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Effects of Some Properties of Drive Tires Used in Horticultural Tractors on Tractive Performance

Şerafettin EKİNCİ[a], Kazım ÇARMAN[b]

[a]*Selcuk University, Faculty of Technology, Department of Mechanical Engineering, Konya, TURKEY*

[b]*Selcuk University, Faculty of Agriculture, Department of Agricultural Machinery, Konya, TURKEY*

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Corresponding Author: Şerafettin EKİNCİ, E-mail: sekinci@selcuk.edu.tr, Tel: +90 (505) 703 43 50
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ABSTRACT

Many studies on tractive performance of tractor tires have been carried out to solve soil-wheel interaction problems in the last decades. The purpose of this study is to experimentally determine effects on tractive performance of radial and bias-ply drive tires at three different tire lug heights, axle loads and inflation pressures. The experiments were carried out in stubble field conditions. To obtain sufficient performance data, a new single wheel tester was designed and manufactured. Travel reduction, net traction ratio and tractive efficiency varied from 3.3% to 34.1%, 0.24 to 0.93 and from 0.27 to 0.78 respectively depending on drawbar pull. The effects of tire type, lug height, dynamic axle load and inflation pressure on tractive efficiency were found significant (P<0.01) by the performed variance analysis and LSD tests. Radial tires provide better tractive performance compared with bias-ply tires. The tractive efficiency increased especially with increasing dynamic axle load and decreased with increasing tire inflation pressure. Tire dynamic axle load was the major contributory factor on tractive performance as compared with other independent variables. For a given drawbar pull, it was observed that tractive efficiency of radial tire can be maximized by selecting appropriate levels of lug height, dynamic axle load and inflation pressure.

Keywords: Dynamic load; Inflation pressure; Lug height; Tire; Tractive efficiency; Tractive performance

Bahçe Traktörlerinde Kullanılan Muharrik Lastiklerin Bazı Özelliklerinin Çeki Performansına Etkileri

ESER BİLGİSİ
Araştırma Makalesi
Sorumlu Yazar: Şerafettin EKİNCİ, E-posta: sekinci@selcuk.edu.tr, Tel: +90 (505) 703 43 50
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ÖZET

Yıllardır, toprak-tekerlek etkileşimi sorunlarını çözmek için traktör lastiklerinin çeki performansı üzerine birçok çalışma yürütülmüştür. Bu çalışmanın amacı, bahçe traktörlerinde kullanılan üç farklı profil yüksekliğine sahip radyal ve çapraz katlı muharrik lastiklerin çeki performansına, aks yükünün ve lastik iç basıncının etkilerini deneysel olarak belirlemektir.

Denemeler anız tarla koşullarında yürütülmüştür. Belirtilen şartlar altında, yeterli performans verileri oluşturabilmek için, yeni bir tek tekerlek deney düzeneği tasarlanmış ve imal edilmiştir. Çeki kuvvetine bağlı olarak; patinaj değerleri % 3.3 ile % 34.1, net çeki oranı değerleri 0.24 ile 0.93 ve çeki verimliliği değerleri 0.27 ile 0.78 arasında değişmiştir. Yapılan varyans analizi ve LSD testi sonuçları; lastik tipi, profil yüksekliği, dinamik aks yükü ve lastik iç basıncının, çeki verimliliği üzerindeki etkisinin önemli olduğu göstermiştir ($P<0.01$). Radyal lastikler çapraz katlı lastiklere göre daha iyi çeki performansı sağlamışlardır. Çeki verimliliği, özellikle dinamik aks yükünün artırılmasıyla artmış, lastik iç basıncı artırıldıkça çeki verimi azalmıştır. Dinamik aks yükünün çeki performansı üzerindeki etkisi diğer bağımsız değişkenlere göre daha büyük olmuştur. Çeki verimliliği, radyal lastiklerin uygun profil yüksekliği, aks yükü ve iç basıncının seçilmesiyle artırılabileceği gözlenmiştir.

Anahtar Kelimeler: Çeki performansı; Çeki verimi; Dinamik yük; İç basınç; Lastik; Profil yüksekliği

1. Introduction

The main power supply of agricultural production is tractor. Due to increasing production of vegetables and fruits, small and powerful horticulture tractors are widely used in agricultural production. Tires are an important part of off-road vehicles; hence the study of its structural and working characteristics are of fundamental importance. The tractive characteristics of tire depend on tire geometry (weight, diameter, section height), tire type (radial, bias-ply), lug design, inflation pressure, dynamic load on the axle, soil type and ground conditions.

Net traction ratio (NTR) and tractive efficiency (TE) are two important factors of tractive performance (Burt et al 1980). Bashford et al (1993) compared the dynamic traction ratio and the tractive efficiency of a tractor equipped with three different sized rear tires at different inflation pressures and on two different surfaces. As a result, the best tractive performance was observed at the lowest inflation pressure.

Generally bias-ply and radial tires are used for agricultural tractors. As for radial tires, much research has been conducted, and it has already been found that lowering inflation pressure increases tractive performance (Lee & Kim 1997). Many studies have demonstrated that there are some advantages in using radial tractor tires over the bias-ply tires. These advantages are due to the construction of radial tires (Al-Hamed et al 1994). Looking at the performance level of the tire types, tractive performance of radial tires is higher than the performance of the bias-ply tire types. Bias-ply tires show lower efficiency of power distribution than radial tires (Turner 1995).

To take advantage of power generated by the tractor, proper axle loads are necessary considering travel reduction limits. Effects of inflation pressure and dynamic load on soil compaction for a forwarder tire were investigated by McDonald et al (1996). Reductions in inflation pressure at a given dynamic load tended to decrease bulk density, soil cone index, and rut depth. Decreases in these variables tended to be affected more from dynamic load than inflation pressure. Çarman & Aydın (2002) reported that dynamic load increased drawbar pull at the rate of 32% at travel reduction of 17%. The tractive efficiency tended to increase as static load increased for a given inflation pressure (Elwaleed et al 2006).

Adjusting tire inflation pressure has been used as a method for improving tractive performance of agricultural tractors. Adjusting inflation pressure has recently attracted attention of many researchers. It is known that optimum tractive performance of a driving tire can be obtained by adjusting the inflation pressure of the tire based on soil conditions (Lee & Kim 1997). A lot of researches have been conducted where the effects of inflation pressure for different tire sizes were investigated. A decrease in inflation pressure results in an improvement tractive performance of the tire. Jun et al (2004) reported that the net traction and the tractive efficiency of the forwarder tire decreased with increasing inflation pressure at constant dynamic load.

Machines for operating a single wheel for traction and soil compaction research are commonly known as single tire testers or single wheel testers. Some single tire testers are large enough to accommodate the largest agricultural tractor drive tires currently available, which are up to about 2090 mm overall diameter. Other single tire testers are designed to accommodate a smaller tire, such as a garden tractor rear tire with an overall diameter of about 600 mm (Way 2009). Various designs of single wheel traction research machines have been developed and used. Machines for operating a single tire on soils in soil bins include those described by Pope (1971), Raheman & Singh (2003), Kawase et al (2006), Yahya et al (2007) and Tiwari et al (2009). There are some disadvantages of them. Soil bins, where the soil is brought to the tester, have been used to acquire a significant amount of data; however, the majority of these tests were conducted with low wheel speeds and wheel slips, and soils used in outdoor or indoor bins do not perform like those found in the field. This lack of data leaves tractor pullers with a trial and error approach to the tractive performance of the vehicle (Upadhyaya et al 1986). At asphalt, concrete, stabilized, stubble field or plowed field conditions, single wheel testers designed to overcome the disadvantages of soil bin used in experiments in order to carry out tractive performance tests, are completely dependent to tractor or semi-independent. Single wheel traction research machines for operating a single tire in a field include those described by Upadhyaya & Wulfsohn (1989), Monroe & Burt (1989), Schmulevich et al (1996), Ferhadbegović et al (2005) and Way (2009). The single wheel tester in our work was selected among others in the literature because of its capability as a tire and can be subjected to performance tests for different types of grounds with this single wheel tester. Also, this single wheel tester was designed for the first time in our country and was used in tractive performance experiments.

In the performance experiments encountered in the literature survey, tests are conducted on relatively big diameter tires of powerful tractors used in big farms. Trials for tires used for horticultural tractors are less in number. The novel part of our study is that it is done for the tires of horticultural tractors. Because it was thought that the dependent and independent parameters in former studies were insufficient in providing a proper view of tire tractive performance, increased number of parameters are accounted in the experiments.

There is very little information about tractive performance of tires based on wheel speed and travel reduction conditions of small structures such as horticulture tractors. Therefore a new single wheel tester was designed and manufactured to create sufficient data under these conditions. With single wheel tester, it was studied to determine tractive performances of two different tire types for three different tire lug heights, three different axle loads and three different tire inflation pressures in stubble ground conditions. Experiments were conducted by mounting single wheel tester to a three point hitch of an agricultural tractor (Ekinci 2011).

2. Material and Methods

2.1. Facilities and equipment

In this study, a new single wheel tester (traction setup) was designed and manufactured for determining tractive performance of tractor tire. This mechanism is capable of controlling peripheral speed of tire, wheel travel reduction and dynamic wheel load sufficiently. Designed and manufactured single wheel tester can carry out performance measurements of up to 10 kN axle load and 3.5 kN m torque (Ekinci 2011).

The single wheel tester used in tractive performance experiments consists of three sections (Figure 1). The first part is traction section. It is connected to three point linkage mechanism of tractor. This part provides mobility to experimental setup, which pushes symmetry axis to tractor (traction carriage).

The second section is driving system. It transfers motion from hydraulic motor driven by hydraulic pump connected to PTO shaft of the tractor to test tire. Power transmission via the hydraulic pump

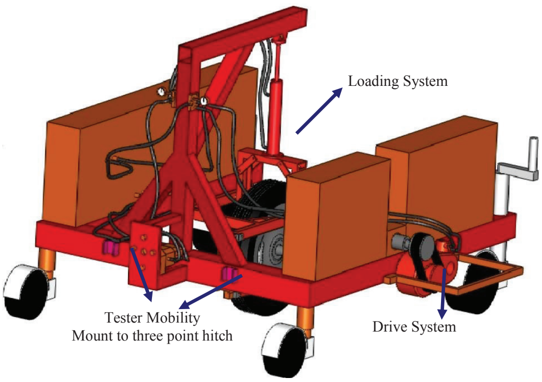

Figure 1- Single wheel tester design concept

Şekil 1- Tek tekerlek deney düzeneğinin tasarım konsepti

and motor combination is provided. The pump was attached to the PTO using a planetary step up gearbox. This planetary gearbox has 1:3 speed increments and was attached to the 540 rpm PTO shaft on the tractor. A variable tandem pump was chosen for this application. The maximum displacement of the pump is 32 cm^3 rev^{-1}. The operating pressure of this pump is 175 bar and pressure limited using pressure regulating valve. The selected motor is a fixed displacement motor with a maximum output torque of 119 Nm. Maximum speed is 1210 rpm and the motor displacement is 50 cm^3 rev^{-1}. Hydraulic motor drives the test wheel. The tire driving system is powered with a 30:1 speed reducing gearbox through a flexible coupling when running in the driving test mode. In order to determine torque, a transducer with the capacity of 3000 Nm was used between gearbox output and the wheel axis input. Input torque to the wheel axle was measured by this torque transducer and recorded in a data logger. Joint shaft was used between these two points in order to intercept the axis eccentricity which is caused by preformed deflections on tire depending on changing dynamic load and internal pressure of tire. Table 1 shows the specifications of load-cells and transducer.

Third section is loading system which consists of a hydraulic piston cylinder mechanism and applied dynamic load to test tire. The hydraulic tandem pump has dual-stage and first stage of the pump was used in the driving system. The second stage operates the cylinder of loading system. The Loading system consists of pressure regulating valve and a hydraulic cylinder which is capable of developing 50 kN force at 25000 kPa pressure. Hydraulic cylinder was connected to upper carrier wheel carriage and dynamic wheel load was transferred from the frame to the tire under test via a hydraulic cylinder connected to an S-type load cell. A 3/8” hose was used in this circuit with JIC 37^o fittings used for the connections. Eight 50 kg concrete blocks were mounted to the frame to provide an increased load to the tire as the cylinder rod was extended. With the included weight of the frame, the tester was able to provide 8 kN wheel load.

Table 1- Specification of loadcells and transducer

Çizelge 1- Yük hücreleri ve torkmetrenin teknik özellikleri

Torque transducer		*Loadcell*	
Specification	*Values*	*Specification*	*Values*
Measurement range	2000~5000 Nm	Capacity	2500 kg
Max axial load	4800 N	Sensitivity	3.0±0.003 mV V^{-1}
Max radial load	1950~4000 N	Input resistance	400±20 Ω
Supply voltage	12V DC ±10%	Output resistance	352±3 Ω
Option speed rev. max	up to 10 000 rpm	Insulation resistance	≥5000 MΩ
Current consumption	Approximately 160 mA	Ultimate overload	180% F S
Voltage output	0 to ±10V	Excitation	10~12 DC

Two types of tires, bias-ply and radial tires, were used during the experiments. The tires had three different lug heights which were h_{Lb1}= 18, h_{Lb2}= 14, h_{Lb3}= 10, h_{Lr1}= 30, h_{Lr2}= 24, h_{Lr3}= 14 mm. Table 2 shows the values of the parameters for the tire manufacturer. h_{Lb}: Bias-ply lug height, h_{Lr}: Radial lug height.

Table 2- Specifications of test tires

Çizelge 2- Test lastiklerinin teknik özellikleri

Specification	*Values*	
	Bias-ply	*Radial*
Tire type	7.50-18	7.50R18
Ply rating	8	-
Tire section height (mm)	205	205
Tire overall diameter (mm)	860	860
Tire carrying capacity (kg)	950	900
Load index and speed symbol	106 A6	104 A8

2.2. Experimental procedure

Prior to the test, the dynamic rolling radius of the tires were determined on a concrete road surface under unloaded condition. Grease was plastered onto lug on tire which contacted the ground. Tire was rotated four cycles at lower velocity through a straight line in test ground. Distance between the first contact trace and the last contact trace was measured and divided by 8π to obtain the dynamic rolling radius. Dynamic radii were determined for the specific experimental conditions for every profile height, dynamic axle load and inflation pressure.

In order to determine the actual forward speed of the wheel for each test, elapsed time between start and finish point of the test area with 100 m distance was measured via a chronometer. Wheel revolution (n) was measured through a magnetic sensor which was on torque transducer to determine the theoretical velocity.

The variables recorded for each test were (W) dynamic axle load on wheel (P_i) tire inflation pressure (F_t) drawbar pull, (T) input torque to the axle, (V_a) actual velocity and (V_t) theoretical velocity.

The traction parameters used to describe the tractive performance are described in Equations 1 to 5.

Tire travel reduction (S), $$S = \left(1 - \frac{V_a}{V_t}\right) \cdot 100 \qquad (1)$$

Drawbar power, $$P_D = F_t \cdot V_a \qquad (2)$$

Axle power (kW), $$P_a = \frac{T \cdot n}{9549} \qquad (3)$$

Tractive efficiency, $$TE = \frac{P_D}{P_a} \qquad (4)$$

Net traction ratio, $$NTR = \frac{F_t}{W} \qquad (5)$$

The tests were conducted on stubble field ground. In order to check the uniformity of the bed conditions, a few important soil parameters such as penetration resistance of a soil, soil shearing strength, moisture content and surface roughness were measured before starting the experiment (Çarman 1997). Soil ground conditions of stubble field are given in Table 3.

Table 3- Soil parameters of stubble field

Çizelge 3- Anız tarlanın toprak parametreleri

Parameter	*Value*
Texture	Clay-loam
Clay (%)	38.00
Silt (%)	38.00
Sand (%)	24.00
Gravimetric moisture content (%) (0-20 cm)	12-13
Penetration resistance (MPa) (0-20 cm)	2.74
Shearing strength (kN m^{-2})	31.74
Surface roughness (%)	6.09

Surface relief was measured using surface profilemeter. This consisted of a set of vertical rods, spaced at 2.5 cm intervals, sliding through an iron bar of 100 cm length. The soil surface roughness was calculated by using the Kuipers equation (Equation 6).

$$R_d = 100 \cdot \log S_d \qquad (6)$$

Where; S_d, standard deviation.

Penetrometers which can measure up to 80 cm depth at each 1 cm distance were used for measuring soil penetration resistance as MPa. Measurements were taken from 0-20 cm depth. Soil shear testing device was used in order to determine the soil shearing strength (τ) which has 10 cm diameter and 12 cm height. Torque arm with measuring range of 0-80 Nm was impaled on shear vane. The maximum torque was obtained via soil shear testing device while shearing strength was obtained by the Equation 7 (Okello 1991).

$$\tau = T / \left[\pi \cdot d_k^{\,2} \left(h_k / 2 + d_k / 6\right)\right] \qquad (7)$$

Where; d_k, paddle switch device diameter and h_k, paddle switch device blade height.

Traction tests were conducted at velocities of about 5 km h^{-1} under stubble field surface conditions which has 100 m distance test area using bias-ply and radial tires having three different lug heights. Axle loads were approximately 5 kN per wheel for horticulture tractors. As experiments were planned by considering these data, axle load was determined respectively as 3.5, 5 and 6.5 kN. Here, values of ±30% of the 5 kN were taken into account. Axle loads were applied on to the tire by means of a hydraulic cylinder. Dynamic axle load was measured with a loadcell between hydraulic cylinder and wheel carriage. The experiments were conducted at three different tire inflation pressures of 230, 260 and 290 kPa. These inflation pressures varied at ±12% of the inflation pressure recommendation by tractor manufacturers. These tractor manufacturers recommend inflation pressures for the practical inflation values that local farmers use in horticulture tractor. Every test combination was conducted at five different hand brake levels of the test tractor, and thus five different brake forces were attained. The measurements were repeated 5 times at each dynamic load and inflation pressure. Test tire was made to move via driving system of single wheel test setup mounted on the tractor and brake was applied to the setup by means of hand brake lever. Four parallel linkages were connected between the main carriage and wheel carriage through load cells. The parallel arms used eliminate the change in vertical reaction force. Drawbar pull is measured using four load cells offset by a vertical distance and symmetric with respect to the tire. Drawbar pull value which was imported via those four load cells was recorded to data taker. Drawbar pull, forward velocity, wheel torque and wheel rotational speed were measured and stored in the data logger. Variance analyses of manipulated variables such as tire type, lug height, axle load and inflation pressure were done in order to determine their effects on tractive efficiency values. MINITAB program was used to obtain the results of variance Analysis and LSD tests were done via ANOVA module.

3. Results and Discussion

Two types of tires were each tested at three different lug heights, three levels of inflation pressure and three different vertical loads in stubble field. Two performance characteristics were compared as TE and NTR. The data collected for each experiment was analyzed in a spreadsheet to develop simple relationships between tire type and NTR. The plotted graphs (Figure 2) show that the tire NTR increased with the travel reduction, but the rate of the increase also decreased with increasing travel reduction.

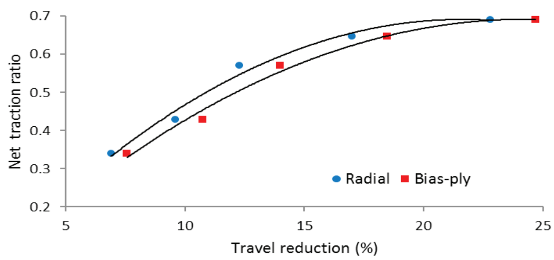

Figure 2- Net traction ratio as a function of travel reduction for the bias-ply with lug height of 14 mm and radial tire with lug height of 14 mm

Şekil 2- 14 mm profil yüksekliğine sahip çapraz katlı ve radyal lastik için patinajın bir fonksiyonu olarak net çeki oranı

Wheel torque and net traction increase with travel reduction or slip, because initial travel reduction is mainly due to elastic deformation of the tire tread. Further increase in wheel torque and net traction results in part of the tire tread sliding on the ground. At all combinations of three levels of inflation pressure and three different vertical loads, bias-ply tires with lug height of 14 mm developed the same NTR at approximately 10% more travel reduction ratio than radial tires with the same lug height. Depending on the structural and operational characteristics of drive tire, minimum travel reduction value was found to be 3.3% and maximum travel reduction value was 34.1%. Upadhyaya & Wulfsohn (1989) and Bashford & Kocher (1999) found that radial tires performed better than bias ply tires.

At same travel reduction ratio, maximum NTR was 0.69 for h_{Lr1} lug height of tire while maximum NTR was 0.58 for h_{Lb3} lug height. Travel reduction ratio for radial tire decreased by 8% when lug height of tire was increased by 71%. Also, travel reduction ratio for radial tire decreased by 25% when lug height of tire was increased by 114%. For bias-ply tire, when lug height of tire was increased by 40% and 80%, travel reduction ratio decreased respectively by 7% and 28%. Although increased lug height increased the hold on tire to soil, decreased lug height increased travel reduction because the tire did not hold on sufficiently to the soil. The results showed that the tire with high lugs can develop higher NTR than the smooth tire. The effect of lug height on the NTR is shown in Figure 3. Plackett (1984) found that as lug height increased, size of the contact area increased, leading to a reduction in mean ground pressure. Thus, NTR increased when lug height of tire was increased. Nakashima et al (2007) stated that higher lugs tend to yield higher net traction.

Figure 4 indicates the effects of travel reduction at variable dynamic load on net traction, respectively. For a given dynamic load, net traction increased as travel reduction increased. During the experiments, average travel reduction values decreased by 21% for bias-ply tires and by 18% for radial tires depending on increased axle load of 86%. Dynamic load affected soil-tire contact pressures differently

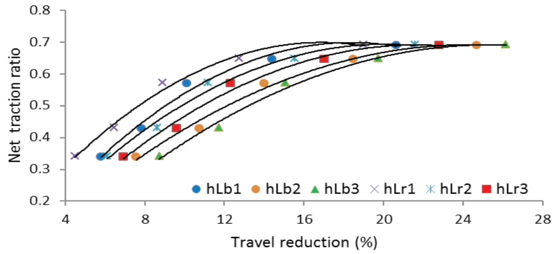

Figure 3- Net traction ratio as a function of travel reduction for six lug heights of tires

Şekil 3- Lastiklerin altı profil yüksekliği için patinajın bir fonksiyonu olarak net çeki oranı

for the different transducer locations. Results from previous research for radial-ply tractor drive tires indicate that an increase in dynamic load caused a decrease in normal stresses on lugs at the lug middle and tire centerline positions and an increase in normal stress at the outside edge of the lug, on firm soil (Burt et al 1980). Çarman & Aydın (2002) observed that NTR and TE showed an increase of 22% and 6% respectively when they increased about 50% of the dynamic load.

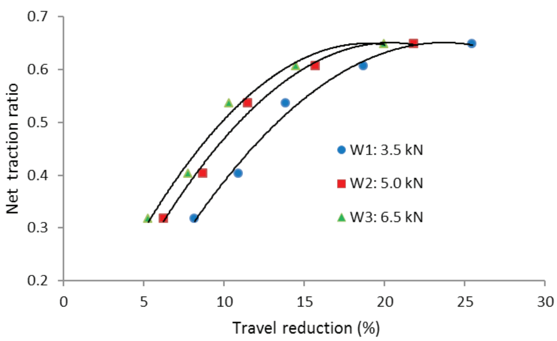

Figure 4- Net traction ratio as a function of travel reduction for three different dynamic loads

Şekil 4- Üç farklı dinamik yükü için patinajın bir fonksiyonu olarak net çeki oranı

The highest value of 0.65 of NTR was reached at inflation pressure of 230 kPa while using bias-ply and radial tires. By increasing tire inflation to 290 kPa, the NTR decreased to 0.62 at same travel reduction ratio. Figure 5 shows the graph of tire NTR for the three inflation pressures (230, 260 and 290 kPa). When tire inflation pressure was increased from 230 to 260 kPa, average travel reduction values increased by 27% for both bias-ply and radial tires. In the slip range of approximately 20-30%, the course follows a linear part, where increase of drawbar pull causes the increase of slip loss. The positive effect of lowering inflation pressure on the improvement of tractive performance was evident when forward velocity was 5 km h^{-1}. Jun et al (2004) claimed that in height inflation pressure and low dynamic load, distributions of contact pressures across tire width were highly non-uniform and pressures were concentrated at the middle of lug. Correct combinations of dynamic load and inflation pressure were used; however, the distributions of contact pressure were relatively uniform. Therefore, net traction and tractive efficiency of tire decreased with increasing inflation pressure at constant dynamic load. At constant inflation pressure, net traction and tractive efficiency increased with increasing dynamic load.

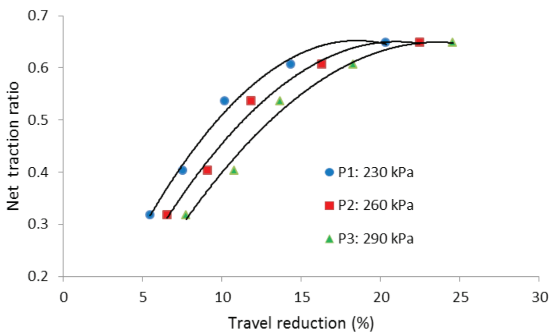

Figure 5- Net traction ratio as a function of travel reduction for three different inflation pressures

Şekil 5- Üç farklı iç basınç için patinajın bir fonksiyonu olarak net çeki oranı

Depending on changing structural and working characteristics of drive tire, tractive efficiency values were determined in a range of 0.27-0.78 at changing travel reduction. The greatest tractive efficiency for both tires was obtained at the lowest inflation pressure of 230 kPa and the highest dynamic load of 6.5 kN. Tractive efficiency of the radial tire was greater at all combinations. Tractive efficiency of radial tire with lug height of 14 mm was 2% more than bias-ply tires with lug height of 14 mm. The greatest difference in terms of tractive efficiency between the radial and bias-ply tire was obtained at 230 kPa inflation pressure, 6.5 kN and 4.6% travel reduction. A certain amount of travel reduction of radial tires was obtained at lower levels than bias-ply tires for same axle loads and inflation pressures. Tractive efficiencies as a function of travel reduction for both radial and bias-ply tires are shown in Figure 6. Analysis of variance (ANOVA) was developed showing effects of of tire type, lug height, axle load and inflation pressure interactions on tractive efficiency (Table 4). As appreciated from Table 4, effect of both tire types on tractive efficiency was found to be important ($P<0.01$). Sümer & Sabancı (2005) indicated that radial-ply tires provided a slight advantage over bias-ply tires. Overall tractor efficiency was increased by 3.44%, while specific fuel consumption was decreased by 3.08% on average with radial-ply tires compared to bias-ply tires.

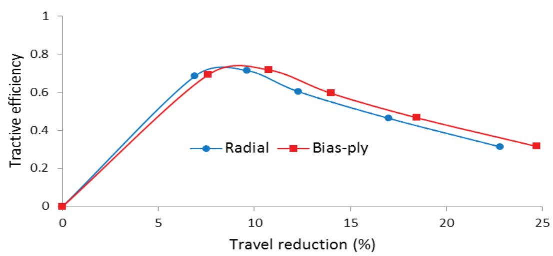

Figure 6- Effect of tire type on tractive efficiency at varies travel reduction levels

Şekil 6- Farklı patinaj seviyelerinde lastik tipinin çeki verimi üzerine etkisi

Particularly, increasing of lug height has a great effect on tractive efficiency on stubble ground. When lug height was increased by 71% for radial tires, the tractive efficiency increased by 4%. Likewise, when lug height of bias-ply tire was increased by 40%, the tractive efficiency increased by 5% (Figure

Table 4- Variance analysis and LSD tests which were carried out for tractive efficiency values at stubble field conditions

Çizelge 4- Anız tarla şartlarındaki çeki verim değerlerinin varyans analizi ve LSD testleri

VS	*DF*	*SS*	*MS*	*F- Statistics*
Tire size (T_s)	1	0.0072558	0.0072558	93.34**
Lug height (h_L)	2	0.0152749	0.0076375	98.25**
Dynamic load (W)	2	0.0124292	0.0062146	79.95**
T_s*W	2	0.0001478	0.0000739	0.95^{ns}
h_L*W	4	0.0010557	0.0002639	3.40^{ns}
Inflation pressure (Pi)	2	0.0029860	0.0014930	19.21**
T_s*P_i	2	0.0000603	0.0000302	0.39^{ns}
h_L*P_i	4	0.0003757	0.0000939	1.21^{ns}
W*P_i	4	0.0003275	0.0000819	1.05^{ns}
T_s*W*P_i	4	0.0001965	0.0000491	0.63^{ns}
Error	26	0.0020210	0.0000777	
Total	53	0.0421306		

**, (P<0.01); ^{ns}, not significant

T_s	h_L	W	P_i
(Bias-ply) 0.557_a	(h_{L1}) 0.590_a	(W_1) 0.552_a	(P_{i1}) 0.575_a
(Radial) 0.581_b	(h_{L2}) 0.571_b	(W_2) 0.568_b	(P_{i2}) 0.571_a
	(h_{L3}) 0.546_c	(W_3) 0.587_c	(P_{i3}) 0.561_b
LSD (5%): 0.004	0.005	0.005	0.005

7). Maximum tractive efficiency obtained for all combinations was 0.78 at h_{Lr1} lug height of radial tire while minimum tractive efficiency was obtained 0.27 at h_{Lb3} lug height of bias-ply tire. Effect of lug height on the tractive efficiency was found to be important (P<0.01).

Depending on increased dynamic axle load, the average tractive efficiency values increased by 6%. When dynamic load was increased from 3.5 kN to 5 kN, the tractive efficiency increased by 2.5%. Dynamic load increased the tractive efficiency by 3.5% when it was increased from 5 kN to 6.5 kN. Increased dynamic load improved adherence of tire to soil and decreased travel reduction. Figure 8 shows the effect on tractive efficiency of different dynamic axle loads. Effect of dynamic axle load on the tractive efficiency was found to be important (P<0.01). There were no significant differences between W2 and W3. Similar reports concerned with tractive performance parameters in the literature confirm the discovered trends in this investigation (Çarman & Aydın 2002; Elwaleed et al 2006; Yahya et al 2007).

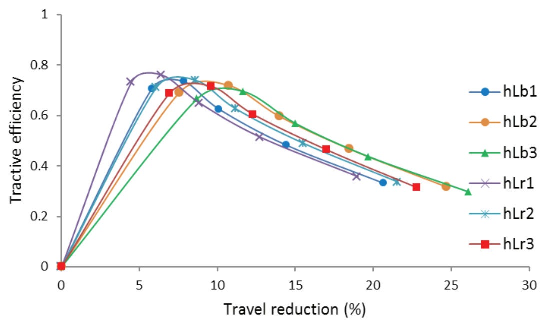

Figure 7- Effect of lug height on tractive efficiency at varies travel reduction levels

Şekil 7- Farklı patinaj seviyelerinde profil yüksekliğinin çeki verimi üzerine etkisi

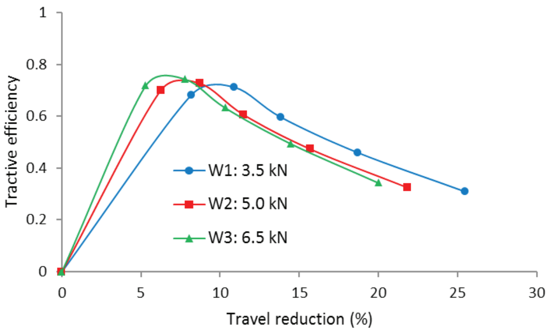

Figure 8- Effect of dynamic load on tractive efficiency at varies travel reduction levels

Şekil 8- Farklı patinaj seviyelerinde dinamik yükün çeki verimi üzerine etkisi

Tire tractive efficiency curves are shown in Figure 9. Figure 9 shows that tractive efficiency of tire increases suddenly with increasing travel reduction to a maximum value and then gradually decreases with the increase in travel reduction. When inflation pressure was reduced from 290 kPa down to 260 kPa; the tractive efficiency increased by 2% with the same amounts of travel reduction. Similarly, the tractive efficiency increased by 1.2% when inflation pressure was decreased from 260 to 230 kPa. Smerda & Cupera (2010) found that reducing tire inflation of appropriate tire types can improve the drawbar characteristics and, consequently, fuel consumption.

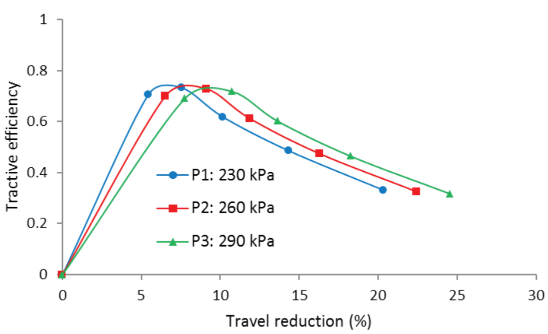

Figure 9- Effect of inflation pressure on tractive efficiency at varies travel reduction levels

Şekil 9- Farklı patinaj seviyelerinde iç basıncın çeki verimi üzerine etkisi

4. Conclusions

As conclusions, effects on travel reduction and tractive efficiency values of manipulated variables such as tire type, lug height, inflation pressure and axle load can thus be summarized as follows.

At all combinations of the variables, radial tires developed more NTR than bias-ply tires. Accordingly, the axle power requirement is 2.7% higher than has occurred. The radial tire had greater tractive efficiency than the bias-ply tire except in one combination of three levels of lug height, three dynamic loads and three inflation pressures selected in the study. Tire tractive efficiency increased suddenly with increasing travel reduction to a maximum value and then gradually decreased with increase in travel reduction.

Travel reduction ratio increased when lug height of tire was decreased. When lug height was increased the tractive efficiency increased for both tires. Tire with high lugs can develop higher tractive force than the smooth tire.

For a given dynamic load, net traction increased as travel reduction increased. During the experiments, depending on axle load increase of 86%, average travel reduction values decreased by 21% for bias-ply tires and by 18% for radial tires. Depending on increased dynamic axle load, the average tractive efficiency values increases by 6%.

The highest value of NTR (0.65) was reached at inflation pressure of 230 kPa while using bias-ply and radial tires. By increasing tire inflation to 290 kPa, the NTR decreased to 0.62 at same travel reduction ratio. When inflation pressure is reduced from 290 kPa to 230 kPa, the tractive efficiency tends to increase by 3%.

The single wheel tester can be used for testing the effects of parameters such as dynamic loads, lug heights and tire inflation pressure on tractive performances of the tire.

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