Scientific quarterly journal ISNN 2083-1587; e-ISNN 2449-5999
Agricultural Engineering
2015: 4(156):5-13
Homepage: http://ir.ptir.org

DOI: http://dx.medra.org/10.14654/ir.2015.156.146

ASSESSMENT OF THE CHANGE IN THE ROLLING RESISTANCE OF A WHEEL IN VARIED FIELD CONDITIONS

Włodzimierz Białczyk, Marek Brennensthul, Anna Cudzik*, Jarosław Czarnecki

Institute of Agricultural Engineering, Wrocław University of Environmental and Life Sciences
Contactdetails: ul. Chełmońskiego 37/41, 51-630 Wrocław; e-mail: anna.cudzik@up.wroc.pl

ARTICLE INFO

Article history:
Received: July 2015
Received in the revised form: September 2015
Accepted: September 2015

Key words:
tractor
tyre
rolling resistance
pulling force
compaction
vertical load

ABSTRACT

The paper presents the research results concerning the rolling resistance of a wheel on agricultural surfaces. Research on traction was carried out in field conditions with the use of a mobile stand; a wheel with 9.5-24 tyre was investigated; values of the rolling resistance and the pulling force were analysed with reference to the wheel slip. A type of surface (soil, sod), its compaction and the vertical load of a wheel were assumed as factors. Based on the obtained results, it was proved that the rolling resistance was by approx. 30% higher on soil than on sod. Differences resulting from the variety of surfaces were higher than the differences caused by various values of their compaction (did not exceed 25%). No significant impact of compaction changes on the rolling resistance and pulling force values were proved but a considerable increase of the rolling resistance value along with the decrease of its compaction were determined. Moreover, it was proved that the increase of the vertical load of a wheel resulted in the increase of the rolling resistance and the pulling force on both grounds but these changes were higher on soil than on sod.

Introduction

Tractor crossings on agricultural surfaces are accompanied by a phenomenon of deformation of surface and tyres. The impact of wheels and a steering system results in stress and deformation in the ground. Each structure of the ground has a specific mechanical resistance. At a low load, ground reacts elastically, whereas at the load exceeding its border resistance, a permanent deformation takes place. As a result of the described phenomenon, energy losses and the rolling resistance occur (Gharibkhani et al., 2012; Kiss, 2009), the size of which, as we know, also has a significant impact on fuel consumption by a vehicle (Goering and Hansen, 2004; Tomaraee et al., 2015). Radius and width of a tyre as well as the air pressure inside are the main parameters of a pneumatic wheel, which influence the size of the rolling resistance (Wulfsohn and Way, 2009). From among the ground properties, the most significant are: type of the soil cover, bearing capacity, particular size and moisture (Schreiber and Kutzbach, 2007).

The rolling resistance is a subject for numerous scientific works, in which factors influencing its size are analysed. Relations between parameters of the wheels and steering system and the speed as well as between the speed and the rolling resistance are most often described (Coutermarsh, 2007; Elwaleed et al., 2006; Kurjenluoma et al., 2009; Taghavifar and Mardani, 2013; Way and Kishimoto, 2004). The rolling resistance is strictly related to soil deformation under a wheel and their measurements at an uncontrolled state of the surface do not ensure fully credible results. Contrary, measurements taken in soil channels do not reflect real conditions of exploitation of a tractor and interaction which take place between a wheel and the surface.

Analysis of factors which influence the rolling resistance is significant from the practical point of view. During exploitation of a tractor at low slip values, the rolling resistance is the main source of losses at transferring the driving force. Knowledge of those issues may allow selection of the method of energy losses reduction in the wheel-surface system.

Objective, conditions and methodology of research

The fundamental objective was to determine the rolling resistance of a wheel on two agricultural grounds of varied properties and determination of its operation in the developed traction force. Determination of the impact of vertical loading of a wheel on the changes of the analysed traction properties on both grounds was assumed as an additional objective.

The results were carried out on the cultivation soil without plants and the meadow sod at a varied condition of those grounds defined on account of their compaction and moisture. Table 1 presents average values of compaction for the scope of depth of 0-0.1 m and the moisture values measured at the depth of 0.05 m.

Table 1
Values of moisture and compaction of tested grounds

Groundtype	Moisture (%)	Compaction (MPa)
Soil	13.8	0.44
	23.3	0.71
	29.2	1.18
Meadow sod	26.9	1.35
	28.8	1.50
	30.9	1.86

Compaction of the ground was measured with Penetrologger device with the use of a cone with a vertical angle of 60º and the area of the base of 1 cm^2; moisture was measured at the use of Theta-probe cooperating with Penetrologger. Each measurement was carried out in five iterations.

Traction properties for a wheel with a diagonal tyre 9.5-24 was determined at the air pressure in a tyre of 0.15 MPa and the vertical load of 6110 and 8060 N.

Research on traction was carried out with the use of a specialist stand aggregated with a farm tractor. Construction of the stand enabled measurement of the pulling force, torque and the value of distance (real and theoretical).

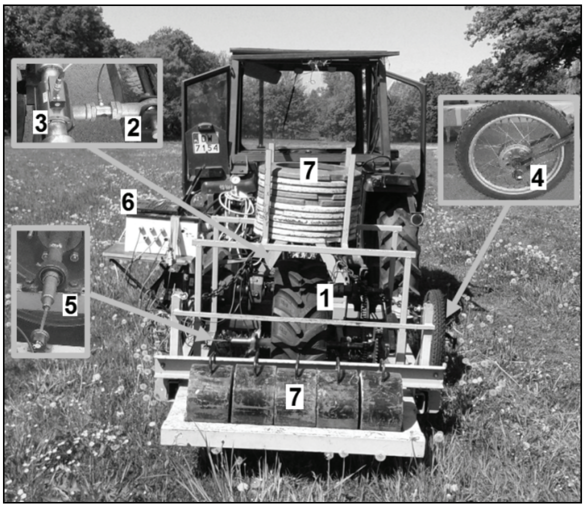

Figure 1. Stand for traction tests (description in the text)

During the research, the stand was moving along with a tractor - theoretical speed was 0.8 $m \cdot s^{-1}$. The investigated wheel was mounted on a shaft (1) and obtained the drive from the PTO shaft through a multi-degree reduction gear. TecSic induction dynamometer (2) with a precision of 40 N and the measurement scope 0-20 kN was used to measure the pulling force, the torque of the investigated wheel was measured with the induction torque measuring device (3) with a measurement precision of 1 Nm within the scope of 0-3000 Nm. The actual and theoretical distance was measured with the use of encoders MOK-40 (4 and 5) – encoder for the measurement of theoretical distance was mounted next to the shaft with the investigated wheel, and for the measurement of the actual distance – at the additional wheel. Data registered during the measurement were sent to the electronic recording device (6) and recorded in the memory of the portable computer. The accepted vertical load of a wheel was obtained by the change in the number of weights (7).

Based on the measured values of the pulling force, torque and distance, a wheel slip and the rolling resistance were calculated according to the relation 1 and 2.

$$\delta = 100 \cdot (1 - \frac{s_R}{s_T}) \tag{1}$$

$$P_f = \frac{M_o}{r} - P_u \tag{2}$$

where:

- δ – wheel slip, (%)
- s_R – actual distance, (m)
- s_T – theoretical distance, (m)
- P_f – rolling resistance, (N)
- M_O – torque, (Nm)
- r – wheel radius, (m)
- P_u – pulling force, (N)

Research results

According to the assumed objective of the paper for a wheel with a 9.5-24 tyre and two variants of vertical load the rolling resistance on soil and meadow sod was determined. For soil, courses of changes of the rolling resistance as a function of slip were presented in figure 2.

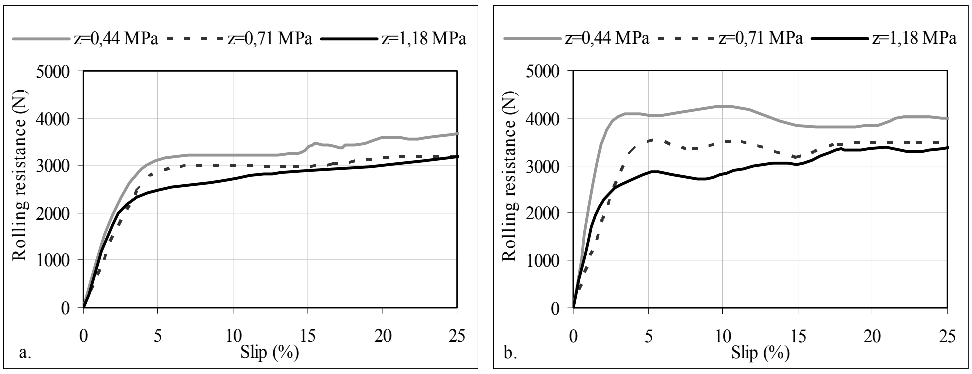

Figure 2. Courses of the rolling resistance as a function of slip determined on soil at the vertical loading of a wheel: a. 6110 N, b. 8060 N (z – compaction of surface)

When analysing the presented courses, one may notice that the biggest changes of the rolling resistance occurred at the wheel slip, which did not exceed 5%. Further increase of the slip resulted in considerably lower fluctuations of the rolling resistance value. Moreover, it was noticed that in case of both wheel loads, which were used on soil with compaction of 0.44 and 0.71 MPa at the slip exceeding 15%, the rolling resistance values were similar. The comparison of courses shows that the values of the rolling resistance decreased along with the increase of the soil compaction. Bigger differences in values of this parameter on soil at its varied compaction were reported at the load of 8060 N.

Figure 3 presents the courses of the rolling resistance of the investigated wheel obtained on the meadow sod with varied values of compaction. The nature of changes of the rolling resistance value along with the increase of the wheel slip was similar as in case of soil without plants. At the slip which was within 0 and 5% an intensive growth of the rolling resistance value took place but at a higher slip its values were changing to a smaller extent. Moreover, it was noticed that the change in the meadow soil compaction did not result in considerable changes of the rolling resistance. This tendency was maintained both at the wheel loading amounting to 6110 as well as to 8060 N.

The obtained results comply only with some works of other authors. The nature of changes in the course of the rolling resistance as a function of slip refers to the results presented by Elwaleeda et al., (2006) and Šmerda and Čupera (2010). However, in the papers by Bashford et al., (1999), Gholkara et al., (2009) and Lyasko (2010) it was proved that stabilization of the courses of the rolling resistance takes place at a higher slip than in the presented results.

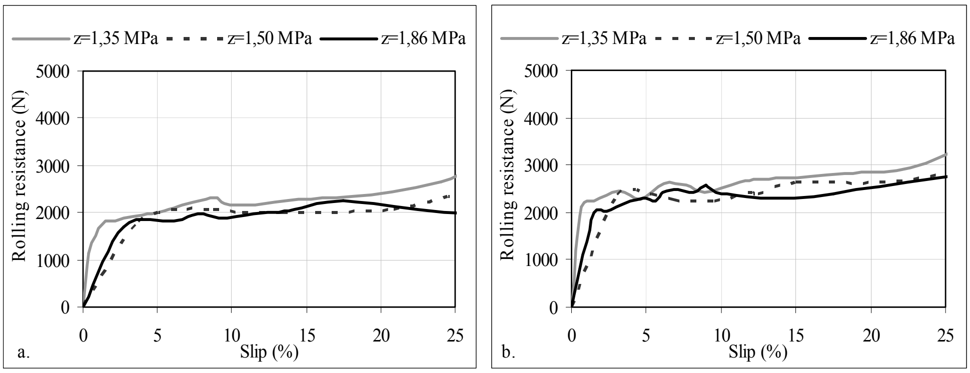

Figure 3. Courses of the rolling resistance as a function of slip determined on the meadow sod at the vertical loading of a wheel: a. 6110 N, b. 8060 N (z – compaction of surface)

In order to determine the impact of both the type and the state of the ground on the value of the developed traction force, figure 4 lists the mean values of the pulling force and the rolling resistance determined on both grounds for the investigated wheel at both sizes of loading. The sum of the pulling force value and the rolling resistance value in the presented list constitutes the traction force.

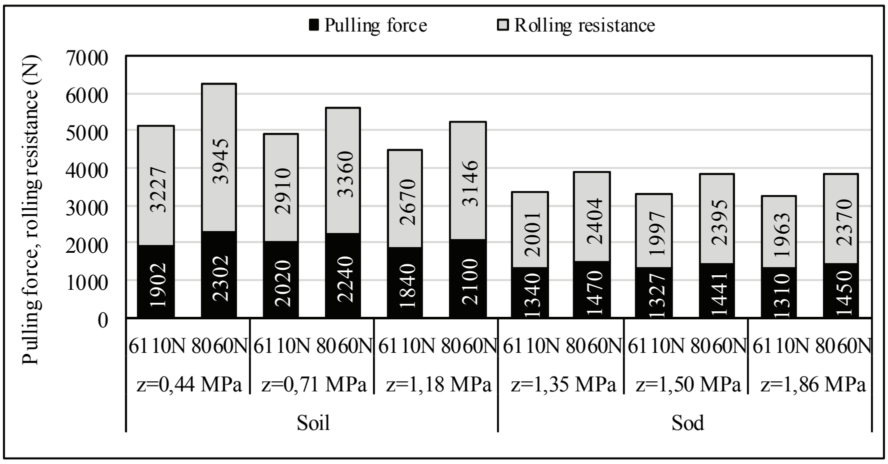

Figure 4. The list of mean values of the pulling force and the rolling resistance for the slip within 0-20% (z – compaction of surface)

The data presented above show that the tested wheel developed a higher traction force on soil. Regardless the soil compaction, the obtained values both of the pulling force and the rolling resistance were higher than in case of meadow sod. Such situation may be justified with the fact that the driving force is transferred differently on both surfaces. On the meadow sod, the driving force was developed mainly as a result of friction; a wheel during a rotation did not sink in the surface and did not sheer it with a tread. A smaller surface of contact of a tyre with sod caused that the pulling force was lower, and lack of deformation of the surface at each analysed compaction did not affect the rolling resistance increase. The increase of the wheel load on meadow sod resulted in the increase of the pulling force as a result of the pressure growth (and as a result of the friction force) and the rolling resistance increase was related mainly to the deformation of a tyre. In case of the cultivated soil, traction force was being developed as a result of friction and shearing and the wheel movement was accompanied by the deformation of the surface. As a result of the increase of the wheel load, both the pulling force and the rolling resistance increase were reported. The described changes in the values of the analysed parameters as a result of the increase of the vertical load of a wheel correspond to the results presented by other researchers. In many papers it was proved that the increase of load causes the growth of the rolling resistance (Battiato and Diserens, 2013; Gharibkhani et al., 2012; Gholkar et al., 2009; Taghavifar and Mardani, 2013). Some dissimilarity with reference to the results of other authors may be observed at the analysis of changes of the pulling force as a result of the vertical load increase. Some papers show that the increase of load is accompanied by the growth of the pulling force value (Senatore and Sandu, 2011; Taghavifar and Mardani 2015), while in the discussed results a considerable increase of the pulling force at the increase of loading was reported only on soil. On the other hand the relations between the ground strength resistance (defined as compaction) and the traction properties are similar to the results obtained by Bashford (1999) and Botta (2012), where it was proved that on grounds with lower compaction the rolling resistance of a wheel is higher. The relation between the ground type and the traction properties complies with the results presented by Abraham et al., (2013) who proved that a wheel used on soil reaches higher pulling force values than on sod.

Figure 5 presents the relation of the pulling force and the rolling resistance to the type and the condition of surface and the wheel load. The increase of the cultivated soil compaction resulted in a considerable decrease of the rolling resistance value and caused a slight reduction of the pulling force. This relation was related to both applied wheel loads. As a result of the compaction increase the possibility that a wheel will sink in the ground was limited. Share of shear and friction in the process of transferring the driving force were modified. It was observed that the higher the soil compaction, the lower the impact of wheel loading on the value of the rolling resistance. Changes in the compaction of the meadow sod did not cause any significant changes of values of the analysed parameters because a wheel did not cause any sink impact on the surface. The driving force was transferred by means of friction. On sod, at varied values of compaction, a comparable impact of loading on the pulling force values and the rolling resistance values were reported. The increase of the wheel loading on this surface to a greater extend caused the increase of the rolling resistance (due to deformation of a tyre) than the improvement of traction properties.

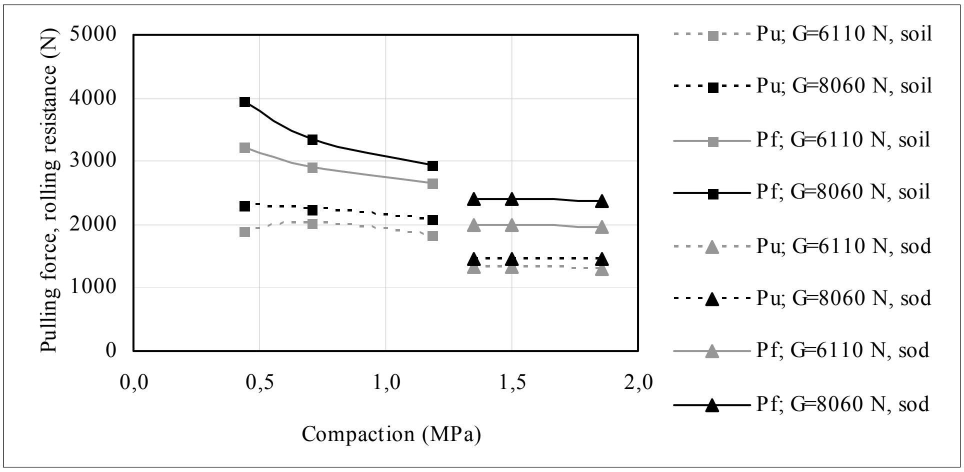

Figure 5. Relation of mean values of the pulling force and the rolling resistance of a wheel with a tyre 9.5-24 at the loading of 6110 and 8060 N to the compaction of the investigated grounds.

In order to prove the impact of the assumed factors on the changes of the values of the analysed traction parameters, the obtained results were subjected to the statistical analysis with the use of *Statistica 12.5*. Firstly, a single factor analysis of variance was carried out on the level of significance of α=0.05, which was to prove significant relations between the type of the ground and the rolling resistance and the pulling force values. Results of the analysis were presented in table 2.

Table 2
Results of the analysis of variance - determination of the surface type impact (F - test function values, p – probability level)

Factor	Pullingforce		Rolling resistance	
	F	*p*	*F*	*p*
Groundtype	699.94	<0.00001*	29.064	0.00001*

*data marked are significant on the significance level of α=0.05

The presented values *p* constitute the probability level of rejecting the hypothesis acc. to which there is no significant impact of a factor on the analysed parameters. In case the value *p* is lower than the assumed level of significance α a given factor has a significant impact. Based on the results of the statistical analysis one may say that the ground type had a significant impact on both the pulling force and the rolling resistance value.

Then, separate statistical analyses for each ground were carried out. A statistical procedure consisted in a double-factor analysis of variance at the level of significance α=0.05. Results of the analyses which were carried out were set in table 3.

Table 3
Results of the analyses of variance for each surface (F – test function values, p – probability level)

Ground type	Factor	Pullingforce		Rolling resistance	
		F	*p*	*F*	*p*
Soil	compaction	16.93	0.00018*	84.66	<0.00001*
	verticalload	153.29	<0.00001*	97.49	<0.00001*
Sod	compaction	1.22	0.32522	2.50	0.12132
	verticalload	101.43	<0.00001*	864.1	<0.00001*

*data marked are significant on the significance level of α=0.05

According to the results presented in table 3 a significant impact of both the accepted factors on the pulling force values and the rolling resistance was reported on soil and no significant impact of compaction on values of both traction parameters was proved.

Conclusions

1. The surface type determines more the size of the rolling resistance than its condition. From among the analysed surfaces on soil without plants, the rolling resistance values were higher (at the average by approx. 30%). Moreover, it was proved that they increased along with the compaction drop. No significant impact of soil compaction both on the rolling resistance values as well as on the pulling force was reported on sod.
2. Wheel loading on soil resulted in the increase of both the pulling force and the rolling resistance but the relation of the increase of the pulling force value to the rolling resistance increase was related to the ground compaction (it was the most advantageous on soil with higher compaction). The increase of the wheel load on sod contributed to the increase of the rolling resistance value (maximally by approx. 20%) than to the increase of the pulling force (maximum growth by 10%).

References

Abrahám, R., Majdan, R., Mojžiš, M. (2013). Effect of driving wheel type on drawbar pull of tractor.*Journal of Central European Agriculture,14*(4). 1336-1346.

Bashford, L. L., Kocher, M. F., Tibbetts, T. S. (1999). Wide tires, narrow tires.*Biological Systems Engineering: Papers and Publications, 174*. 1-7.

Battiato, A., Diserens, 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.

Botta, G. F., Tolon-Becerra, A., Tourn, M., Lastra-Bravo, X., Rivero, D. (2012). Agricultural traffic: Motion resistance and soil compaction in relation to tractor design and different soil conditions. *Soil and Tillage Research, 120*, 92-98.

Coutermarsh, B. (2007). Velocity effect of vehicle rolling resistance in sand.*Journal of Terramechanics, 44*(4).275-291.

Elwaleed, A. K., Yahya, A., Zohadie, M., Ahmad, D., Kheiralla, A. F. (2006).Effect of inflation pressure on motion resistance ratio of a high-lug agricultural tyre.*Journal of Terramechanics, 43*(2), 69-84.

Gharibkhani, M., Mardani, A., Vesali, F. (2012).Determination of wheel-soil rolling resistance of agricultural tire.*Australian Journal of Agricultural Engineering, 3*(1), 6-11.
Gholkar, M. D., Salokhe, V. M., Keen, A. (2009). The Effect of axle load and tire inflation pressure on the tractive performance of a two wheel drive tractor on soft clay paddy field.*An ASABE Meeting Presentation Paper, 096606*, 1-12.
Goering, C. E., Hansen, A. C. (2004). *Engine and Tractor Power*.ASAE Publication.ISBN 1892769425.
Kiss, P. (2009). Determination of Rolling Resistance Components.*JárművekésMobilgépek 1*, 237-246.
Kurjenluoma, J., Alakukku, L., Ahokas, J. (2009). Rolling resistance and rut formation by implement tyres on tilled clay soil. *Journal of Terramechanics, 46*(6), 267-275.
Lyasko, M. I. (2010). Multi-pass effect on off-road vehicle tractive performance.*Journal of Terramechanics, 47*, 275-294.
Schreiber, M., Kutzbach, H. D. (2007) Comparison of different zero-slip definitions and a proposal to standardize tire traction performance. *Journal of Terramechanics, 44*.75-79.
Senatore, C., Sandu, C. (2011). Torque distribution influence on tractive efficiency and mobility of of-road wheeled vehicles.*Journal of Terramechanics, 48*, 372-383.
Šmerda, T., Čupera, J. (2010). Tire inflation and its influence on drawbar characteristics and performance – Energetic indicators of a tractor set. *Journal of Terramechanics, 47*, 395-400.
Taghavifar, H., Mardani, A. (2013). Investigating the effect of velocity, wheel load and inflation pressure on rolling resistance of radial ply tire. *Journal of Terramechanics, 50*, 99-106.
Taghavifar, H., Mardani, A. (2015). Evaluating the effect of tire parameters on required drawbar pull energy model using adaptive neuro-fuzzy inference system.*Energy, 85*, 586-593.
Tomaraee, P., Mardani, A., Mohebbi, A., Taghavifar, H. (2015). Relationships among the contact patch length and width, the tire deflection and the rolling resistance of a free-running wheel in a soil bin facility. *Spanish Journal of Agricultural Research, 13*(2), e0211, 7 pages. Pozyskano z: http://dx.doi.org/10.5424/sjar/2015132-5245
Way, T. R., Kishimoto, T. (2004). Interface pressures of a tractor drive tyre on structured and loose soils. *Biosystem Engineering, 87*(3), 375-386.
Wulfsohn, D., Way, T. R. (2009). Factors that influence tractive performance of wheels, tracks and vehicles.*Advances in Soil Dynamics vol. 3. St Joseph Michigan ASABE*, 209-252.

OCENA ZMIAN OPORU PRZETACZANIA KOŁA W RÓŻNYCH WARUNKACH POLOWYCH

Streszczenie.W pracy przedstawiono wyniki badań dotyczące oporu przetaczania koła ciągnika na podłożach rolniczych. Badania trakcyjne wykonano w warunkach polowych z wykorzystaniem mobilnego stanowiska, badano koło z oponą 9.5-24, analizowano wartości oporu przetaczania oraz siły uciągu w odniesieniu do poślizgu koła. Jako czynniki przyjęto rodzaj podłoża (gleba, darń łąkowa), jego zwięzłość oraz obciążenie pionowe koła. Na podstawie uzyskanych wyników wykazano, że na glebie wartości oporu przetaczania były o ok. 30% wyższe niż na darni. Różnice wynikające z odmienności podłoży były większe niż różnice powodowane różnymi wartościami ich zwięzłości (nie przekraczały 25%). Na darni nie wykazano istotnego wpływu zmian zwięzłości na wartości oporu przetaczania i siły uciągu, natomiast na glebie stwierdzono znaczny wzrost wartości oporu przetaczania wraz ze spadkiem jej zwięzłości. Ponadto wykazano, że zwiększanie obciążenia pionowego koła skutkowało wzrostem oporu przetaczania i siły uciągu na obu podłożach, przy czym na glebie zmiany te były większe niż na darni.

Słowa kluczowe: ciągnik, opona, opór przetaczania, siła uciągu, zwięzłość, obciążenie pionowe