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POWER CIRCULATION IN DRIVELINE SYSTEM WHEN THE WHEELS OF TRACTOR AND TRAILER ARE DRIVEN

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Abstract. In off-road "tractor–trailer" vehicle combinations, the trailer can be equipped with one or more driving wheels. The distinguishing feature of vehicles with two or more driving axles is distribution of total power between the driving wheels. In machines with several driving axles, kinematic mismatch between theoretical wheel speeds nearly always takes place. The wheels of tractor and trailer can slip uniformly and differently, some of them may even slide. It is unfortunate when the wheels slide, as power circulation takes place. In this paper, power circulation of a vehicle composed of a tractor and trailer having driving wheels and driving wheels' interaction with soil is investigated. The conclusion is that in a vehicle composed of two machines having two driven axles each, circulation of power can be avoided or reduced by turning off one driving axle in the machine, which delivers more power and has advancing driving wheels.

Keywords: tractor; trailer; driving axle; driving wheel; slippage; power circulation; driveline system; kinematic mismatch; load; traction force.

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Introduction

In agriculture, the main vehicle is a tractor with trailer. Tractor-pulled off-road machine combinations may have driving wheels on the tractor and also on the trailer. The trailer can be equipped with one or more driving axles. Such machines produce significantly more traction and slip less, because more weight is utilized for their grip with the soil or road (Giedra, Janulevičius 2004, 2005; Wong 2008; Janulevičius, Giedra 2009). However, the simple addition of a driving axle can drastically increase fuel consumption and negatively impact the overall vehicle dynamics and performance. The problem is that the performance of multi-wheel-drive vehicles depends on the distribution of the engine power among the driving axles, and also left and right wheels of each axle (Vantsevich 2007; Vantsevich, Gray 2009; Żebrowski 2010). Power distribution between the wheels is determined by the vehicle's driveline systems, which consist of a set of power dividing units. Many researchers are of the opinion that, for example, the use of two driving axles instead of one unalterably increases the vehicle's fuel consumption, irrespective of the parameters of power dividing units and of driving conditions (Vantsevich 2008; Stoilov, Kostadinov 2009; Vantsevich, Gray 2009). The researchers' main argument usually is that by providing motion to the driving components of the additional driving axle, higher power consumption is required (Zoz, Grisso 2003; Vantsevich 2007). A distinctive feature of vehicles with four or more driving wheels is that fuel efficiency and mobility depends not only on the total power applied to all the driving wheels, but also on the distribution of total power among the wheels. The same vehicle with the same total power for all the driving wheels, but with different power distribution among the driving wheels, will demonstrate different fuel consumption, mobility, and traction (Zoz *et al.* 2002; Vantsevich, Gray 2009).

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Kinematic mismatch between theoretical wheel speeds nearly always takes place in machines with several driving axles (Becheru *et al.* 2006; Stoilov, Kostadinov 2009; Żebrowski 2010). This happens because it is difficult to select such transmission proportions to driving axles that the wheels would have the same theoretical speeds in all conditions, especially if the wheels are of unequal dimensions. It is possible to choose the exact speeds for some conditions, but with change in working conditions these speeds change, as the tires deform differently because of the load changes (Juostas, Janulevičius 2008; Sapragonas, Dargužis 2011). This problem is especially noticeable when off-road machine combinations are made of separate machines having driving wheels; example of such combination may be the tractor and the trailer with driving wheels. Usually, tractor wheels are rolling over soil; they deform the ground and deform themselves in one way, and the trailer wheels are rolling over the tracks made by the tractor wheels, so they deform differently. In addition, tires of different machines can be designed for different air pressures and loads, their treads can be worn down unevenly, and, finally, tires of different machines cannot be fully consistent with each other; see Goncharenko *et al.* (2007). While theoretical speeds of the individual machines' driving wheels are not the same, driven axles are forced to rotate at the same speed, which corresponds to the speed of the whole combination of machines. Then the tractor and the trailer wheels can slip uniformly or differently, some of them may even slide (Becheru *et al.* 2006; Stoilov, Kostadinov 2009; Żebrowski 2010).

Kinematic mismatch coefficient is the term used to describe the ratio of theoretical speeds between different axles' driving wheels. Ideally, this ratio should be equal to one. However, this may happen only when tractor's working conditions do not vary. If the wheels of lagging axle roll normally or slip less than those of the advancing axle – situation is normal, because the combination of machines is driven by the axles of two machines. The least favorable situation is when lagging wheels slide instead of slipping. In this case, advancing (main) drive wheels are much more loaded, as lagging (sliding) wheels are breaking instead of helping motion, so the main drive wheels slip much more (Szente 2005; Żebrowski 2010; Molari *et al.* 2012).

The phenomenon of power circulation has been known for a long time, but no proper analysis of the theoretical model has been made. The model has seen a lot of inter-related factors, which disturb the verification of theoretical assumptions.

The purpose of this work is to investigate power circulation of a vehicle composed of a tractor and trailer having drive wheels and drive wheels' interaction with the soil, and to identify the factors influencing for power circulation and provide a means of reduction.

1. Theoretical analysis

Theoretical speeds of the wheels of multi-wheel-drive vehicle are the same when multiplication products of their rolling radiuses and angular speeds are equal (Becheru *et al.* 2006):

$$\omega_{a1} \cdot r_{a1} = \omega_{a2} \cdot r_{a2} = \cdots = \omega_{an} \cdot r_{an}, \tag{1}$$

where: ω_{a1}, ω_{a2i}, ω_{an} are angular velocities, respectively, of the first, second, and the n-th axle; r_{a1}, r_{a2i}, r_{an} are wheel radiuses, respectively, of the first, second, and the n-th axis.

Kinematic mismatch coefficient is the term used to describe the ratio between theoretical speeds of different axles' driving wheels (Szente 2005; Vantsevich 2007; Żebrowski 2010):

$$k_n = \frac{v_i^t}{v_m^t} = \frac{r_i \cdot \omega_i}{r_m \cdot \omega_m} = \frac{1 - \delta_m}{1 - \delta_i}, \tag{2}$$

where: v_m^t, v_i^t and δ_m, δ_i are, respectively, theoretical speeds of the main and the i-th axle wheels and the slippage.

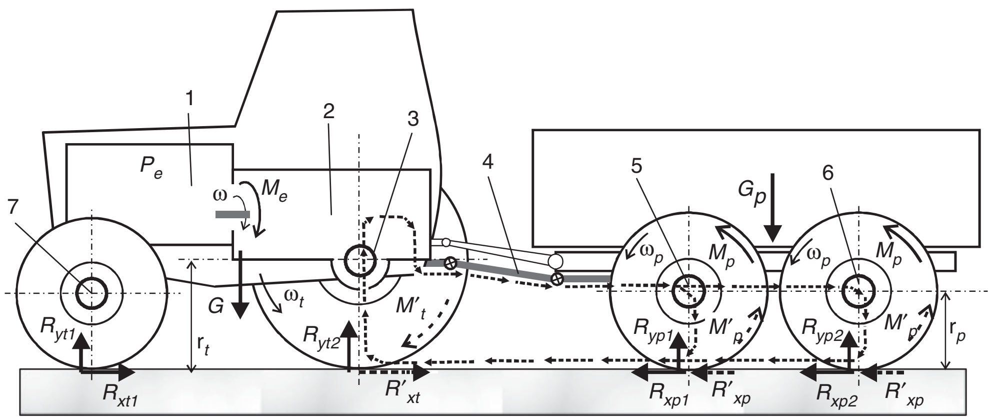

Fig. 1. "Tractor–trailer" kinematic diagram (with the circulation of power), when all the wheels are driven, except the front axle of the tractor: 1 – engine; 2 – transmission of the tractor; 3 – rear driving axle of the tractor; 4 – power take-off (PTO) shaft from tractor to trailer, 5 and 6 – front and rear driving axles of the trailer; 7 – front axle of the tractor

Kinematic mismatches between different wheels of multi-wheel-drive vehicle often are different. Further we will analyze the particular case, i.e. when a vehicle is composed of the tractor MTZ 820 and the trailer PALMS 96. Kinematic diagram is presented in Fig. 1.

Transmission of this tractor is equipped with such front axle drive, which turns on automatically when the rear wheels start to slip more than 4÷5%. The front axle is automatically activated through one-way clutch, mounted in the front axle gear. One-way clutch can be blocked, and then, the front axle will be activated all the time. Furthermore, the front axle can be turned off completely. When one-way clutch is blocked, the rear wheels are forced to slip 4÷5% more than the front wheels or front wheels are forced to slide (Vantsevich 2007). In order to avoid uncertainties because of the tractor's front axle drive and simplify the analysis, this study was conducted with the tractor's front axle completely switched off.

All four drive wheels of the trailer are of the same size and are rotated at the same angular speed. When all four drive wheels of the trailer are loaded equally, they deform in the same way. Kinematic mismatch between the wheels of the trailer is not taking place.

Kinematic mismatch of a "tractor–trailer" combination was defined as the ratio between angular velocity of the dynamic radius of the tractor's rear wheel and the angular velocity of the dynamic radius of the trailer's wheel:

$$k_n = \frac{v_t^t}{v_p^t} = \frac{\omega_t \cdot r_t}{\omega_p \cdot r_p} = i_{tp} \cdot \frac{r_t}{r_p}, \tag{3}$$

where: r_t is dynamic radius of tractor's rear wheel; r_p is dynamic radius of the trailer's wheel; v_t^t is theoretical speed of tractor's rear wheel; v_p^t is theoretical speed of trailer's wheel; ω_t is angular velocity of tractor's rear wheel; ω_p is angular velocity of trailer's wheel; and i_{tp} is transmission ratio between the tractor's rear wheels and trailer's wheels.

The axle with a higher theoretical wheel speed is called advancing, and that with a lower theoretical wheel speed is called lagging. The wheels of advancing axle are slipping more than the wheels of lagging axle, which may even slide. The least favorable situation is when the wheels of tractor are lagging and they slide instead of slipping (Fig. 1). Sliding wheels do not create a traction force; vice versa – they resist to motion of the machine (Żebrowski 2010; Senatore, Sandu 2011). In this case, the engine – through the tractor's transmission and driveline system to the trailer – rotates the drive wheels of the trailer by torque M_p and develops traction forces R_{xp1} and R_{xp2}. Sliding rear wheels of the tractor create an additional drag force R'_{xt} and torque M'_t, which are transferred to the trailer through the tractor's transmission and driveline system and help propel the driving wheels of the trailer. They create an additional torques M'_p and additional traction forces R'_{xp}.

Thus, when the rear wheels of the tractor are sliding, the driving wheels of the trailer push the tractor; its rear wheels create a certain torque again and transfer it back to the driveline system; in other words, the result in the power circulation. This circulating power is harmful, because it increases the load on tractor's transmission and "tractor–trailer" driveline system; consequently, it increases tractor's fuel consumption, tire wear, and so on. The main drive wheels (of the trailer in this case) are much more loaded, because their movement is hindered by the tractor's wheels. Although the tractor's sliding wheels return the power, a considerable part of it is lost due to additional load on the "tractor–trailer" driveline system, which increases friction losses. The sequence of transferred engine power and its losses is shown in Fig. 2.

Effective engine power is consumed as follows (Vantsevich, Gray 2009):

$$P_e = P_{tr} + P_{drl} + P_{ts} + P, \tag{4}$$

where: P_{tr} is power loss in transmission of tractor; P_{drl} is power loss in driveline system; P_{ts} is power loss due to tire and soil deformations; and P is power of the vehicle motion.

P_{ts} is power loss in tire soil interaction, which is composed of two components, as seen in the following equation:

$$P_e = P_{tr} + P_{drl} + P_{\delta\Sigma} + P_{f\Sigma} + P, \tag{5}$$

where: $P_{\delta\Sigma}$ is power that is lost due to the tire soil longitudinal deflection (slippage power); $P_{f\Sigma}$ is power loss due to normal deflection of the tire and soil (rolling resistance power) (Jun *et al.* 1998; Gus'kov 2007; Vantsevich, Gray 2009).

The two components of the power-balance equation (4), $P_{\delta\Sigma}$ and $P_{f\Sigma}$, make driveline system's influence on the power loss, hence the energy efficiency of the vehicle.

The power supplied to the driving wheels of tractor and trailer is as follows:

$$P_w = \sum_{i=1}^{n} M_i^{*(\bullet)} \cdot \omega_i^{*(\bullet)} = \sum_{i=1}^{n} R_{xi}^{*(\bullet)} \cdot v_i^{t\,*(\bullet)}, \tag{6}$$

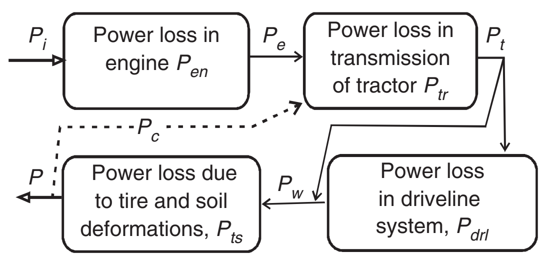

Fig. 2. Flowchart of power transference and losses when the wheels of tractor and trailer are driven

where: M is the wheel torque; ω is the angular wheel velocity; R_x is the driving force of the wheel; v^t is the theoretical wheel speed (with no slip); symbols "*" and "•" relate to the left and right wheels; and n is the number of driving axles.

With reference to Fig. 2, the loss of mechanical power in the driveline system P_{drl} and the power loss $P_{\delta\Sigma}$ due to slippage can be expressed as follows:

$$P_{drl} = \frac{P_w \cdot (1 - \eta_{Mdrl})}{\eta_{Mdrl}}; \tag{7}$$

$$P_{\delta\Sigma} = P_w \cdot (1 - \delta), \tag{8}$$

where: η_{Mdrl} is total mechanical efficiency of the driveline system and δ is wheel slip efficiency.

The efficiency η_{Mdrl} characterizes the effect of power distribution among the driving wheels, including mechanical power loss in driveline system, and δ characterizes the power lost in wheel slipping.

By substituting expressions from equations (7)–(8) into equation (5), we obtain:

$$P_e = \frac{P_{tr} + P_w \cdot (1 - \eta_{Mdrl})}{\eta_{Mdrl} + P_w \cdot (1 - \delta) + P_{f\Sigma} + P}. \tag{9}$$

Power circulation (P_c) between the tractor's and trailer's driving wheels is given by the following equation:

$$P_c = P_w \cdot (1 - s), \tag{10}$$

where: s is wheels' sliding efficiency.

The value of power circulation in the "tractor–trailer" driveline system depends on the value of slippage of lagging driving wheels, which is determined through testing.

2. Materials and method

2.1. Equipment, site, and layout

For the test of driving wheels' interaction with soil and kinematic compatibility, when the wheels of tractor and trailer are driven, a trailer PALMS 96 was used, which was equipped with two driving axles. Balancing suspension was used to connect driving axles with trailer's body. For the tests, the trailer was combined with a tractor MTZ 820. A level and plowed field was selected, with moisture content 19.8% and hardness 0.85 MPa in 5 cm depth, and hardness 1.08 MPa in 15-cm depth. The 120-m section of the field with uniform structure was chosen for the measurements. Tests were carried out by driving to one direction on plowed and untouched field, and back on the same tracks. Tests were carried out with the following options: both trailer's axles disabled, one trailer's axle enabled, and two trailer's axles enabled. All tests were carried out with disabled tractor's front axle. During tests, the tire pressures were 1.5 bar in tractor's front and rear tires, and 2.5 bar in trailer's tires. Tests were carried out while running without a load and with loads of 1500, 3000, and 4500 kg. For each combination of load, three runs were performed to ensure repeatability and reliability of the results obtained. Loads were piled onto the trailer so that only the trailer wheels would be loaded. During tests, tractor's and trailer's driving wheel speeds were counted in 100-meter-long stretches. The main technical characteristics of the tractor and trailer are given in Table 1.

To measure the distance, laser gauge Bosch PLR 50 was used, having a measurement error of $\pm$ 2 mm. Vertical loads of tractor wheels were determined by electronic portale axle weigher WPD-2, having a measurement error of 1 kg.

Table 1. Characteristics of the tractor and trailer

Tractor's:	
Power	58.7 kW
Operating weight	3900 kg
Wheel base	2450 mm
Number of axles/driven axles	2/2
Front tires	11.2 R 20
Rear tires	620/75 R 26
Speed of synchronous PTO shaf	3.5 rpm
Trailer's:	
Weight	1900 kg
Weight-carrying capacity	10,000 kg
Number of axles/driven axles	2/2
Wheels	500/50-17
Length of the loading bay	3700 mm
Total length	5960 mm
Weight of the loader	1300 kg
Transmission ratio	10.42

2.2. Calculations

Percentage slippage (sliding) of tractor and trailer wheels was calculated using the following equation:

$$\delta = \frac{n - n_0}{n} \cdot 100\%, \tag{11}$$

where: n is number of the driving axle's wheel rotations in the test stretch; n_0 is number of the non-loaded by traction force axle's wheel rotations in the test stretch.

Kinematic mismatch between tractor and trailer driving wheels is calculated by the following equation (Stoilov, Kostadinov 2009):

$$k_n = \frac{1-\delta_p}{1-\delta_t}\ \%, \qquad (12)$$

where: δ_t, δ_p are slipping (sliding) of the tractor and trailer driving wheels.

The vertical load factors for vehicle axle wheels were calculated using the following equation:

$$k_w = \frac{R_w}{G}\%, \qquad (13)$$

where: R_w is the vertical load force of axle wheels; G is total force of the vehicle weight.

3. Results and discussion

The tests of driving wheels' interaction with soil and kinematic mismatch, when wheels of the tractor and trailer were driven, were carried out using the four wheel load combinations: while running without a load and with loads of 1500, 3000, and 4500 kg. Combinations of the tests included the vehicle driven by:

1) only the wheels of the rear tractor's axle;
2) the wheels of the rear tractor's axle and all four wheels of the trailer;
3) the wheels of the rear tractor's axle and two trailer's wheels, namely, the front axle wheels of the trailer.

Total weight of "tractor–trailer" combination and axle vertical load coefficients in the test combinations are presented in Fig. 3.

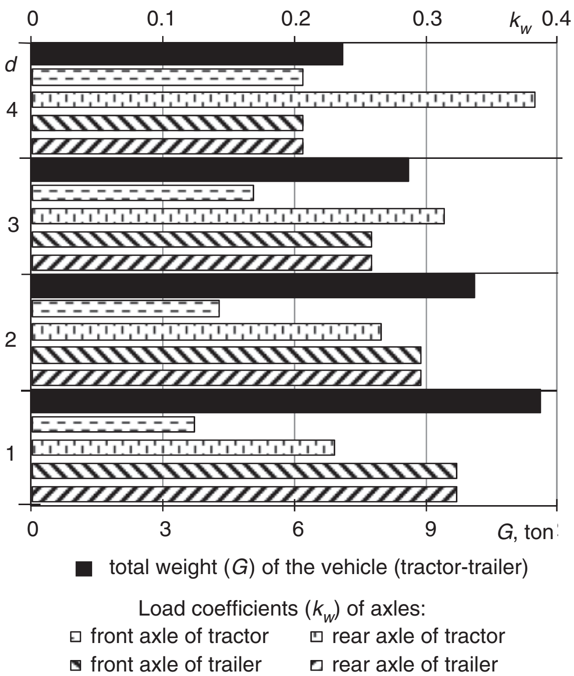

Fig. 3. Total weight (G) of "tractor–trailer" combination and axle vertical load coefficients in the test combinations (d)

Tests show that if we increase the weight of the load, this changes the values of weight distribution between the tractor and trailer and load coefficients of the driven wheels. For example, when driving without a load (total weight of the vehicle – 7.1 tons), tractor's wheels carried 58%, and the trailer's wheels – 42% of total vehicle weight. Tractor's driving (rear) wheels carried 38% of total vehicle weight, and trailer's driving wheels carried 42% of total vehicle weight when both trailer's axles were activated, but 21% of total vehicle weight when one trailer's axle was activated. When the load was 4500 kg (total weight of the vehicle – 11.6 tons), tractor's wheels carried 36%, and the trailer's wheels – 64% of total vehicle weight. Tractor's driving (rear) wheels carried 23% of total vehicle weight, and trailer's driving wheels carried 64% of total vehicle weight when both trailer's axles were activated, but 32% of total vehicle weight when one trailer's axle was activated.

Individual axles' maximum power outputs (limited by the wheel grip) of the vehicle are proportional to the vertical axle loads (Zoz, Grisso 2003; Janulevičius, Giedra 2008; Wong 2008).

In Fig. 4, the research results are presented, how driving wheels interact with the soil (slipping/sliding) when only the rear tractor's axle wheels are activated for driving.

Fig. 4 shows that when the trailer's driving wheels were inactive, tractor's driving wheels' slippage, while driving on the plowed field, was in the range from 10.5% (no load) to 14.5% (when carrying 4500 kg of load). While driving on the tracks made by the vehicle, the tractor's wheels slipped on average 3÷4% less. The variation was from 7.3% (no load) to 10.7% (when carrying 4500 kg of load).

The results of driving wheels' interaction with soil, when the tractor rear axle's wheels and the trailer's wheels were activated for driving, are presented in Figs 5–8.

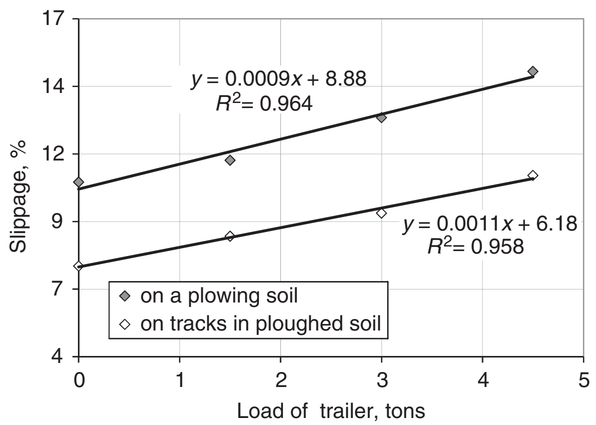

Fig. 4. Dependences of tractor wheels' slippage on the load carried in the trailer when the trailer's driving axles are disabled

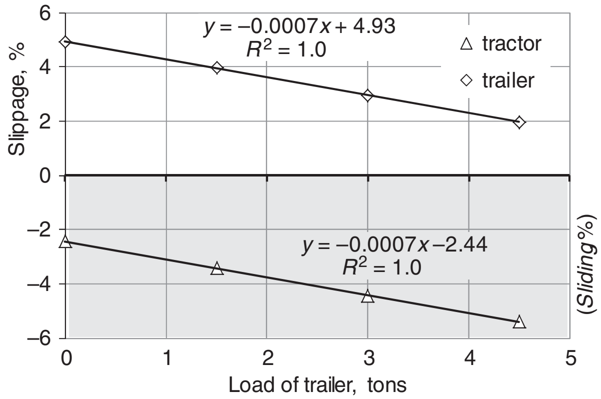

Fig. 5. The dependences of driving wheels' slippage on the load carried by trailer, while the trailer's both driving axles are activated and driving is executed on a plowed soil

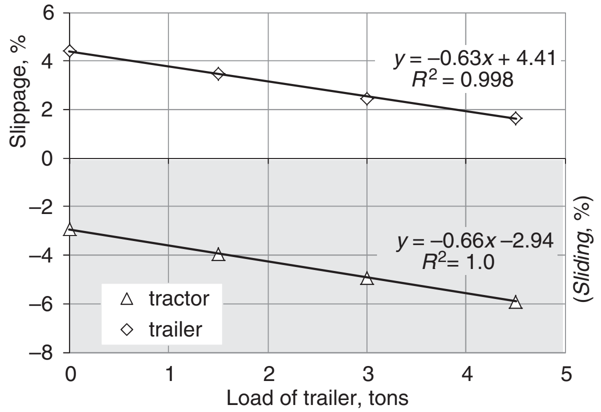

Fig. 6. The dependences of driving wheels' slippage on the load carried by trailer, while the trailer's both driving axles are activated and driving is executed on the tracks made by previous driving

Figs 5 and 6 show that when both driving axles of the trailer were activated, their wheels were slipping, and the wheels of tractor's rear driving axle were sliding. This shows that kinematic mismatch was taking place between theoretical wheel speeds of the tractor and trailer. Slipping trailer's wheels are advancing, and sliding rear wheels of the tractor are lagging. By increasing the load, slippage of trailer's driving wheels decreased, and sliding of tractor's wheels increased. From Fig. 5, we can see that, while driving on a plowed soil, slipping of trailer's driving wheels decreased from 4.93% (at no load) to 1.95% (when carrying 4500 kg of load). At the same time, sliding of tractor's driving wheels increased from 2.43% (at no load) to 5.40% (when carrying 4500 kg of load). From Fig. 6, we can see that, while driving on the tracks that were made by previous driving, slipping of trailer's driving wheels decreased from 4.43% (at no load) to 1.65% (when carrying 4500 kg of load). At the same time, sliding of tractor's driving wheels increased from 2.93% (at no load) to 5.90% (when carrying 4500 kg of load). In off-road wheeled machines' dynamics such situation

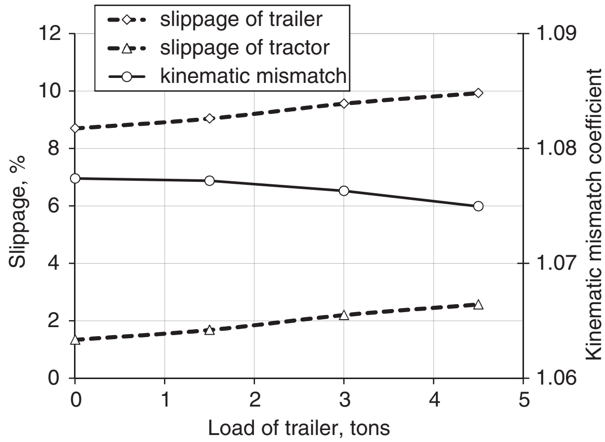

Fig. 7. The dependences of driving wheels' slippage and kinematic mismatch coefficient on the load carried in the trailer, when tractor's rear and trailer's front driving axles are enabled and driving is executed on the plowed ground

is undesirable, as power circulation is taking place (Szente 2005; Vantsevich 2007; Stoilov, Kostadinov 2009; Żebrowski 2010).

From Figs 7 and 8, we can see that while the rear driving axle of the tractor and the front driving axle of the trailer were activated, their wheels were slipping differently. Obvious wheel sliding was not taking place. But the different slipping shows that kinematic mismatch was taking place between theoretical wheel speeds of the tractor and trailer. More slipping trailer's driving wheels are advancing, and sliding rear wheels of the tractor are lagging. By increasing the load, slipping of both trailer's and tractor's driving wheels increased.

From Fig. 7, we can see that, while driving on plowed soil, slipping of trailer's driving wheels increased from 8.70% (at no load) to 9.93% (when carrying 4500 kg of load). At the same time, slipping of tractor's driving wheels also increased from 1.34% (at no load) to 2.57% (when carrying 4500 kg of load). By driving the tracks and increasing the load from 0 to 4500 kg, slipping of driving wheels rose slightly, about 1.3%, and was, on average: trailer's wheels, about 8%; tractor's wheels, 0.6%. In off-road wheeled machines' dynamics, such situation is treated as favorable, as all the driving wheels deliver traction force and power circulation is not taking place (Szente 2005; Becheru *et al.* 2006; Vantsevich 2007; Stoilov, Kostadinov 2009; Żebrowski 2010).

In Figs 7 and 8, in addition to the test results of the tractor and trailers' interaction with soil, kinematic mismatch between the tractor and trailer driving wheels' theoretical speeds' dependence on the trailer's load is presented.

Kinematic mismatch coefficient of driving wheels of the vehicle was 1.077. By increasing the load from 0 to 4500 kg, kinematic mismatch coefficient decreased slightly to 1.075. This is due to deformations of tire.

The dependence of driving wheels' interaction with soil on the number of activated axles and their load, when researched vehicle was composed of a tractor and trailer with driving wheels, is presented in Figs 9 and 10. In Part I of the figures, test results are presented, when only the rear axle of the tractor was activated. In Part II of the figures, test results are presented, when tractor's rear axle and one of the trailer's driving axles was activated. In Part III of the figures, test results are presented, when tractor's rear axle and both driving axles of the trailer were activated. Test results marked with "1" mean that the vehicle was traveling without a load and those marked with "2" mean that the vehicle was carrying 4500 kg of load.

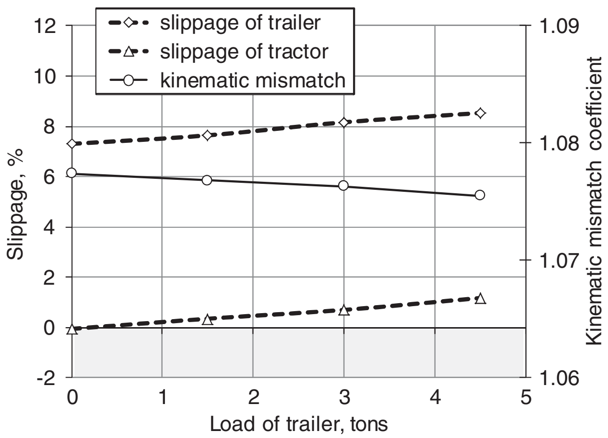

Fig. 8. The dependences of driving wheels' slippage and kinematic mismatch coefficient on the load carried in the trailer, when tractor's rear and trailer's front driving axles are enabled and driving is executed on the tracks made by previous driving

The results presented in Figs 9 and 10 show that the smallest slippages are obtained when both trailer's and the rear wheels of the tractor are activated. But, in this case, power circulation is taking place in the "tractor–trailer" driving system. In this situation, vertical loads of trailer's wheels were sufficient, so its wheels slipped not much, and tractor's driving wheels, which were loaded less, were sliding. By increasing the load, vertical loads of trailer's driving wheels increased, and those of the tractor remained nearly unchanged, so the trailer's wheels slipped less, and the tractor's wheels were sliding more.

Ideally, kinematic mismatch ratio should be equal to one. If the wheels of lagging axle are rolling normally or slipping less than those of advancing axle – situation is normal, because the vehicle is driven by axles of both machines (Szente 2005; Becheru *et al.* 2006; Vantsevich 2007; Stoilov, Kostadinov 2009; Żebrowski 2010). The results suggest that when one of trailer's driving axles is activated (of course, the rear axle of tractor is also activated), we get the case when the driving wheels of both machines deliver traction force and power circulation is not taking place.

The unfavorable situation is when the lagging wheels slide instead of slipping. In that case, advancing (main) driving wheels are loaded much more, as lagging (sliding) wheels brake instead of helping motion. Such situation we obtained when a vehicle was driven by the tractor's rear wheels and all the wheels of the trailer.

For the researched vehicle, consisting of the tractor and trailer with driving wheels, when driving is executed on a plowed field having 19.8% moisture content and 0.85 MPa hardness in 5-cm depth, and 1.08 MPa hardness in a depth of 15 cm, it is

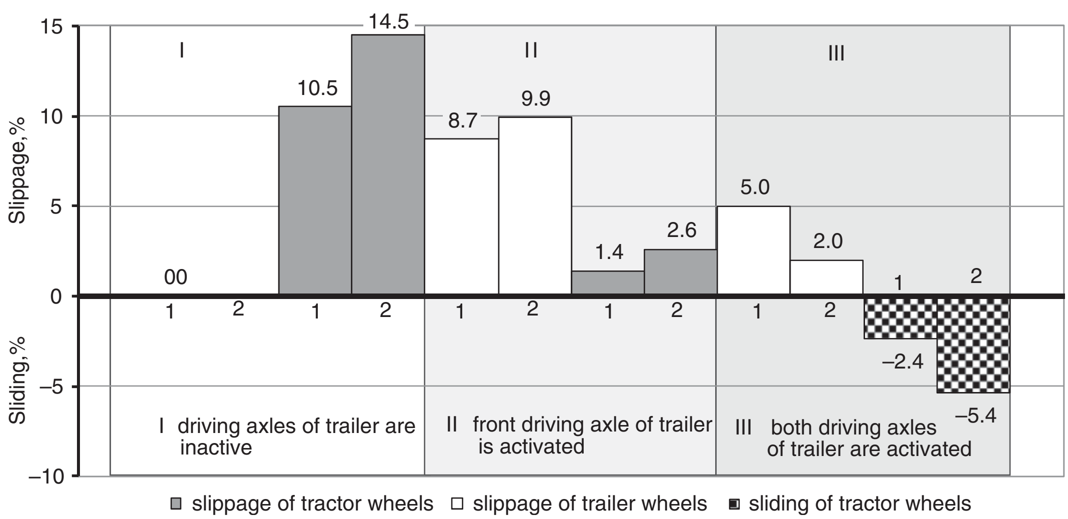

Fig. 9. The dependences of vehicle's driving wheel's slippage on the number of activated driving axles and their load, while driving on a plowed field: 1 – when total weight of the vehicle is 7100 kg, axle load rates: tractor's front – 0.21, tractor's rear – 0.38, trailer's front – 0.21 and trailer's rear – 0.21; 2 – when total weight of the vehicle 11,600 kg; axle load rates: tractor's front – 0.12, tractor's rear – 0.23, trailer's front – 0.32, and trailer's rear – 0.32

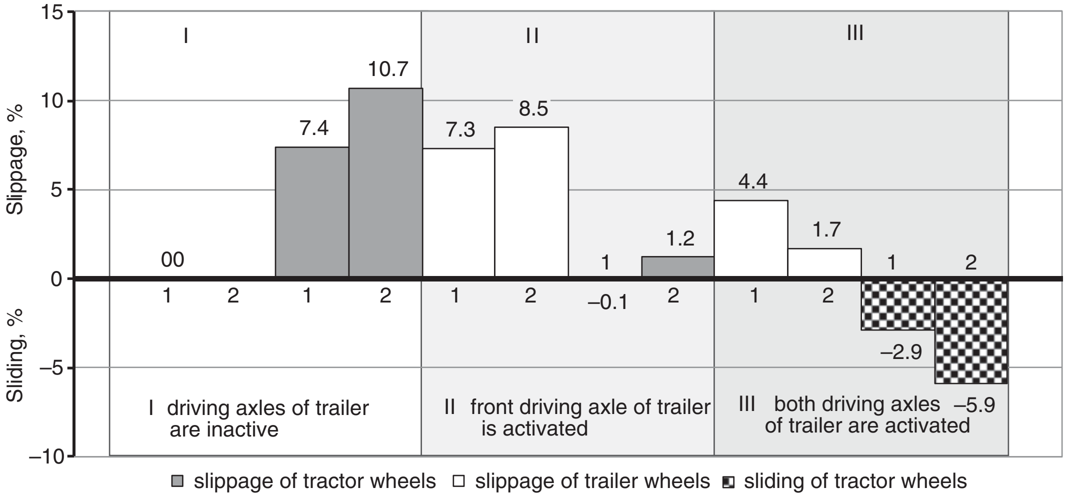

Fig. 10. The dependences of vehicle's driving wheel's slippage on the number of activated driving axles and their loads, while driving on a tracks in a plowed field: 1 – when total weight of the vehicle is 7100 kg, axle load rates: tractor's front – 0.21, tractor's rear – 0.38, trailer's front – 0.21 and trailer's rear – 0.21; 2 – when total weight of the vehicle 11,600 kg; axle load rates: tractor's front – 0.12, tractor's rear – 0.23, trailer's front – 0.32 and trailer's rear – 0.32

reasonable to activate only one of trailer's driving axle (working together with tractor's rear driving axle). In this case, activation of one driving axle of the trailer gives positive results while driving with 4500 kg of load, and driving without a load as well. When driving on previously made tracks in a plowed soil without a load, it is reasonable to turn off both driving axles of the trailer, and when transporting a load – to activate one driving axle of the trailer.

Conclusions and recommendations

1) In the researched vehicle, trailer's driving wheels were advancing, and the tractor's driving wheels – lagging. When tractor's rear driving axle and both trailer's driving axles were activated, advancing wheels were slipping 5÷2%, and lagging wheels were sliding 2.4÷5.4%. The situation was unfavorable, as the power circulation took place.
2) When tractor's driving axle and one of the trailer's driving axles were activated, all driving wheels of the vehicle were slipping: tractor's – 1.4÷2.6%; trailer's – 8.5÷10%.
3) Kinematic mismatch coefficient of driving wheels of the vehicle was 1.077. By increasing the load from 0 to 4500 kg, kinematic mismatch coefficient decreased to 1.075.
4) In a vehicle composed of two machines having two driven axles each, circulation of power can be avoided or reduced by turning off one driving axle in the machine with advancing driving wheels.

References

Becheru, G.; Babeu, T.; Chiriac, A. 2006. On the power circulation in longitudinal plan at a four wheel drive vehicle, *Annals of the Oradea University: Fascicle of Management and Technological Engineering* 15(5): 237–240.

Giedra, K.; Janulevičius, A. 2004. Traktoriaus traukos ir svorio jėgų bei ratų buksavimo sąveika, *Žemės ūkio inžinerija* 36(4): 108–123 (in Lithuanian).

Giedra, K.; Janulevičius, A. 2005. Tractor ballasting in field transport work, *Transport* 20(4): 146–153.

Goncharenko, C. V.; Godzhaev, Z. A.; Stankevich, Je. B.; Mir-Kasimov V. V.; Bykadorova, Z. U.; Koren', V. V. 2007. Identifikaciya shin po jekspluatacionnym pokazatelyam, *Traktory i Sel'skohozyajstvennye Mashyny* 7: 16–19 (in Russian).

Gus'kov, A. V. 2007. Optimizaciya tyagovo-scepnyh kachestv traktornyh shin, *Traktory i Sel'skohozyajstvennye Mashyny* 7: 19–21 (in Russian).

Janulevičius, A.; Giedra, K. 2008. Tractor ballasting in field work, *Mechanika* 5(73): 27–34.

Janulevičius, A.; Giedra, K. 2009. The slippage of the driving wheels of a tractor in a cultivated soil and stubble, *Transport* 24(1): 14–20. http://dx.doi.org/10.3846/1648-4142.2009.24.14-20

Jun, H.; Kishimoto, T.; Way, T. R.; Taniguchi, T. 1998. Three-directional contact stress distributions for a pneumatic tractor tire in soft soil, *Transactions of the ASABE* 41(5): 1237–1242.

Juostas, A.; Janulevičius, A. 2008. Investigation of tractor engine power and economical working conditions utilization during transport operation, *Transport* 23(1): 37–43. http://dx.doi.org/10.3846/1648-4142.2008.23.37-43

Molari, G.; Bellentani, L.; Guarnieri, A.; Walker, M.; Sedoni, E. 2012. Performance of an agricultural tractor fitted with rubber tracks, *Biosystems Engineering* 111(1): 57–63. http://dx.doi.org/10.1016/j.biosystemseng.2011.10.008

Sapragonas, J.; Dargužis, A. 2011. Model of radial deformations of protector of vehicle tire, *Mechanika* 17(1): 21–29. http://dx.doi.org/10.5755/j01.mech.17.1.199

Senatore, C.; Sandu, C. 2011. Torque distribution influence on tractive efficiency and mobility of off-road wheeled vehicles, *Journal of Terramechanics* 48(5): 372–383. http://dx.doi.org/10.1016/j.jterra.2011.06.008

Stoilov, S.; Kostadinov, G. D. 2009. Effect of weight distribution on the slip efficiency of a four-wheel-drive skidder, *Biosystems Engineering* 104(4): 486–492. http://dx.doi.org/10.1016/j.biosystemseng.2009.08.011

Szente, M. 2005. Slip calculation and analysis for four-wheel drive tractors, *Progress in Agricultural Engineering Sciences* 1(1): 7–31. http://dx.doi.org/10.1556/Progress.1.2005.1.2

Vantsevich, V. V. 2007. Multi-wheel drive vehicle energy/fuel efficiency and traction performance: objective function analysis, *Journal of Terramechanics* 44(3): 239–253. http://dx.doi.org/10.1016/j.jterra.2007.03.003

Vantsevich, V. V. 2008. Power losses and energy efficiency of multi-wheel drive vehicles: a method for evaluation, *Journal of Terramechanics* 45(3): 89–101. http://dx.doi.org/10.1016/j.jterra.2008.08.001

Vantsevich, V. V.; Gray, J. P. 2009. Fuel economy and mobility of multi-wheel drive vehicles: modeling and optimization technology, in *Proc. of the 2009 Ground Vehicle Systems Engineering and Technology Symposium (GVSETS)*, 17–22 August 2009, Troy, Michigan, USA, 1–8.

Wong, J. Y. 2008. *Theory of Ground Vehicles*. 4th edition. Wiley. 592 p.

Zoz, F. M.; Grisso, R. D. 2003. *Traction and Tractor Performance*. ASAE Publication Number 913C0403. ASAE Distinguished Lecture Series: Tractor Design No. 27 48 p. Available from Internet: http://bsesrv214.bse.vt.edu/Dist_Lecture_27/Resources/Traction_Tractor_Performance.PDF

Zoz, F. M.; Turner, R. J.; Shell, L. R. 2002. Power delivery efficiency: a valid measure of belt and tire tractor performance, *Transactions of the ASAE* 45(3): 509–518.

Żebrowski, J. 2010. Traction efficiency of a wheeled tractor in construction operations, *Automation in Construction* 19(2): 100–108. http://dx.doi.org/10.1016/j.autcon.2009.09.007