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IMPACT OF THE INFLATION PRESSURE OF THE TIRES ON LEAD OF FRONT DRIVE WHEELS AND MOVEMENT RESISTANCE FORCE OF TRACTORS

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Abstract. The transmission of mechanical front-wheel drive tractors normally has a front axle lead ratio, which is equal to 1.5…2.5%. Naturally, when ballast masses are added to the tractor or when inflation pressure in the tires is reduced, distortion of the tires is inevitable, which changes the lead of the front wheels. In this paper, we present the impact of tire inflation pressures on the lead front drive wheels and movement resistance force when the tractor travelled with a front drive axle enabled and was engine braking with the fuel supply off. It was found that the variation in front and rear tires inflation pressure combination can significantly change the lead of the front drive wheels. For the tested tractor up to 6.9%. The result is that when the tractor travelled with the front axle enabled and was engine braking, the engine-braking efficiency decreases with increasing lead of the front wheels. Front (slipping) wheels create the opposite-direction torque, which is transferred to the rear wheels through the tractor's front-rear axle drive system. Additional losses of the engine braking occur in transmission due to power circulation, and the result is that the tractor wheels receive less braking torque from the engine.

Keywords: tractor, lead front wheels, tire pressure, kinematic discrepancy, engine braking, movement resistance force.

Introduction

Tractors are the main power machines used in agriculture. They are used for soil preparation, crop planting, maintenance, harvesting, and transport operations. Wheeled tractors are mostly used as transport vehicles (transporting of loads, driving to the fields with or without implements, etc.). Most agricultural tractors are made with the all (four) drive wheels. Such machines deliver more traction power and less slip because the entire tractor weight is used for the grip of wheels with the ground or the surface of the road (Osinenko *et al.* 2015; Stoilov, Kostadinov, 2009). Tractors with Four-Wheel Drive (4WD) perform better in soil tillage and other field work, but on dry, hard ground or roads, much of their energy is wasted in driving the front (second) axle (Molari *et al.* 2012). Tractors having front wheels smaller than the rear wheels and torque to the front axle delivered by mechanical drive are identified as Mechanical Front-Wheel Drive (MFWD) tractors (Battiato, Diserens 2013). This means that angular speeds of the front and rear wheels are is proportional to the wheels radius. In most cases, the rear axle of such tractors is driven directly from the gearbox, and the front axle is driven from the torque distribution box, or both axles are driven via the torque distribution box. The transmission of MFWD tractors normally has a front axle lead ratio, which is equal to 1.5…2.5%. The value of the lead front wheels is dependent on differences in front and rear wheel rolling radiuses and differences in transmission ratios to the front and rear wheels. Values of transmission ratios to the front and rear wheels do not alter during a tractor exploitation, therefore, changes in lead front wheels are possible only due to disproportionate tire deformations. Therefore, variations in the rolling radii of the front and rear wheels, due to change of inflation pressure and tire deflection, could cause significant torsional wind-up (Szente 2005; Żebrowski 2010). This may even develop breaking forces on the wheels of the "slower" axle. In this case, a MFWD tractors will suffer a marked reduction of tractive performance, overloading in transmission and accelerating tire wear.

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1. Literature review

The traction performance of a tractor depends on several parameters related to its equipment and the road/soil properties. Some of the tractor parameters, such as the tire inflation pressure and the wheel load, can be easily managed, therefore, enabling an optimisation of the fuel consumption and work efficiency due to lower wheel slip, limitation of wear of the tire, and reduction in the time required for work operations (Battiato, Diserens 2017).

Although tractors are used with all-wheel drive in agriculture today, the problem of adjustment of their slip remains particularly acute. Tractor slip is usually reduced by adding ballast masses and/or reducing the air pressure in the tires (Battiato, Diserens 2017; Lee *et al.* 2016). Ballast of the tractor is needed not only to reduce slippage but also to ensure steering performance (Hamersma, Els 2014). Lately, for adjusting the slip, an increasing number of scientists recommend reducing air pressure in the tires in the first place. Based on such scientific advice, tractor manufacturers equip tractors with tires adapted to still lower pressures. For a tractor driving on the soft soil, the lower the inflation pressure in the tires is, the shallower the track and the lower the rolling resistance are. With enlargement of the contact area between tires and soil, the tractor has less negative impact on the soil, and the result is less compacted soil under the tracks (Ani *et al.* 2018; Shahgholi, Abuali 2015).

Information sources state that in field work, MFWD tractors deliver the highest traction force when the front wheels' lead is 3…4%, and in transport operations, MFWD tractors deliver the highest traction force when the front wheels' lead is 1…2% (Andreev *et al.* 2010; Janulevičius *et al.* 2017; Molari *et al.* 2012). In addition, it is known that the front wheels' lead improves dynamics of tractors in turning manoeuvres (Andreev *et al.* 2010; Vantsevich 2014). Additionally, Wong (2009) and Vantsevich (2008) noted that under certain circumstances, a tendency exists for 4WD tractors to incur a reduction in power delivery efficiency and an increase in fuel consumption as a result of interaction between the front and rear wheels being less than optimal. Agricultural MFWD tractors are characteristic with 1.5…2.5% value of the front wheels' lead (Molari *et al.* 2012). Analysis of technical literature shows that when ballast masses are added to the tractor or when air pressure in the tires is reduced, distortion of the tires is inevitable, which changes in rolling radiuses of the wheels. Disproportionate changes in the rolling radiuses of the wheels causes varied lead of front wheels (Janulevičius *et al.* 2014; Stoilov, Kostadinov 2009).

When the front wheels' lead is too high, excessive speed difference occurs, which causes the wheels to slip at different sizes, and the tractor start to jump and vibrate. When the front wheels' lead is too low or negative, rear wheels push the front wheels. Then, the rear wheels get additional load, because the front wheels obstruct their movement. Of course, sliding front wheels return part of the power to the rear wheels, but circulating power increases losses in the driveline (Andreev *et al.* 2010). In addition, so, the incorrect value of front wheels' lead not only increases wear of tires and transmission components but also increases the overall movement resistance force of the tractor (Andreev *et al.* 2010). Research by Ismailov and Melikov (2015), Molari *et al.* (2012) has shown that if blocked drive of driving axle easy, it is able to provide the best traction drive qualities of the all-wheel vehicle, if compensation of kinematic discrepancy in movement of front and rear wheels.

Wheeled tractors are usually used as a transport means (transporting of loads, driving to the fields with or without implements, etc.). For transporting of loads, tractors are combined with various trailers or semi-trailers. Stability of the tractor/trailer assemblage depends on the coordination between tractor and trailer braking systems and their effectiveness. The best braking process is when braking efficiency of the tractor and the trailer are equal (Ghazali *et al.* 2016; Nastasoiu, Ispas 2014). Service braking is intended to reduce the speed of the running vehicle or to completely stop it. However, tractor braking also occurs in other ways:

- by disconnecting the engine and allowing a gradual decrease in speed due to the road resistance;
- by not disconnecting the engine but reducing or terminating fuel supply.

Engine-braking effect is possible due to the torque that is required to turn the engine and compress the air inside the cylinders (Hamersma, Els 2014).

One must remember that today there are many MFWD tractor models that are equipped with brakes on the rear wheels only. For such tractors, when brakes are applied, in order to make braking more efficient (which includes using all the weight of the tractor), the front axle is automatically switched on; therefore, braking dynamics of MFWD tractors is inseparable from the value of the front wheels' lead.

It is understandable that the final tractor movement resistance depends on the rolling resistance force of the tractor, the force of wheels' interaction with the road due to kinematic discrepancy between front and rear wheels and the force of braking, and depends on the system that transfers torque, its transformation and distribution to the wheels. The force of wheels' interaction with the road due to kinematic discrepancy between front and rear wheels appears only on hard roads and soil surfaces with high adhesion coefficients and only within the low drawbar pull range (Szente 2005; Żebrowski 2010).

Most of the previous researches have been conducted in rolling resistance dependency to tire inflation pressure, while the simultaneous effect of kinematic discrepancy and tire longitudinal slip has been neglected (Ani *et al.* 2018; Gharibkhani *et al.* 2012; Taghavifar, Mardani 2013). This is mainly due to measuring the rolling resistance by a laboratory test of a single tire, not with a movement resistance test on a vehicle.

This study was intended to determine the impact of the inflation pressure in the tires on the lead of the front wheels and movement resistance when the MFWD tractor travelled with the front drive axle enabled and was engine braking with the fuel supply off.

2. Materials and methods

2.1. Theoretical analysis

Let us analyse the case when the MFWD tractor travelled with the front drive axle enabled and gear activated while fuel flow to the engine was cut-off (tractor is engine braked). Upon termination of the fuel supply to the engine, it develops a braking torque, which is transmitted to the wheels through the transmission (Figure 1).

This is due to the torque required to turn the engine while compressing the air inside the cylinders. Engine braking torque was researched by Hamersma and Els (2014). In the event of the MFWD tractor travelling at a constant speed with the drive gear activated, while fuel flow to the engine is cut-off, the tractor braking force can be expressed by the following formula:

$$F_b = \frac{T_{eb} \cdot i_{tr} \cdot \eta_{tr}}{r_w}, \tag{1}$$

where: T_{eb} is the engine braking torque [N·m]; i_{tr} is transmission ratio; r_w is the dynamic radius of the wheel [m]; η_{tr} is the transmission coefficient of efficiency.

To achieve greater efficiency, the braking torque of the MFWD tractor (Figure 1) should be distributed to the front and rear axles' wheels in proportion to the products of multiplication of their vertical loads and dynamic radiuses (Janulevičius, Damanauskas 2015):

$$\frac{T_{b_f}}{T_{b_r}} = \frac{R_{y_f} \cdot r_{w_f}}{R_{y_r} \cdot r_{w_r}}, \tag{2}$$

where: T_{b_f}, T_{b_r} are braking torques of the front and rear wheels [N·m]; R_{y_f}, R_{y_r} are road reaction forces to the front and rear wheels [N]; r_{w_f}, r_{w_r} are dynamic radiuses of the front and rear wheels [m].

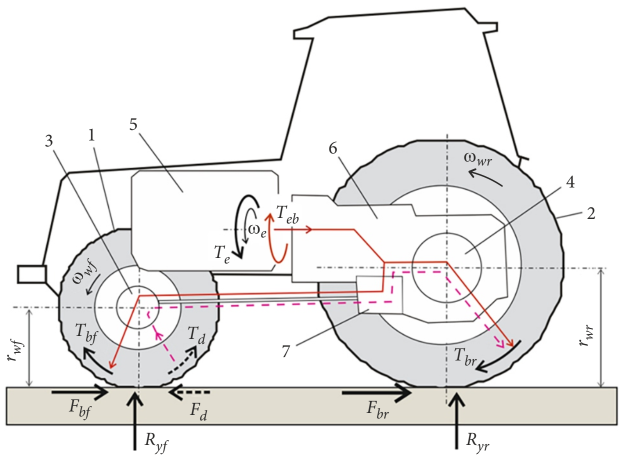

Figure 1. Kinematic diagram of engine-braked MFWD tractor when there is power circulation between the front and rear wheels: 1, 2 – front and rear wheels; 3, 4 – front and rear driving axles; 5 – engine; 6 – transmission (gearbox); 7 – front axle driving mechanism (distribution box)

When braking torques of the front and rear wheels correspond to the Equation (2), braking efficiency of both axles' wheels is uniform, and the force of gravity of the tractor is effectively used for braking. However, in real conditions, vertical loads of the front and rear wheels usually do not retain these proportions, therefore the braking torque distribution between the axles does not correspond to the Equation (2).

Theoretical speeds of kinematically connected front and rear axle wheels are the same when products of multiplication of rolling radiuses and angular speeds are equal as follows: $r_{w_f} \cdot \omega_{w_f} = r_{w_r} \cdot \omega_{w_r}$. The ratio between theoretical speeds of the front and rear axle wheels shows the value of kinematic discrepancy, which is expressed as a kinematic discrepancy factor (Andreev *et al.* 2010; Janulevičius, Damanauskas 2015; Vantsevich 2014):

$$K = \frac{v^t_{w_f}}{v^t_{w_r}} = \frac{r_{w_f} \cdot \omega_{w_f}}{r_{w_r} \cdot \omega_{w_r}}. \tag{3}$$

To fully exploit the advantages of 4WD, the peripheral speed of the front tires must be higher than the rear, on unequal wheel tractors. The transmission of MFWD tractors is constructed to have a lead ratio l_f for the front wheels that is defined by (Molari *et al.* 2012):

$$l_f = \frac{v_{p_f} - v_{p_r}}{v_{p_r}} = K - 1, \tag{4}$$

where: v_{p_f}, v_{p_r} are the peripheral speeds of the front and rear wheels [m/s].

MFWD tractors almost always are characterized by a kinematic discrepancy between theoretical speeds of the front and rear wheels; thus, at the moment of braking the tractor, the lagging wheels skid more than the advancing wheels, which may even slip (slip means wheel shift against the direction of motion, and skid means wheel shift in the direction of the motion of the tractor). During braking of the tractor, the disadvantage is when advancing wheels slip instead of skidding. Slipping wheels create a force in the opposite direction that helps the tractor to move forward instead of stopping.

Let us concentrate on the case where a MFWD tractor on a horizontal path with the front drive axle enabled is being stopped by an engine, the front wheels of the tractor are advancing, and the rear wheels are lagging (Figure 1). The rear axle (4) is driven directly from the gearbox (6), and the front axle (3) is driven directly from the distribution box (7). In this case, the engine, through the transmission, is braking the rear wheels of the tractor by braking torque T_{b_r} and the front wheels by braking torque T_{b_f}, and it develops a braking force F_{b_r} and F_{b_f} for the rear and front wheels, respectively. The kinematic discrepancy between the rear and the front wheels makes the rear wheels skid, and the front wheels slip a certain amount. Front (slipping) wheels create the opposite-direction force F_d and torque T_d, which is transferred to the rear axle wheels through the tractor's front axle drive and the transmission. Subsequently, the final result is that the front wheels generate less braking torque and less braking force. Additional braking power losses occur in the transmission due to power circulation (Battiato, Diserens 2013; Patterson *et al.* 2013); therefore, the increase of braking force of the rear wheels is lower than that of the reduction in the braking force of the front wheels.

For the present case, the tractor braking power balance equation can be written down as follows:

$$P_{tb} = P_{eb} + P_{tr} + P_{TR} - P_{MFWD}, \quad (5)$$

where: P_{tb} is the tractor's braking power [kW]; P_{eb} is the braking power created by the engine [kW]; P_{tr} is the resistance power loss in the transmission of the tractor [kW]; P_{TR} represents a change in movement resistance power due to interaction between the tires and the road [kW]; P_{MFWD} is the loss of braking power in the front and rear wheels' drive system [kW].

P_{TR} is the movement resistance power component resulting from the tire/road interaction, which is composed of two components (P_{rr} and P_{sw}), as seen in the following equation:

$$P_{tb} = P_{eb} + P_{tr} + P_{rr} + P_{sw} - P_{MFWD}, \quad (6)$$

where: P_{rr} represents extra movement resistance power resulting from normal deflection of the tire and the road (rolling resistance power) [kW]; P_{sw} means movement resistance power that is formed due to the tire-road longitudinal deflection (slip/skid) [kW].

The braking power of the engine transferred to the wheels of the tractor is as follows:

$$P_{bw}^{in} = \sum_{i=1}^{n} T_{bw_i}^{*(**)} \cdot \omega_{w_i}^{*(**)} = \sum_{i=1}^{n} F_{bw_i}^{*(**)} \cdot v_{bw_i}^{t*(**)}, \quad (7)$$

where: T_{bw} is the wheel braking torque [N m]; ω_w is the angular wheel velocity [s^{-1}]; F_{bw} is the braking force of the wheel [N]; v_w^t is the theoretical wheel speed [m/s]; *, ** relate to the left and right wheels; n is the number of braking axles.

With reference to Figure 1, the loss of power in the tire-road longitudinal deflection (slip/skid) can be expressed as follows:

$$P_{sw} = \sum_{i=1}^{n} P_{bw_i}^{*(**)} \cdot \left(1 - S_{w_i}^{*(**)}\right) = \sum_{i=1}^{n} F_{bw_i}^{*(**)} \cdot v_{w_i}^{t*(**)} \cdot \left(1 - S_{w_i}^{*(**)}\right), \quad (8)$$

where: S_w is the wheel slip coefficient.

Wheel slip/skid occurs only when the wheel grip with the road is outweighed (Andreev *et al.* 2010; Panáček *et al.* 2016; Patterson *et al.* 2013). With this in mind, Equation (8) can be written as follows:

$$P_{sw} = \sum_{i=1}^{n} \varphi_{w_i}^{*(**)} \cdot R_{yw_i}^{*(**)} \cdot v_{w_i}^{t*(**)} \cdot \left(1 - S_{w_i}^{*(**)}\right), \quad (9)$$

where: φ_w is the friction coefficient between the tires and the road.

Power circulation between the front wheels and rear wheels is represented by the following equation:

$$P_c = \sum \varphi_{w_f}^{*(**)} \cdot R_{yw_f}^{*(**)} \cdot v_{w_f}^{t*(**)} \cdot \left(1 - \delta_{w_f}^{*(**)}\right), \quad (10)$$

where: δ_{w_f} is wheel slippage coefficient of the front wheels.

By knowing the coefficient of efficiency η_{MFWD} for the front and rear wheel drive system, it is possible to calculate the power that the rear wheels receive from the front wheels due to power circulation:

$$P_{cw_2} = \sum \varphi_{w_f}^{*(**)} \cdot R_{yw_f}^{*(**)} \cdot v_{w_f}^{t*(**)} \cdot \eta_{MFWD} \cdot \left(1 - \delta_{w_f}^{*(**)}\right). \quad (11)$$

Therefore, we established that the front (slipping) wheels create the opposite-direction torque, which is transferred to the rear axle wheels through the tractor's front/rear axle drive system. However, part of this circulating power is lost in the front and rear drive systems. In the final result, the increase in the braking force of the rear wheels is less than that of the reduction in the braking force of the front wheels. Therefore, it can be argued that a non-optimal lead of front drive wheels reduces the overall braking power of the tractor.

It is known, that changes in vertical load and tire inflation pressure change the tire deflection and dynamic radius of the wheel inevitably. Disproportionate changes in the dynamic radiuses of the front and rear wheels causes varied lead of front wheels According to Lee *et al.* (2016) the tire deflection of the tractor can be defined by the following formula:

$$\Delta = r_s - \sqrt{\left(r_s^2 - \left(\frac{W}{2 \cdot p \cdot b}\right)\right)}, \quad (12)$$

where: r_s is unloaded radius of tire [m]; W is vertical tire load [N]; p is tire inflation pressure [Pa]; b is unloaded tire section width [m].

The details and example application of the tire deflection model can be found by the paper of Osinenko *et al.* (2015). In this study, the dynamic radius of the front and rear tires was estimated by the following formula:

$$r_w = \sqrt{\left(r_s^2 - \left(\frac{W}{2 \cdot p \cdot b}\right)\right)}. \quad (13)$$

After combining Equations (3), (4) and (13), the mathematical expression for the correlation between the lead ratio for the front wheels and vertical load and inflation pressure of the front and rear tires is:

$$l_f = \frac{\omega_{w_f} \cdot \sqrt{\left(r_{s_f}^2 - \left(\frac{W_f}{2 \cdot p_f \cdot b_f}\right)\right)}}{\omega_{w_r} \cdot \sqrt{\left(r_{s_r}^2 - \left(\frac{W_r}{2 \cdot p_r \cdot b_r}\right)\right)}} - 1, \quad (14)$$

where: f (character index) is for front wheel; r (character index) is for rear wheel.

In this paper, we present our experimental research on how front wheels' slip, rear wheels' skid and tractor's resistance to movement depend on the lead of the front wheels when constant engine braking is employed. We will confirm that additional engine braking power losses occur in the transmission due to power circulation, and the final result is that the tractor wheels receive less braking torque from the engine. In addition, in this experimental study, we will determine how the lead of front drive wheels depends on the combination of front and rear tire inflation pressures, and we will validate Equation (14).

2.2. Equipment, site and measurements

To investigate dependencies of MFWD tractor movement resistance force and front wheels' lead on the inflation pressure of the tires, we used a Zetor 10540 tractor (manufacturer: Zetor; factory: Brno, Czech Republic). This tractor has a mechanical transmission and mechanical front axle drive. The rear axle is driven by the torque that is transferred directly from the gearbox, and the front axle is driven by the torque that is transferred directly from the distribution box. Table 1 shows the main specifications of the tractor that was used for the research.

We carried out the tests on a solid surface in an asphalted area located on the grounds of Vytautas Magnus University Agriculture Academy (Lithuania). We selected a straight and horizontal 80 m long section for the tests. During the test, the pavement surface was dry, and the ambient temperature was 16…19 °C.

Our studies were limited to determine the MFWD tractor's lead of the front wheels and movement resistance force dependences on the inflation pressure of the tires, when the tractor is braked with a constant braking force while moving at a constant speed. Constant braking force was obtained by braking the tractor by the engine, i.e., when the tested tractor was pulled with the gear (H 2–1, forward) activated while fuel flow to the engine was cut off.

During tests, the Zetor 10540 tractor was pulled by the Case Farmall 115U tractor, with a nominal power of 83 kW. Tractors were connected by rigid joints, in which the force gauge PCE–FB 50K was installed. Technical characteristics of the measuring instrument are provided in Table 2.

Various front-wheel drive lead values were obtained by making various air pressures in the Zetor 10540 tractor front/rear tires. Tire pressure combinations were as follows: *front tire pressure* [kPa] / *rear tire pressure* [kPa] = 230/80, 230/130, 230/180, 230/230, 180/230, 130/230 and 80/230.

During the tests, we measured tractor resistance to movement and the number of revolutions of the front and rear wheels at non-zero and zero wheel torque under the

Table 1. Technical data of the Zetor 10540 tractor

Characteristics	Value	Unit
Engine	Zetor 4.2 L, 4 cylinder, in-line, liquid-cooled, turbocharged diesel	–
Rated speed	2200	min^{-1}
Rated power	78.3	kW
Transmission	synchromesh, 18 forward and 6 reverse (three gears in high/low/reverse ranges with a three-speed torque multiplier)	–
Chassis	MFWD, 4WD	–
Front tires	Barum 12.4 R28; 121 A8, wear of tires – 8…9	%
Rear tires	Barum 16.9 R38; 141A8, wear of tires – 6…8	%
Total tractor mass	4530*	kg
Distributions mass on front/rear axles	1857*/2673*; 41/59	kg; %
Wheel base	2.37	m
Steering	hydrostatic power	
Brakes	hydraulic wet disc	
Hydraulics	open; 184.9	bar

Note: * measured by axis scales WPD–2.

Table 2. Specifications of measurement devices

Instrumentation	Measurements	Range	Resolution	Accuracy
Distance measurement, Bosch GLM 150/250VF	distance	0.005…250 m	0.1 mm	±0.05 mm / 1 m
Force gauge PCE–FB 50K	force	50000 N	10 N	±0.1% FS
Axis scales WPD–2	mass	5…15000 kg	1.0 kg	0.1%/1.0 kg

condition that the wheels' travel (D = 50 m) is the same in both modes. As reference (Gray *et al.* 2016) and practice shows, the distance of 50…60 m gives a sufficient accuracy of experimental studies. For calculation of MFWD tractor's lead of front wheels and movement resistance force dependences on the inflation pressure of the tires, we conducted the abovementioned measurements when the tractor was travelling in the following modes:

- when the tested tractor was pulled with the front drive axle enabled and gear (H 2–1, forward) activated while fuel flow to the engine was cut-off (i.e., with non-zero wheels' torque);
- when the tested tractor was pulled with the front drive axle disabled and gear (H 2–1, forward) activated while fuel flow to the engine was cut-off (i.e., with zero front wheels' torque and non-zero rear wheels' torque);
- when the tested tractor was pulled with the front drive axle enabled and gear deactivated (i.e., with non-zero wheels' torque);
- when the tested tractor was pulled with the front drive axle disabled and gear deactivated (i.e., with zero wheels' torque).

We conducted measurements with all tractor travel modes and pressure combinations in the front/rear tires by pulling the tested tractor at a constant 1.39 m/s speed and made three repetitions for each setup. These tests were carried out for the tractor with its weight distribution of 41 and 59% between the front and rear wheels, respectively.

2.3. Calculation of measured parameters

When the tractor is in motion in 4WD mode, the kinematic discrepancy between the front and rear wheels causes them to slip/skid to some extent. In vehicle tests, the tire slippage is determined by the number of revolutions of the wheel in the driving n_{drive} and driven n_{driven} modes (i.e., with a non-zero and zero wheel torque) under the condition that the wheel travel is the same in both modes (Basrah *et al.* 2017; Gray *et al.* 2016; Misiewicz *et al.* 2016). We calculated the coefficient of slip (or skid – in the case of negative values) for the front and rear wheels of the tractor according to the following equations:

$$S_f = \frac{n_{f\,drive} - n_{f\,zero}}{n_{f\,drive}};$$

$$S_r = \frac{n_{r\,drive} - n_{r\,zero}}{n_{r\,drive}}, \tag{15}$$

where: $n_{f\,drive}$, $n_{r\,drive}$ are the number of revolutions of the front and rear wheels in four wheel drive condition; $n_{f\,zero}$, $n_{r\,zero}$ are the number of revolutions of the front and rear wheels, respectively, in the driven modes (i.e., with the zero wheel torque). Zero wheel torque conditions according to the ANSI/ASAE S296.5 W/Corr. 1 (2003) standard were created when the tested tractor was pulled with the gear deactivated and front drive axle disabled.

Kinematic discrepancy between the rear and the front wheels was calculated according to the following formula (Janulevičius, Damanauskas 2015):

$$K = \frac{1 - S_{w_r}}{1 - S_{w_f}}. \tag{16}$$

The lead of the front axle wheels (percentage) was calculated according to the following equation (Janulevičius *et al.* 2017):

$$l_{w_f} = 100 \cdot \frac{S_{w_f} - S_{w_r}}{1 - S_{w_f}}. \tag{17}$$

3. Results and discussion

When a MFWD tractor moves with the front axle drive enabled (4WD drive mode), in many cases, there is a greater or lesser kinematic discrepancy between theoretical speeds of the front and rear wheels. A disproportionate change in the front and the rear tire pressures changes the kinematic discrepancy accordingly. When the tractor moves without being applied pull/push forces, kinematic discrepancy causes one pair of wheels to skid while the other slips (Janulevičius *et al.* 2014; Janulevičius, Damanauskas 2015).

Figure 2 presents the slip/skid of the front and rear wheels of the tested tractor for different front and rear tire inflation pressures. In this figure, wheel slip/skid results are presented for the tractor travel mode that included 4WD, 1.39 m/s speed and the gear switched off, i.e., when engine-braking was not applied to the tested tractor and for the same tractor travel mode when engine-braking was applied to the tested tractor.

Figure 2 shows that almost all front/rear tire inflation pressure combinations were characteristic with the fact that the front wheels were slipping, and the rear wheels were skidding. The wheels were rolling nearly without slip/skid when the inflation pressure of the front tires was 80 kPa and that of the rear was 230 kPa. At the most, the front wheels were slipping for approximately 3.65%, and the rear wheels were skidding for approximately 3.0%, when the inflation pressure in the front tires was 230 kPa and when the inflation pressure in the rear tires was 80 kPa.

From Figure 2, it is easy to note that while engine-braking the tractor, the rear wheels' skid increased, and the front wheels' slip decreased. Changes in values for rear wheels' skid increase and front wheels' slip reduction are more or less the same, i.e., the value of increase in the rear wheels' skid is almost equal to the value of reduction in the front wheels' slip.

Summarizing the results presented in Figure 2, we can say that different air pressure combinations in the front/rear tires showed different kinematic discrepancy between theoretical speeds of the front and rear wheels, because the front wheels' slip and rear wheels' skid values were changing. Figure 3 presents dependence of the front wheels' lead of the tractor on different front and rear tire inflation pressures.

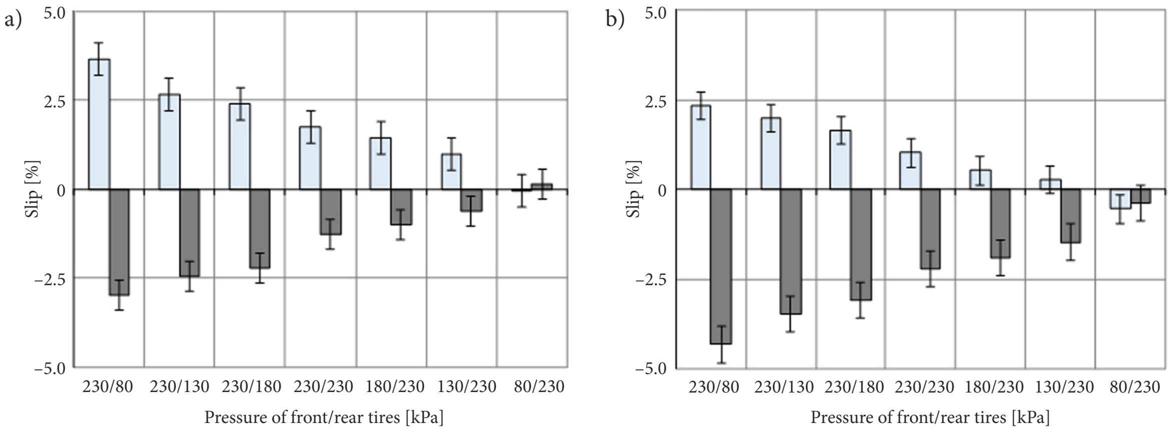

Figure 2. Front and rear wheels' slip for the pulled tractor travel mode that included 4WD and 1.39 m/s speed for different front and rear tire pressures: a – when the tractor was pulled with the gear switched off; b – when the tractor was pulled with the gear enabled but the fuel feed was cut off; *light-toned columns* – the front wheels; *dark-toned columns* – the rear wheels

Figure 3 shows that there is no significant difference in the lead of the front wheels of the tractor values calculated from the experimental results of the tests, when travelling in 4WD drive mode with tractor undergoing engine braking and when it was not braking. In addition, Figure 3 shows (white-coloured columns with dotted lines) the theoretical dependence calculated on the basis of Equation (14). The maximum absolute differences between the experimentally and theoretically derived lead of front wheels values did not exceed 5%.

This test shows that for the Zetor 10540 tractor with 12.4 R28, 121 A8 "Barum" front tires and 16.9 R38, 141 A8 "Barum" rear tires, the variations in tire inflation pressures can change the lead of the front wheels by approximately 6.9%. The lead of the front wheels of the tractor was almost non-existent when inflation pressure in the front tires was 80 kPa and when inflation pressure in the rear tires was 230 kPa. The maximum lead of the front wheels was present when the inflation pressure in the front tires was 230 kPa and when the inflation pressure in the rear tires was 80 kPa. For such tire pressures, the kinematic discrepancy coefficient value was 1.068, and the lead of front wheels was 6.8%. When the front and rear tires had equal pressures of 230 kPa, the kinematic discrepancy coefficient value was approximately 1.036. Thus, when the front and rear tires had equal pressures of 230 kPa, the lead of the front wheels was approximately 3.6%. Figure 4 shows the dependence of the front and rear wheels' slip/skid on the lead of the front wheels of the tractor.

Figure 4 shows that the lead of the front wheels made the front wheels slip and the rear wheels skid. Increasing the lead of the front wheels increased the slip of the front wheels and increased the skid of the rear wheels. For example, 5% lead of the front wheels made the front wheel slip for approximately 2.65%, and the rear wheels skid for approximately 2.4%. From Figure 4, it is easy to note that while engine-braking the tractor, rear wheels' skid increased, and the front wheels' slip decreased. When the lead of the front wheels was at 5% and the tractor was

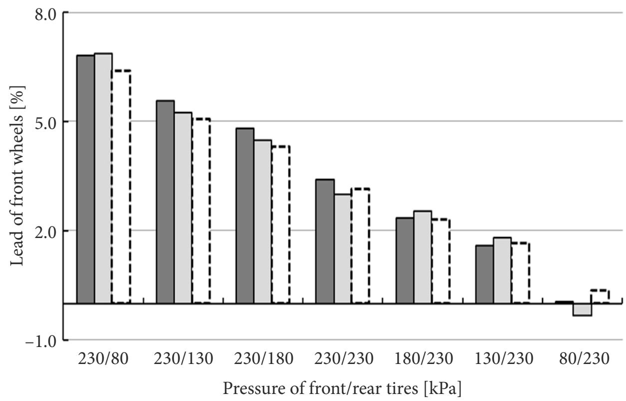

Figure 3. Lead of front wheels of the tractor values for 4WD drive mode for different front and rear tire pressures: *dark-coloured columns* – when the tractor was engine braking; *light-coloured columns* – when the tractor was not braking; *white-coloured columns with dotted lines* – calculated on the basis of Equation (14)

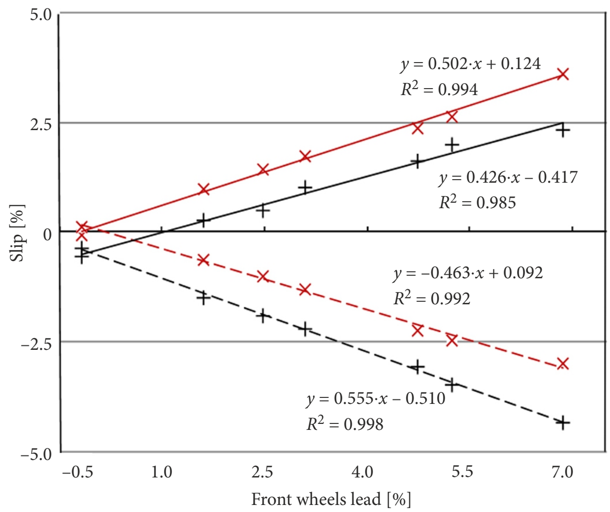

Figure 4. Dependencies of the front (*solid line*) and rear (*dashed line*) wheels slip/skid on the lead of front wheels for the tractor travelling in 4WD mode: "+" – when the tractor was engine braked; "×" – when the tractor was not braking

braked by the engine, the slipping of the front wheels dropped from 2.65 to 1.80%, while the skid of the rear wheels increased from 1.7 to 3.3%. Figures 5, 6 and Table 3 represent resistance to movement force when the tractor travelled for different front and rear tire pressures.

In tests, when the tractor travelled in 2WD mode with a deactivated drive gear, we measured the total movement resistance force of the tractor. In this case, only the rolling resistance force resisted the movement of the tractor. Figure 5 shows that the minimum tractor rolling resistance force of approximately 1.0 kN was present for maximum pressures in the front and rear tires, i.e., 230 kPa. When inflation pressures in both the rear and the front tires were reduced, the tractor rolling resistance force increased. Figure 5 also includes values of tractor resistance to motion when the tractor in the 4WD mode was pulled with the gear switched off. This force comprises tractor wheels rolling resistance force and the force of wheels' interaction with the road due to the kinematic discrepancy between the front and rear wheels. Thus, in Figure 5, height differences between light-coloured and dark-coloured columns show that part of the tractor resistance to motion, which was present due to the kinematic discrepancy between the front and rear wheels. Similar trends have been confirmed by other authors. Research by Ismailov and Melikov (2015) has shown the similar relationship between the difference of rolling radius of the wheels of different axles and the difference of the tractor movement resistance. Studies of Ismailov and Melikov (2015) have shown that for the K-701M tractor with 100/180 kPa inflation pressures in the front/rear tires the resistance-to-movement force increased by 1.52 kW.

Figure 6 shows values of tractor resistance to motion when the tractor was pulled at a speed of 1.39 m/s in 2WD and 4WD modes with drive gear (H 2–1) enabled, but the fuel feed switched off. In Figure 6, dark-coloured columns represent tractor resistance to motion values, when the tractor travelled in the 2WD mode at a speed of 1.39 m/s and was engine braked with the fuel supply off. This force comprises the tractor rolling resistance and braking forces, i.e., engine resistance force transferred to the tractor's rear wheels through its transmission. Evaluation of the rolling resistance force values given in Figure 5 led us to conclude that the tractor engine braking at test conditions was about equally effective at different front and rear tire inflation pressures. The braking force by engine of the tractor is reflected by the height differences between the dark-colours in Figures 6 and 5. The value of the force of the tractor engine braking was within the range from 4.1 to 4.2 kN. The engine braking is applied to the power train when the driver removes his foot from the throttle pedal while the tractor is moving and in gear. Characterisation of the engine braking was done by Hamersma and Els (2014). The torque required to turn the engine is multiplied by all the gear, transfer ratios that form part of the tractor's power train and is applied to the driving wheels (Hamersma, Els 2014).

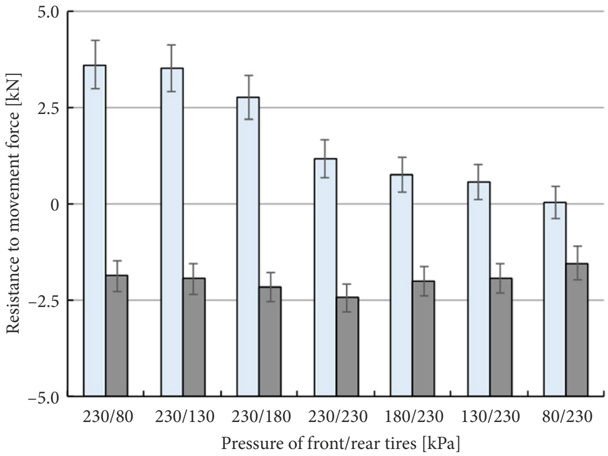

Figure 5. Forces of tractor resistance to motion, when tractor was pulled at a speed of 1.39 m/s at different front and rear tire pressures: *dark-coloured columns* – 2WD mode; *light-coloured columns* – 4WD mode

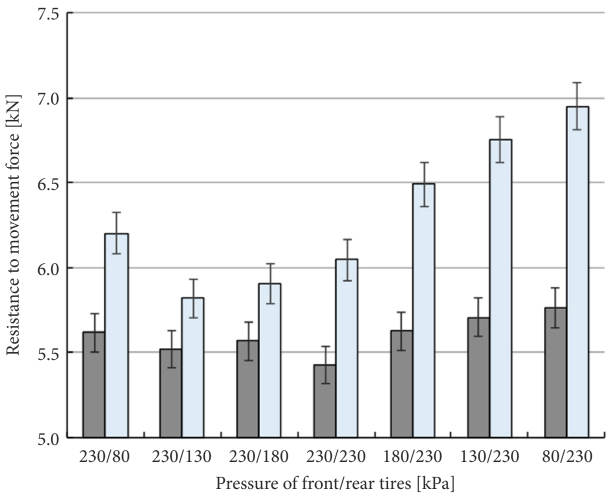

Figure 6. Forces of tractor resistance to motion, when the tractor was engine braked, at different front and rear tire pressures: *dark-coloured columns* – 2WD mode; *light-coloured columns* – 4WD mode

Comparing tractor resistance-to-movement forces when it travelled in 4WD mode without braking (the light-colours in Figure 5) and braked by the engine (the light-colours in Figure 6), we can see opposite trends. When the tractor was travelling in 4WD mode with the gear switched off, the maximum resistance-to-movement force was reached at the front/rear tire inflation pressures of 230/80 kPa, respectively; while it was travelling in 4WD mode braked by the engine, the maximum resistance-to-movement force was reached at front/rear tire inflation pressures of 80/230 kPa, respectively. We may presume that such difference trends were due to variation of the kinematic discrepancy between the front and rear wheels. We will substantiate this phenomenon by analysing the dependence of the tractor movement forces on the lead of the front wheels.

The front/rear tire pressure combinations that we selected for our research showed different front/rear tire distortion rate values; thus, the change in the pressure combinations resulted in the lead of the front wheels. Each tractor test version in the 4WD drive mode with the particular front and rear tire pressures resulted in the particular tire distortion ratio, which corresponded to the particular lead of the front wheels. This lead of the front wheels made front and rear wheels' skid or slip, and this impacted the tractor's resistance to movement. Figure 7 presents the dependence of resistance-to-movement force of the tractor, travelling in 4WD mode, on the lead of the front wheels.

Graph 1 (Figure 7) shows the dependence of resistance to movement force of the tractor on the lead of the front wheels, when the tractor travels by 4WD mode with the drive gear disabled. This force comprises the rolling resistance force of the tractor and the force of the wheels' interaction with the road due to lead of the front wheels. This dependence shows that when the lead of the front wheels increases, the tractor's resistance to movement also increases. For example, when the lead of the front wheels is increased by 5%, the tractor's resistance to movement increased by approximately 0.6 kN. Graph 2 (Figure 7) shows the dependence of resistance to movement on the lead of the front wheels, when the tractor travels is 4WD mode with the drive gear enabled while fuel flow to the engine was cut off, i.e., when travelling, the tractor is engine braked. This force comprises the rolling resistance force of the tractor, the force of the wheels' interaction with the road due to the lead of the front drive wheels and the force of engine braking. The latter force is reflected by the distance between Graphs 1 and 2. These dependences (Figure 7) show that when the lead of the front wheels increases, the tractor's resistance to movement decreases, i.e., tractor engine-braking efficiency decreases. For example, when the lead of the front wheels is increased by 5% [kN], the tractor's engine-braking force decreased by approximately 1.34 kN, and the tractor's resistance to movement decreased by approximately 0.74 kN. Thus, the experimental results confirmed that when the lead of the front wheels increases, tractor's braking force decreases. This confirms that when the tractor is braked, the lead of the front drive wheels makes the front wheels slip and this creates the opposite-direction torque, which is transferred to the rear axle wheels through the tractor's front/rear axle drive system.

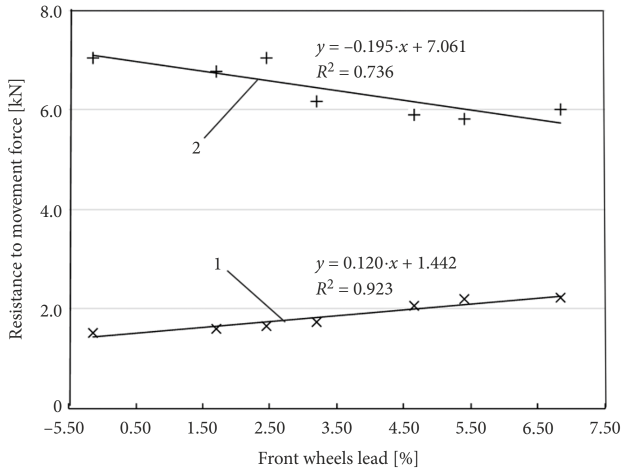

Figure 7. Dependences of resistance to movement on the lead of front wheels of the tractor: graph 1 – when the tractor travels in 4WD mode with the drive gear switched off; 2 – when the tractor travels in 4WD mode and is engine braked

Summary and conclusions

This test shows that for a MFWD tractors with front and rear radial tires, the variations in tire inflation pressures can significantly change the lead of the front drive wheels. For the tested tractor up to 6.9%. When the tested tractor travelled with 80/230 kPa inflation pressure in the front/rear tires, respectively, the lead of the front wheels was approximately –0.13%, and when the tested tractor travelled with the 230/80 kPa inflation pressure in the front / rear tires, respectively, the lead of front wheels was approximately 6.82%. The maximum absolute difference between the theoretically and experimentally derived lead of front wheels values did not exceed 5%.

When the tested tractor travelled at a speed of 1.39 m/s with 80/230 kPa inflation pressures in the front/rear tires, the front drive axle enabled, and gear deactivated the overall resistance-to-movement force of the tractor was 1.51 kN, while at the 230/80 kPa inflation pressures, the overall resistance-to-movement force of the tractor was 2.22 kN.

When the tested tractor travelled at a speed of 1.39 m/s with 80/230 kPa inflation pressures in the front/rear tires,

Table 3. Resistance-to-movement force when the tractor travelled for different front and rear tire pressures

Resistance-to-movement force [kN]:	Pressure of front/rear tires [kPa]						
	230/80	230/130	230/180	230/230	180/230	130/230	80/230
when the tractor travelled in 2WD mode with the gear switched off	1.13	1.11	1.07	1.01	1.10	1.11	1.19
when the tractor travelled in 2WD mode and was engine braked	5.62	5.42	5.56	5.42	5.63	5.71	5.76
when the tractor travelled in 4WD mode with the gear switched off	2.22	2.20	2.05	1.73	1.65	1.61	1.51
when the tractor travelled in 4WD mode and was engine braked	6.01	5.82	5.91	6.16	7.03	6.75	7.05

front drive axle enabled and was engine braked (gear H 2–1, forward activated, with fuel flow to the engine cut off) the overall resistance-to-movement force of the tractor was 7.05 kN, while at the 230/80 kPa inflation pressures, the overall resistance-to-movement force of the tractor was 6.01 kN.

The result is that when the tested tractor travelled with the front drive axle enabled and was engine braking with the fuel supply off, the engine-braking efficiency decreases with increasing lead of the front wheels. The lead of the front wheels makes the front wheels slip and the rear wheels skid. Front (slipping) wheels create the opposite-direction torque, which is transferred to the rear axle wheels through the tractor's front-rear axle drive system. Additional power losses of the engine braking occur in transmission due to power circulation, and the final result is that the tractor wheels receive less braking torque from the engine.

The analysis of the tractor driving system, presented in this paper, is useful for determination of relationships between slips as well as forces and torques acting on the wheels of a MFWD tractor depending on how the particular wheels are driven. Determination of the direction of power flow through the wheels is essential if we are to avoid occurrence of circulating power in the driving system of tractor.

The results of the tests confirm the theoretical assumptions and create a basis for future research, which could help to establish firmly the borders between the characteristic stages during the MFWD tractor's movement, both when accelerating and when decelerating.

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Disclosure statement

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