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Effect of Lug Angles of Rigid Wheel on the Tractive Performance on Hard Soil Terrain

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Abstract: On a certain ground, the tractive performance of an off-road vehicle depends largely on the interaction of its tires with the terrain. Accordingly, studying the behavior of tires has a great importance. It is aimed to provide information about the effect of different tire circumferential lug angles on the tractive performance in this study. A single wheel test setup was designed and produced for this purpose. Tractive performance of a pneumatic tire used as drive tire of off-road vehicles and a rigid wheel having different circumferential lug angles was investigated with this setup. Various axle loads, hard soil ground and lug angles were selected as work parameters. As a result, it was determined that effects of controlled variables on slip ratio and tractive efficiency obtained by drawbar pull were important. Average slip ratio of the rigid wheel with 0º circumference lug angle was the highest, because adherence to ground of this rigid wheel is insufficient. The maximum tractive efficiency was achieved at a value of 66 % on a rigid wheel with a 45 ° circumferential lug angle. It was seen that the performances of the pneumatic wheel with 45º circumferential lug angle and the rigid wheel with 45º circumferential lug angle were so close to each other. The rigid wheel with 15º circumferential lug angle performed best in low axle loads, while the rigid wheel with 45º performed best in high axle loads. A reference can be constituted for optimum tire lug angle determination by analyzing the rolling resistance in the future studies.

Keywords: Rigid wheel, tire, tractive efficiency, tractive performance single wheel tester

Sert Toprak Zemin Üzerinde Rijit Tekerleğin Profil Açılarının Çeki Performansına Etkisi

Özet: Belli bir zeminde, bir yol dışı taşıtının çeki performansı, büyük ölçüde, lastiklerinin arazi ile etkileşimine bağlıdır. Bu nedenle, lastiklerin davranışını çalışmak büyük bir öneme sahiptir. Bu çalışma ile, farklı lastik çevresel profil açısının, çeki performansı üzerinde ne ölçüde etkili olduğu konusunda bilgi sağlamayı amaçlanmaktadır. Bu amaçla bir tek tekerlek test düzeneği tasarlanmış ve imal edilmiştir. Bu düzenek ile yol dışı taşıtlarda muharrik lastik olarak kullanılan bir pnömatik lastiğin ve farklı çevresel profil açılara sahip rijit tekerleğin çeki performansı incelenmiştir. Çalışma parametreleri olarak çeşitli aks yükleri, sert toprak zemin ve profil açıları seçilmiştir. Sonuç olarak, kontrollü değişkenlerin, çeki kuvvetine bağlı olarak elde edilen patinaj ve çeki verimi üzerindeki etkilerinin önemli olduğu saptanmıştır. 0 ° çevresel profil açısına sahip rijit tekerleğin zemine tutunmasının yetersiz olması sebebiyle bu rijit tekerlekte ortalama patinaj en yüksek değerde olmuştur. Maksimum çeki verimliliği 45° çevresel profil açısına sahip rijit tekerlekte %66 değerlerinde elde edilmiştir. Yapılan çalışmada 45 º çevresel profil açısına sahip pnömatik tekerleğin performansıyla 45 º çevresel profil açısına sahip rijit tekerleğin performansı birbirine çok yakın değerlerde olduğu gözlenmiştir. Gelecek çalışmalarda yuvarlanma direnci de incelenerek optimum lastik profil açısının belirlenmesinde kullanılacak bir referans teşkil edilebilir.

Anahtar kelimeler: Çeki performansı, çeki verimi, lastik, rijit tekerlek, tek tekerlek test düzeneği

1. Introduction

Significant changes have happened in structural and technical properties of off-road vehicles used in agriculture and forestry during the recent years. Tractors that are used in agriculture have undergone several changes as well. The changes in the constitutive properties of the tires (radial or bias-ply), increment in the power of the tractors and alterations (2WD and 4WD/MFWD) in the configuration of the tractors are the remarkable examples. There is the need for well-rounded studies on the vehicle systems because of the complex problems arising out of the relationship between moving mechanisms of the vehicles and the land conditions (Yahya et al., 2007). The changes in the tractive performance are mainly based on the connections between the wheel and the working platform. Therefore, these relationships should be completely understood, and the information that will guide the manufacturer and the user to choose the proper tire the working conditions should be revealed for minimizing the energy loss and providing the optimum productivity in various operating conditions (Sümer and Sabancı, 2005).

Tractive performance parameters of the drive wheels constitute the crucial operational mission of the agricultural tractors (Taghavifar and Mardani, 2005). The tire parameters such as the wheel load, travel reduction, forward speedand inflation pressure affect the tractive performance of the wheels at different significance levels. Net drawbar pull is accepted as one of the most important criterions of the tractive performance parameters (Elwaleed et al., 2006).

Slippage is the decrement occurred because of the flexibility of the traction element, the slip between ground-tire and the shearing stress in the soil (Zoz and Grisso, 2003). The slip ratio is a significant variable in the studies about tractive performance parameters such as drawbar pull, tractive efficiency (Ding et al.,2009). Working productivity of an agricultural tractor rides on the tireslippage, tire parameters, terrain parameters and the other operational parameters. Slippage is one of the essential parameters need to be considered to maximum the tractive efficiency. Slippagedepend on the drawbar pull of the vehicle and slippage increases when the drawbar pull is increased (Kumar et al., 2016).

The tires enable to transform the energy that is obtained from the vehicleengine into the useful works (action), that is why it affects the dynamic and mobility of the vehicle. The dynamics of the tires and the vehicle body need to be well modeled to realistically evaluate the tractive efficiency of a full-sized vehicle (Senatore and Sandu, 2011).

There are tire types that are designed to meet the needs of specific operating activities and used in off-road vehicles. It can be mentioned about various tasks that need to be achieved by the tractor tire. The drivetires of the vehicles have tirelugs with different heights, angles, and designs for the special and general purposes. A good progress stability, drive safety and drive comfort are of capital importance besides the tire performance (El-Gawwad et al., 1999). Drawbar and braking forces are the important performance characteristics of the tires used in the agricultural area. The design of a tire shape is an essential factor, and it needs to be understood about how the reaction forces affect the tire performance on a tirelug surface (Shao et al., 2017). The analyses were conducted to discover the effects of the relationships between tire parameters such as the height, number and angle of the tirelug on the tireperformance (Ding et al., 2011) El-Gawwad et al. (1999) conducted a series of studies to determine the interaction between the lug angle of the tire used in off-road vehicles and the ground; to compare the forces created by the off-road tires with lug angle and without lug angle; to review the effect of the modulus of deformation, wheel slip, lug height and lug angle on the wheel forces. Du et al. (2017) actualized analyses to research the effects of the off-road vehicle wheels like the lug height, lug type, point of intersection and central angle on the tractive performance. They observed by research realized by tires which have five different simulated lug heights, seven different lug central angles and three different circumferential lug angles that the tire with 45° lug inscribed angle provides the maximum tractive efficiency.

It is possible to place lug with the sizes and angles required in the rigid wheel. Thus, the effects of the different lug angle and lug interval on the performance of the wheelcan be determined. In many studies, rigid wheels have been used to investigate tire profile effects. Some of the performance determination studies are summarized by designing a rigid wheel to work with different lug angles and lug intervals. Hermawan et al. (1998) tested to specify the tractive performance of a lugged wheel can move along in asoil bin test apparatus and measured the soil reaction forces on the lugs. They applied similar experiments with this wheel by designing a rigid wheel with changeable lugs. They also researched the effects of lug moving pattern, lug spacing, horizontal load and vertical load on the tractive performance.The tractive efficiency increased when the vertical load is increased and occurred fractional rolling resistances. But, the horizontal force does notshow a significant increase. Salokhe et al. (1990) measured the normal and tangential forces of the wheel lugondeveloped single model cage wheel in wet clayed soil canal. It is observed that the normal forces and drawbar pull increased by turning the lug to a certain degree; these forces decreased after reaching the peak value.Watyotha et al. (2001) analyzed the effect of the lug circumferential angle, lug spacing and the travel reduction of the forces produced in a wheel cage that they developed by a rigid wheel. At the end of the tests, they mentioned that the resistances on the lug might decrease by increasing the circumferential lug angle. Also, these same resistances may havefractional effect on the draft and levitation forces. Ding et al. (2009) performed the wheel-terrain interaction tests via the two types of rigid wheels have different heights, radiuses and lug angles. They stated in the study actualized with four different slip ratios that the wheels can develop the drawbar pull at zero slip ratio. Nakashima et al. (2010) carried performance works out on a sloped terrain area by using 2D discrete element method (DEM) that was developed for horizontal terrain and a rigid wheel with vertical lugs to the wheel axis. They compared the relationships of the travel reduction, sinking of the wheel, wheel torque and the slope angle obtained by DEM with the test results. Ding et al. (2011) performed tests to determine driving performance of wheelsby the rigid wheel with different radii, widths, lug heights, numbers of lugs, and lug inclination angles under different slip ratios. They searched the effects of three different axle loads and four different forward speed on the performance. The experimental results show that the optimum wheel design will be beneficial to develop the wheel-soil relationship. Pradhan et al. (2017) actualized performance tests on the wet land by using rigid wheels with 730 mm radius and 30°, 45° and 60° lug angles. Concerning these tests, the cage wheel with 730 mm diameter and 30° lug angle performed better than other cage wheels.

This paper aims to research the effects of the tires used in off-road vehicles on the tractive performance. The vital contribution of this study is to provide the reference the relationship of tire lug effect and energy efficiency to the next studies besides the empirical research results and analysis methods. Performance tests are actualized by the rigid wheel designed by using profiles at different angles; the best-fit lug angle is tried to be determined in terms of the tractive efficiency.

2. Materials and Methods

In this research,a single wheel tester setup operating by the help of a tractor was used. The single wheel test setupwas manufactured in Konya/Turkey. This configuration that was improved by modificationsbecame capable of conducting better measurements. The single wheel tester shown in Figure 1 consists of three main parts.

Figure 1. Testing system developed for different grounds
Şekil 1. *Farklı zeminler için geliştirilen test sistemi*

The first part is the tractive part and it is connected to the three-point linkage of the tractor. The second part is called as the driving part and it transfers the motion to the test wheel by being connected to the power take-off. The third part is called as the loading part. This part applies a dynamic load on the test wheel(Ekinci and Çarman, 2017).

The single wheel testercan push thetraction carriage (tractor) in the axis of symmetry. In the developed arrangement, three-point hitch connection was made through the arms stretched from the base frame. The maneuverability of the setup was enhanced by this way. The required force for the movement of the wheel was obtained via the hydraulic pump-motor.A gearbox with 1/3 gear ratio was used to increase the revolution received from the power take-off. The hydraulic pump is driven (25 000 kPa pressure in 1500 d d^{-1}) by obtaining 1 500 d d^{-1} rotation due to this gearbox. The motion from the pump drives the hydraulic motor (50 cm^3 d^{-1}, 100 Nm torque at 900 rpm). The hydraulic motor drives the test wheel. To control the speed of the test wheel, the speed of the hydraulic motor was reduced by using a reducer with a gear ratio of 30/1.At the entrance of the gearbox, a torque transducer with a capacity of 1 800 Nm was used to determine the input torque and revolution.For the measurement of the drawbar pull in the tests, load cells with capacities of 25 kN were used at the connection point of the base frame of the four arms for pushingwheel which was articulated to the wheel chassis.The drawbar pulls values obtained from four points were recorded in the datalogger by taking 2 data per second.The loading unit consists of a hydraulic cylinder and pressure regulating valve with the ability to develop a force of 50 kN at 25 000 kPa.The dynamic wheel load was transferred to the wheelfrom the chassis by means of this cylinder that was connected to the upper part of the wheel carrier chassis.In this loading system, which can apply different axle loads to the test wheel, a load cell with a capacity of 25 kN is placed between the hydraulic cylinder and the test wheel, and the applied dynamic loads are measured.

280/70R20 pneumatic radial tire (Pw) with outer diameter of 912 mm, section width 282 mm and static load radius of 416 mm was used for the performance measurements in the study. The circumferential lug angle of the tire is 45º. It is found that the selected tire is also used in five different brands horticulture tractor that are widely used in our country besides the front axles of the 4 WD farm tractors. The main structure of the rigid wheel (Rw) used in the experiments is formed by a cylinder with 282 mm width, 852 mm diameter and 10 mm wall thickness. On this cylinder, 34 steel profiles were placed at 30 mm high, 0, 15, 30 and 45 degree circumferential angles with reference to the lug height of the radial tire.The rigid wheels designed can be seen in Figure 2. Table 1 gives the measurements of the rigid wheel.

Table 1. Technical specifications of rigid wheels
Çizelge 1. *Rijit tekerleklerin teknik özellikleri*

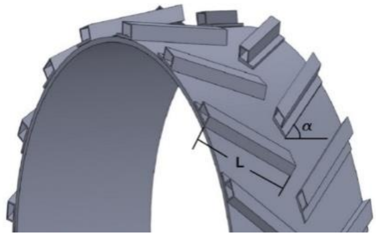
Wheel overall diameter	912 mm			
Cylinder diameter	852 mm			
Cylinder width	282 mm			
Rim diameter	508 mm			
Rim width	280 mm			
Lug height	30 mm			
Lug width	25 mm			
Modified lug at circumferential angle (α)	0º	15º	30º	45º
Lug lengths (L)	141 mm	146 mm	163 mm	199 mm

Handbrake and transmission mechanisms of the tractor were utilized to create the different drawbar pull (braking). TD90D New Holland tractor with 88 horsepower which can develop 356 Nm torque at 1 400 d d^{-1} was used as a traction carriage (braking device). The turning movement required by the single wheel tester is provided by this tractor. It also makes it possible to carry out tests with different drawbar pull using hand brake and auxiliary shift stages.

The actual travel velocity was determined by measuring the elapsed time between the entrance and exit to the trial area of 20 m long of the single wheel tester. This time is measured by a chronometer. Besides, the actual travel velocity in all the combinations was measured via the acceleration sensor that was mounted on the tractor. The obtained data were checked by comparing with the values determined by the chronometer. The revolutionwas measured via the signals received from the magnetic sensors on the torque transducerto specify the theoretical travel velocity. This velocity was calculated by considering the dynamic radii of the wheel in different operating conditions. Drawbar power was calculated using the measured drawbar pull and actual travel velocity values for each combination. To determine the axle power, the torque and revolutionvalues taken from the torquetransducer in each combination are recorded on a computer. The total efficiency was determinedas ($\eta T = \eta_{d1}.\eta_{d2}.\eta_{pm}.\eta_{hm}$) $\eta T = 0.71$ taking into accountthe total transmission efficiency of the gearbox (98 % for η_{d1} and η_{d2}) and the hydraulic pump and hydraulic motor efficiencies (86 % for η_{pm} and η_{hm}). The axle power was calculated according to thistotalefficiency ratio.

Skid resistance was determined in order to reveal the properties of the ground. For this purpose, a portable pendulum skid testerwith ASTM E303 and BS EN 13036-4: 2003 standards were used. The measurements were made according to TS EN 1436 standard of the Turkish Standards Institute (Terzi et al., 2009). As a result of the measurement, 47 SRT skid resistance value was obtained on dry hard terrain and 61 SRT skid resistance value was obtained on wet road.

In agricultural activities, the tractor speed usually ranges from 3 km h^{-1} to 8 km h^{-1}. By taking the average of these speeds, the tests were carried out at a speed of about 5 km h^{-1}. Total weights of the horticulture tractors vary by 1 000-1 380 kg. The axle load for per wheel is about 280-500 kg. While the experiments were planned, the axle load was set at 3.0, 4.5, 6.0 and 7.5 kN, taking this data into consideration. In the study, a total of 20 combinations (1 hard soil ground x 4 axle loads x 5 different wheel lugsconsisting of 1 pneumatic tire and 4 rigid wheel lugs) were taken into consideration.The data in each combination were taken within 20 m when the test tractor was idle, in a handbrake stage and at three different auxiliary shift stages. Each experiment was made in 3 iterations.Variance analyzes were conducted to determine the effects of controlled variables such as type of wheels, axle load and drawbar pull on slip ratio and tractive efficiency values. MINITAB program is utilized to obtain the results of the variance analyses.



(0º) (15º) (30º) (45º)

Figure 2. Experimental rigid wheels with different circumferential lug angles

Şekil 2. *Farklı çevresel profil açılarına sahip rijit deney tekerlekleri*

3. Results and Discussion

The slip ratio value ranges obtained by the drawbar pull varying depending on the structural characteristics and operating conditions of the wheels are given in Table 2.

Table 2. Slip ratio values range of all wheels

Çizelge 2. *Tüm tekerleklerin patinaj oranı değerlerinin aralığı*

Wheel type	Slip ratio (%)	
	Min.	Max.
Pneumatic tire	2	66
Rigid wheel with a 45° lug angle	1.8	73
Rigid wheel with a 30° lug angle	2	70
Rigid wheel with a 15° lug angle	3.5	68
Rigid wheel with a 0° lug angle	2	76

The pneumatic wheel performed better than rigid wheels at almost every load. For low axle loads, the rigid wheel with a circumferential lug angle of 15° has improved more drawbar pull than other rigid wheels.

Pneumatics tire that was tested in the research has 45º circumferential lug angle. It is desirable to design a rigid wheel with 45° circumferential lug angle, in order to determine how close the performance values of these wheels are with each other in respect of to the performance values of the pneumatic wheel. The aim here is to assign the rigid wheel having 45º circumferential lug angle as the reference wheel when comparing the performances of the rigid wheels.

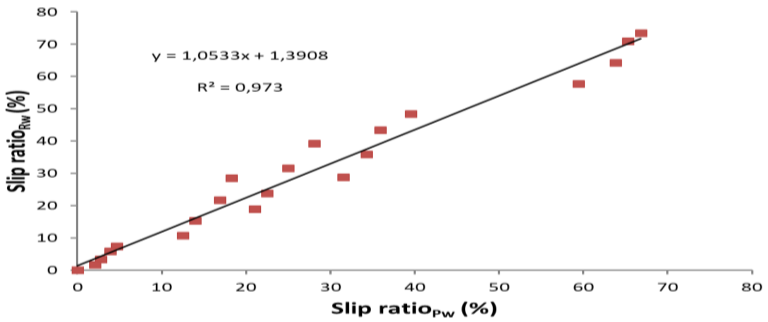


Figure 3. Comparison of slip ratio values of rigid wheel with a 45° lug angle with pneumatic tire
Şekil 3. *45° profil açılı rijit tekerleğin patinaj oran değerlerinin pnömatik lastikle karşılaştırılması*

Figure 3 shows refer to the connection between the pneumatic tire and the rigid wheel which has 45º circumferential lug angle by considering the slip ratio values in all combinations. As can be understood from the figure, there is a linear relationship between both the wheels, a high correlation (R = 0.986) and an acceptable accuracy. The pneumatic tire provided the same drawbar pull at 12 % lower slip ratio than rigid wheels in combination with all axle loads. Hermawan et al. (1998) stressed out that the drawbar pull of rigid wheel increases by the increment of the travel reduction. Pneumatics wheel provided a better road holding than the rigid wheels due to the structural characteristics. Cushion gum of the tires are hard; tire shoulders are soft; this structure ensured remaining of the area of the tire as the same width. Because of the flexibility of the tire wheel the contact area is more than the rigid wheel. This condition provided tires to hold on to the ground and develop higher drawbar pull in lower slip ratio values. Watyotha et al. (2001) reported that the lug angle on rigid wheels with different circumferential lug angles has little effect on the drawbar pull as a result of working with a single axle load. They achieved the best performance on a rigid wheel with a 15º circumferential lug angle. Similar results were obtained in our study. Due to performance experiments were actualized in four different axle loads, the wheel with 15º circumferential lug angle performed best in low axle loads while the wheel with 45º circumferential lug angle performed best in high axle loads.

Figure 4 shows the relationship between the slip ratio and drawbar pull values depending on the axle load of driven tires and rigid wheels worked on the hard soil ground.

50 % increase in the axle load caused slip ratio decrement in tire wheel as 7 %, 45° circumferential lug angle rigid wheel as 12 %, 30°rigid wheel as 17 %, 15° rigid wheel as 5 % and 0°rigid wheel as 11 %. A 150 % increase in axial load resulted for 20%, 40 %, 27%, 9 % and 32 % reduction in average slip ratio of the pneumatic tire and rigid wheels with 45, 30, 15, 0 circumferential lug angles, respectively. When looking at the performance values of the rigid wheels, it was appeared that rigid wheels with 5° circumferential profile angle at 3 kN axle load developed a higher drawbar pull than the others. At axle loads of 6 kN and 7.5 kN, the rigid wheel with 45 ° circumferential lug angle improved more drawbar pull. It was observed that the slip ratio values decreased due to the increased axle load. When the axle load was increased by 50 %, the average slip ratio values are reduced by 11 %

for all wheel combinations, and when the axle load is increased by 100 %, the average slip ratio value is reduced by 19 %. In this case, it can be said that the increase of the tire contact area and the increase of adherence between the wheel and the hard soil ground are due to the increased axial load. Ferhad begovic et al. (2005) denoted that the difference between drawbar pull and slip ratio increased as the tire deflection increased with increasing axle load. Hermawan et al. (1998) mentioned as a result of the experiments performed by the rigid wheel that the slip ratio decreases by an increment of the axle load. According to the observation of Ding et al. (2011), the performance increases by the increment of the axle load. Upadhyaya and Wulfshon. (1989) stated that the increase in axial load improved performance on the clayey soil. It is expressed by Çarman and Aydın (2002) that as axle load increases, drawbar pull increases by 32 % at 17 % slip ratio. Table 3 shows the results of variance analysis performed on the slip ratio values obtained from the changing operation conditions of the rigid wheel having four different circumferential lug angles.

The results of variance analysis show that the effect of the axle load and the drawbar pull on the slip ratio is significant ($P<0.01$).

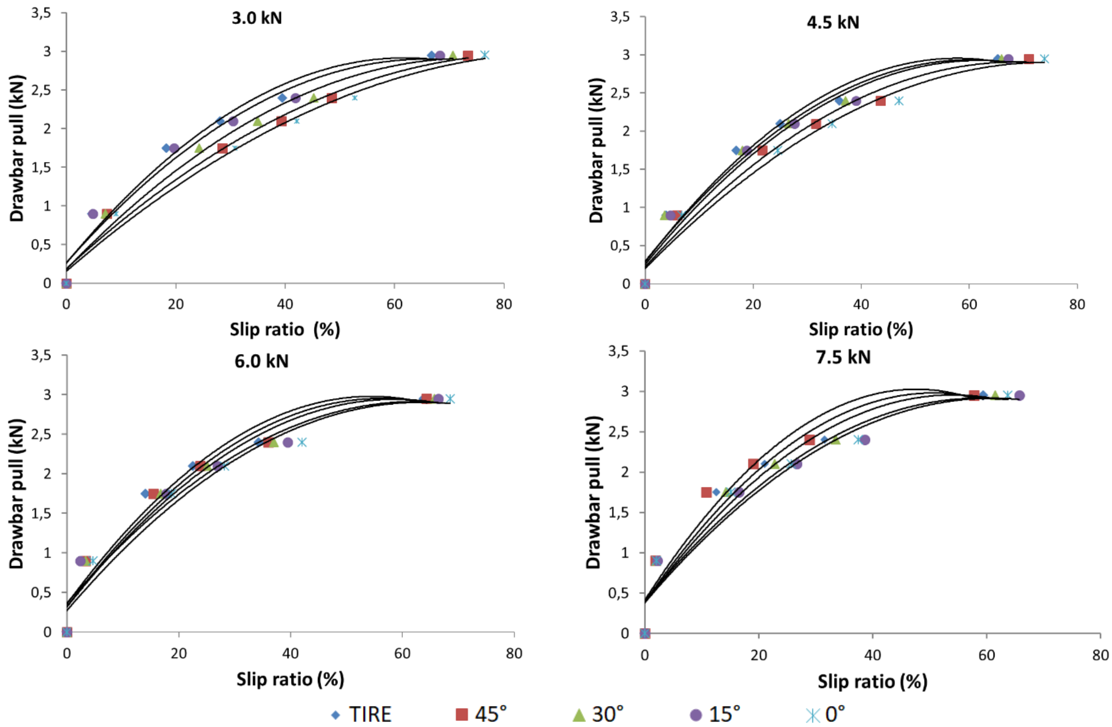


Figure 4. Relationship between slip ratio and drawbar pull values depending on the axial loads
Şekil 4. *Aks yüklerine bağlı olarak patina oranı ve çeki kuvveti değerleri arasındaki ilişki*

Depending on the different structural and operating characteristics of the test wheels, the tractive efficiency values varied between 0.14-0.66 for varying slip ratio values. The average tractive efficiency of the rigid wheels in all combinations was obtained 42 %, while the tractive efficiency of pneumatic wheel was obtained 45 % on average. The maximum tractive efficiency was obtained 10 % slip ratio value for the pneumatic wheel and 12 % for the rigid wheel with 45° circumferential lug angle. With reference to Değirmencioğlu and Way (2004), the tractive efficiency was a function of tire in flation pressure and the slip ratio; the maximum tractive efficiency was obtained at 7.5 % slip ratio value and at the lowest tire inflation pressure; the tractive efficiency decreased as the slip ratio increased. For all axle loads; an increase of 50 % in the axle load caused increase of average tractive efficiency. These increases were6% for pneumatic wheel,4 % for rigid wheel with 45° circumferential lug angle, 9 % for rigid wheel with 30 °, 3 % for rigid wheel with 15 ° and 5 % for rigid wheel with 0°. The 150 % increase in axial load caused 12 %, 25 %, 13 %, 6 % and 16 % increase in average slip ratio on tire and 45, 30, 15, 0 degrees rigid wheels, respectively. Burt et al. (1983) stated that the tractive efficiency increased when the axle load was increased. According to Çarman and Aydın (2002), the axle load was increased by 50 % the tractive efficiency increased by 6%. The change of the tractive efficiency based on the slip ratio can be seen in Figure 5.

Maximum tractive efficiency was achieved between 10-12 % slip ratio values depending on operating conditions. It is confirmed by Akıncı and Sabancı (1991) that optimum slip ratio value in stubble field was between 12-17 %.

Table 4. refers to the results of the variance analysis performed on the tractive efficiency values. With reference to these results, the effect of the axle load and the drawbar pull on the tractive efficiency is significant (P<0.01).

Table 3. Results of variance analysis for slip ratio values
Çizelge 3. *Patinaj oranı değerleri için varyans analizi sonuçları*

VS	DF	SS	MS	F- Statistics	P
Tire size (T_s)	3	417.4	139.1	1.95 ^{ns}	0.176
Axle load (W)	3	1 657.3	552.4	321.61**	0.000
Drawbar pull (F_d)	4	107 469.6	26 867.4	374.56**	0.000
T_s*W	9	15.5	1.7	0.87^{ns}	0.560
T_s* F_d	12	860.8	71.7	36.34**	0.000
W*F_d	12	120.1	10.0	5.07**	0.000
T_s*W*F_d	36	71.1	1.8	0.08 ^{ns}	1.000
Error	160	3 784.3	23.7	-	
Total	239	114 396.1	-	-	

**, (P<0.01); ns, not significant

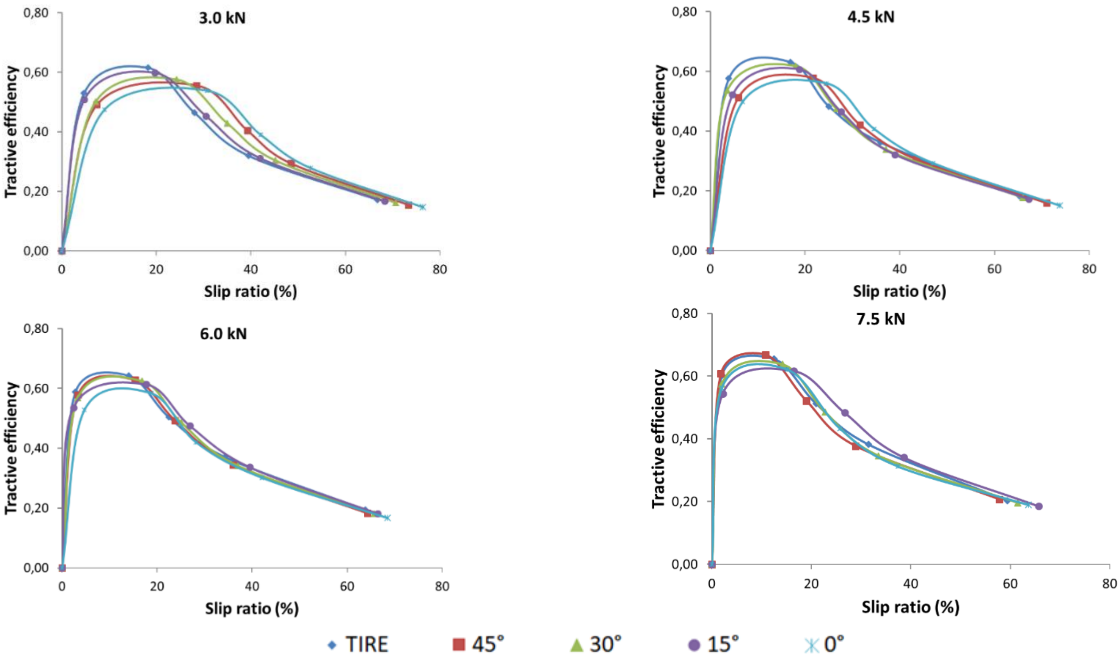


Figure 5. Tractive efficiency versus slip ratio for the rigid wheels and the pneumatic tire
Şekil 5. *Rijit tekerlek ve pnömatik lastik için patinaj oranına karşı çeki verimi*

Table 4. Results of variance analysis for tractive efficiency values
Çizelge 4. *Çeki verimi değerleri için varyans analizi sonuçları*

VS	DF	SS	MS	F- Statistics	P
Tire size (T_s)	3	0.015776	0.005259	4.70^{ns}	0.031
Axle load (W)	3	0.039546	0.013182	10.04**	0.001
Drawbar pull (F_d)	4	1.877898	0.469474	1 849.45**	0.000
T_s*W	9	0.010060	0.001118	19.21**	0.000
T_s* F_d	12	0.003577	0.000298	5.12**	0.000
W*F_d	12	0.003046	0.000254	4.36**	0.000
Error	36	0.002095	0.000058	-	-
Total	79	1.951998	-	-	-

**, (P<0.01); ns, not significant

4. Conclusion

This work is about the tractive performance of the lug effect on driven tires used in small-sized tractors such as horticulture tractors. The main aim is to constitute relevant data. The results and suggestions for this study are as follows. It has been determined that the effects of the controlled variables on the slip ratio values obtained due to the varying drawbar pull values on the hard soil ground conditions are significant. Average slip ratio of the rigid wheel with 0º circumference lug angle was the highest, because adherence to ground of this rigid wheel is insufficient. There was a decrement in the slip ratio based on the increasing axle load. The wheel with 15º circumferential lug angle performed best in low axle loads while the wheel with 45º circumferential lug angle performed best in high axle loads. We can say that the effects of the controlled variables on the slip ratio are more important (P<0.01).

Depending on the changing structural and operating characteristics of the driven wheels, the tractive efficiency values according to the changing slip ratio values were found between 0.14-0.66. The results of the analysis showed that the effect of the axial load on the tractive efficiency was significant (P <0.01). Maximum tractive efficiency was obtained in the rigid wheel with 45º circumferential lug angel as 66 % values. Maximum tractive efficiency occurred between 10-12 % slip ratio values based on the working conditions.

It has seen that the performances of the pneumatics wheel with 45º circumferential lug angle and the rigid wheel with 45º circumferential lug angle were the values that are so close to each other. Thus, two important issues can be mentioned. Being the performances so close of pneumatics wheel and the rigid wheel means that the rigid wheels that have other circumferential lug angles may show close performance values with the pneumatic wheels with the same angles. In other words, the pneumatic wheel that has the best lug angle can be produced and used as the front wheel of the garden and farms tractors so that a higher efficiency will be gained. Secondly, since rigid wheels perform approximately with pneumatic wheels, a modular rigid wheel, in which the lug angles can be changed, can be manufactured to achieve an efficient operation by adjusting to the desired circumferential profile depending on the axle load and the operating conditions. It has been observed that the tractive performance increases in direct proportion to the axle load for both the wheel types. The soil compaction increases by the increment of the dynamic axle load. For this reason, it is recommended that an optimum axle load be selected for agricultural activities. Besides, the available tractor force ought to be used as more efficiency by carefully choosing the parameters such as tire type, lug angle, inflation pressure and axle load instead of using a more powerful tractor.

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