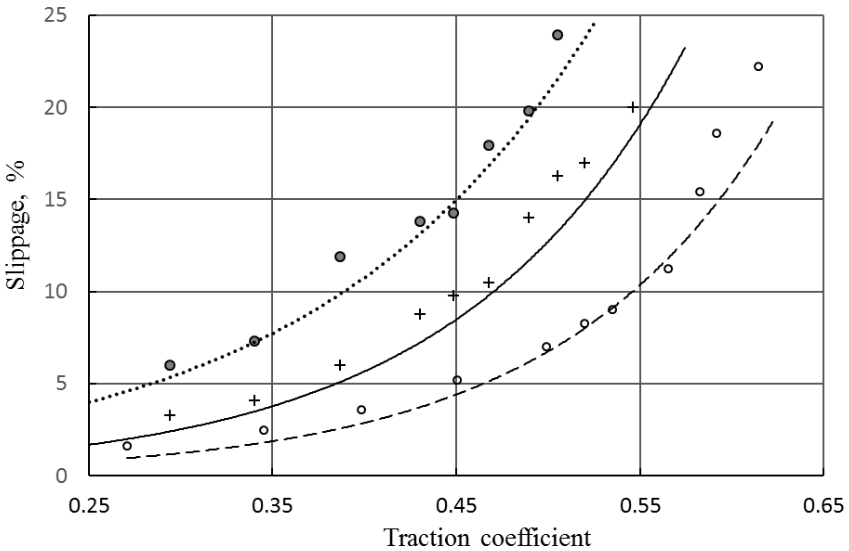

Fig. 1. **Experimental (points) and theoretically calculated (curves) showing tire slippage as a function of the traction coefficient and tire inflation pressure for the tractor on wheat stubble:** (• and ···) at 190 kPa, (+ and —) at 130 kPa, (o and ---) at 70 kPa

These results confirm that at lower inflation pressures, the tractor's drive wheel slippage is less. This is due to the fact that at lower inflation pressures, the tires have higher deformation and increase the contact area of the driving tires with the ground. Figure 1 shows that reducing the tire inflation pressure from 190 kPa to 70 kPa increased the traction coefficient at 15% slippage by about 0.15. Or by reducing the inflation pressure from 190 kPa to 70 kPa, the slippage of the drive wheels at a coefficient of traction of 0.45 is reduced by about 10%. Similar results of tractor wheel slippage are observed in the work of other researchers: Oh, et al., 2019 [8]; Kumar et al., 2019 [16]; Raper et al., 1995 [4]. Raper et al. The test results [4] showed a larger radial tire contact area when the tire slippage is 10%. Figure 1 also shows that the difference between the values of slippage of the tractor drive wheels determined by the test method and those calculated in accordance with formula 2 is small, not exceeding 5%. Here, slightly higher wheel slippage values were experimentally set than calculated. Figure 2 shows the theoretical dependences of the radius of the tractor drive wheels on the inflation pressure of the tires (calculated according to equations 1 and 4).

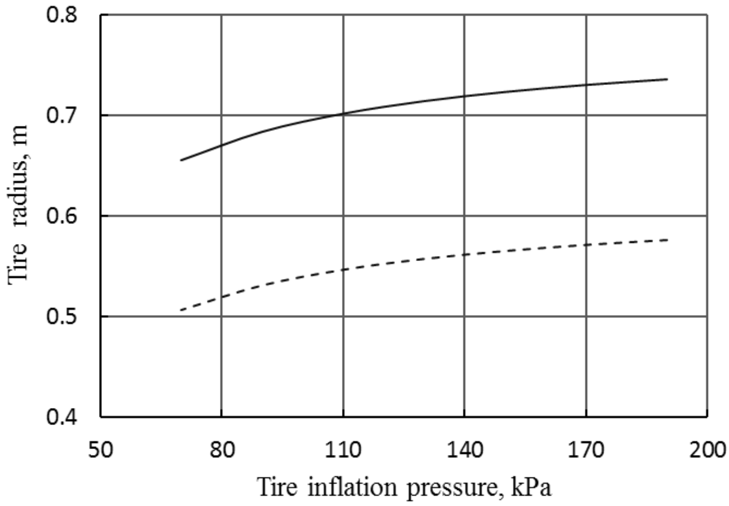

Fig. 2**. Dependences of the radius of the tractor drive wheels on the inflation pressure of the tires, the solid line shows the dependence of the rear wheels and the dotted line the front wheels**

Typically, the radius of the tractor drive wheels depends nonlinearly on the inflation pressure of the tires, and the nonlinearity depends on the material and construction of the tire [1]. The relationship between tire stiffness and tire size at defined inflation pressure levels is given in the scientific articles [1; 9]. Scientific sources have also confirmed that for the vertical loads recommended at a given inflation pressure, the empirical formula provides estimates that may be appropriate in most cases [5; 17]. However, the accuracy of some tires may not be very high, so it may be necessary to measure the vertical deformation and then perform a regression analysis [5]. Figure 3 shows the experimental and theoretical (calculated according to equation 1) dependences of the actual tractor speed on the inflation pressure of the tires at traction coefficients of 0.4, 0.45 and 0.5 in wheat stubble.

As it can be seen from Figure 3, the actual tractor speed on wheat stubble was lower at a lower tractor traction coefficient. At a tractor traction coefficient of 0.4, 0.45 and 0.5 at a theoretical speed of 1,29 $m \cdot s^{-1}$ and a tire pressure of 190 kPa, the actual tractor speeds were approximately 1.16, 1.12 and 1.02 $m \cdot s^{-1}$, respectively. Figure 3 shows that reducing the inflation pressure of the tires from maximum to medium pressure increased the actual speed of the tractor and reducing the inflation pressure from medium to minimum reduced the actual speed of the tractor. For example, with the tractor's traction coefficient of 0.45, reducing the inflation pressure from 190 kPa to 130 kPa increases the actual tractor speed from 1.12 $m \cdot s^{-1}$ to 1.15 $m\ s^{-1}$, and reducing the inflation pressure from 130 kPa to 0.7 kPa reduces the actual tractor speed from 1.15 $m \cdot s^{-1}$ to 1.11 $m \cdot s^{-1}$. This can be explained by the fact that reducing the inflation pressure of the tires from maximum to medium pressure results in a more intense change in the slippage of the drive wheels and a slower change in the rolling radius of the wheels, and reducing the inflation pressure of the tires from medium to minimum pressure results in a more intense change in the rolling radius of the drive wheels and a slower change in the slippage of the drive wheels.

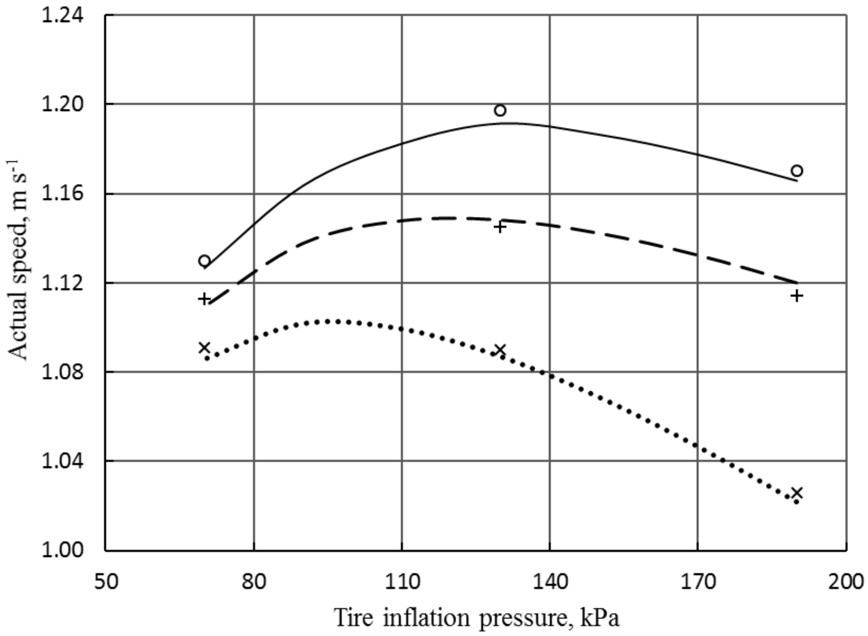

Fig. 3. **Experimental (points) and theoretically calculated (curves) showing the actual tractor speed as a function of the tire inflation pressure and traction coefficient:** (o and —) when the traction coefficient of the tractor on the wheat stubble is 0.4, (+ and ---) - 0.45, (× and ···) - 0.5

Conclusions

1. Recent sources have shown that low-pressure tires and selecting their inflation pressure are currently widely used to normalize slippage of the tractor drive wheels. Changes in the tire inflation pressure change not only their slippage, but also their rolling radius and travel speed. The examined method confirmed the possibility to theoretically predict the change of the tractor travel speed according to the inflation pressure of the tires, which includes the change of the speed due to the slippage and rolling radius of the drive wheel.
2. Studies have shown that reducing the inflation pressure of the tires from maximum to medium pressure increased the actual speed of the tractor and reducing the inflation pressure from medium to minimum reduced the actual speed of the tractor.
3. The obtained results suggested that by reducing the inflation pressure of the tires from maximum to medium pressure, the change in slippage of the driving wheels is more intense and the rolling radius changes more slowly, and by reducing the inflation pressure of the tires from medium to minimum pressure, the change in slippage of the drive wheels is slower and the rolling radius changes more intensively.
4. For further research, it is advisable to test this method under different field conditions with tractors and tires of a different size.

Author contributions:

Conceptualization, J.A.; methodology, J.A. and D.V.; validation, J.A. and D.V.; formal analysis, D.V.; investigation, J.A. and D.V.; data curation, J.A.; writing—original draft preparation, D.V.; writing—review and editing, J.A. and D.V.; visualization, J.A. and D.V.; project administration, J.A.; funding acquisition, J.A. Both authors have read and agreed to the published version of the manuscript.

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