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Comparison of tractor slip at three different driving wheels on grass

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Abstract. The paper deals with a possibility of tractor slip reduction on a grass and evaluates an use of two versions of special wheels. Both prototypes were developed at the Department of Transport and Handling of the Slovak University of Agriculture in Nitra. The first system was designed in 2010 year as blades wheels. The second system (spikes device) consists of spikes which are mounted onto standard tractor tyres with special cuts, was designed in 2014 year. The spikes are settled in these cuts while moving on road surface. The second one is placed near the drive wheels and uses the blades. The spikes and blades are ejected to reduce wheels slip when tractor operates on grass or soil. The base position allows tractor transport on road with standard tyres. The goal of experiments realized on grass surface was to compare mutually slip behaviour achieved. The measurements were realized with standard tyres without any modification, too. A tractor with three types of drive wheels were loaded by heavier tractor. Drawbar pull and wheel rotation speed for slip calculation were measured in tests. The results show a fact that a loss of energy due to the wheels slip increases, while a penetrometric resistance in the surface layers of a soil decreases, at soil humidity 33.2%. An application of both prototypes is very advantageous because they reduce the wheels slip, increase tractor operation efficiency and so protect the soil.

Key words: tyres modification, spikes wheels, soil moisture, slip.

INTRODUCTION

The testing of tractors used in agriculture is continuously increasing because these machines directly influence the results of agricultural production. Adamchuk et al. (2016) presents that the tractor's energy saturation rate as the ratio between the installed engine power rating and the operating mass of the power unit is the criterion of its belonging either to the traction or the traction and power concepts, each of which feature their own system of unitising agricultural equipment. This criterion should be understood by the designers of any new mobile power units for operation in the agricultural industry.

Agricultural tractors are losing a lot of energy by the slip of drive wheels. To reduce the tyre slip, tractors are loaded with a heavy weight, which increases the drawbar pull but excessively increases soil compaction and tyre wear on a hard surface (Semetko et al., 2004; Jobbágy et al., 2016). The compacted soil is a problem for all ecosystems because worse water infiltration (Chyba et al., 2013; Chyba et al., 2014) is causing often flood on the present.

Nowadays, diesel oil and petroleum products belong to the most used fuels. Unfortunately, fossil fuels are non-renewable and exhaustible sources of energy (Müllerová, et al., 2012). The increase of tractor drawbar pull influences the fuel consumption and emissions of exhaust gases.

The drawbar pull, travel reduction (slip), and rolling resistance are the main criteria to describe the traction behaviour of off road vehicles. Besides the engine performance, the drawbar pull is influenced by the traction conditions such as soil and the tire parameters (Schreiber & Kutzbach, 2008).

The drawbar pull of tractor is influenced by various factors. Very significant parameter influencing the drawbar pull is a tyre pressure. Noréus & Trigell (2008) realized the measurement of drawbar pull at various tyre pressure. The test showed that the drawbar pull is vastly improved at lower tyre pressure.

Dabrowsky at al. (2006) realized the tests of terrain vehicle equipped with different tyre types. All-season tyres installed in a military truck provide slightly better traction for both terrain surfaces, at all three loading levels, or the differences between traction measures are not significant. Soil stress analysis showed that the difference between the two tread patterns is not significant. Generally, on soft surfaces all-season tyres performed no worse than snow tyres, while they are pronouncedly better for highway use.

Agricultural tractors can have different types of undercarriage such as two wheel drive, four-wheel drive, and steel tracks. Despite a higher tractive performance and lower soil compaction, steel-tracked tractors are not popular due to their complexity and the difficulties of moving steel-tracked vehicles on roads. Recently, rubber belt tracks have become a notable solution for agricultural tractors, because they unite tractive performance and lower soil compaction with a better trafficability (Molari et al., 2012).

We can concluded that as tractor power increases and as soil becomes weaker and less frictional, then the balance of advantage changes from two wheel to four wheel drive. The type of tyres is the next important factor to increase the drawbar pull and influence tractive performance, as well as soil stresses under a vehicle.

The results of a theoretical analysis reveal that, for a four-wheel-drive tractor to achieve the optimum tractive performance under a given operating condition, the thrust (or driving torque) distribution between the front and rear axles should be such that the slips of the front and rear tyres are equal. Field test data confirm the theoretical findings that, when the theoretical speed ratio is equal to 1, the efficiency of slip and tractive efficiency reach their respective peaks, the fuel consumption per unit drawbar power reaches a minimum, and the overall tractive performance is at an optimum (Wong et al., 1998).

MATERIALS AND METHODS

Two prototypes of drive wheels for tractors were developed and designed in Slovak University of Agriculture in Nitra, Faculty of Engineering, Department of Transport and Handling. Both drive wheels modify the properties of common tyres to improve the drawbar properties of tractor. The prototypes should decrease wheels slip and so protect the soil again damage, improve an operation economic of the tractor and increase drawbar pull if tractor cannot move due to 100% wheels slip. Design of prototypes which reduce the wheels slip and allow the tractor transport on standard road using the common tyres was aim of this research. We name the prototypes as spikes device and blades wheels. The first one requires a tyre-tread pattern modification but it is very simple, low cost design characterised by easy installation on common tyres. The second one doesn't require any tyre modification because it is installed near the tractor wheels. Design of blades wheels is more complicated and expensive. It can be predicted that the blades wheels will reach better drawbar properties compare with spikes device during the same test due to stronger construction but simplicity is the main advantage of spikes device.

Test procedure

Testing properties of both prototypes, a wheels slip and drawbar power were used in compare with common tyres TS-02 6.5/75-14 4PR TT type (Mitas a. s., Czech Republic). These parameters characterise the operation economic and influence of tractor on soil condition mainly soil compaction. To calculate wheels slip and drawbar power a measurement procedure according to following steps was realized.

Tractor type Mini 070 (Fig. 1) was equipped with different wheels to test prototypes properties. Characteristics of Mini 070 are listed in Table 1

Figure 1. The tractor type Mini 070 equipped with the spikes device.

Table 1. Specifications of the tractor type Mini 070

Characteristic	Value
Year of manufacture	1989
Construction weight	310 kg
	1.53 km h^{-1} at 1st gear
	2.72 km h^{-1} at 2nd gear
	4.96 km h^{-1} at 3rd gear
	14.4 km h^{-1} at 4th gear
	1 cylinder
	400 cm^3 (displacement)
	8 kW (maximum performance)
	3,600 rpm (rated rotation speed)

Preparing prototypes tests, a measuring sector (30 m) was staked on grass using two rods at the sector start and finish. Nest, a white mark was drawn on the tractor wheel perimeter for number of wheel revolves counting.

In first measurement, the tractor with no load passed whole sector, number of wheel revolves was counted and time measured. Return of the tractor to the start of measuring sector.

Attachment of a loading tractor (no gear engaged) to the tractor with tested wheel prototype via drawbar pull sensor (Fig. 1). Technical parameters and specification of tractor type TZ-4K14 used to brake the first one are listed in Table 2.

Table 2. Specifications of the bracking tractor type TZ-4K-14

Characteristic	Value
Year of manufacture	1987
Construction weight	820 kg
	1 cylinder
	900 cm^3 (displacement)
	12 kW (maximum performance)

Removal of heater plug from engine head of the loading tractor to achieve constant drawbar pull with 3rd and 4st gear engaged and stopped engine.

Start the stopwatch when the tractor front part passing the staring rods, start the drawbar pull measurement system and count the drive wheel rotates. The drawbar pull measurement of the tractor type Mini 070 (Fig. 1) equipped with different wheels was performed by means of a tensometric force sensor marked as 150 EMS (Emsyst s. r. o., Slovak Republic), as shown in Fig. 2. The force sensor was connected between the loading tractor TZ-4K-14 and the tractor type Mini 070 through a chain. A portable recording unit type HMG 3010 (Hydac GmbH, Germany) was used to record an electrical signals from the force sensor. A description of measurement devices and sensors are presented in the work published by Tulík et al. (2013). The tractor type Mini 070 was set the first gear (I gear) during the measurement. The connection of both tractors was realized according to work presented by Jablonický et al. (2014) and Procházka et al. (2015). Universal battery source (UANS) contains two accumulators (12 V) connected in series or parallel to supply the sensor and the recording unit with a direct voltage (12 V or 24 V). The power supply was manufactured as a portable device according to works presented by Takáč et al. (2011) and Cviklovič et al. (2012).

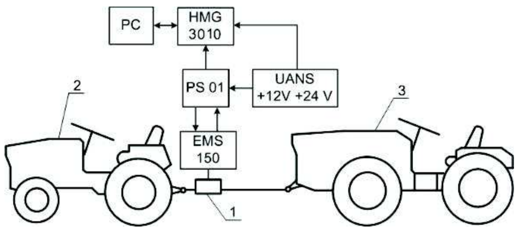

Figure 2. System for measurement of tractor drawbar pulls (Abrahám et al., 2014): 1 – force sensor EMS 150; 2 – tractor type Mini 070 equipped with different wheel types; 3 – loading tractor type TZ-4K-14, HMG 3010 – digital portable recording device, UANS – universal battery source, PC – personal computer, PS 01 – junction box.

Stop the stopwatch and counting of drive wheel rotates when tractor front part passes finish rods. Next, record values to table and repeat the measurement with loading tractor attached with fourth and then third gear engaged to spend all possibilities.

Calculation of wheels slip and drawbar power

Tractor slip moving on elastic base support measurement is realised according to common methodology mentioned above. First, measuring sector was staked on the grass plot using measuring tape and marked by two rods at the start and at the finish. Tractor movement time was measured using stopwatch starting when front part of tractor passes the start rods and ending when the same tractor part passes the finish rods. Tractor wheels slip was measured using line drawn on wheel serving to count number of revolves of drive wheel in the measuring sector. Actual tractor speed was calculated according to formula:

$$v = \frac{s}{t} \tag{1}$$

Theoretical speed is calculated according to formula:

$$v_t = \frac{2\,\pi\, r_d\, n_m}{i_c} \tag{2}$$

where r_d is the dynamic radius of drive tyre, m; n_m is the nominal engine speed, s^{-1}; s is the staked sector (length 30 m), m; t is the time to move over the sector, s.
Slip of the tractor drive wheels is calculated according to formula:

$$\delta = \left(1 - \frac{n_t}{n_{sk}}\right) \tag{3}$$

where n_t is the theoretic wheel speed with no load in the measuring sector, s^{-1}; n_{sk} is the actual wheel speed with load in the same measuring sector, s^{-1}.

Slip of drive wheels can be verified according to formula:

$$\delta = \left(1 - \frac{v}{v_t}\right) \tag{4}$$

where v is the actual speed, m s^{-1}; v_t is the theoretic speed, m s^{-1}.

The drawbar power is determined by drawbar pull and motion speed of tractor. Drawbar characteristics of tractor determine tractor drawbar capacity defined by its drawbar pull F_t at particular motion speed, specifying tractor drawbar power P_t. Tractor drawbar power determines significantly driving mechanism slip δ, particularly on unpaved supports. Slip values are therefore accompanying specification of drawbar parameters.

Tractor drawbar power can be calculated according to:

$$P_t = F_t\, v. \tag{5}$$

where F_t is the drawbar pull, N; v is the actual speed, m s^{-1}.

Prototypes of drive wheels

Both prototypes namely spikes device and blades wheels were designed for tractor type Mini 070. Using the small tractor the design was less expensive and the test of wheels properties sampler compare with standard size of tractor.

Spikes device (Fig. 3) consists of four segments (Fig. 4) connected together by carrying wire rope 3 and operated by control wire rope 4. Control wire 4 provides spikes tipping from tyre body and mutual holding of individual segments in the same position. Spikes are tilting to avoid need for removal when moving on the road and reduce the health risks for operator. The tilting is realised by spikes 1 rotation to tangential position not outreaching the tyre body (tread). Spikes 2 eject automatically due to tractor drive wheel slip, when mechanism 5 is locked-off. It is necessary to lock tilted position of spikes 1 using levers 5 to prevent spikes recline to transport position when generating drawbar pull back in reverse motion. Locked transport position suitable for movement on paved roads using levers 5 holding spikes 1 reclined is depicted in Fig. 3.

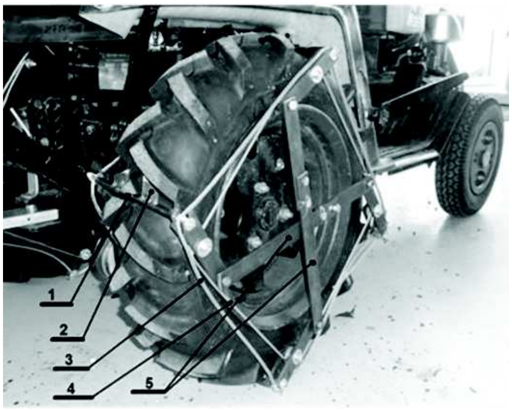

Figure 3. Spikes device on tractor wheel type TS – 02: 1 – cross-beam; 2 – spike; 3 – carrying wire rope; 4 – control wire rope; 5 – locking levers setting tilted/reclined position.

Blades wheels (Fig. 5) are equipped with automatically extensible blades. Wheels equipped with the blades were designed according to the work published by Sloboda et al. (2008). A main advantage is that they do not have to be removed from the tractor when passing on the road and also that they are automatically extended when the tractor drive wheels are slipping. Re-folding of driving blades occurs with the reverse movement of the tractor. The tractor needs not be equipped with additional load weights because they are replaced by wheels equipped with automatically extensible blades. Wheels equipped with automatically extensible blades are mounted to the wheel disc, and according to Fig. 5, they consist of the following parts.

Figure 4. Detail of one spike segment.

Figure 5. Blades wheel: 1 – support tube; 2 – locking tab; 3 – bracket fastening the mechanism to the wheel disc; 4 – spacer plates; 5 – blade; 6 – driving disc; 7 – blade control disc; 8 – guide pin; 9 – locking hole; 10 – blade pin; 11 – buffer plate.

A support tube (1) is a basic part of the whole mechanism. It enables the remaining parts of the whole mechanism to be attached to each other. On the support tube, there are welded three locking tabs (2), three brackets (3) by which the whole mechanism is connected to the tractor wheel, and a driving disc (6) containing blades (5) mounted by means of ten pins. On the support tube, there are also welded spacer plates (4) through which the mechanism position is centred with respect to the tractor wheel disc. After the driving disc (6), the support tube contains a freely rotating disc for the control of blades (7). The blade control disc contains on its circumference twenty pressed guide pins by means of which blades move into the extended and retracted positions. On the other side of the blade control disc, there are four locking holes (9) to fix the position of blades in the retracted position. Three buffer plates (11), attached by six screws to the locking tabs (2), fix the blade control disc on the support tube.

RESULTS AND DISCUSSION

The measurements were realised in March 2016 with average volume soil humidity 33.2% and soil volume weight 1.66 g cm^{-3}. The measurement were realised on the grass plane surface at sunny weather in Slovak Agricultural Museum in Nitra. The area for measurement was approximately 0.5 ha. Measuring sector limited by rods had rectangular shape with dimensions 30 x 25 m.

Results achieved (Tables 3, 4, 5) were divided for evaluation according to gear used on tractor MINI 070 when testing. Variances were observed in drawbar pull when using common tyre, blades wheels and spikes device, as it is shown in Fig. 6. These differences are caused by higher motion speed (Fig. 7) achieved by tractor with spikes device leading to higher engine speed of tractor TZ-4K-14, resulting in recorded higher drawbar pull and higher mechanical resistance. Similar variances were observed with second gear engaged (Fig. 8), with differences even more significant due to higher motion speed (Fig. 9).

Table 3. Measured values of drive tyres (30 m sector)

Tractor motion speed measurement with first gear engaged on grass							
	Travelling using common tyres						
	Travel time s	Speed, m s^{-1}	Theoretic wheel revolution	Wheel revolution under load	Wheels slip	Average drawbar pull, N	Drawbar power, W
No load	71	0.423		16			
No gear	78	0.385		16.9	0.053	1,174.879	451.876
4	83	0.361		17.3	0.075	2,336.123	844.382
3	110	0.273		23.0	0.304	2,986.495	814.499
Tractor motion speed measurement with second gear engaged on grass							
No load	39	0.769		16			
No gear	45	0.667		17.6	0.091	924.535	616.357
4	58	0.517		20.3	0.212	2,765.980	1,430.679
3	98	0.306		25.0	0.360	3,467.780	1,061.565

Table 4. Measured values of drive spikes tyres (30 m sector)

Tractor motion speed measurement with first gear engaged on grass							
	Travelling using spikes device						
	Travel time s	Speed, m s^{-1}	Theoretic wheel revolution	Wheel revolution under load	Wheels slip	Average drawbar pull, N	Drawbar power, W
No load	71	0.423		16			
No gear	74	0.405		16.8	0.048	1,094.605	443.759
4	78	0.385		18.2	0.121	2,542.857	978.022
3	103	0.291		23.3	0.313	3,210.570	935.117
Tractor motion speed measurement with second gear engaged on grass							
No load	39	0.769		17			
No gear	41	0.732		18.0	0.111	712.036	521.002
4	49	0.612		20.5	0.220	2,875.230	1,760.345
3	57	0.526		22.3	0.283	3,267.750	1,719.868

Table 5. Measured values of drive blades wheels (30 m sector)

Tractor motion speed measurement with first gear engaged on grass							
	Travelling using blades wheels						
	Travel time s	Speed, m s^{-1}	Theoretic wheel revolution	Wheel revolution under load	Wheels slip	Average drawbar pull, N	Drawbar power, W
No load	71	0.423					
No gear	73	0.411		16.5	0.002	706.357	290.284
4	77	0.390		17.3	0.049	2,456.860	957.218
3	102	0.294		23.0	0.284	3,224.495	948.381
Tractor motion speed measurement with second gear engaged on grass							
No load	39	0.769					
No gear	40	0.750		16.5	0.030	924.191	693.144
4	48	0.625		17.1	0.064	3,414.691	2,134.182
3	55	0.545		20.3	0.212	4,450.225	2,427.395

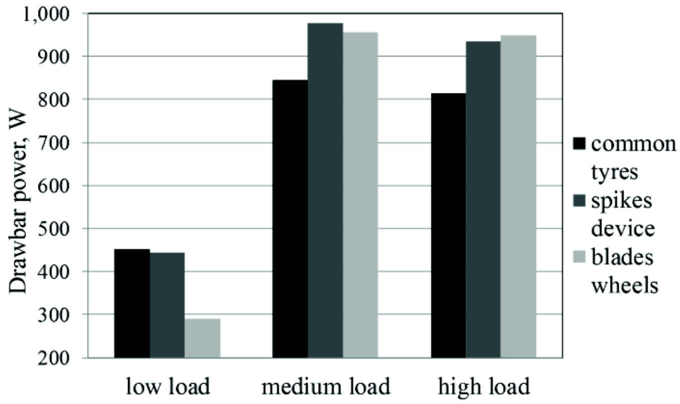

Figure 6. Drawbar power of tractor with two drive wheel prototypes and common tyres at the first gear.

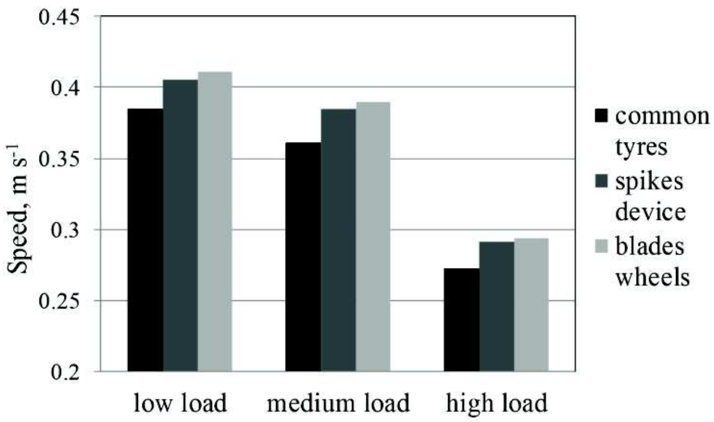

Figure 7. Speed of tractor with different drive wheels at the first gear.

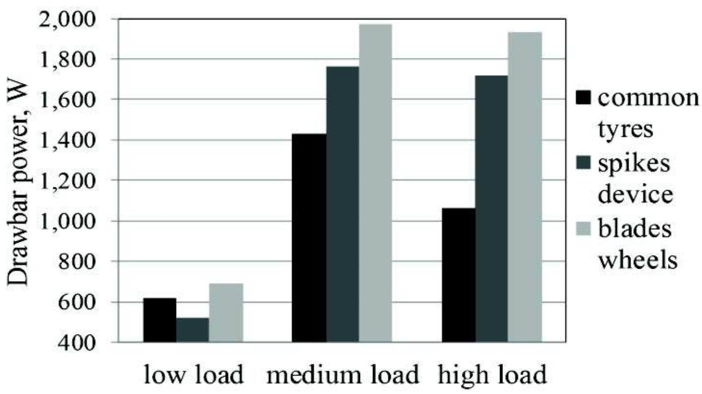

Figure 8. Drawbar power of tractor with two drive wheel prototypes and common tyres at the second gear.

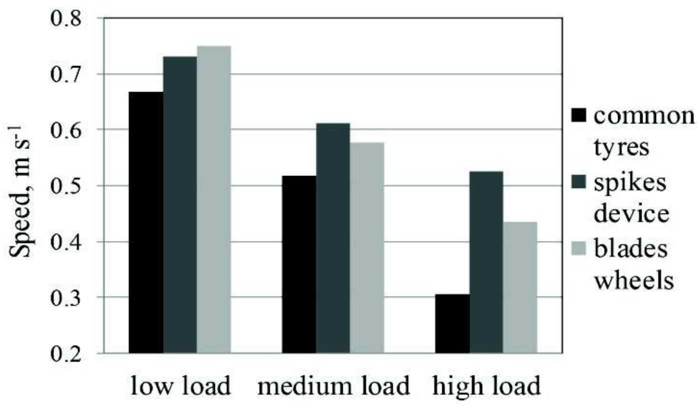

Figure 9. Speed of tractor with different drive wheels at the second gear.

Figs 10, 11 represent the best a comparison of efficiency of drawbar pull by wheel to surface transfer. Based on dependency of slip on drawbar power at 1st gear (results shown in Fig. 10), an improvement of drawbar pull is observed when both special wheels are used. This improvement can be characterized as linearly increasing slip with drawbar power rising up to some value in case of all three types of the drive wheels. The spikes device allow for higher drawbar power from 850 W approximately keeping linear dependency of slip on drawbar power up to value 1,000 W approximately, as it is apparent from Fig. 10. The tyres though change the dependency to parabolic from linear one and slip jumping up already at the drawbar power value 850 W. The most favourable slip dependency was found in case of the blade wheels with the linear dependency and considerably lower slip values. The dependency changed to parabolic one later at 950 W almost in same manner as in case of spikes device. It results from this comparison the efficiency of driving power transfer using blade wheels is most favourable till the moment of cohesion strength of soft base.

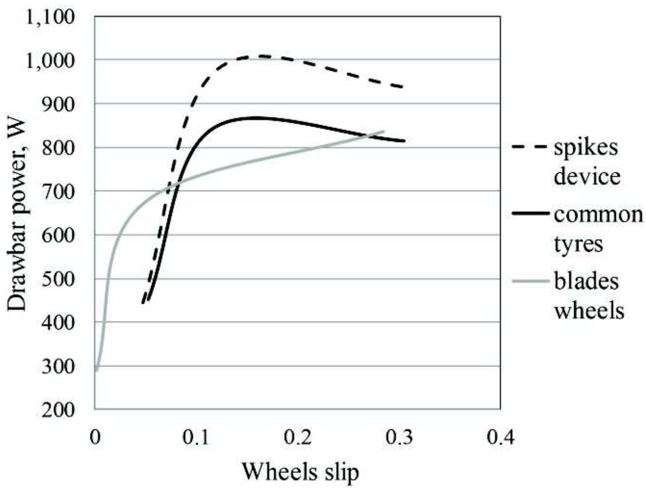

Figure 10. Comparison of the three types of slip on the drive wheels first gear.

Based on the dependency of the slip on drawbar power results (see Fig. 11) with 2nd gear, even higher improvement of the drawbar pull transfer to base is observed when spikes device as well as tyres with blade wheels used. This improvement can be characterized as linearly growing slip with increasing drawbar power up to certain value in all three drive wheel variations (Kielbasa & Korenko, 2006) The spikes device and even more blades wheels can generate higher drawbar power and keep linear dependency of slip on drawbar power longer, approximately up to value 1,800 W, as it is visible in Fig. 11. The dependency changes from linear to parabolic and slip raises sharp at the value 1,430 W in case of tyres. An improvement of the drawbar pull transfer from tyre to base efficiency compare to 1st gear should be noticed, the efficiency being slightly better compare to spikes tyres up to value 1,250 W.

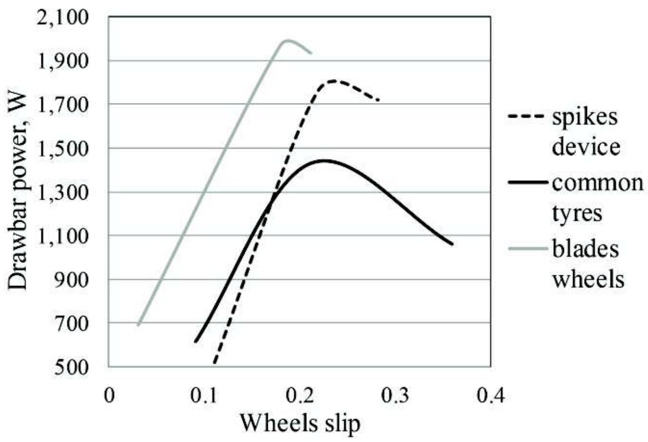

Figure 11. Comparison of the three types of slip on the drive wheels second gear.

Battiato & Diserens (2013) present in their work that, although the tractor developed higher drawbar pull both when tyre inflation pressure was decreased and wheel load was increased, only the decrease in tyre pressure produced improvements in terms of coefficient of traction, tractive efficiency, power delivery efficiency, and specific fuel consumption, while the only significant benefit due to the increase in wheel load was a reduction in the specific fuel consumption at a tyre pressure of 160 kPa and a slip of under 15%. Nadytko et al. (2015) and Kučera et al. (2016) present the tractive performance of tractor depending on tyre inflation, too. When comparing these results with those obtained in our study, we improved the tractor performance using a special spikes device. In this case the wheel load and tyre inflation do not be changed because the, as mentioned above, makes the slip lower in compare with tire without any modification.

Curves showing the dependence of drawbar power, tractive efficiency and specific fuel consumption on dynamic traction ratio and slip are presented in a work of Jenane et al. (1996).

The drive wheels drawbar properties improvement influences the soil compaction as well (Rataj et al., 2009). Lower slip causes less compacted soil and higher motion speed provide for gentle soil compaction. It comes from results achieved the higher motion speed were observed at the constant load when used spikes wheels and blade wheels. This implicates the soil compaction and deformation in the drive wheels track was lower.

CONCLUSIONS

The proposed prototypes for an improvement of drawbar properties of the tractor drive wheels was designed using structural steel grade S355J0 (STN EN 10025 : 2004) and made from common material profiles at the Faculty of Engineering SUA in Nitra. We designed two prototypes namely spikes device and blades wheels. Their properties were tested on the basis of wheels slip and drawbar power of the tractor operated on grass. The prototypes were compared with common tyres. The spikes and blades were designed to improve drawbar properties and allow tractor transport on road if they are placed in base position. Regarding automatic ejection, numbers and shape of spikes and blades were proposed. For function verification the spikes device was designed in the basic version with four spike segments. It is the base version to verify the strength, drawbar properties, self-cleaning of tyre-tread pattern and function of this prototype. The tests pointed out that the simply construction of spikes devices is suitable for drive wheels by reason of simply montage on wheel similar to snow chains, function of automatic ejection, only minimal impact on self-cleaning and improvement of drawbar properties. On the basis of stale fact that the numbers of segments around the wheel perimeter influences the drawbar properties, the number of the spike segments will be doubled to eight in a next research and tests with the same control system as in case of four segment device described. We predict that this solution will increase the drawbar pull of the tractor with the spikes device.

The blades wheels reached the best drawbar properties. The blades with sharp ending will be used for the next research by the reason of better penetration to the hard soil at low humidity. Under this soil condition may become a loss of contact between drive wheels and ground due to ineffective blades penetration.

From Figs 10 and 11 it can be observed that, once a certain amount of the wheel slip is exceeded, the drawbar power decreases. This commonly observed phenomenon mentions maximum drawbar power reached using the blades wheels. The spikes tyres reached lower drawbar power but higher than common tyres because rubber tire-tread pattern limited their drawbar properties. The spikes or blades of prototypes penetrate to the grass plot and therefore reached higher drawbar power due to better force transmission between drive wheels and ground.

The three wheel types were tested at high soil humidity intentionally to maximize display of differences in drawbar properties of the common tyres and both prototypes of drive wheels. The wheels were compared first time in these tests, assuming the improvements in drawbar properties will be even more considerable at the surfaces as the soil covered by manure or frozen subsurface with melted surface layer are.

As it arises from the results achieved of drawbar properties of the tractor tyre improvement, the spikes device have desirable effect on drive wheels slip reduction and improvement of the drawbar pull to soft base transfer efficiency at higher soil humidity 33.2% compare to common tractor tyres.

Both prototypes are also applicable for higher tractor size. Only one condition has to be meeting namely a possibility of tread with change. It creates the space between tyre and mudguard for spikes or avoids exceeding maximum tractor width in case of blades wheels. In addition the blades wheels have to be mounted straight on a wheel disc without ballast weight by the reason of tight connection with drive wheel. The weight of the blades wheels is so much to be ballast weight for drive wheels.

Experiment plans for the next future comprise tests of the spikes device inserted in the car off-road tyre body. The long term tests should include comparison of unpaved road ride in forest and driving in winter conditions. Certainly, the tyre tread deteriorates while using these devices. The tyre tread wear rate will be observed therefore as well. Anyway, the tyre can be used regardless of the changes made on it to apply spikes devices.

The tractor manufacturers should be interested not only in number of drive wheels and types of tractor undercarriage but also drive wheels modification because they show very interesting drawbar properties improvement.

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REFERENCES

Abrahám, R., Majdan, R. & Tkáč, Z. 2014. Research streamlining traction drive wheels of the tractor. Nitra: SUA.

Adamchuk, V., Bulgakov, V., Nadykto, V., Ihnatiev, Y. & Olt, J. 2016. Theoretical research into the power and energy performance of agricultural tractors. *Agronomy Research* **14**(5), 1511–1518.

Battiato, A. & Diseren, E. 2013. Influence of Tyre Inflation Pressure and Wheel Load on the Traction Performance of a 65 kW MFWD Tractor on a Cohesive Soil. *Journal of Agricultural Science* **5**(8), 197–215.

Cviklovič, V., Olejár, M., Palková, Z. & Pap, M. 2012. Methodology for measuring the efficiency of sine wave inverters. *Acta technologica agriculturae* **15**(3), 60–63.

Dąbrowski, J.B, Pytka, J., Tarkowski, P. & Zając, M. 2006. Advantages of all-season versus snow tyres for off-road traction and soil stresses. *Journal of Terramechanics* **43(**2), 163–175.

Chyba, J., Kroulík, M., Krištof, K., Misiewicz, P.A. & Chaney, K. 2014. Influence of soil compaction by farm machinery and livestock on water infiltration rate on grassland. *Agronomy Research* **12**(1), 59–64.

Chyba, J., Kroulík, M., Lev, J. & Kumhála, F. 2013. Influence of soil cultivation and farm machinery passes on water preferential flow using brilliant blue dye tracer. *Agronomy Research* **11**(1), 25–30.

Jablonický, J., Máchal, P., Žikla, A., Kosiba, J., Hujo, Ľ. & Hajdák, V. 2014 Comparing the hydraulic control of tractor three-point hitch. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis* **62**(5), 939–944.

Jenane, C., Bashford, L.L. & Monroe, G. 1996. Reduction of fuel consumption through improved tractive performance. *Journal of Agricultural Engineering Research* **64**(2), 131–138.

Jobbágy, J., Krištof, K. & Findura, P. 2016. Soil compaction caused by irrigation machinery. *Agronomy Research* **14**(3), 790–800.
Kielbasa, P. & Korenko, M. 2006. Influence of machine working resistance on slippage rate of driving wheels of tractor. *Acta Technologica Agriculturae* **9**(3), 44–47.
Kučera, M., Helexa, M. & Čedík, J. 2016. Link between static radial tire stiffness and the size of its contact surface and contact pressure. *Agronomy Research* **14**(4), 1361–1371.
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.
Müllerová, D., Jablonický, J., Hujo, Ľ., Tkáč, Z., Kučera, M. & Kosiba, J. 2012. Measurement of operating parameters and emissions of tractor with diesel oil and biofuel. In: TEAM, Josip Juraj Strossmayer University, Osijek-Baranja, 299–302.
Nadykto, V., Arak, M. & Olt, J. 2015. Theoretical research into the frictional slipping of wheel-type undercarriage taking into account the limitation of their impact on the soil. *Agronomy Research* **13**(1), 48–157.
Noréus, O. & Trigell, A. 2008. Measurement of terrain values and drawbar pull for six wheeled vehicle on sand. In*: 16th International Conference of the International Society for Terrain Vehicle Systems.* ISTVS, Turin, pp. 250–257 (in Italy).
Procházka, P., Novák, P., Chyba, J. & Kumhála, F. 2015 Evaluation of measuring frame for soil tillage machines draught force measurement. *Agronomy Research* **13**(1), 186–191.
Rataj, V., Galambošová, J. & Macák, M. 2009. Experiences in GPS application in Slovak Republic (Skúsenosti so zavedením systému CTF na Slovensku). In: *GPS autopilots in agriculture.* Czech University of Life Sciences Prague, Prague, pp. 34–38 (in Czech Republic).
Schreiber, M. & Kutzbach, H. 2008. Influence of soil and tire parameters on traction. *Research in Agricultural Engineering* **54(**2), 43–49.
Semetko, J., Janoško, I. & Pernis, P. 2004. Determination of power of multidrive vehicles. *Acta technologica agriculturae* **7**(1), 20–23.
Sloboda, A., Ferencey, V., Hlavňa, V. & Tkáč, Z. 2008. *Construction of tyres and crawlers vehicles.* Vienala, Košice, 552 pp. (in Slovak).
STN EN 10025: 2004. Hot rolled products of structural steels. Slovak Standards Institute.
Takáč, O., Hrubý, D. & Cviklovič, V. 2011. Possibilities of navigation of mobile agricultural robots on the principle of the geometrical objects detections. *Scientific papers* **11**(1), 203–205.
Tulík, J., Kosiba, J., Hujo, Ľ., Jablonický, J. & Šinský, V. 2013. The durability of a tractor gear-hydraulic circuit. In: *Trends in agricultural engineering 2013*. Czech University of Life Sciences Prague, Prague, pp. 617–621 (in Czech Republic).
Wong, J.Y., McLaughlin, N.B., Knezevic, Z. & Burtt. S. 1998. Optimization of the tractive performance of four-wheel-drive tractors. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering* **212**(4), 285–297.