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DRAWBAR PERFORMANCE OF TRACTOR TYRES WITH STEEL SPIKES AT 100%-WHEEL SLIP

Rudolf ABRAHÁM[1], Tomáš ZUBČÁK[1], Radoslav MAJDAN[1], Katarína KOLLÁROVÁ[1]*, Eva MATEJKOVÁ[1], Soňa MASAROVIČOVÁ[2], Róbert DRLIČKA[1]

[1]Slovak University of Agriculture in Nitra, Slovakia
[2]University of Žilina, Slovakia

A driving wheel is a part of a tractor, which transmits forces from a tyre to the ground. Therefore, it affects the tractor movement and the pulling of an implement. The paper is aimed at a tractive performance evaluation of special driving wheels based on drawbar pull at 100%-slip. These wheels consist of steel spikes to be applied in the base or working position. The design is characterized by the spikes placed in a tyre-tread pattern. The rubber lugs of the tyre are higher than spikes, therefore, they are not in contact with the ground in the base position. The spikes in the working position exceed the tyre diameter to be in contact with the ground. Tests were performed on a grass plot at a relatively low soil moisture. The spike tyres were compared with the standard tyres using a sub-compact tractor. An increase in drawbar pull reached a statistically significant value of 15.9% in the 2nd gear and 16.7% in the 1st gear.

Keywords: driving wheels; steel grouser; load cell; soil texture; drawbar pull

The driving wheel is the only part of a vehicle which interacts with the ground. Force interactions affect the tractive efficiency and effectivity of machine operation. Besides fuel consumption, exhaust gases are produced in higher measure in case of a low tractive efficiency of agricultural machinery. The properties of standard tyres can be improved in various ways. There are, for example, snow chains which improve the tractive properties of tyres on snow. In certain countries, it is allowed using studded tyres. As mentioned above, the improvement of tyre traction properties is often based on the combination of rubber tyre-tread pattern with steel components.

Drawbar pull, travel reduction (slip) and rolling resistance are the main criteria to describe the traction behaviour of tractors. Besides engine performance, drawbar pull is influenced by the traction conditions, such as soil and tyre parameters (Schreiber and Kutzbach, 2008). Tyre diameter and width are the basic parameters significantly affecting the driving wheels performance. Variable inflation pressure is also used to modify the tyre contact patch to better transmit the forces from a tyre to the ground. Finally, the selection of a modern tyre-tread pattern type and tyre construction is very important to achieve the effective tractor operation (Freitag, 1965).

There are two essential ways how to reduce the slip of tractors. The first one lies in increasing the tractor weight by adding ballast. The other possibility is to enlarge the contact area between the tyres and surface (Šmerda and Čupera, 2010). Tractors often use tracks to improve the tractive performance. Steel and rubber are the two kinds of materials which are often used for tracks. Tractor tracks are mainly used to increase the drawbar pull and eliminate the slippage during the operation under worse tractive conditions due to higher soil moisture content. Semetko, Janoško and Pernis (2002); Semetko, Janoško and Pernis (2004) and Molari et al. (2020) researched the drawbar properties of four-wheel drive, four-wheel drive ballasted, half-tracked and fully tracked tractors. Their results showed a better tractive efficiency for the solution with four rubber tracks with respect to the other axles. Ge, Wang and Kito (2016) studied the tractive performances of steel and rubber grouser shoes under different soil moisture contents. Based on experimental results, they concluded that the steel single grouser shoe performed better than the rubber single grouser shoe in traction for the soil used in this study.

The increase in tractor load is the measure often used to improve the tractive efficiency because it increases the net traction ratio. On the other hand, the high weight of tractors negatively affects soil compaction after field traffic (Forster et al., 2020; Malý and Kučera, 2014; Malý et al., 2015).

As mentioned above, employment of a special wheel using various steel elements represents a way of improving the interactions of forces with the ground. This paper presents an original design of spike tyres for tractors to be operated without the additional ballast weight. Tractors frequently work at optimal wheel slip, however, operation at the maximum wheel slip cannot be expected. Using the special driving wheels, tractor movement can be provided in this situation. The study objectives were to experimentally test and compare the spike tyres to the standard tyres at 100%-wheel slip.

Contact address: Katarína Kollárová, Slovak University of Agriculture in Nitra, 949 76 Nitra, Slovakia,
e-mail: katarina.kollarova@uniag.sk

Material and methods

Principle and design of spike tyres

The special driving wheels were designed to improve the tractor tractive properties. The principle of the spike tyres is shown in Fig. 1a. The spikes can be in the base or working position. Spikes in the base position do not exceed the tyre-tread pattern and do not interact with the soil. The working position of spikes is set by adjusting the spike segment. In this position, spikes are in contact with the ground to achieve a higher drawbar pull. The base position of spikes is suitable for tractor transportation on hard surfaces and roads.

The spike tyres (Fig. 1) use four spike segments [1] with spikes [2], control [3] and carrier wire strands [4], and levers of control mechanism [5]. The carrier wire strand [4] supports the spike segments [2] in the tyre-tread pattern. The control wire strand [3] protrudes the spikes from the tyre and holds all the parts in the same working position. The spike segments are placed in the tyre grooves [6] made in the tyre-tread pattern. The dimensions and shape of the spike segments were adapted to a space in the tyre-tread pattern because they cannot exceed the tyre diameter in the base position. Removing a safety screw [7], the lever of the control mechanism [5] is released to allow an automatic protrusion (working position) of spikes from the tyre due to wheel rotation. A reverse tractor gear helps to place the spikes aback in the base position.

The design of spike tyres was developed at the Slovak University of Agriculture in Nitra (Slovak Republic) and investigated by Majdan et al. (2018); Abrahám, Majdan and Drlička (2019); Abrahám et al. (2012). The tyres TS-02 6.5/75-14 4PR TT (Mitas, a. s., Prague, Czech Republic) were used for the special driving wheels. The spike tyres were compared with this tyre type without spike segments.

Drawbar pull measurement system

The measurement system shown in Fig. 2 was used to measure the drawbar pull of the tractor with special driving wheels. Generally, when the test tractor is gradually loaded by the load tractor, drawbar pull and wheel slip also gradually increase up to the maximum value. The driving wheels rotated at 100% slip while the tractor was not moving. The gradual decrease in velocity helps to eliminate the inertia moments of the test tractor. Drawbar pull measurements were performed in accordance with STN ISO 789-9 and repeated four times. The test tractor was operated at rated engine speed in the 1st and 2nd gear. The load cell was placed between the load and the test tractor. Rasool and Raheman (2018) and Varani et al. (2020) also used the load tractor to measure the test tractor drawbar pull. The load and the test tractor were connected by a steel chain. The load tractor was pulled in reverse direction because this tractor type is not equipped with a front hitch. Back hitches of both tractors allowed an easy setting of the connecting chain to the level position.

The main parts of the measurement system are as follows:

– The rear-wheel drive sub-compact tractor with a gasoline engine (volume capacity: 400 cm^3, rated engine power: 8 kW, rated engine speed: 3600 min^{-1}) pulling the load tractor. The test tractor was equipped with the standard tyres and the spike tyres to compare its properties based on the maximum drawbar pull reached at the 100%-wheel slip. The parameters of the tractors are listed in Table 1. The tractor weight on rear axle of 205 kg was measured by weighting pads (Majdan et al.,

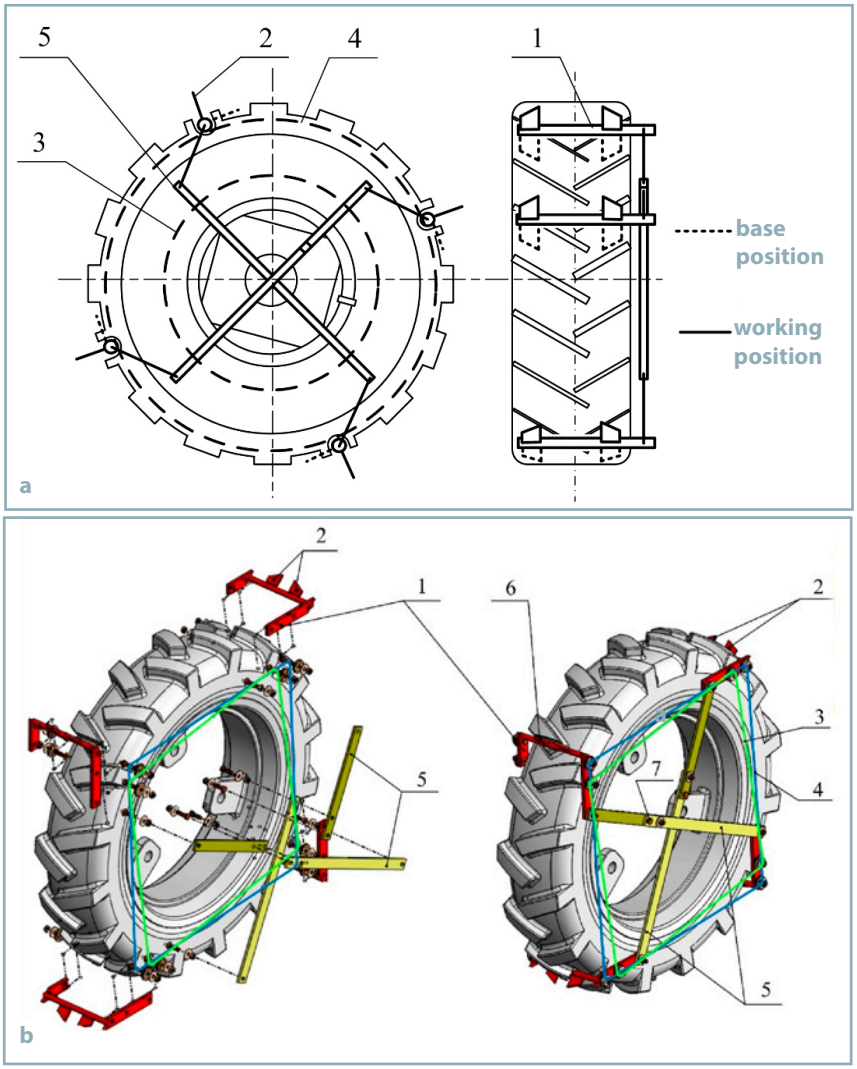

Fig. 1 Spike tyres: a) principle, b) main parts and design
1 – spike segment; 2 – spikes; 3 – control wire strand; 4 – carrier wire strand; 5 – levers of control mechanism; 6 – groove in tyre; 7 – safety screw

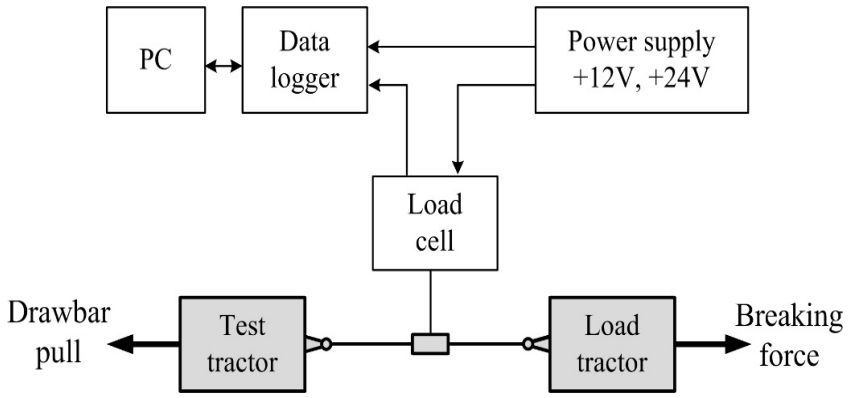

Fig. 2 Measurement system

2021). Considering the rear wheel ballast weight of 30.5 kg (weight in one wheel is 15.25 kg), the driver weight of 92 kg and the spike system weight of 9 kg (one spike system is 4.5 kg), the total weight on rear axle was 336.5 kg.

- The load tractor with a diesel engine (volume capacity: 661.6 cm^3, maximum output power: 13 kW) loading the test tractor during the measurement of drawbar pull. Table 1 shows the parameters of the load tractor.
- The load cell EMS 150 (Emsyst, s.r.o., Trenčín, Slovak Republic) with a strain-gauge bridge in a steel housing (accuracy class: 0.2, rated capacity: 10 kN, rated output: 0–10 V). The load cell is a cylindrical industrial type for heavy-duty operation conditions. The body of the sensor is made of steel. The cylinder diameter is 80 mm, and the total length is 150 mm. The electronic converter EMS168 provides a standard voltage output. The recommended excitation is 20–26 V.
- The data logger HMG 3010 (Hydac GmbH, Sulzbach/Saar, Germany) is a high-performance portable measuring and data-logging device (Hujo et al., 2021; Tkáč et al., 2017; Kosiba et al., 2011) with a measurement accuracy of voltage input (0–10 V): ≤±0.1% of full scale. Sampling frequency was 1 kHz. It communicates with a computer via a USB or serial port. A 3.5" colour display with graphics capabilities shows the measured values either as text, or as a measurement curve.
- The power supply contains two accumulators (12 V) connected in series or parallel to supply the sensor and the data logger with direct voltage (12 V or 24 V). It was manufactured as a portable device.

Statistical data processing

The drawbar pull of the test tractor was measured and statistically processed to evaluate the drawbar properties of special driving wheels. Drawbar pull fluctuates periodically with rotation angle, and the period corresponds approximately to the interval of angular spike segments spacing. The mean values of drawbar pull at the same level of wheel slip were almost the same (Hermawan, Yamazaki and Oida, 1998). The mean value of drawbar pull was calculated considering the same slip condition due to the same soil properties during one tractor stop. A *t*-test of statistical program SAS EG (version 7.1) was used to determine whether differences between the statistics from two driving wheel types are statistically significant. The *t*-test was used to test the specific hypothesis about the difference between the means of drawbar pulls. The test also constructed the confidence intervals for each mean and determined whether the experimental data come from normal distributions.

Experimental conditions

The experimental measurements of drawbar pulls to compare the spike tyres and the standard tyres were performed in the mown grass areas of the Slovak Agricultural Museum in Nitra (Slovak Republic). Tractors often work on grass fields where the tractive performance of driving wheels plays an essential role. Therefore, this type of ground was used for experiments. Soil type and properties significantly affect the tyre-soil interaction. To characterise soil properties, soil samples were collected and analysed in laboratory. The soil was sampled at the depths of 0–100 mm regarding the maximum driving wheels sinkage during the 100%-slip. The diameter of sampling cylinders was 100 mm. The results of soil analysis are listed in Table 2. Besides the analysed parameters, soil moisture is a very important parameter affecting the tractor drawbar performance. Experiments were performed at a relatively low soil moisture of 18.8% because tractors operation at high soil moisture is not required due to grass field damage. Soil type was chernozem (World Reference Base for Soil Resources) with loamy sand soil texture.

Table 1 Test and load tractors specification

Characteristic	Test tractor	Load tractor
Manufacturer	Agrozet (České Budějovice, Czech Republic)	
Type	MT8-070 Mini	4K-14
Total tractor mass (kg)	310	870
Length/width/height (mm)	1810/800/1090	2600/1170/1300
Wheelbase/gauge (mm)	650/1150	700/1100

Table 2 Soil properties of experimental area

Parameter	Unit	Value
Gravel	%	15.3
Sand	%	45.2
Silt	%	35.4
Clay	%	4.1
Organic matter	%	6.62
Frictional angle	°	47.5
Cohesion	kPa	8.4
Particle density	$g \cdot cm^{-3}$	2.6

Results and discussion

Properties and application of special driving wheels

The spike tyre used on the test tractor is shown in Fig. 3a. The datalogger with power supply was placed to the tractor cargo space behind the driver seat (Fig. 3b). This place is near the load cell connected between the test and load tractors. A simple design of the spike system removed from the tyre is shown in Fig. 3c. All parts of the system are connected by the steel wire strands without solid connections. Low weight and free construction allow an easy manipulation and requires a little storage space.

The special wheels are universally applied to increase the tractor drawbar pull on various grounds. To increase the drawbar pull on a sandy terrain, Yang, Yi and Shugen (2014) compared the actively actuated lugged wheels with the fixed lugged wheels and smooth wheels. The actively actuated lugged wheels achieved the highest drawbar pull, but their planetary gear did not allow changing the lugged wheel to the smooth wheels in case of transportation on hard landscaping. The spike tyres can be an alternative to the aforementioned lugged wheels and presented by Wang, Yamazaki and Tanaka (1995); Gasparetto et al. (1992); Salokhe, Manzoor and Gee-Clough (1989); and Watyotha, Gee-Clough and Salokhe (2001). The spike tyres can be used for the driving wheels of agricultural and forest machinery, army vehicles or planetary rovers.

On the other hand, the design of special driving wheels allows transport on roads with the standard tyres. The spikes of these wheels do not exceed the tyre diameter in the base position. By removing the safety bolt or screw, the spikes are protruded due to a grip on the ground. The spikes return to the base position due to a reverse drive of the vehicle after operation. The base and working positions are easily locked using the screw or safety bolt.

Battiato and Diseren (2013) stated that the tractor developed higher drawbar pull when tyre inflation pressure decreased and wheel load increased. Gee-Clough, McAllister and Evernden (1977); Helexa (2014); Kučera, Helexa and Molenda (2016); Helexa et al. (2022) presented the concept of tractor tractive performance depending on tyre inflation as well. In case of the spike tyres, wheel load and tyre inflation pressure do not have to be changed because the wheels grip is improved by the steel spikes.

The advantage of the spike tyres is that the spikes are acting on a soil below the tyre contact area compressed by tractor weight. The soil below the tyre is compressed (cohesively) and creates a support for the spikes. The disadvantage of such tyres can be a worse self-cleaning effect in the place where the spikes are located, and a need of the grooves made in the tyre-tread pattern. Considering the only four spike segments, the negative effect of spikes on self-cleaning properties is only minimal.

Measured courses of drawbar pull

Drawbar pull measurements were repeated four times. When the tractor driving wheels rotated at the 100% slip, drawbar pull reached the maximum value. Drawbar pull cannot be measured for arbitrary time because the driving wheels sink into the ground during the slip. The process depends on

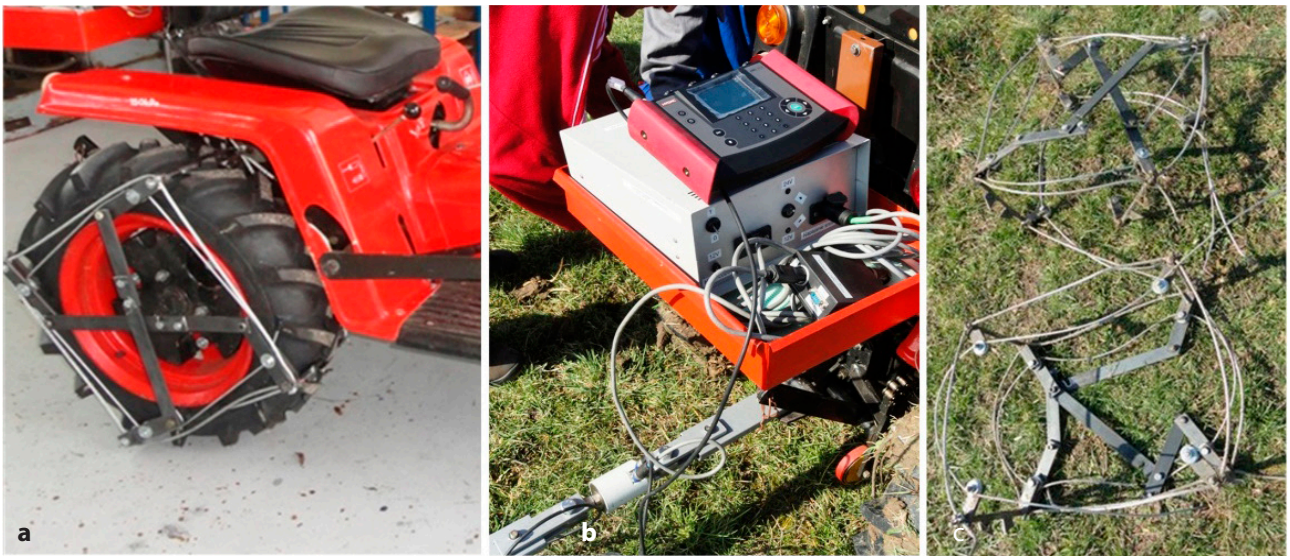

Fig. 3 Experimental test
a) spike tyres on the driving wheels of the test tractor; b) data logger, power supply and load cell; c) spike system

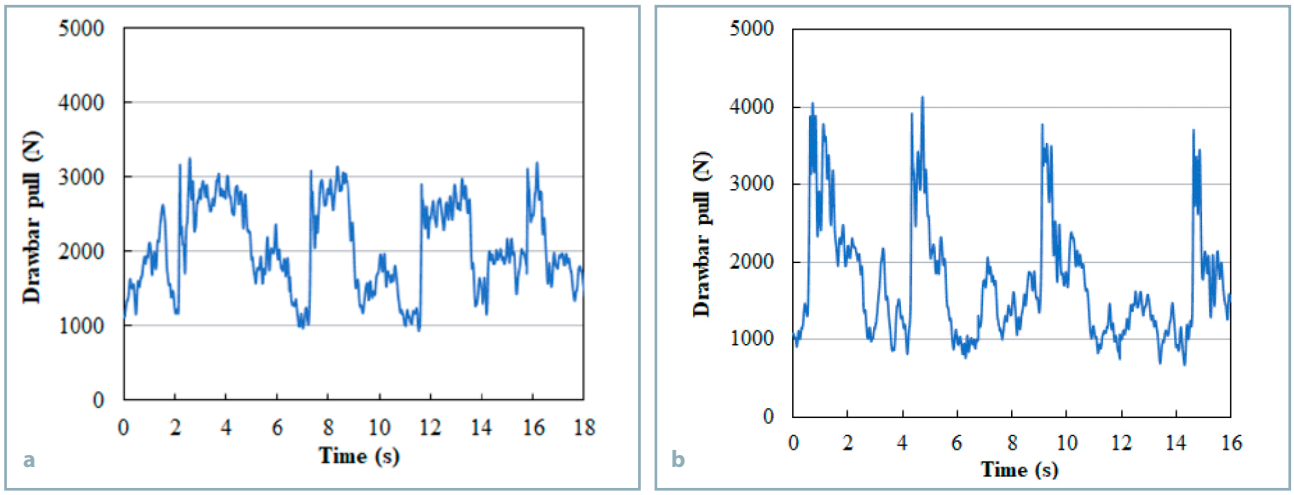

Fig. 4 Drawbar pulls of the tractor in the 2nd gear
a) standard tyres; b) spike tyres

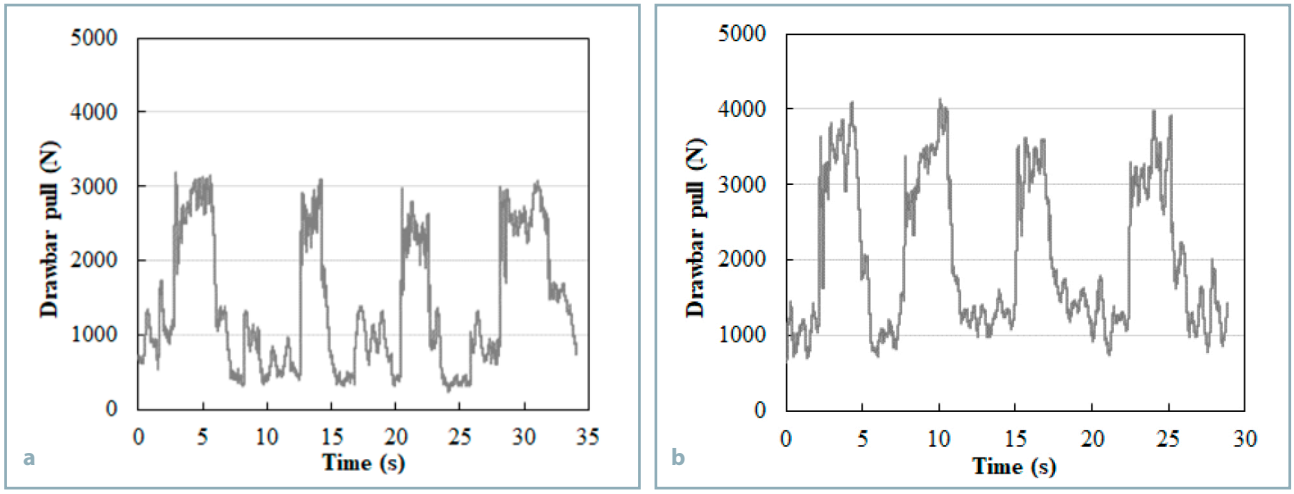

Fig. 5 Drawbar pulls of the tractor in the 1st gear
a) standard tyres; b) spike tyres

the surface type and driving wheels. Measurements were stopped when engine rotation speed critically decreased. The test tractor engine drove the standard tyres without any problems because the rubber tyre-tread pattern slipped on the grass plot. On the other hand, the spike tyres caused a decrease in engine speed due to interaction between the spikes and ground. Therefore, the time of measurements in the spike tyres was shorter in comparison to the standard tyres, as shown in Figs 4 and 5.

Drawbar pulls measured at the 100% slip oscillated due to driving wheels rotation. It was caused by the force interactions of the tyre-tread pattern or spikes with the grass plot. The extreme values were caused by ground inhomogeneities and the field nature of experiments. Vertical load acting on the tyre-tread pattern was decreased due to spike penetration into the ground. Considering the spike tyres in the working position on a hard surface (concrete or asphalt), the driving wheels can be lifted in dependence on spike height and tyre elasticity. In case of the grass plot

Table 3 Data on four measurements repetition of drawbar pulls (N)

Gear	Wheel type	Number of measurements							
		1		2		3		4	
		MV	SD	MV	SD	MV	SD	MV	SD
2nd	standard tyres	2659	271	2773	230	2592	164	2748	214
	spike tyres	3169	450	3042	418	3255	241	3013	282
1st	standard tyres	2863	276	2789	230	2621	238	2642	212
	spike tyres	3287	443	3258	274	3076	257	3138	285

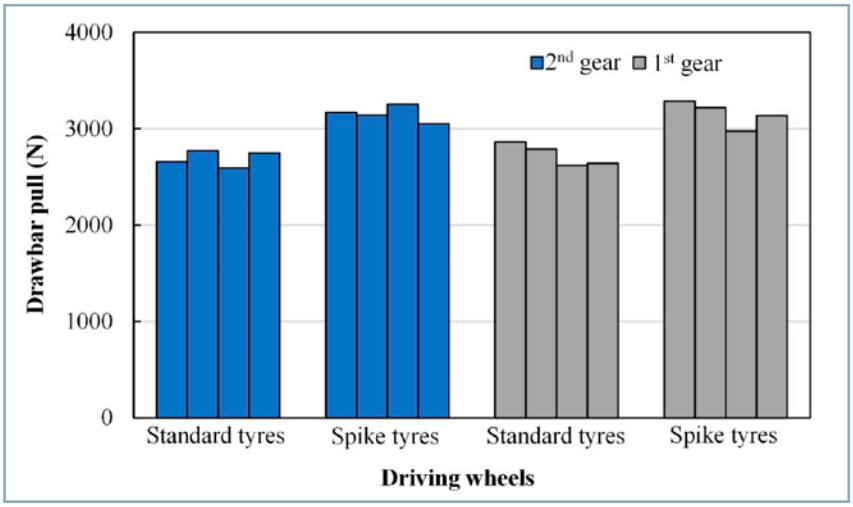

Fig. 6 Mean values of drawbar pull (individual measurements)

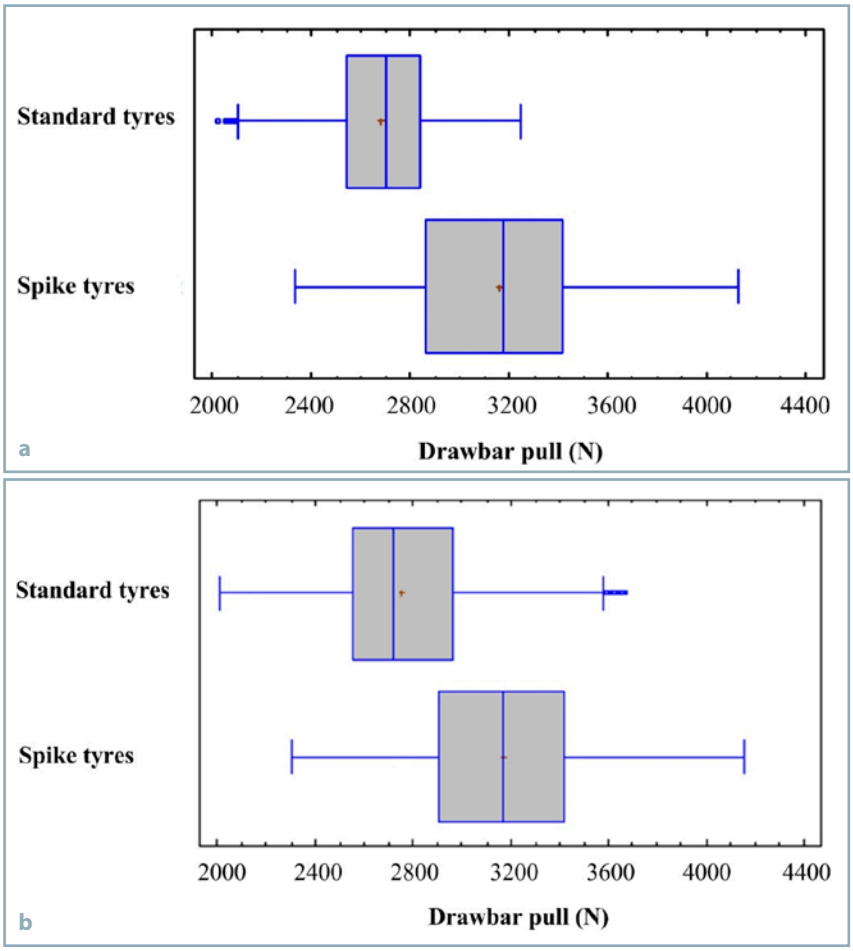

Fig. 7 Box-and-Whisker plot of driving wheels comparison
a) 2nd gear; b) 1st gear

used for experiments, the spikes were loaded only by a certain part of vertical load depending on soil penetrometer resistance and spike area penetrating the ground (Bulko and Gago, 2017). Therefore, soil mechanical properties affected the contact pressure below spikes and force oscillation during the wheel rotation. Analysing the drawbar pull signals by Fast Fourier transformation, Abrahám et al. (2021) identified the frequency spectra typical for the spike segments. It showed the dependency of the number of spike segments on oscillation frequency. Irani, Bauer and Warkentin (2011) also analysed the oscillation of drawbar pull generated by driving wheels with steel grousers.

Drawbar pulls oscillated around the mean values (MV), which were calculated from each of the four single measurements, as listed in Table 3. To illustrate the drawbar pulls of individual measurements, the graph in Fig. 6 was plotted. The drawbar pulls of the spike tyres reached higher mean values than the standard tyres in case of all measurements. Standard deviation (SD) was also calculated to represent the variability of measured data. Calculated parameters varied due to the nature of soil mechanical properties because the soil is not a homogenous substance. The highest values of standard deviation were observed in the spike tyres using the tractor in the 1st and 2nd gears. The values result from the interactions of steel spikes with the ground. On the other hand, the lowest standard deviations characterize the tractor with the standard tyres. The higher variation of experimental data measured in the tractor with the spike tyres than in the vehicle with the standard tyres is also shown by the Box-and-Whisker plot in Fig. 7.

The *t*-test was used to determine whether there are statistically significant differences between the standard tyres and the spike tyres. Standardized kurtosis was used to determine whether experimental data come from normal distributions. The values of these statistics inside the range of -2 to +2 indicate normality for the standard tyres and the spike tyres. A 95% confidence interval for the mean of the standard tyres was between 2664 N and 2698 N (between 2734

N and 2745 N) and between 3106 N and 3210 N (between 3015 N and 3165 N) for the spike tyres when the tractor was in the 2nd gear (1st gear). Considering the test statics (t = -22.3 and -94.6) and p-value (0), there is a statistically significant difference between the two driving wheel types (tractor in the 2nd and 1st gear) at the 95% confidence level (Fig. 7).

Mean drawbar pulls reached the value of 2681 N for the tractor with the standard tyres and 3158 N for the tractor with the spike tyres in the 2nd gear. The tractor in the 1st gear generated the drawbar pull of 2729 N in case of the standard tyres and 3190 N in case of the spike tyres. The increase in drawbar pull was 15.9% in the 2nd gear and 16.7% in the 1st gear. Using the lugged wheels, Hendriadi and Salokhe (2002) recorded the maximum increase in drawbar pull from 37.6% to 55%. Watyotha and Salokhe (2001) presented an increase in drawbar pull from 49% to 55%, and Triratanasirichai, Oida and Honda (1990) from 60% up to 65%. The aforementioned authors reached higher increases in drawbar pulls because the steel lugs had a larger contact area with the ground in comparison with studs.

Conclusion

Tractor tractive performance affects the effective usage of engine power by an efficiency of force transmission between the driving wheels and ground. The paper presents the design, practical application, and tests of special driving wheels using spikes to improve the tractor tractive performance. The spike tyres can be used not only under agricultural conditions but can also improve the energy efficiency of all tractors, various off-road vehicles, planetary rovers, or wheeled robots under various difficult tractive conditions. The main benefits of the spike tyres are as follows:

- Drawbar pulls measured in the vehicle with the spike tyres reached higher values than with the standard tyres. The statistically significant increase in drawbar pull was calculated to express the improvement of tractor tractive performance using the spike tyres.
- The low weight of the spike system eliminates soil compaction in case of agricultural application. A compact design can be utilized for various mobile robots if wheel size is limited.

The next research will be aimed at the improvement of drawbar properties of the spike tyres, as the potential of this design has not been fully utilized. Therefore, the influence of spike modifications on vehicle drawbar performance and an automatic control of spikes without the need of a manpower will be further studied.

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