Original scientific paper

Tractive Performance of Tyres in Forest Conditions – Impact Assessment of Ground and Tyres Parameters

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Abstract

This article deals with the assessment of traction properties of tyres on forest grounds. The research was carried out on skid trails located in pine stands. The tested grounds were different due to the cover of the soil and its mechanical properties. The study also deals with the evaluation of ways to improve traction by reducing the inflation pressure and using the tyre chain. The research was carried out using a specialized traction test stand for two tyres (9.5–24 and 400/55–22.5) different in width and tread pattern. The studies showed significant effect of ground conditions on traction. As a result of changes in the ground conditions, the values of drawbar force, rolling resistance and tractive efficiency were altered by 25%, 23% and 6%, respectively. The higher values of the drawbar force and tractive efficiency on all tested trails were obtained for 400/55–22.5 tyre. Both the use of tyre chains and the reduction of inflation pressure resulted in the increase in drawbar force and tractive efficiency. A better way to improve traction properties was the reduction of the tyre inflation pressure, which caused the increase in drawbar force and tractive efficiency. The use of tyre chains caused an increase in drawbar force over the entire slip range, while an increase in tractive efficiency has only been shown for the slip larger than 15%.

Keywords: forest ground, tyre, drawbar force, rolling resistance, traction efficiency, inflation pressure, tyre chains

1. Introduction

In forestry operations, the use of ground-based machinery for logging is common practice around the world. A wide range of equipment, such as skidders, forwarders and tractors, is used (Seixas and McDonald 1997, Jansson and Johansson 1998, Agherkakli et al. 2010, Picchio et al. 2011).

Traction abilities of any off-road vehicle depend on several key factors such as: soil strength, vertical wheel/track load, contact area between wheels and the soil surface (Zoz and Grisso 2003, Molari et al. 2012, Battiato and Diserens 2013). Tractive performance is affected both by the soil normal strength and its shear strength. Generally, normal strength has the most effect on motion resistance, while shear strength has most effect on wheel slip (Zoz and Grisso 2003). Soil moisture content, soil texture and soil cover affect mechanical behaviour and soil strength (Schreiber and Kutzbach 2008). Studies indicate that about 20–55% of the power delivered to the vehicle drive wheels is wasted in the tyre-soil interaction, because of the wheel slip and the rolling resistance (Muhsin 2010, Šmerda and Čupera 2010, Taghavifar et al. 2014).

On the one hand, the slip of vehicle drive wheels causes energy losses in the process of interaction between the tyres and the topsoil; on the other hand, the slip may increase the risk for wheel rutting in the forest (Olsen and Wästerlund 1989), cause damage to ground vegetation and superficial roots (Greacen and Sand 1980) and reduce the growth of nearby standing forest trees (Wästerlund 1990).

To reduce the slip of vehicle wheels, various ways are pointed out in terramechanics. One way is to increase the vertical load of drive wheels. As a result of increase in vertical load in tillage works, drawbar force can be increased by up to 15% depending on the value of ballast weights (Serrano et al. 2007, Serrano et al. 2009, Muhsin 2010). Increase in dynamic load of forwarder equipped with Trelleborg Twin 421 Mark II 600/55–26.5 tyres also resulted in significant increase in tractive efficiency at 5% slip (Jun et al. 2004). This method to improve traction abilities has a very important drawback – compacting of the soil and damaging its structure even to great depths, which can reduce soil productivity (Grečenko and Prikner 2014, Barbosa and Magalhaes 2015). Unfortunately, increase in vertical load of vehicle drive wheels may also lead to increased rolling resistance and consequently decrease the tractive efficiency, and increase tyre wear, fuel consumption and greenhouse gas emissions (Patel and Mani 2011, Lacour et al. 2014, Damanauskas et al. 2015, Damanauskas and Janulevičius 2015).

The other way to reduce the slip is to increase the contact area between tyres and ground. Currently, tractor performance researchers recommend the reduction of inflation pressure in the tyres (Šmerda and Čupera 2010, Battiato and Diserens 2013). It means that vehicle weight is spread across a larger area, wheels »sink« less into the soil, ruts are not so deep and the rolling resistance is reduced (Nam et al. 2010). Kurjenluomar et al. (2009) reported that the reduction of tyre inflation pressure resulted in reduced rolling resistance and rut depth only on soft soil, when the soil strength was low, while in hard soil conditions the effect on rolling resistance was quite the opposite. Depending on the tractor, tyre size and type, the drawbar force may be increased by up to 8% (Sumer and Sabanci 2005, Elwaleed et al. 2006, Taghavifar and Mardani 2013).

Important factors influencing the traction performance are tyre parameters, such as radius, width and tread pattern. Tyre diameter has a significant effect on the traction force. The larger tyre width increases traction capability due to increasing flexibility of the tyre and assists in the development of uniformity of pressure application, but it can also produce more motion resistance (Nkakini and Fubara-Manuel 2014).

Forest soils, in general, are susceptible to compaction as they are loose, with high organic-matter content and are generally low in bulk density, high in porosity, and low in strength (Froehlich et al. 1985, Horn et al. 2007, Jourgholami and Majnounian 2011). These conditions are unfavourable for forest vehicle traffic. One way to improve the traction abilities of wheeled forest machines is the use of tyre chains. Chains may improve traction by increasing the soil shear area through better penetration to the soil surface, without using wide tyres or tracks to increase the contact area. Only two publications were found that quantitatively documented the effect of forestry tyre chains on traction performance. Vechinski et al. (1999) reported that traction performance of tyres with chains depends on the type and cover of soil. The improved performance of the tyre with chains on clay soils with pine straw and sod cover was due to the penetration into the surface cover by chains. The use of tyre chains caused an increase in net traction of up to 11%. Tractive efficiency increased (by 7%) when chains were added to new tyres, but decreased (by 5–8%) when they were used on worn tyre. Stoilov (2007) showed that, on deformable forest roads, the use of tyres equipped with chains caused slight decrease (2%) of net traction due to higher motion resistance and enlarged windage between the tyres and chains.

The majority of previous studies about the traction performance concerned farm tractors and agricultural soils. In regards to forest conditions, the most of research relates to the impact of machinery and vehicles on the forest soils. Only a few publications concern the issues related to tyre traction performance on forest grounds. The issue of traction performance of an off-road vehicle is very important, because of high energy losses and soil disturbance as a result interaction between drive wheels of vehicle and soil. In this context, the aim of the present study was to evaluate:

⇒ the effect of soil conditions on the traction abilities of drive wheel

⇒ the influence of tyre dimensions on traction properties

⇒ the effect of tyre inflation pressure and the tyre chains use on the traction performance.

2. Materials and methods

2.1 Study site

The study was carried out in Poland (Lower Silesia Province) in Forest District Oława, Forest Sub-district Chrząstawa Wielka. Research on traction performance of tyres was conducted in lowland pine forest stands of different age on three selected skid trails (ground forest roads). All analysed skid trails were used with low intensity, because of young age of stands and limited wood harvesting of these stands. These skid trails also fulfil the function of territorial forestry division – as a border between forest stands. The skid trails were constructed on typical acidic brown soils. The analysis of soil particle size distribution indicated that all analysed soils are sands. Detailed description of the soil parameters of skid trails is presented in Table 1.

Table 1 Study site description

	Skid trail 1	Skid trail 2	Skid trail 3
Location	Pine forest		
Landform, slope, °	Flat terrain 0 – 1°		
Surface cover	Bare soil and pine litter mix	Grass and pine litter mix	Grass
Soil particular size at a depth of 0–0.2 m, %			
Sand, 0.05–0.2 mm	89	83	88
Silt, 0.002–0.05 mm	11	17	12
Clay, <0.002 mm	0	0	0
Gravel, 0.2–2 mm	15	10	13
Specific density of the soil, g·cm^{-3}	1.60	1.57	1.54
Soil moisture content, % vol. *	7.5	8.3	9.1
Maximum shearing stress, kPa *	88	126	140
Soil penetration resistance, MPa *	2.26	3.20	3.40

* at a depth 0–0.1 m; cone base area of 1 cm^2, cone angle of 60°

carried out for two inflation pressure values of 200 and 80 kPa. The study concerning the effect of tyre chains on traction properties was carried out for the wheel fitted with 9.5–24 tyre. The »traktor doppelspur 3334d« chains type was used. The vertical load of tested tyres was 6110 N.

The field trials were conducted using the mobile stand mounted on the three-point linkage of Massey Ferguson 235 tractor. The tested wheel was powered by tractor PTO, using a reduction gear. During the study, the test stand was moved by tractor. The data from all measurement devices were recorded by a data recording system. In the final phase of measurement, the test stand was stopped, using the basic tractor brake (for the full range slip of the tested wheel). The measuring equipment consisted of: inductive dynamometer for the measurement of the drawbar force, located between the external (immobile) and internal (moving) part of the frame, and the inductive torquemeter for the measurement of the drive torque. The actual and theoretical distance was measured using two rotational encoders MOK40, mounted on the extra wheel and on the shaft with the tested wheel, respectively. The overall view of research stand is presented in Fig. 1. Detailed specifications of measurement devices are presented in Table 3.

All tests (for both tyres in all conditions) were carried out for the ride in one direction, with 5 repetitions.

Table 2 Technical data of tyres

Tyres designation manufacturer	Tread type	Overall diameter mm	Section width mm	Height of tread lugs mm	Maximum load capacity kg	Nominal inflation pressure kPa
9.5–24 Mitas	TD02 Universal tread pattern	1000	241	30	1120	250
400/55–22.5 Trelleborg	T404T Twin	1000	400	18	1120	250

2.2. Equipment, test procedures and calculations

Traction properties were analysed for tyres with the same maximum load capacity, nominal inflation pressure and overall diameter, but with treads of different width and design. The main parameters of the tested tyres are presented in Table 2. These types of tyres are commonly used in machinery and tractors working in forests.

Evaluation of traction performance improvement by reduction of tyre inflation pressure or use of tyre chains was conducted on skid trails with the worst traffic conditions (the lowest soil penetration resistance and the lowest shearing strength). The effect of changes in tyre inflation pressure on the traction parameters was assessed for 400/55–22.5 tyre. Tests were

Table 3 Specifications of measurement devices

Instrumentation	Measurements	Range	Accuracy
Inductive dynamometer	Pulling force	0–20 kN	± 20 N
Inductive torquemeter	Torque	0–3000 Nm	± 3 Nm
Rotational encoder MOK40	Angle of the wheel rotation	0–360 ° × n*	0.36 °

* the number of rotation

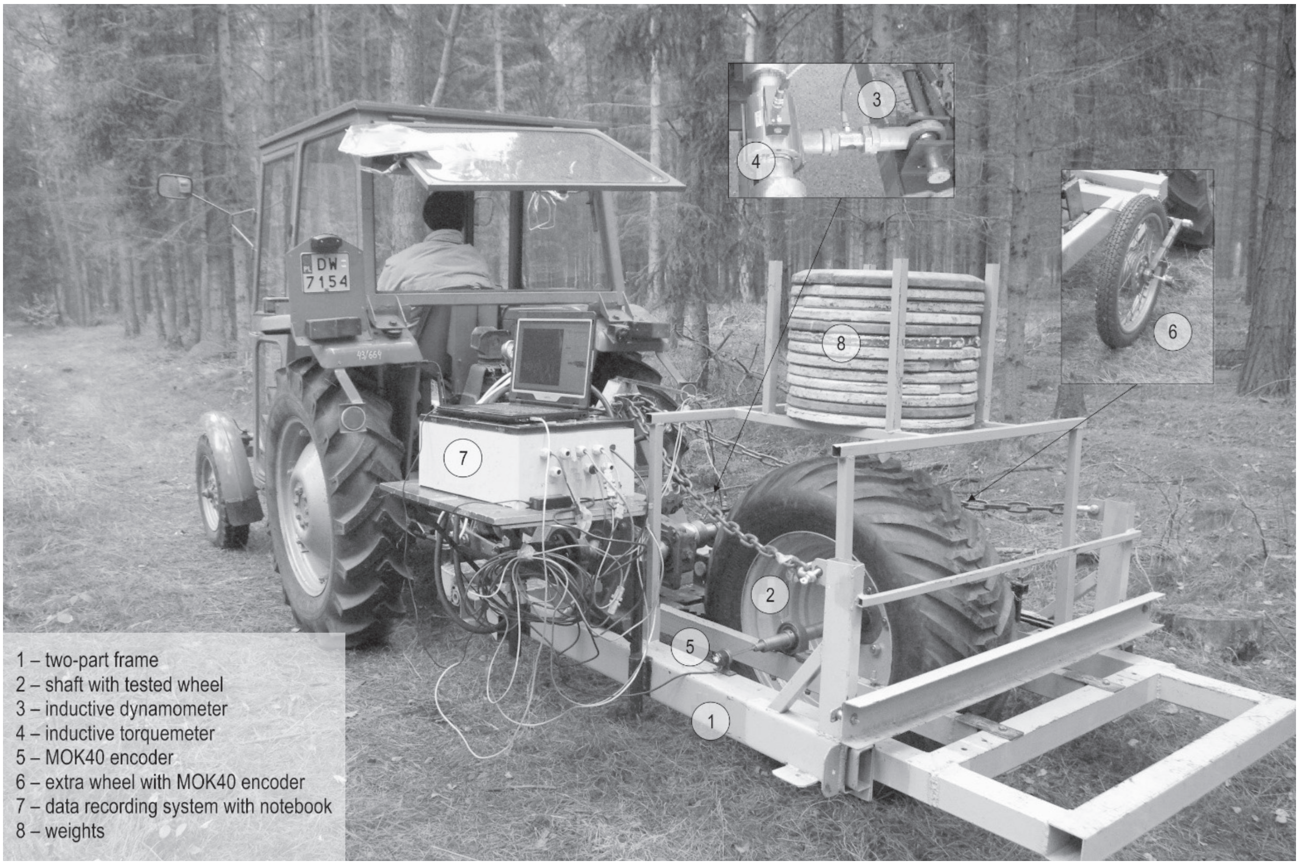

Fig. 1 The stand for testing traction properties of tyres

From the obtained results, the mean values were calculated.

Based on the measured parameters, slip of the wheels, traction force, rolling resistance and tractive efficiency values were calculated using Eq. 1–4:

$$\delta = \left(1 - \frac{S_R}{S_T}\right) \times 100 \qquad (1)$$

$$T_F = \frac{M_O}{r_D} \qquad (2)$$

$$R_R = T_F - D_F \qquad (3)$$

$$\mu = \frac{D_F}{T_F} \times (100 - \delta) \qquad (4)$$

Where:

Δ wheel slip, %

s_R actual distance of the wheel, m

s_T theoretical distance of the wheel, m

T_F traction force, N

M_O wheel torque, Nm

r_D dynamic radius of the wheel, m

R_R rolling resistance, N

D_F drawbar force, N

H tractive efficiency, %

The values of the wheel dynamic radius (r_D) were determined based on the measured distance covered by the wheel during five full rotations.

2.3. Statistical analysis

The statistical analysis was done using Statistica 12.5 software. To evaluate the impact of factors on traction parameters, the analysis of variance (ANOVA) was used, with the significance level (α) of 0.05. Before carrying out the ANOVA tests, the normal distribution and homogeneity of variance were verified (using Shapiro-Wilk and Levene tests, respectively). Moreover, the post-hoc tests (homogenous groups tests – LSD Fisher) were done – these tests should point out the differences between the factor levels.

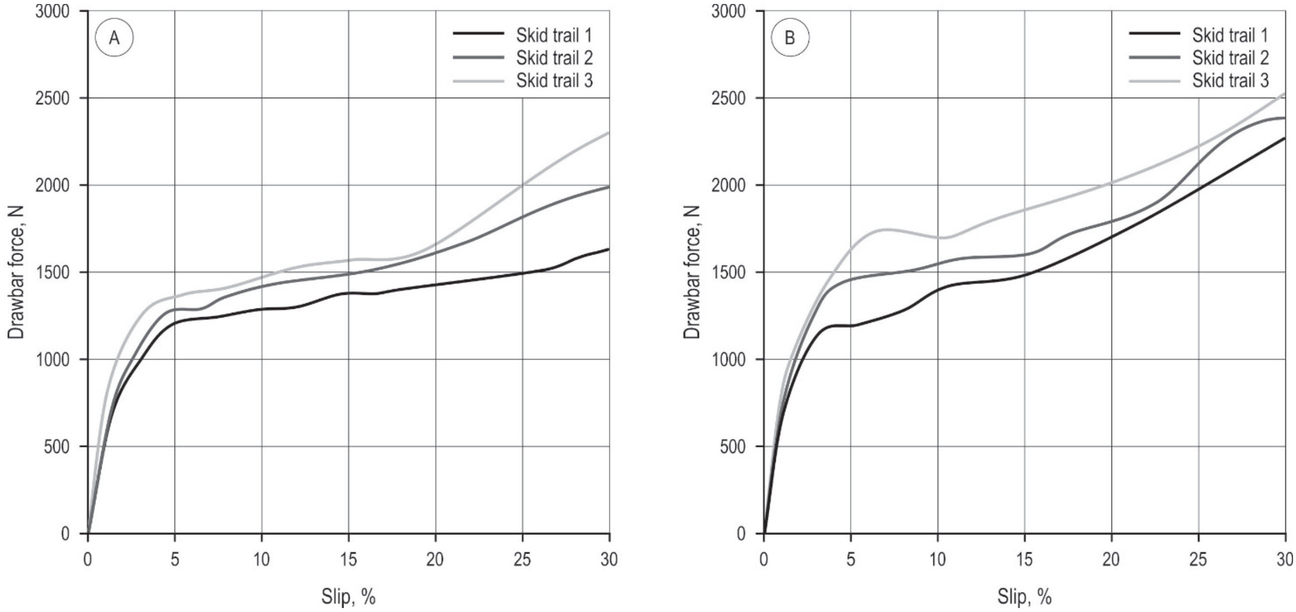

Fig. 2 Drawbar force as a function of slip a) 9.5–24 tyre, b) 400/55–22.5 tyre

3. Results

The analysed traction parameters were presented for the slip in the range 0–30%. At larger wheel slip, the operation of the vehicle is neither economically nor ecologically justified, due to high energy losses and damage to the soil.

The drawbar forces, as a function of slip for 9.5–24 and 400/55–22.5 tyres, at three skid trails are shown in Fig. 2. For both tyres, the highest values of drawbar force were obtained on skid trail 3. The lowest values of drawbar force were observed on skid trail 1. Differences in cover type and soil compactness of skid trails contributed to the significant differences in drawbar force values obtained by the tested tyres. For 9.5–24 tyre, the average drawbar force values measured on skid trail 2 and skid trail 3 were greater than on skid trail 1 by 8% and 14%, respectively. The drawbar force

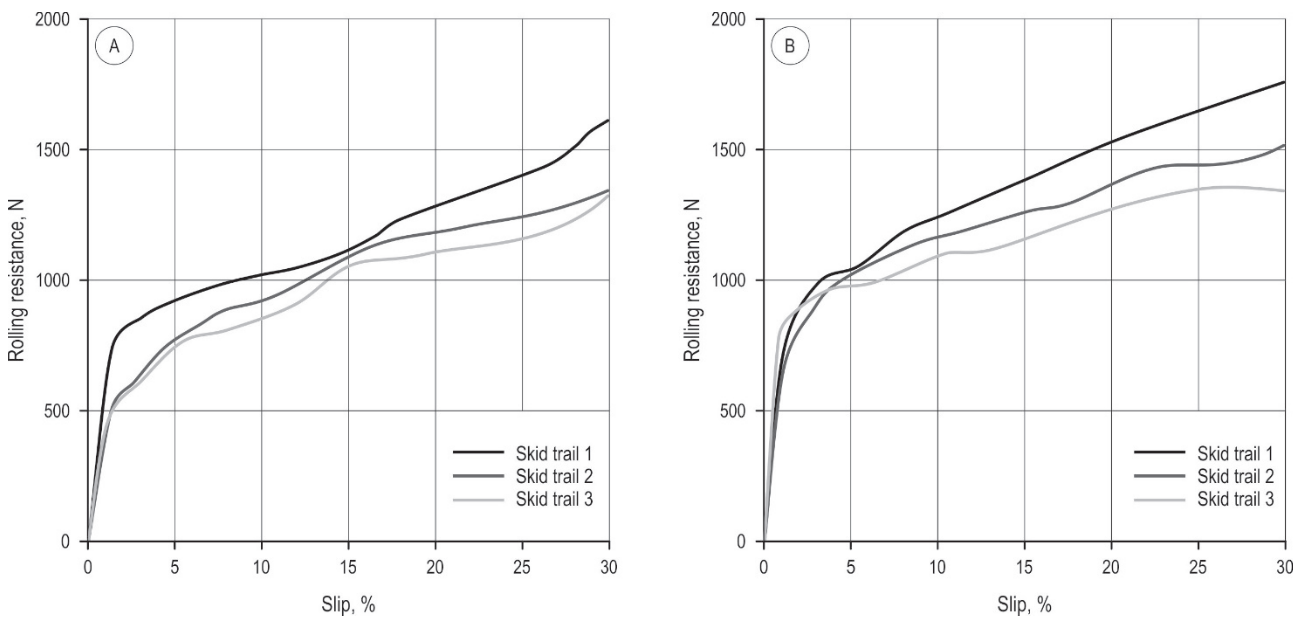

Fig. 3 Rolling resistance as a function of slip a) 9.5–24 tyre, b) 400/55–22.5 tyre

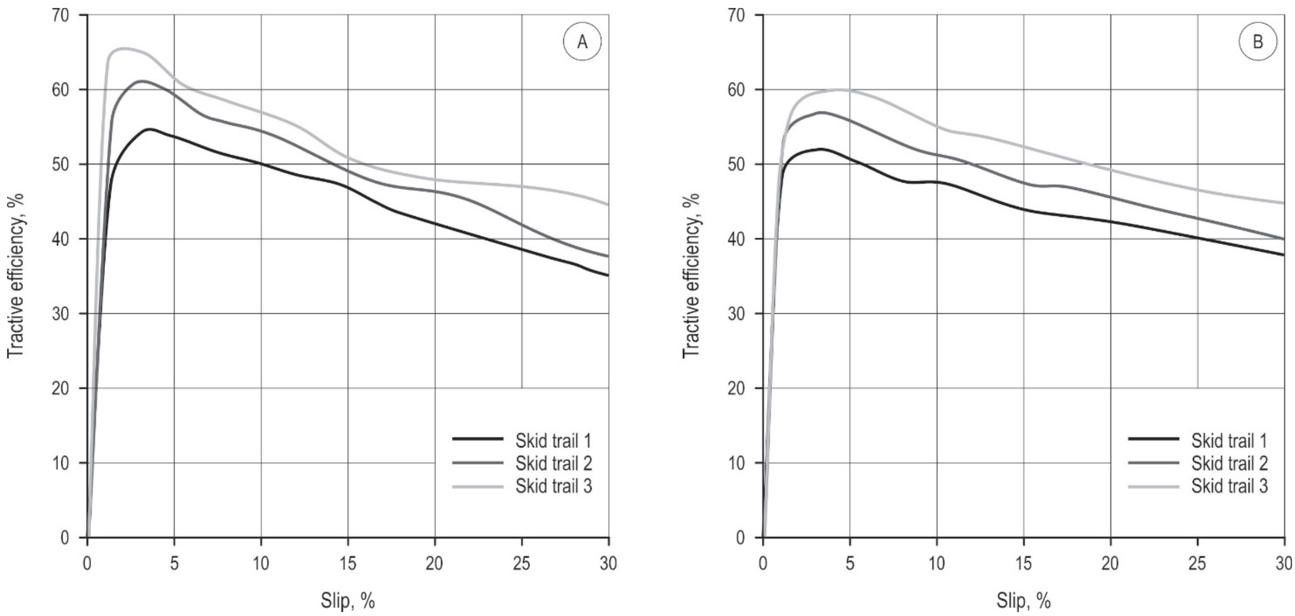

Fig. 4 Tractive efficiency as a function of slip a) 9.5–24 tyre, b) 400/55–22.5 tyre

measured for 400/55–22.5 tyre on skid trails 2 and 3 was higher by 15% and 25%, respectively, than on the skid trail 1.

On all analysed skid trails, the higher drawbar force was obtained for a 400/55–22.5 tyre. Differences in the average values of drawbar force obtained by the tested tyres occurred at slip in the range of 7–18%, the largest were observed on skid trail 3. Greater increase in drawbar force along with the increase of slip was observed for 400/55–22.5 tyre.

Fig. 3 shows the relationship between rolling resistance and wheel slip. The greatest motion resistance for both tested tyres was found on skid trail 1, and the lowest on skid trail 3. The rolling resistance values of 9.5–24 tyre on skid trails 2 and 3 were lower by 20% and 23%, respectively, compared to the values obtained on skid trail 1. For 400/55–22.5 tyre on skid trails 2 and 3, the average rolling resistance values were lower than those obtained on skid trail 1 by 11% and 22%, respectively. Greater rolling resistance was found for 400/55–22.5 tyre; the value of this parameter was higher than for 9.5–24 tyre by 13–26%.

Tractive efficiency is a very important parameter characterizing the process of generating driving force. It illustrates the losses of energy delivered to the drive wheel. The relationship between the tractive efficiency and slip is shown in Fig. 4. The lowest values of tractive efficiency for both tested tyres were obtained on skid trail 1. Soil mechanical parameters within skid trails 2 and 3 showed higher traction efficiency, with relative differences of 10% and 17% for 9.5–24 tyre, and 9% and 15% for 400/55–22.5 tyre, respectively. The maximum tractive efficiency of 58–65% (depending on skid trail), for 9.5–24 tyre, was reached at slip of up to 3%, in the case of 400/55–22.5 tyre, the maximum values of 52–60% were reached at slip of 3–6%. For 9.5–24 tyre, the highest differences in tractive efficiency values obtained on individual trails were observed at slip range of 0–5% and 17–30%. Significant differences in the tractive efficiency values obtained by 400/55–22.5 tyre on individual routes were visible throughout the whole slip range. Furthermore, in the case of the 400/55–22.5 tyre, less drop in tractive efficiency values due to increase in wheel slip was observed. On all tested trails, higher tractive efficiency of 4–6% (relative difference in mean values) was obtained for 9.5–24 tyre.

Table 4 shows the results of statistical analysis regarding the impact of ground conditions (trails) on traction parameters, separately for 9.5–24 and 400/55–22.5 tyre. Presented p-values represent the level of probability of basic hypothesis acceptance (when the p-value is smaller than significance level $\alpha = 0.05$, the factor is significant).

Based on results of statistical analysis, it can be stated that in all cases the trail type was a significant factor for all analysed parameters. The post-hoc tests showed that the skid trail 1 was classified as a separate group, while the trails 2 and 3 were considered as one group.

Table 4 Results of statistical analysis; factor: ground conditions; SD – standard deviation, *p*-value – probability level, A, B – homogeneous groups

Analysed parameter	Tyre	Ground conditions	Mean	±SD	*p*-value
Drawbar force	9.5–24	Skid trail 1	1295^{A}	32.4	0.042879
		Skid trail 2	1400^{B}	26.2	
		Skid trail 3	1481^{B}	33.3	
	400/55–22.5	Skid trail 1	1392^{A}	37.9	0.038489
		Skid trail 2	1602^{B}	45.4	
		Skid trail 3	1748^{B}	44.8	
Rolling resistance	9.5–24	Skid trail 1	1137^{A}	34.9	0.035530
		Skid trail 2	910^{B}	19.3	
		Skid trail 3	875^{B}	26.6	
	400/55–22.5	Skid trail 1	1284^{A}	32.9	0.037977
		Skid trail 2	1101^{B}	31.5	
		Skid trail 3	1000^{B}	38.6	
Tractive efficiency	9.5–24	Skid trail 1	$45,9^{A}$	0.57	0.001174
		Skid trail 2	52.8^{B}	0.55	
		Skid trail 3	55.8^{B}	0.59	
	400/55–22.5	Skid trail 1	46.6^{A}	0,66	0.005006
		Skid trail 2	50.1^{B}	0.57	
		Skid trail 3	53.1^{B}	0.59	

Analysis of traction properties of tyres performed on three skid trails showed that the skid trail 1 was the worst for the forest vehicles traffic. For that reason, the assessment of ways to improve the traction abilities was carried out on this skid trail. The dependence between the drawbar force, rolling resistance and slip for 9.5–24 tyre with and without chain is shown in Fig 5. The use of the tyre chain contributed to a comparable increase in drawbar force, and the average increase in values was of 8%. Fitting the tyre with chain caused a slight increase in rolling resistance values at the slip in the range of 0–20%. For the higher slip values, the rolling resistance of tyre with chain was lower than for tyre without chain.

The effect of the use of tyre chain on the wheel tractive efficiency is shown in Fig. 6. At slip in the range of 2–9% for tyre with chain, a slight decrease in tractive efficiency was observed. At slip of 10–15%, the values of the tractive efficiency of the tyre with and without chain did not differ. At slip over 15%, the

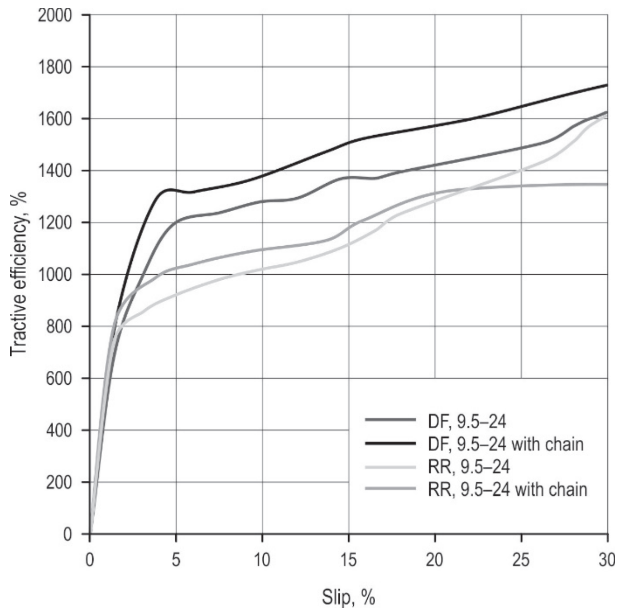

Fig. 5 Comparison of drawbar force and rolling resistance of 9.5–24 tyre – without and with chain

higher traction efficiency was achieved by the wheel with chain, and the observed difference in the values of this parameter increased as the slip increased. It has also been observed that tractive efficiency values of the tyre with chain varied significantly less than the values of the tyre without chain due to the increase in wheel slip.

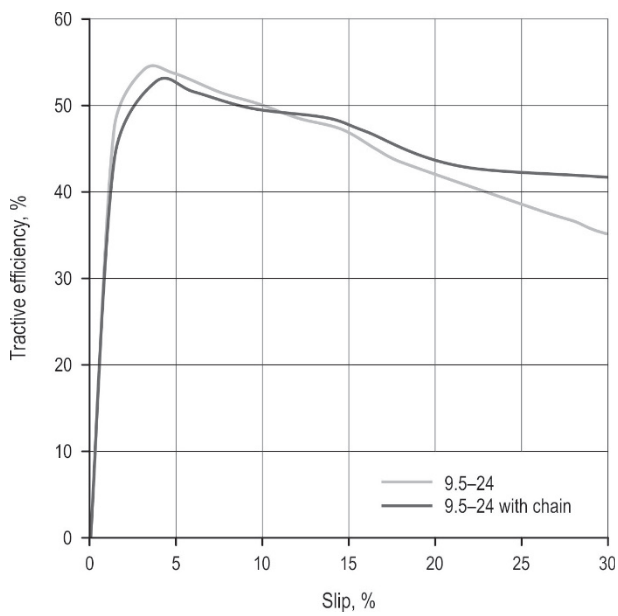

Fig. 6 Comparison of tractive efficiency of tyre with and without chain

Table 5 Results of statistical analysis; factor: use of tyre chain, SD – standard deviation, *p*-value – probability level, A, B – homogeneous groups

Analysed parameter	Slip range	Tyre	Mean	±SD	*p*-value
Drawbar force	<10	9.5–24	1079[A]	33.7	0.001740
		9.5–24 with chain	1192[B]	25.5	
	10–20	9.5–24	1360[A]	38.8	0.001509
		9.5–24 with chain	1504[B]	35.0	
	>20	9.5–24	1565[A]	24.8	0.053979
		9.5–24 with chain	1610[A]	28.0	
Rolling resistance	<10	9.5–24	905[A]	28.0	0.008499
		9.5–24 with chain	980[B]	28.1	
	10–20	9.5–24	1143[A]	29.9	0.291183
		9.5–24 with chain	1171[A]	39.2	
	>20	9.5–24	1516[A]	46.9	0.000588
		9.5–24 with chain	1326[B]	39.2	
Tractive efficiency	<10	9.5–24	51.4[A]	0.62	0.001972
		9.5–24 with chain	49.4[B]	0.54	
	10–20	9.5–24	46.0[A]	0.54	0.032505
		9.5–24 with chain	47.1[B]	0.58	
	>20	9.5–24	36.6[A]	0.54	0.000006
		9.5–24 with chain	42.5[B]	0.58	

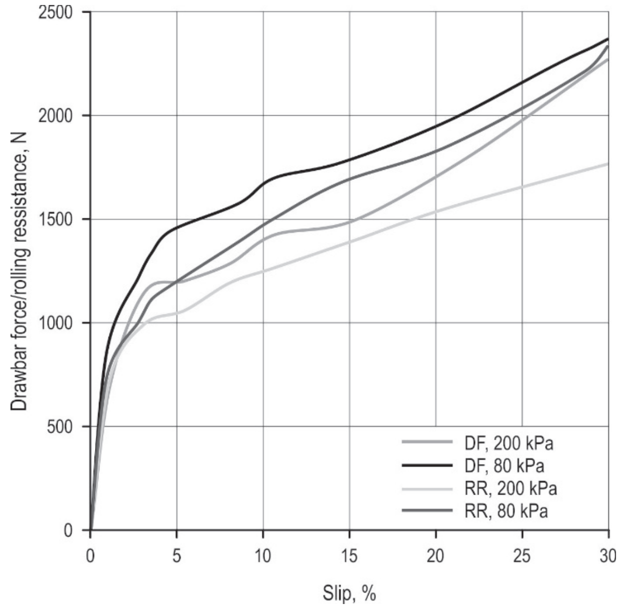

Fig. 7 Comparison of drawbar force and rolling resistance values of 400/55–22.5 tyre at different inflation pressure

The effect of the use of tyre with chain on traction parameters of 9.5–24 tyre is shown in Table 5. The analysis was done separately for three ranges of wheel slip.

For the drawbar force, the use of chain was statistically insignificant only at the wheel slip higher than 20%. In the case of rolling resistance, the significant impact of the use of chain occurred at the wheel slip of up to 10% and over 20%. However, the significant impact of the use of tyre chain on tractive efficiency values was found over the whole slip range.

The effect of the change in tyre inflation pressure on changes in drawbar force and rolling resistance is shown in Fig. 7.

Reduction of tyre inflation pressure contributed to the increase in drawbar force (average) of 13%, wherein the greatest differences were observed for the slip of 5–20%. At 80 kPa, the tyre rolling resistance values were higher by 10% than at 200 kPa, wherein the difference in the values of this parameter increased with the increase of slip. The greater increase in drawbar force and rolling resistance with an increase in slip was observed for lower inflation pressure.

Effect of changes in tyre inflation pressure on tractive efficiency is shown in Fig. 8. Reduction of the tyre inflation pressure resulted in a slight increase in tractive efficiency (the average relative increase in tractive efficiency was 6%). The highest increase in tractive efficiency due to the reduction of the tyre inflation pressure was found at slip lower than 10%. It was observed that the change in tyre inflation pressure did not result in changes of tractive efficiency as a function of slip. Maximum tractive efficiency (52% at 200 kPa and 54% at 80 kPa) was achieved at slip lower than 5%. The increase in slip resulted in a decrease in tractive efficiency.

Table 6 shows the results of statistical analysis for 400/55–22.5 tyre, with the inflation pressure as a factor. Three slip ranges were analysed separately.

In accordance with the obtained results, the change of inflation pressure had significant impact on all analysed parameters. This relationship was observed for all ranges of wheel slip.

4. Discussion

The results of the study show that values of all analysed traction parameters depend on the soil con-

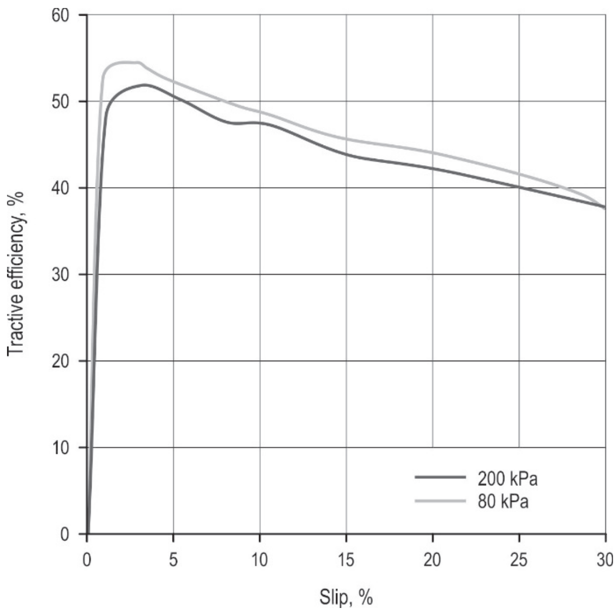

Fig. 8 Comparison of tractive efficiency of 400/55–22.5 tyre at different inflation pressure

ditions, determined by soil cover, soil compactness and shear strength. The highest values of drawbar force and tractive efficiency for both tested tyres were obtained on skid trail 3, where the soil was characterized by greater resistance to shearing by tyre treads and their limited depth impact. This resulted in lower energy losses associated with rolling resistance and consequently higher tractive efficiency. The most susceptible to the deep impact of the tyres was trail 1 covered by bare soil with a local pine litter, which was reflected in higher values of rolling resistance and lower tractive efficiency. The presented results are in line with the results of Vehinski et al. (1998, 1999), who examined the drawbar force and tractive efficiency of tyres in forest conditions on different types of soil and various cover. They also obtained the greatest values of analysed traction parameters on soils with grass cover and with greater compactness.

The present study has shown that the rate of increase of the drawbar force, along with the increase of slip, was mainly determined by tyres parameters, which was confirmed by comparable waveforms of all trails. The greatest increase in drawbar force was observed at slip range of 0–5% and 20–30% for 9.5–24 tyre. A greater and more intensive increase in drawbar force with the increase of slip was observed for 400/55–22.5 tyre. Hittenbeck (2013) obtained similar results in the study on relationship between the slip and drawbar force of forwarder equipped with: worn tyres, new tyres, tyres with reduced inflation pressure and combination of tracks and chains. This experiment was conducted on loess soil with moisture content of 32.1%. He reported that, with increasing wheel slip, the values of the drawbar force rise immediately up to a level of about 30% slip. Above that, the increase of the drawbar force is still clear but less rapid.

Battiato and Diserens (2017) reported that the influence of slip on rolling resistance and tractive efficiency is controlled by many factors, of which the most considerable are the soil deformation parameters under normal and horizontal stress, tyre width and tyre stiffness. The statement was confirmed in our study. According to the presented results, the greatest rolling resistance values for both tested tyres was observed at skid trail 1 – located on soil of smaller compactness and the lowest shear strength. Due to higher width, greater rolling resistance was found for 400/55–22.5 tyre. The distribution of the tractive efficiency, as a function of slip, is due to the fact that at low slip (<4–6%), a small increase in slip occurs and consequently soil shear displacement results in a great increase in traction force, this resulting in an overall rise in traction efficiency. At slip greater than 4–6%, an increase in slip and in soil shear displacement results in a slight increase in traction force with reduction in traction efficiency. Battiato and Diserens (2017) also showed that tractive efficiency sharply rises at low slip and reaches a peak with slip ranging between 6–12%. Beyond this peak, it decreases progressively with slip.

The present study has shown that the tyre equipped with chain caused an increase of about 8% in drawbar force for the whole slip range. The increase in rolling resistance was found only at slip of 0–20%. These results are in line with the results of Stoilov (2007), who showed that the use of chains for LKT skidder 16.9–30 tyres caused an increase in drawbar force and rolling resistance. Vehinski et al. (1999) reported that, on bare soil, adding chains to the new tyre increased the average drawbar force and tractive efficiency, by 10% and 7%, respectively. They also showed that the use of chains on worn tyres resulted in an increase in drawbar force, but a decrease in tractive efficiency.

Our study has shown that reducing the inflation pressure in 400/55–22.5 tyre resulted in an increase both in drawbar force (13%) and rolling resistance (10%). The changes in the values of both traction parameters were the result of the increase of soil-tyre contact area.

Under conditions of low humidity and relatively high soil compactness, the wide tyre did not penetrate into the ground. The reduction of tyre inflation pressure caused an increase in the tyre-soil contact surface, but mainly due to tyre deformation. The manufac-

Table 6 Results of statistical analysis; factor: inflation pressure, SD – standard deviation, *p*-value – probability level, A, B – homogeneous groups

Analysed parameter	Slip range	Tyre inflation pressure, kPa	Mean	±SD	*p*-value
Drawbar force	<10	200	1081^{A}	42.0	0.000249
		80	1289^{B}	34.0	
	10–20	200	1459^{A}	37.8	0.000026
		80	1738^{B}	30.7	
	>20	200	1792^{A}	34.1	0.000002
		80	2197^{B}	31.3	
Rolling resistance	<10	200	991^{A}	31.9	0.004853
		80	1084^{B}	27.9	
	10–20	200	1395^{A}	29.5	0.000130
		80	1589^{B}	33.6	
	>20	200	1653^{A}	37.4	0.000002
		80	2082^{B}	28.2	
Tractive efficiency	<10	200	49.6^{A}	0.60	0.000797
		80	52.6^{B}	0.37	
	10–20	200	45.6^{A}	0.72	0.011742
		80	47.1^{B}	0.33	
	>20	200	39.9^{A}	0.66	0.019644
		80	41.2^{B}	0.46	

turer states that 400/55–22.5 tyre is characterized by high flexibility on both hard and soft ground. Our results are partially compliant with the results of the traction test of the skidder LKT 81 T carried out by Stoilov (2007) on brown forest soil with a moisture content of 20.3%. The author showed that the reduction of tyre inflation pressure from 230 to 190 kPa caused an increase in the drawbar force value of 6.8% and a drop in the rolling resistance value of 7.69%. Kurjenluomar et al. (2009) showed that, on firm soil, lower tyre inflation pressure resulted in higher rolling resistance values, which is in agreement with evidence presented in this study. Our results also confirm the results of Gharibkhani et al. (2012), who reported that reduction in inflation pressure increases the rolling resistance of tyre in their experiment conducted on hard soil. Jun et al. (2004) showed that the reduction in inflation pressure from 240 to 100 kPa in the Trelleborg Twin 421 Mark II 600/55–26.5 tyre resulted in an increase in drawbar force of 23% measured at 5% slip. In our study, the reduction of inflation pressure from 200 to 80 kPa in the Trelleborg 400/55–22.5 tyre caused an increase in drawbar force of 21% at 5% slip.

The present study has also shown that the reduction of tyre inflation pressure contributed to better tractive efficiency; the average relative increase of this parameter was 6%. Similar results have been obtained by Jun et al. (2004), who showed that the reduction of the inflation pressure in 600/55–26.5 tyre resulted in an increase in tractive efficiency of 9% at 5% slip. In our study, the relative increase in traction efficiency at 5% slip was lower and amounted to 5%.

5. Conclusions

The soil conditions had a significant influence on the values of all traction parameters. The highest values of drawbar force and tractive efficiency and the smallest rolling resistance values for both tyres were obtained on skid trail 3. The highest motion resistance and the lowest values of drawbar force and tractive efficiency were found on skid trail 1. Differences in the analysed traction parameters between the best and the worst substrate due to traffic conditions amounted to even 25% for drawbar force, 23% for rolling resistance and 17% for tractive efficiency.

The 400/55–22.5 tyre is better for forestry applications, as higher drawbar forces were achieved with it than with 9.5–24 tyre. This tyre had a slightly lower tractive efficiency than the 9.5–24 tyre, but was characterized by a smaller decrease in the value of this parameter as a result of increase in wheel slip. It means less energy loss in the wheel-soil system due to changes in traffic conditions. The lower tractive efficiency of the 400/55–22.5 tyre is due to greater rolling resistance resulting from greater width and deformability of this tyre. In practice, greater tyre width means lower ground pressure and smaller susceptibility to rut formation.

The better way to improve traction properties on the tested skid trail was to reduce the tyre inflation pressure, resulting in an increase of 13% and 6%, respectively, both in drawbar force and tractive efficiency. The use of tyre chain proved to be most advantageous for wheel slip of more than 15%, due to the increase in drawbar force and tractive efficiency of about 15% and 6%, respectively.

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Received: April 8, 2017
Accepted: July 7, 2017

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