ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.26, n.5, p.356-364, 2022
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v26n5p356-364

Energy performance of farm tractor with single radial versus dual diagonal wheels in harrowing operations[1]

Desempenho energético de trator agrícola com rodas radiais simples versus diagonais duplas em operação de gradagem

Gabriel G. Zimmermann[2]*, Daniel Savi[2], Samir P. Jasper[2],
Leonardo L. Kmiecik[2], Lauro Strapasson Neto[2] & Luiz R. Sobenko[3]

[1] Research developed at Universidade Federal do Paraná, Curitiba, PR, Brazil
[2] Universidade Federal do Paraná/Departamento de Solos e Engenharia Agrícola, Curitiba, PR, Brazil
[3] Valley Irrigation - Valmont Industries, Uberaba, MG, Brazil

HIGHLIGHTS:

Single radial tires supply greater energy performance compared to dual diagonal tires.
Regardless of the arrangement of the wheels, the levels of efficiency in the agricultural operation are related to speed.
The single radial arrangement resulted in similar efficiency to the dual diagonal at the highest speeds tested.

ABSTRACT: The farm tractor wheel interacts directly with the soil, affecting its energy and operational performance. Several works study the particularities between configurations of wheelset seeking to interpret the most efficient type and arrangement of the wheelset. However, there is still a demand for studies that elucidate decision-making regarding changing the type of wheelset or improving the pre-existing arrangement. The experiment aimed to evaluate the energy performance of farm tractors equipped with Single radial and Dual diagonal wheels in rear axle in intermediate harrowing operation. The experiment was conducted in a randomized block design. Two-wheel arrangements (Single radial and Dual diagonal) were used in the blocks, and four target velocities (4, 6, 8, and 10 km h^{-1}), with four replicates in the subblocks, totalizing 32 experimental units. Slip of wheels, engine rotation, hourly and specific fuel consumption, force, power, and efficiency in the drawbar, operational velocity, and engine thermal efficiency were monitored. The data collected were submitted to analysis of variance and, when significant, to the Tukey test and regression analysis. The Single radial tires provided an increase in velocity and drawbar force without increasing fuel consumption, consequently providing an increase in energy and operating performance in intermediate harrowing operation.

Key words: wheel arrangements, fuel consumption, engine thermal efficiency

RESUMO: A roda do trator agrícola interage diretamente com o solo, afetando seu desempenho energético e operacional. Diversos trabalhos estudam as particularidades entre configurações de rodado buscando interpretar o tipo e arranjo mais eficiente de rodagem, entretanto ainda há uma demanda de estudos que elucidem a tomada de decisão quanto a necessidade da troca do tipo de rodado ou melhoria do arranjo pré-existente. O experimento teve como objetivo avaliar o desempenho energético do trator agrícola quando equipado com rodas radiais simples e diagonais duplas no eixo traseiro, em operação de gradagem intermediária. O experimento em faixas foi conduzido no delineamento de blocos casualizado, nas parcelas dois arranjos de rodados (radiais simples e diagonais duplas) e nas subparcelas quatro velocidades alvo (4, 6, 8 e 10 km h^{-1}), com quatro repetições, totalizando 32 unidades experimentais. Foi monitorado a patinagem dos rodados, rotação do motor, consumo horário e específico de combustível, força, potência e rendimento na barra de tração, velocidade operacional e eficiência térmica do motor. Os dados coletados foram submetidos a análise de variância e, quando significativo, ao teste de Tukey e análise de regressão. Os pneus radiais simples proporcionaram acréscimo da velocidade e força na barra de tração sem acréscimo do consumo de combustível, proporcionando, consequentemente, um incremento no desempenho energético e operacional em operação de gradagem intermediaria.

Palavras-chave: arranjo de rodas, consumo de combustível, eficiência térmica do motor

• Ref. 253173 – Received 10 Jun, 2021
* Corresponding author - E-mail: gabrielganancini@gmail.com
• Accepted 15 Nov, 2021 • Published 28 Dec, 2021
Editors: Josivanda Palmeiras Gomes & Hans Raj Gheyi

INTRODUCTION

With the advance of agriculture, new requirements emerge to maximize the energy efficiency of tractors. Thus, research related to internal pressure and the type of tires used in agricultural operations is required (Battiato & Diserens, 2017).

The pneumatic wheels of farm tractors present functions as displacement, direction, and road-soil interaction, etc. It is highlighted that the incorrect dimensioning of the wheel for the operation or tractor can lead to power losses of up to 55%, harming the operational and energy performance of the agricultural activity (Kumar et al., 2018).

In crops that need the conventional operation of soil preparation, the same must be used correctly, with proper dimensioning of the implement/machine pulled by the tractor. The suitable dimensioning of implement/machine aims to optimize the operational and energy performance, which directly reflects the reduction of fuel consumption, time, and emission of pollutants into the environment (Janulevičius et al., 2019).

The intermediate or heavy harrowing operation is characterized by turning over the superficial layers to reduce compaction, incorporate correctives and fertilizers, increase porous spaces, and the permeability and storage of air and water. The soil texture, equipment, depth, and operational velocity must be considered to succeed in this operation of soil preparation (Ahmadi, 2018).

The analyzed variable to determine the energy and operational performance of the tractor are the drive wheel slip, velocity, and hourly fuel consumption (Janulevičius et al., 2018), power and drawbar performance, and specific fuel consumption and engine thermal efficiency (Strapasson Neto et al., 2020).

Diagonal tires use linings superimposed at different angles, besides presenting characteristics of high impact resistance and elasticity. In contrast, the linings of radial tires are arranged in the radial direction of the tire circumference (Fedorko et al., 2019).

The constructive variation of radial tires provides a more uniform deformation in the transverse direction of the wheel, compared with the diagonal (Kutzbach et al., 2019), providing an increase of the contact area, improvement in tire/soil interaction and traction capacity, besides decreasing specific fuel consumption values (Kumar et al., 2019).

Sümer & Sabanci (2005) compare two-wheel configurations (Single and Dual) assembled with diagonal and radial tires, noting that radial tires promote a slight advantage over the diagonals in the traction efficiency while specific fuel consumption decreased by 3.1%. The tractor efficiency increased 14.7% when the Dual diagonal tires were used, reducing specific fuel consumption by 12.8% and slipping by 34%.

The present study aimed to evaluate the energy performance of farm tractors equipped with Single radial and Dual diagonal wheels on the rear axle in intermediate harrowing operation.

MATERIAL AND METHODS

This study was conducted in Pinhais, PR, Brazil (-25º 22' 38" S, -49º 09' 05" W, and altitude of 920 m), in a steady soil with no vegetation cover, classified as a Latossolo Vermelho-Amarelo distrófico típico, with a 1% slope longitudinal direction of the tractor displacement.

The banded experiment, conducted in a randomized block design, was composed of two-wheel types (R) and four target velocities (TV), totaling eight treatments with four replicates each.

The types of wheels used were single radial on both tractor axles, dual diagonal on the rear axle, and single on the front axle. The evaluated velocities allocated in the subblocks were 4.0, 6.0, 8.0, and 10 km h^{-1}, corresponding to A4, B2, C2, and C3 gears, operating at engine rotation in the test with 1970 RPM.

The tractor used in the experiment was a New Holland®, model T6050 PLUS series, with rated power (ISO TR 14396) of 93 kW (126.44 cv), Electroshift® transmission 16 ×16 and front-wheel assist (AFWD), which remained actioned in the test. An intermediate harrow, model CRI 18-F (Baldan®) with 18 26-inch discs, spacing of 0.27 m, and a static mass of 2.601 kg, was used to provide a load on the tractor drawbar.

The Single radial arrangement adopted consisted of Continental® 380/85R28 tires in the front, and Continental® 460/85R38 in the rear axle, with pressures of 83 kPa (12 psi) 83 kPa (12 psi), respectively. The second consists of diagonal tires Single at the front and Dual at the rear, using Pirelli® TM95 14.9-28 tires, with a pressure of 110 kPa (16 psi), and the set Pirelli® TM95 18.4-38, with 110 kPa (16 psi), for the inner and outer tires, respectively. The anticipation of the front wheel when connected to AFWD was 3.4 and 3.1% for the arrangement of radial and diagonal tires.

The static masses on the tractor axles were determined with a scale (Celmig®) CM-1002, with four shoes. When adopted the Single tires, a 40% hydraulic ballast on the front and rear axles was used with a metallic ballast, using ten metal plates of 45 kg on the front, and rings of 65 kg on the rear axle, resulting in 6,917 kg of total mass, approximately distributed 42% on the front axle and 58% on the rear axle.

In the condition of the diagonal tires, only the metallic ballast was used by adding ten metal plates of 45 kg on the front and four 65 kg rings on the rear axle, totalizing 6880 kg of mass, approximately distributed 40% on the front and 60% on the rear (Schlosser et al., 2020). These configurations provided the relation between mass and power of 74 kg kW^{-1} (55 kg cv^{-1}) for both wheel arrangements.

During the experiment, the data acquisition system (SAD) was used with a printed circuit board (Jasper et al., 2016), composed by the sensors described below, with a one Hertz frequency of data acquisition, transferred to a hard drive for later tabulation and analysis.

The slip of drive wheels was measured using Autonics® encoders model E100S, which generate 100 pulses per lap, obtained through the rotations of the wheels, determined by Eq. 1.

$$SLP = \left(\frac{NPL - NPWL}{NPWL}\right)100 \quad (1)$$

where:

SLP - slip of wheels in %;
NPL - number of wheel pulses with load; and,
NPWL - number of wheel pulses without load.

The relation of transmission between the engine crankshaft and the PTR was obtained by Victor® digital tachometer model DM6236P, establishing the relation of deduction corresponding to 3.66. Thus, it was possible to measure the engine rotation (ER) by monitoring the power take-off (PTO) rotation regime with an Autonics® encoder, model E100S.

Two flowmeters Flowmate OVAL MIII®, model LSF 41L0-M2, were installed in the fuel supply system (inlet and return), measuring the hourly fuel consumption (HFC).

The drawbar force (DBF) was measured from load cell Bermann® with a capacity of 100 kN, adequately assessed and installed on the tractor drawbar.

The operational velocity (OV) of the tractor was determined with a Vansco® radar, model 740030A, installed in the tractor chassis and previously assessed with the tractor, moving a timed and known distance.

The power available on the drawbar was obtained by the ratio of force and velocity, following Eq. 2.

$$PDB = DBF \cdot OV \quad (2)$$

where:

PDB - drawbar power, kW;
DBF - drawbar force, kN; and,
OV - displacement velocity, m s^{-1}.

Based on the power available in the drawbar and the tractor engine, it was possible to determine the efficiency in the drawbar by Eq. 3.

$$EDB = \left(\frac{PDB}{EP}\right)100 \quad (3)$$

where:

EDB - efficiency in the drawbar, %;
PDB - drawbar power, kW; and,
EP - engine power, kW.

The fuel density was obtained through the temperatures measured by type K thermocouples installed next to the flowmeter to return the fuel to the tank and determined according to Eq. 4.

$$D = 844.14 - (0.53T) \quad (4)$$

where:

D - Diesel oil density, g L^{-1};
T - Diesel oil temperature, °C; and,
844.14 and 0.53 - parameters of density regression.

The hour consumption based on mass was determined through Eq. 5.

$$HMF = \left(\frac{HFC[844.14 + (-0.53T)]}{1000}\right) \quad (5)$$

where:

HMF - hour consumption of fuel based on mass, g h^{-1};
HFC - hour consumption of fuel based on volume, L h^{-1}; and,
1000 - conversion factor.

The specific consumption of fuel was determined considering the hour consumption based on mass in the ratio with the power in the bar, according to Eq. 6.

$$SCF = \left(\frac{HMF}{PDB}\right) \quad (6)$$

where:

SCF - specific consumption of fuel, g kW h^{-1};

The engine thermal efficiency was obtained through the specific consumption and the lower calorific value of the fuel by Eq. 7, according to Farias et al. (2017).

$$ETM = \left(\frac{3600}{SCF \cdot LCP}\right) \quad (7)$$

where:

ETM - engine thermal efficiency, %; and,
LCP - lower calorific power, 42,295 MJ kg^{-1}.

The data collected passed through tests of normality (Shapiro-Wilk) and homogeneity of variance (Brown-Forsythe). Following these assumptions, the data were submitted to analysis of variance to verify the factor effects (R and TV) and their interaction through the statistical software Sigmaplot 12. When the F-test presented a significant probability ($p \leq 0.05$) value, the means were compared by the Tukey test ($p \leq 0.05$) for qualitative factors (R). The polynomial regression test was applied for quantitative factors (TV and Interaction) with selected models by the criterion of highest R^2 and significance ($p \leq 0.05$) of the parameters of equations.

RESULTS AND DISCUSSION

Table 1 shows the synthesis of analysis of variance and test of means of operational performance, having no need to transform the means of all the studied variables, denoting normality (Shapiro-Wilk) and homogeneity of the residual of variances (Brown-Forsythe). In addition, all the variation coefficients are categorized as stable, expected the SLP variable, which presented variation coefficient categorized as medium dispersion, according to the classification of Ferreira (2018).

The results show a significant difference between target velocity (TV) and all the variables evaluated and between wheel

Table 1. Statistical synthesis of analysis of variance and the test of means for the operational performance variables evaluated

Analyses	Evaluated variables				
	SLP (%)	ER (RPM)	HFC ($L h^{-1}$)	DBF (kN)	OV ($km h^{-1}$)
Normality					
SW	0.987	0.253	0.628	0.976	0.995
Homogeneity					
BF	0.053	0.756	0.445	0.567	0.411
F-test					
R	10.99^{*}	7.50^{NS}	4.09^{NS}	27.73^{**}	32.83^{**}
TV	3.96^{*}	150.17^{**}	345.78^{**}	13.84^{**}	$1.728.45^{**}$
R x TV	2.47^{NS}	1.78^{NS}	3.75^{*}	1.68^{NS}	31.88^{**}
CV (%)					
R	18.65	1.60	5.17	1.79	2.82
TV	15.94	0.44	3.05	2.98	1.84
R x TV	17.30	1.44	3.72	3.33	2.44
Means Test – R					
Radial Single	9.23 A	2,017	17.67	21.00 A	6.86 A
Diagonal Dual	7.41 B	1,986	17.03	20.31 B	6.48 B

Variables: Slip of wheels (SLP), Engine rotation (ER), Hourly fuel consumption (HFC), Drawbar force (DBF), and Operational velocity (OV). Shapiro-Wilk Normality Test: SW ≤ 0.05 - Data abnormality; SW > 0.05 - Normality in data. Brown-Forsythe Homogeneity Test of variances: BF ≤ 0.05 - Heterogeneous Variances; BF > 0.05 - Homogeneous variances. F-Test of the analysis of variance (ANOVA): NS - Not significant; $^{*}p < 0.05$ and $^{**}p < 0.01$; CV - Coefficient of variation. In each column, for each factor, means followed by the same capital letters do not differ according to Tukey's test ($p < 0.05$)

(R) and SLP, DBF, and OV, denoting the interaction between the factors and HFC and OV. However, the variables ER and HFC did not differ concerning the use of radial and diagonal tires arrangement, corroborating Monteiro et al. (2011) that evaluated the performance of a tractor with Single radial and Dual diagonal tires.

Analyzing the effects of wheel arrangements on SLP, it is observed that only the Radial Single was contained in the interval recommended by ASABE (2011) for steady soil, which varies between 8 and 10%. The Dual Diagonal arrangement resulted in values of SLP lower than recommended, demonstrating waste of tractive force (Janulevičius & Damanauskas, 2015). The Radial Single arrangement presented SLP 1.82% higher than Diagonal Dual, resulting in a higher DBF, which was 0.69 kN (3.40%) higher for the first arrangement.

The higher DBF in the Radial Single arrangement is due to the increase of soil shear caused by higher levels of SLP. This deformation of the structure expresses the disruption of its cohesive forces. It corroborates Battiato & Diserens (2017), which identified that the increase of soil shear displacement due to greater wheel slip results in a significant increase in tractive force and, consequently, interferes in traction efficiency.

These results differ from Farias et al. (2019), they verified higher values of DBF when the tractor was operated with Diagonal Dual wheel arrangement compared with Radial Single with different loads in the drawbar and relations between mass and power. According to the authors, this higher tractive force occurred due to the increase of pressure exerted by the wheel on the soil due to its smaller contact area than the Radial Single arrangement.

Concerning OV, it is observed that the Radial single arrangement presented 0.38 km h^{-1} more than the Diagonal Dual even with higher SLP indexes. This result can be attributed to a higher ER, as the transfer of movement, torque, and power occurs through a defined gear ratio, which was not altered during the test. Therefore, the increase in motor rotation increases the tangential speed of the wheelset and, consequently, on the OV.

Analyzing the effect of target velocities on the studied variables (Figure 1), a linear performance of HFC and DBF is observed, and a second-order polynomial for ER and OV, both with a coefficient of determination higher than 95%. However, the variation of target velocity did not provide any tendency on the variable SLP (Figure 1A). Therefore, the mathematical models were not able to explain this factor with a significant coefficient of determination.

Concerning engine rotation (Figure 1B), a non-linear decrease of this variable at the expense of target velocity is observed due to the increase of the load on the engine and the increase of the power demanded in the drawbar. Concerning hourly fuel consumption (HFC), in Figure 1C, a growing tendency of 1.32 L h^{-1} with an increase of 1 km h^{-1} is observed. This increase of HFC can be explained by the higher energy demand when performing the work (PDB) in a lower time interval, corroborating Martins et al. (2018) by determining higher fuel consumption at higher gears.

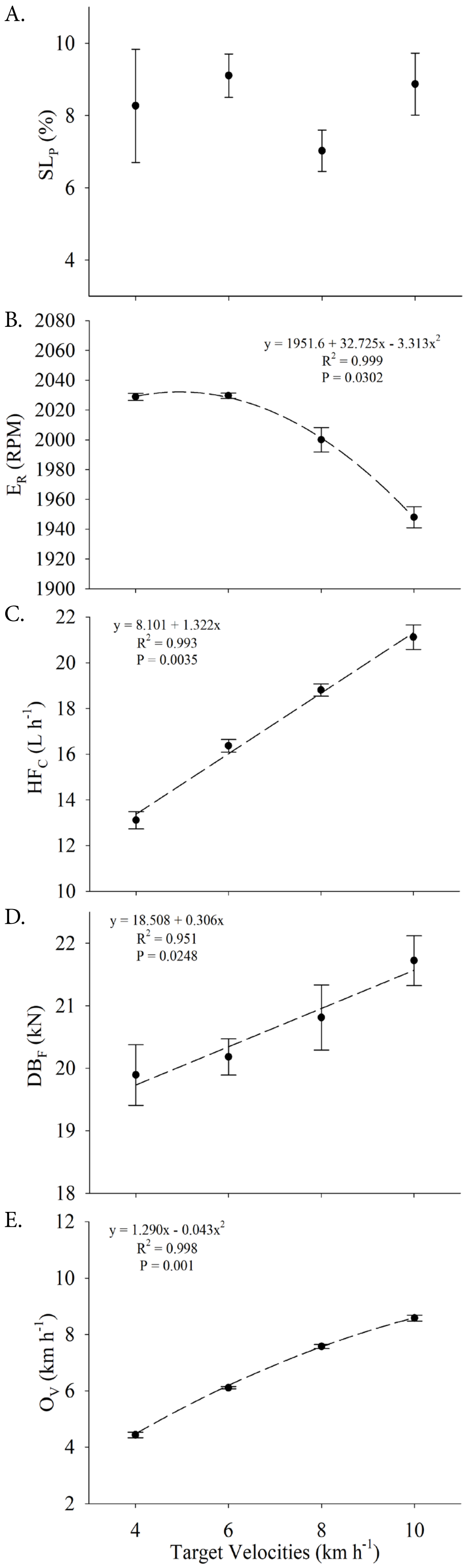
The tractive force required by agricultural implements is directly related to operational velocity, width, and work depth, as well as soil conditions (ASABE, 2006). It justifies the increase of DBF at the expense of target velocity; according to the linear equation generated, an increment of 0.306 kN with the addition of 1 km h^{-1} is observed.

Analyzing the operational velocity (OV), a non-linear growth is observed related to target velocity; according to the equation generated, an increase of 1.29 times the target velocity is verified. However, it is suppressed by 0.041 times the square of velocity, showing the inefficiency in maintaining the target velocity. This non-linear performance of OV is due to the reduction of ER caused by the increase of loads on the engine at higher velocities, besides the influence of SLP on this variable (Damanauskas & Janulevičius, 2015).

The influence of working velocity on energy and operational efficiency increases the working area in a shorter time. Martins et al. (2018) described similar results when evaluating the energy optimization of farm tractors in three types of harrowing operations (hard, intermediate, and light) and different gears.

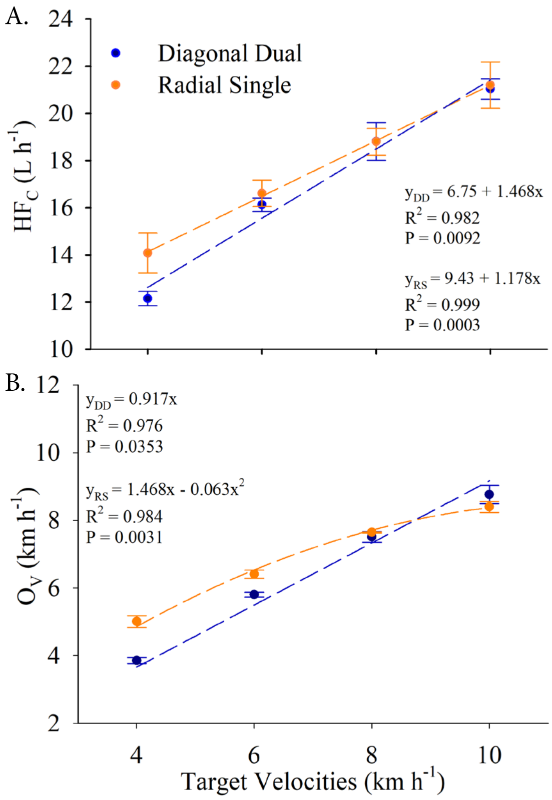
The interactions observed between the target velocity and the wheel arrangement on HFC and OV generated equations representing them (Figure 2). Concerning interaction deployment between the different wheel arrangements and velocity on the HFC (Figure 2A), it is observed that the statistical model of linear regression explains the results in more than 98% of the cases for both types of tires. Regarding the interaction between the factors on the OV, in Figure 2B, a linear tendency to the Dual Diagonal arrangement and a second-order polynomial for Radial Single are observed, with a determination coefficient higher than 97%.

When analyzing the influence of wheel arrangement and target velocity factors on the hourly consumption fuel (HFC), a linear increase in the consumption at the expense of the target velocity for both wheels is observed, denoting



The vertical bars refer to means ± standard error (n = 4 replications)

Figure 1. Regression analysis for the isolated factor of target velocity. Slip of wheels - SL_P (A), engine rotation - E_R (B), hourly fuel consumption - HF_C (C), drawbar force - DB_F (D), and operational velocity - O_V (E)



The vertical bars refer to the means ± standard error (n = four replicates)

Figure 2. Regression analysis for the interaction between the wheel arrangement, Diagonal Dual (DD) and Radial Single (RD) with hourly fuel consumption - HF_C (A), and target velocity O_V (B)

the higher demand of the Radial Single arrangement at the lowest velocities. According to the equations generated, the increment of this variable is slightly higher when operated with the Dual Diagonal arrangement. However, the values of HFC are equivalent when in the highest target velocities.

The highest HFC of the Radial Single arrangement at the lowest target velocities can be explained by its highest OV (Figure 2B). This result corroborates with Damanauskas et al. (2019), which described that the hourly fuel consumption is proportional to the resistance force to the bearing and the working velocity. It highlights that the tractor movement requires higher energy to overcome the inertial forces of soil at higher velocities.

Concerning the interaction of factors about the working velocity (Figure 2B), linear growth of OV is observed when the set operated with the Dual Diagonal arrangement, which, according to the equation generated, permitted to reach 91.7% of target velocity. This fact highlights the importance of this variable to fit the necessities of the high operational yield of modern agriculture (Balsari et al., 2021). Concerning the Radial Single arrangement, the set presented OV superior to the radial arrangement at the lowest target velocities, 4 and 6 km h^{-1}; however, due to its non-linear behavior, the OV values became similar at the higher target velocities. This behavior can be explained by the greater slip observed when operating with the simple radial arrangement, which is intensified with the increase of the target velocity.

Table 2 presents the results of the synthesis of the analysis of variance and mean test regarding the energy performance

Table 2. Statistical synthesis of the analysis of variance and the test of means for the energy performance variables evaluated

Analyses	Evaluated variables			
	PDB (kW)	EDB (%)	SFC (g kW h^{-1})	ETM (%)
Normality				
SW	0.580	0.580	0.793	0.312
Homogeneity				
BF	0.690	0.690	0.129	0.206
F-test				
R	215.52**	215.52**	12.78*	11.64*
TV	795.93**	795.93**	78.84**	70.29**
R x VA	19.10**	19.10**	9.62**	6.34**
CV (%)				
R	1.71	1.71	6.04	5.49
TV	3.06	3.06	4.03	4.02
R x TV	2.65	2.65	3.50	3.44
Means Test - R				
Radial single	40.29 A	43.32 A	380 B	22.60 A
Diagonal dual	36.87 B	39.65 B	410 A	21.15 B

Variables: Drawbar power (PDB), Efficiency in the drawbar (EDB), Specific fuel consumption (SFC), and Engine thermal efficiency (ETM); Shapiro-Wilk Normality Test: SW ≤ 0.05 - Data abnormality; SW > 0.05 - Normality in data. Brown-Forsythe Test of homogeneity: BF ≤ 0.05 - Heterogeneous Variances; BF > 0.05 - Homogeneous variances. F-test of analysis of variance (ANOVA): *$p < 0.05$ and **$p < 0.01$; CV - Coefficient of variation. In each column, for each factor, means followed by the same capital letters do not differ from each other according to the Tukey test ($p < 0.05$)

of the set, with no need to transform the means of all studied variables, denoting normality (Shapiro-Wilk) and homogeneity of the variance residue (Brown-Forsythe). Furthermore, all coefficients of variation are categorized as stable, according to the classification of Ferreira (2018).-

While evaluating the wheel arrangement and target velocities effect on the PDB, EDB, SCF, and ETM, a statistic distinction for both factors is observed, denoting its interaction.

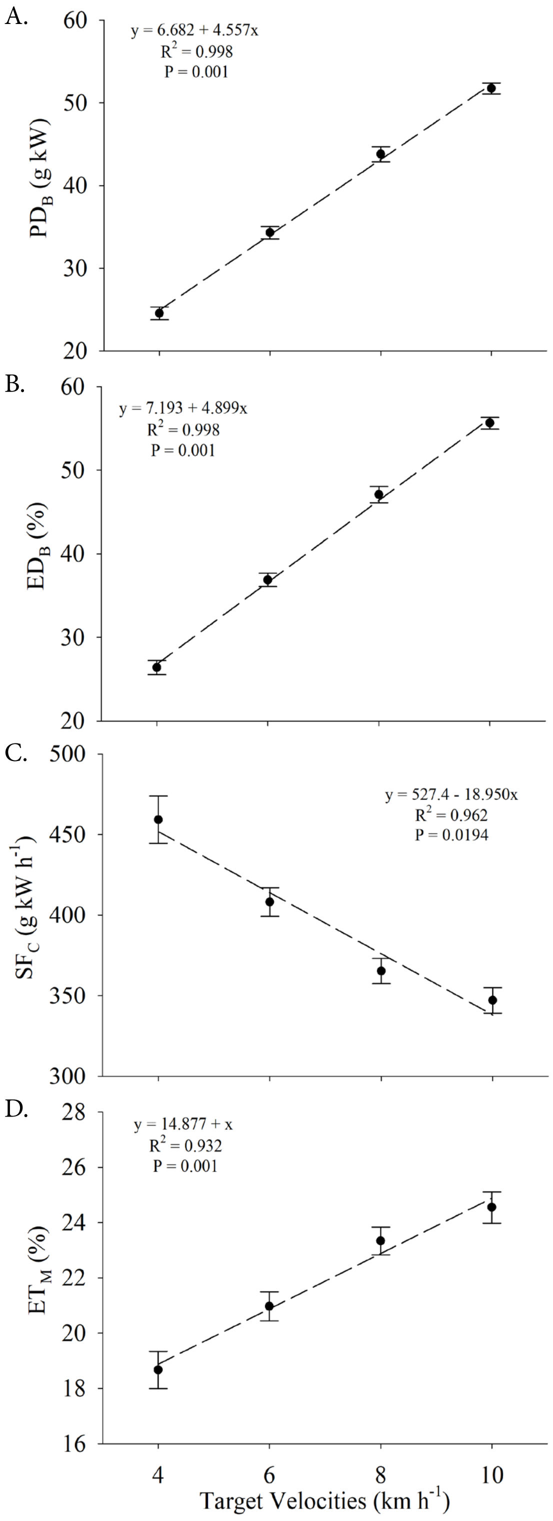
Concerning the drawbar power (PDB) (Table 2), it is verified that the arrangement of the Radial Single wheel provided an increase of 3.42 kW due to higher DBF and OV. According to Serrano et al. (2007) and Regazzi et al. (2019), the engine power is degraded due to the mechanical efficiency of the transmission and active traction efficiency, which in turn is directly related to the degree of interaction between the wheelset and the ground; therefore, it can be observed that the Radial Single set provided a higher traction efficiency to the powertrain.

On the other hand, the higher PDB (Table 2) permitted the tractor to provide 3.67% more energy available by the engine, demonstrated by higher EDB, and, therefore, presents lower energy expenditure. These results corroborate Kumar et al. (2019), which determined a greater rolling resistance in diagonal wheels, providing a lower tractive and active power capacity.

The wheel arrangement Diagonal Dual presented a value of SCF higher than the Radial Single arrangement, needing plus 30 g (7.89%) of fuel to generate 1 kW h^{-1}. Therefore, higher efficiency of the Radial Single arrangement is observed in the transformation of fuel into work, as Mayet et al. (2019) explained. Concerning the variable ETM, higher use of calorific power of fossil fuels with the arrangement is observed, an essential factor for developing more sustainable agriculture (He et al., 2019).

Analyzing the isolated effect of the target velocities on the studied variables, the performance of second-order polynomial to the factor SCF and linear to PDB, EDB, and ETM is observed, both with a determination coefficient higher than 96% (Figures 3A and D).

The drawbar power (PDB) presented an increasing behavior at the expense of target velocity (Figure 3A). An increment of 4.56 kN with an increase of 1 km h^{-1} was observed due to the growing tendency of DBF and OV with the rise of the target velocity. It denotes the better efficiency in transforming the



The vertical bars refer to means ± standard error (n = 4 replications)

Figure 3. Regression analysis for the isolated effect of target velocities on drawbar power - PD$_B$ (A), engine power - ED$_B$ (B), specific fuel consumption - SF$_C$ (C) and thermal efficiency of motor -ET$_M$ (D)

mechanical energy provided by the engine at work, making possible the expansion of EDB with the velocity increment. According to the equation generated, an increase of 4.9% of the engine power with an addition of 1 km h^{-1} can be perceived (Figure 3B).

The highest levels of tractive energy performance (PDB and EDB) with the addition of velocity corroborate with the results found by Gabriel Filho et al. (2010), which evaluated the tractive capacity of a tractor submitted to a load of 25 kN in different gears.

Due to the non-proportional increase of the fuel consumption (HFC) and the drawbar power (PDB) with the rise of target velocity, the non-linear reduction of SCF (Figure 3C) is observed at the expense of target velocities. According to the experimental results, the fuel consumption demand to generate 1 kW h^{-1} is reduced on an average of 18.95 g with the addition of target velocity in 1 km h^{-1}. It demonstrates the simultaneous optimization of engine performance, tractive efficiency, and adequacy of implementing the energy power supply.

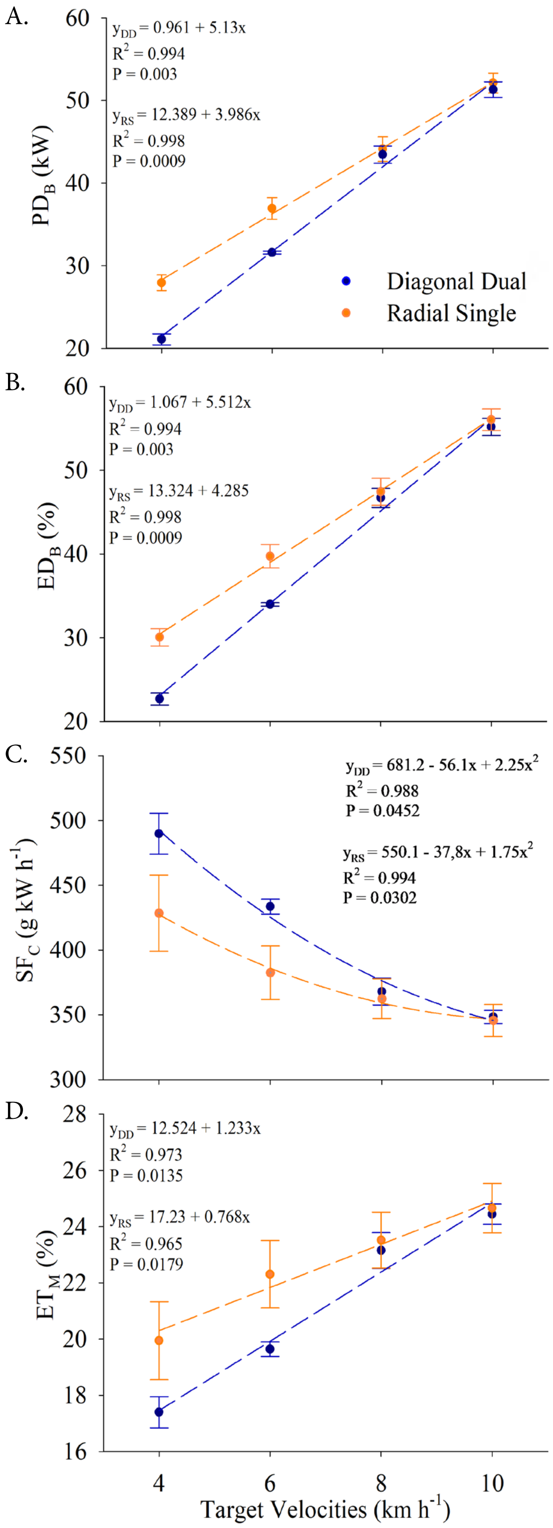
Simultaneously to the reduction in the volume of fuel required to generate equivalent power, an increase in the thermal efficiency of the motor (Figure 3D) is observed, which, following the linear equation generated, the ETM is equivalently increased to the target velocity. This occurs due to the reduction of engine rotation with the increase of target velocity, approaching the engine's maximum torque regime rotation and favoring the set's energy performance, as described by Serrano et al. (2007).

The interactions observed between the target speed and the wheel arrangement in the DB_P, DB_N, FC_S, and ET_M and the generated equations to represent them are shown in Figure 4.

Analyzing the interaction of the factors evaluated on PDB and EDB (Figures 4A and B), a growing tendency of energy availability in the drawbar is verified at the expense of the velocity increase in both arrangements. However, it is observed that the Radial Single configuration in the velocities of 4 and 6 km h^{-1} presented 32.6% (6.87 kW) and 16.9% (5.34 kW) more than PDB compared with the Dual Diagonal arrangement, respectively. However, this variation was 1.5% in other target velocities. The higher PDB exerted when operating with the Radial Single arrangement in the lowest target velocities, 4 and 6 km h^{-1}, increased EDB in 7.37 and 5.74%, respectively.

SCF (Figure 4C) presented a second-order polynomial tendency for both wheel arrangements, with a determination coefficient higher than 98%, showing significant gains in the energy performance of farm tractors operating with higher velocities and tractive load. Such results corroborate with Damanauskas et al. (2019), highlighting the importance of correct dimensioning between mechanized set, implement, and velocity, aiming to optimize operational and energy efficiency of agricultural activity.

According to the equations generated, both wheel arrangements presented minimum values of SCF in velocities higher than those experimentally evaluated. Nevertheless, the Radial Single arrangement reduced the fuel demand to generate 1 kW h^{-1}, independently of the target velocity. However, the discriminated increment of target velocity to obtain higher operational and energy efficiency levels causes the effect called fluctuation during harrowing and, consequently, prevents mobilization to the required depth (Martins et al., 2018).



The vertical bars refer to means ± standard error (n = 4 replications)

Figure 4. Regression analysis of the interaction between the wheel arrangement, Diagonal Dual (DD) and Radial Single (RD), and target velocity on drawbar power - PD_B (A), engine power - ED_B (B), specific fuel consumption - SF_C (C) and thermal efficiency of motor - ET_M (D)

The reduction of SCF shows higher efficiency during the transformation of chemical energy contained in fuels in work (Farias et al., 2017), providing a linear increment of ETM at the expense of target velocity (Figure 4D), for both wheel arrangements. When analyzing the independent factor of the equations generated, the Radial Single arrangement presented a higher effective efficiency than the Diagonal Dual; however, its ETM increased 0.47 more with the addition of 1 km h^{-1} and consequently equaled the Radial Single arrangement in the highest velocities evaluated.

By the results experimentally obtained, operational and energy efficiency maximization can be verified with the correct dimensioning between the wheel arrangement and operational velocity. The highest efficiency level occurred when the set was equipped with the Radial Single arrangement on the variables of force and drawbar power, velocity, fuel consumption, and engine thermal efficiency, especially in the lowest target velocities.

In this way, the use of radial tires should be prioritized instead of the increment of one more additional set of diagonal wheelset (dual), given the operational and energetic performance criteria of the motor-mechanized set.

Concerning operational velocity, the increment of force, power, and efficiency in the drawbar and engine thermal efficiency was perceived at the expense of an increase in target velocity, consequently reducing specific fuel consumption, besides a higher operational efficiency.

CONCLUSIONS

1. The radial tires Single provided a velocity increase, resulting in higher levels of force and power in the drawbar without a significant increase in fuel consumption, providing greater operating and energy efficiency to the motor-mechanized set.

2. The increase in speed, regardless of the wheel arrangement, increases the efficiency levels of the agricultural operation.

3. The greater efficiency of the Radial Single arrangement is minimized with the increase of the target speed, becoming equivalent to the Diagonal dual at the highest speeds tested.

LITERATURE CITED

Ahmadi, I. A draught force estimator for disc harrow using the laws of classical soil mechanics. Biosystems Engineering, v.171, p.52-62, 2018. https://doi.org/10.1016/j.biosystemseng.2018.04.008

ASABE - American Society of Agricultural and Biological Engineers. ASABE 497.5. Agricultural machinery management data. St. Joseph, 2006. 33p.

ASABE - American Society of Agricultural and Biological Engineers. ASABE 496.3. Agricultural machinery management data. St. Joseph, 2011. 6p.

Balsari, P.; Biglia, A.; Comba, L.; Sacco, D.; Alcatrao, L. E.; Varani, M.; Aimonino, D. R. Performance analysis of a tractor-power harrow system under different working conditions. Biosystems Engineering, v.202, p.28-41, 2021. https://doi.org/10.1016/j.biosystemseng.2020.11.009

Battiato, A.; Diserens, E. Tractor traction performance simulation on differently textured soils and validation: A basic study to make traction and energy requirements accessible to the practice. Soil and Tillage Research, v.66, p.18-32, 2017. https://doi.org/10.1016/j.still.2016.09.005

Damanauskas, V.; Janulevičius, A. Differences in tractor performance parameters between single-wheel 4WD and dual-wheel 2WD driving systems. Journal of Terramechanics, v.60, p.63-73, 2015. https://doi.org/10.1016/j.jterra.2015.06.001

Damanauskas, V.; Velykis, A.; Satkus, A. Efficiency of disc harrow adjustment for stubble tillage quality and fuel consumption. Soil and Tillage Research, v.194, 2019. https://doi.org/10.1016/j.still.2019.104311

Farias, M. S. de; Schlosser, J. F.; Martini, A. T.; Santos, G. O. dos; Estrada, J. S. Air and fuel supercharge in the performance of a diesel cycle engine. Ciência Rural, v.47, 2017. https://doi.org/10.1590/0103-8478cr20161117

Farias, M. S. de; Schlosser, J. F.; Russini, A.; Negri, G. M.; Casali, L. Agricultural tractor performance with different wheel and tire configurations. Científica, v.47, p.15-20, 2019. https://doi.org/10.15361/1984-5529.2019v47n1p15-20

Fedorko, G.; Molnar, V.; Dovica, M.; Toth, T.; Soos, L.; Fabianova, J.; Pinosova, M. Failure analysis of irreversible changes in the construction of car tyres. Engineering Failure Analysis, v.104, p.399-408, 2019. https://doi.org/10.1016/j.engfailanal.2019.05.035

Ferreira, P. V. Estatística experimental aplicada as ciências agrarias. Viçosa: UFV, 2018. 126p.

Gabriel Filho, A.; Lanças, K. P.; Leite, F.; Acosta, J. J.; Jesuino, P. R. Desempenho de trator agrícola em três superfícies de solo e quatro velocidades de deslocamento. Revista Brasileira de Engenharia Agrícola e Ambiental, v.14, p.333-339, 2010. https://doi.org/10.1590/S1415-43662010000300015

He, P.; Li, J.; Fang, E.; Voil, P. de; Cao, G. Reducing agricultural fuel consumption by minimizing inefficiencies. Journal of Cleaner Production, v.236, 2019. https://doi.org/10.1016/j.jclepro.2019.117619

Janulevičius, A.; Damanauskas, V. How to select air pressures in the tires of MFWD (mechanical front-wheel drive) tractor to minimize fuel consumption for the case of reasonable wheel slip. Energy, v.90, p.691-700, 2015. https://doi.org/10.1016/j.energy.2015.07.099

Janulevičius, A.; Damanauskas, V.; Pupinis, G. Effect of variations in front wheels driving lead on performance of a farm tractor with mechanical front-wheel-drive. Journal of Terramechanics, v.77, p.23-30, 2018. https://doi.org/10.1016/j.jterra.2018.02.002

Janulevičius, A.; Šarauskis, E.; Čiplienė, A.; Juostas, A. Estimation of farm tractor performance as a function of time efficiency during ploughing in fields of different sizes. Biosystems Engineering, v.179, p.80-93, 2019. https://doi.org/10.1016/j.biosystemseng.2019.01.004

Jasper, S. P.; Bueno, L.; Laskoski, M.; Langhinotti, C. W.; Parize, G. L. Tractor performance of power 157 kw on condition manual and automatic gears of management. Revista Scientia Agrária, v.17, p.55-60, 2016. https://doi.org/10.5380/rsa.v17i3.50998

Kumar, S.; Noori, M. T.; Pandey, K. P. Performance characteristics of mode of ballast on energy efficiency indices of agricultural tyre in different terrain condition in controlled soil bin environment. Energy, v.182, p.48-56, 2019. https://doi.org/10.1016/j.energy.2019.06.043

Kumar, S.; Pandey, K. P.; Kumar, R.; Kumar, A. A. Effect of ballasting on performance characteristics of bias and radial ply tyres with zero sinkage. Measurement, v.121, p.218-224, 2018. https://doi.org/10.1016/j.measurement.2018.02.043

Kutzbach, H. D.; Bürger, A.; Böttinger, S. Rolling radii and moment arm of the wheel load for pneumatic tyres. Journal of Terramechanics, v.82, p.13-21, 2019. https://doi.org/10.1016/j.jterra.2018.11.002

Martins, M. B.; Sandi, J.; Souza, F. L. de; Santos, R. de S.; Lanças, K. P. Otimização energética de um trator agrícola utilizando normas técnicas em operações de gradagem. Revista Engenharia na Agricultura, v.26, p.52-57, 2018. https://doi.org/10.13083/reveng.v26i1.852

Mayet, C.; Welles, J.; Bouscayrol, A.; Hofman, T.; Lemaire-Semail, B. Influence of a CVT on the fuel consumption of a parallel medium-duty electric hybrid truck. Mathematics and Computers in Simulation, v.158, p.120-129, 2019. https://doi.org/10.1016/j.matcom.2018.07.002

Monteiro, L. de A.; Lanças, K. P.; Guerra, S. P. S. Performance of an agricultural tractor equipped with radial and bias ply tires on three levels of liquid ballast. Engenharia Agrícola, v.31, p.551-560, 2011. https://doi.org/10.1590/S0100-69162011000300015

Regazzi, N; Maraldi, M; Molari, G. A theoretical study of the parameters affecting the power delivery efficiency of an agricultural tractor. Biosystems Engineering, v.186, p.214-227, 2019. https://doi.org/10.1016/j.biosystemseng.2019.07.006

Schlosser, J. F.; Catalán, H.; Bertinatto, R.; Farias, M. S. de; Mas, G. D.; Cella, M. C. Power hop in agricultural tractors. Ciência Rural, v.50, 2020. https://doi.org/10.1590/0103-8478cr20200199

Serrano, J. M.; Peça, J. O.; Silva, J. M. da; Pinheiro, A.; Carvalho, M. Tractor energy requirements in disc harrow systems. Biosystems Engineering, v.98, p.286-296, 2007. https://doi.org/10.1016/j.biosystemseng.2007.08.002

Strapasson Neto, L.; Kmiecik, L. L.; Jasper, S. P.; Zimmermann, G. G.; Savi, D. Interference of the number of remote control valves in use on the energy performance of an agricultural tractor with productivity management. Engenharia Agrícola, v.40, p.356-362, 2020. https://doi.org/10.1590/1809-4430-eng.agric.v40n3p356-362/2020

Sümer, S. K.; Sabanci, A. Effects of different tire configuration on tractor performance. Turkish Journal of Agriculture and Forestry, v.29, p.461-468, 2005.