Ciência Rural, Santa Maria, v.56:7, e20250043, 2026 http://doi.org/10.1590/0103-8478cr20250043
ISSNe 1678-4596
RURAL ENGINEERING

Operational performance of an agricultural tractor with different tire technologies on two surfaces

Gabriel Ganancini Zimmermann[1*] Samir Paulo Jasper[1] Eduardo Affonso Jung[1] Eduardo Alves Gracietti[1] Anderson Muniz Calhabeu[2] Fábio Volkmer Soares[2]

[1]Programa de Pós-graduação em Ciência do Solo, Departamento de Solos e Engenharia Agrícola, Universidade Federal do Paraná (UFPR), 80035-050, Curitiba, PR, Brasil. E-mail: gabrielganancini@gmail.com. *Corresponding author.
[2]Prometeon Tyre Group, Santo André, SP, Brasil.

ABSTRACT: Standard, IF, and VF radial tire technologies have brought significant advancements in load capacity and the operational efficiency of modern agricultural tractors. These improvements have contributed to reduced fuel consumption and greater sustainability in agricultural operations. However, limited research exists on the performance of agricultural tractors equipped with different tire technologies under real field conditions. Therefore, this study evaluated the operational performance of an agricultural tractor fitted with standard, IF, and VF radial tires on both concrete and firm soil surfaces. The experiment followed a strip-plot randomized block design with three tire technologies (standard, IF, and VF) as main plots and two surfaces (concrete and soil) as subplots, with five replicates, totaling 30 experimental units. Parameters monitored included engine speed, wheel slip, operating speed, drawbar pull, drawbar power and efficiency, hourly and specific fuel consumption, and engine thermal efficiency. Results showed that the concrete surface enabled higher speeds and lower fuel consumption, while the firm soil required greater engine speed and exhibited higher slip. VF tires outperformed standard tires in energy efficiency, traction, and contact area, offering higher speeds and reduced slip. However, under firm soil conditions, VF tires required additional ballast to reach optimal performance. IF tires demonstrated intermediate performance.
Key words: agricultural tires, drawbar pull, tractor traction, soil compaction.

Desempenho operacional de um trator agrícola com diferentes tecnologias de pneus em duas superfícies

RESUMO: As tecnologias de pneus radiais do tipo standard, IF e VF proporcionaram avanços significativos na capacidade de carga e no desempenho operacional de tratores agrícolas modernos. Esses avanços contribuíram para a redução do consumo de combustível e maior sustentabilidade nas operações agrícolas. No entanto, há poucas pesquisas que avaliem o desempenho de tratores agrícolas equipados com essas diferentes tecnologias de pneus em condições reais de campo. Deste modo, este estudo teve como objetivo avaliar o desempenho operacional de um trator agrícola equipado com pneus radiais standard, IF e VF em duas superfícies: concreto e solo firme. Além disso, o experimento foi conduzido em delineamento em blocos ao acaso em faixas, com três tecnologias de pneus (standard, IF e VF) como parcelas principais e duas superfícies como subparcelas, com cinco repetições, totalizando 30 unidades experimentais. Ademais, foram monitoradas as seguintes variáveis: rotação do motor, patinagem, velocidade de operação, força na barra de tração, potência e eficiência na barra de tração, consumo horário e específico de combustível e eficiência térmica do motor. Os resultados indicaram que a superfície de concreto possibilitou maiores velocidades e menor consumo de combustível, enquanto o solo firme exigiu maior rotação do motor e apresentou maior patinagem. Por outro lado, os pneus VF superaram os standards em eficiência energética, tração e área de contato, proporcionando maiores velocidades e menor patinagem. Contudo, no solo firme, os pneus VF exigiram lastro adicional para alcançar desempenho ideal e os pneus IF apresentaram desempenho intermediário.
Palavras-chave: pneus agrícolas, força na barra de tração, tração de tratores, compactação do solo

INTRODUCTION

Achieving high efficiency in agricultural operations is essential for ensuring productivity and sustainability. Within this context, tire selection significantly influences traction, fuel consumption, and overall machinery performance. The wheel system of a tractor – comprising the rim and tire – plays a key role in support, traction, and steering (CHANDRAKAR & RAHEMAN, 2024).

In Brazil, most agricultural tractors are equipped with bias-ply tires, which have a rigid sidewall structure that limits contact area and increases ground pressure. In contrast, radial tires allow for independent movement between the sidewall and tread, enhancing flexibility, traction, and contact area (ALKHALIFA et al., 2024).

In addition to the two traditional categories of agricultural tires – bias-ply (diagonal) and radial – there are three specific technologies within radial

Received 01.28.25 Approved 06.13.25 Returned by the author 02.22.26
CR-2025-0043.R1
Editor: Leandro Souza da Silva

tire design: standard (STD), increased flexion (IF), and very high flexion (VF). Recently introduced on the market, IF and VF tires offer greater sidewall flexibility and can support heavier loads: up to 20% more for IF and 40% more for VF tires, all while maintaining the same inflation pressure. This allows for the transportation of high loads at relatively low pressures, reducing ground pressure and potential soil compaction (SCHJØNNING et al., 2015; VANDERHASSELT et al., 2024).

According to ANIFANTIS et al. (2020), the structural evolution enabled by IF and VF technologies not only increases load capacity but also introduces new tread profiles that differ from traditional designs. This highlighted the importance of ongoing tire modeling improvements to meet modern agricultural demands. Consequently, research focused on the compatibility between tractors and tire technologies contributes to greater operational and energy efficiency (ZIMMERMANN et al., 2023).

Among the various parameters used to evaluate the performance of agricultural tractors, key indicators include wheel slip, forward speed, fuel consumption, drawbar pull and power, drawbar efficiency, specific fuel consumption, and engine thermal efficiency (JASPER et al., 2025).

TEKESTE et al. (2023) conducted a study evaluating different inflation pressures applied to STD, IF, and VF radial tires mounted on a 250-kW agricultural tractor paired with a planter. Their findings showed that the rear tires of the tractor were the main contributors to soil compaction during planting. Moreover, standard radial tires induced greater compaction and required higher energy expenditure compared to IF and VF tires.

Given the importance of evaluating tractor performance under different tire technologies, there remains a gap in the literature particularly regarding studies under field-like conditions. Therefore, this study assessed the operational performance of an agricultural tractor equipped with STD, IF, and VF radial tires on both concrete and soil surfaces.

MATERIALS AND METHODS

The study was conducted in the municipality of Pinhais, Paraná, Brazil, using two types of travel surfaces: concrete and firm soil, following the guidelines of ASABE standard EP 496.3 (2011). The experiment was arranged in a strip-plot randomized block design, with three radial tire technologies (Standard, IF, and VF) assigned to the main plots, and two travel surfaces (concrete and soil) assigned to the subplots, resulting in six treatment combinations. Each treatment was replicated five times, totaling 30 experimental units, each 100 meters in length.

The soil surface was a bare, firm layer classified as a typical *Latossolo Vermelho-Amarelo Distrófico* (Oxisol), with no vegetation cover and an average slope of 1% in the direction of tractor movement. The soil texture consisted of 234 g kg^{-1} of sand, 98 g kg^{-1} of silt, and 668 g kg^{-1} of clay.

The tractor used in the experiment was a New Holland® T7 260, featuring a net engine power of 161 kW (DIN 70020) and an 18x6 Full Powershift® transmission. The target operating speed (OS) was set at 1.94 m s^{-1} (7.0 km h^{-1}), achieved using gear B9 at an engine speed of 1950 rpm, which corresponds to 540 rpm at the PTO, as described by KMIECIK et al. (2022).

Initially, standard radial tires were installed with inflation pressures of 117 kPa (17 psi) on the front axle and 103 kPa (15 psi) on the rear axle. Static loaded radii were measured at 665 mm (front) and 882 mm (rear), and these values were maintained for the IF and VF tires to ensure comparable rolling circumference, adjusting only the inflation pressures.

For the IF tires, pressures were set to 96 kPa (14 psi) at the front and 86 kPa (12.5 psi) at the rear. For the VF tires, pressures were 83 kPa (12 psi) at the front and 72 kPa (10.5 psi) at the rear. Maintaining similar static radius ensured equivalent ground speed across all tire types, as rolling radius directly affects travel speed (BATTIATO & DISERENS, 2017).

The measured advance ratio was 2.11% for the standard tire, 2.05% for IF, and 2.00% for VF.

Metal ballasts of 13 kN were added to the front and 18 kN to the rear, resulting in a total tractor mass of 107 kN, distributed 42% over the front axle and 58% over the rear axle (ZIMMERMANN et al., 2022). The resulting mass-to-power ratio was 68 kg kW^{-1}.

The determination of the tire–surface contact area was conducted under a completely randomized design. This parameter serves as a key indicator of the tire's ability to distribute load over the travel surface. The method used followed the procedure described by MAZETTO et al. (2004).

The experiment employed the convoy method, in which the test tractor pulled a second tractor, used as a braking unit, via a drawbar connection. The brake tractor was a New Holland® T8 440 equipped with a 21x5 Full Powershift transmission. Braking was applied using pre-set gears to simulate target drawbar pulls of 65 kN (concrete) and 48 kN (soil), based on traction curves proposed by Wendel Bowers and adjusted for a 4 × 2 TDA tractor configuration. These settings corresponded to estimated drawbar power outputs of 126 kW and 93 kW, respectively. During testing, both tractors operated with front-wheel assist (TDA) engaged and full fuel tanks.

Data collection was performed using a custom data acquisition system (DAS) with an integrated printed circuit board. The system included the sensors described below and operated at a frequency of 1 Hz. All data were recorded and stored on a hard drive for subsequent processing and analysis.

Wheel slip was calculated based on engine speed and ground travel speed under loaded and unloaded conditions, as shown in equation 1.

$$WS=\left(1-\frac{S_W \text{ x } E_W}{S_A \text{ x } E_U}\right)\text{x100} \quad (1)$$

Where:
WS - wheel slippage in %;
S_W - tractor travel speed with load, m s^{-1};
S_A - tractor travel speed absent load, m s^{-1};
E_U - engine speed under load, rpm;
E_W - engine speed without load, rpm.

Engine speed (ES) was measured from the power take-off (PTO) using an Autonics® encoder, model E100S. The transmission ratio was obtained using a Victor® digital tachometer, model DM6236P ($R^2 = 0.99$).

Operating speed was obtained using an SVA-60 speed antenna (Agrosystem®), which measures displacement based on the number of pulses emitted.

Two Flowmate OVAL M-III® flow meters (model LSF 45L0-M2) were installed in the fuel supply system (inlet and return lines to the tank), enabling the measurement of hourly fuel consumption (HFC). Consumption was calculated from the difference in the number of pulses emitted by the flow meters and subsequently converted into volume.

Drawbar pull (DP) was measured using a Bermann® load cell with a capacity of 196 kN, sensitivity of 2.0 ± 0.002 mV V^{-1}, and accuracy of 0.01 kN. The load cell was properly calibrated and installed on the tractor's drawbar.

Based on the power available at the drawbar and engine output, drawbar efficiency was calculated using equation 2.

$$DBE=\left(\frac{DBP}{EP}\right)\text{x100} \quad (2)$$

Where:
DBE - drawbar efficiency, %;
DBP - drawbar power, kW;
EP - engine power, kW.

Diesel density (D) was obtained from temperatures measured by K-type thermocouples installed near the flowmeter in the tractor fuel return. Density was determined according to KLANFAR et al. (2016), who used a usual diesel fuel density of 850 g L^{-1}.

Mass-based hourly fuel consumption was calculated using equation 3.

$$MHC=\left(\frac{HFC \text{ x } D}{1000}\right) \quad (3)$$

Where:
MHC - mass-based hourly fuel consumption, g h^{-1};
HFC - hourly fuel consumption based on volume, L h^{-1};
1000 - conversion factor.

Specific fuel consumption (SFC) was determined based on mass-based hourly fuel consumption relative to drawbar power, as shown in equation 4.

$$SFC=\left(\frac{MHC}{DBP}\right) \quad (4)$$

Where:
SFC - specific fuel consumption, g kW h^{-1};

The engine's thermal efficiency was obtained through the specific consumption and the lower calorific value of the fuel by equation 5, according to FARIAS et al. (2017).

$$ETE=\left(\frac{3600}{SFC \text{ x } LCV}\right) \quad (5)$$

Where:
ETE - engine thermal efficiency, %;
LCV - lower calorific value, 42.295 MJ kg^{-1}.

The collected data were subjected to normality (Shapiro-Wilk) and homogeneity of variance (Brown-Forsythe) tests. When assumptions were met, analysis of variance (ANOVA) was performed to assess the effects of surface type, tire technology, and their interaction, as well as the effect of tire and technology on contact area. All analyses were conducted using R software. When the F-test indicated a significant effect ($P \leq 0.05$), treatment means were compared using Tukey's test ($P \leq 0.05$).

RESULTS AND DISCUSSION

Table 1 presents the results of the analysis of variance and mean comparisons for the operational performance data. Data transformation was not required for any of the variables analyzed. Only engine speed (ES) residuals did not meet the normality assumption. All parameters met the homogeneity of variance requirement, and the coefficient of variation remained within acceptable limits, as noted by FERREIRA (2018).

Most variables in table 1 showed significant effects for both surface type and tire technology. However, operating speed at working load (OS WL), engine speed (ES), and drawbar pull did not

Table 1 - Analysis of variance and tests of means for operational performance data.

Tests	--OS WL (km h^{-1})--	-----ES (RPM)-----	------WS (%)------	----OS (km h^{-1})----	------DP (kN)------
Normality					
SW	0.878	0.035	0.279	0.838	0.299
Homogeneity					
BF	0.762	0.963	0.593	0.998	0.982
Anova					
Surface (F1)	332.40**	26.661**	22346.41**	58.367**	169.80**
Tire Technology (F2)	1.698^{NS}	1.364^{NS}	452.06**	6.143*	0.618^{NS}
F1 x F2	126.44**	2.989^{NS}	33.56**	19.638**	1.481^{NS}
Surface (F1)					
Concrete	7.02 A	1,876 B	4.83 B	6.42 A	69.19 A
Firm soil	6.90 B	1,957 A	8.00 A	6.15 B	42.20 B
Tire Technology (F2)					
STD	6.98	1,923	7.26 A	6.08 B	54.46
IF	6.96	1,906	6.49 B	6.32 AB	55.46
VF	6.95	1,920	5.49 C	6.45 A	57.16
CV (%)					
F1	0.25	2.22	0.91	1.56	10.19
F2	0.43	1.26	2.05	6.84	9.86
F1 x F2	0.23	1.45	1.27	3.17	9.52

OS WL - operating speed without load; ES - engine speed; WS - wheel slip; OS - operating speed; DP – drawbar pull. Shapiro-Wilk normality test: SW ≤ 0.05 – Data abnormality; SW > 0.05 - Data normality. Brown-Forsythe homogeneity of variances test: BF ≤ 0.05 - Heterogeneous variances; BF > 0.05 - Homogeneous variances. F test of analysis of variance (ANOVA): NS - Not significant; *($P < 0.05$) and **($P < 0.01$). In each column, for each factor, means followed by the same uppercase letter do not differ from each other by the “Tukey test” ($P < 0.05$). CV %: Coefficient of variation.

exhibit significant differences in relation to the tire technology factor. A similar pattern was observed for the interaction effects, where ES and DP also showed no significant differences.

Operating speed without load (OS WL) was 1.72% higher on the concrete surface compared to soil. This difference can be attributed to the lower rolling resistance and reduced tire deformation on concrete. In contrast, soil characteristics such as texture and micro-relief tend to absorb part of the tractor’s traction energy, thereby reducing speed, as reported by BOTTA et al. (2012).

Engine speed was 4.32% higher on the soil surface compared to concrete, as ES is directly related to the amount of work required by the engine to overcome movement resistance consistent with the findings of SERRANO et al. (2007).

The wheel slip values were within the limits recommended by ASABE D496.3 (2011), which defines acceptable ranges of 4-8% for concrete and 8-10% for firm soils. On average, the soil surface resulted in 3.17% higher WS than concrete, thereby demanding greater ES. Regarding tire technology, VF tires exhibited 1% lower WS than IF tires and 1.77% lower than standard tires, due to their larger contact area, as described by TEKESTE et al. (2023).

When analyzing OS, the concrete surface exhibited a higher speed 0.27 km h^{-1} greater compared to the firm soil, which can be attributed to its lower rolling resistance. Regarding tire technology, the VF tire showed greater efficiency in this parameter, with a 5.75% increase over the STD tire, but no significant difference compared to the IF tire. This result is likely due to the lower WS observed with the VF tire, which helps maintain effective speed.

The drawbar power (DP) was higher on the concrete surface due to the differences in the applied loads, with the concrete offering greater traction, as previously discussed regarding rolling resistance conditions and surface micro-relief uniformity. The load applied on the concrete surface was within the range recommended by the ASABE standard (EP 496.3, 2011). However, on firm soil, the load was below expectations due to a mass-to-power ratio lower than the ideal 75 kg kW^{-1}. If the load were increased, both engine speed and wheel slip would likely decrease, potentially resulting in values outside the recommended range, as noted by KMIECIK et al. (2022).

Table 2 presents the results of the analysis of variance and mean comparison tests for the energy performance data. There was no need to transform the means, indicating normality and homogeneity of the variance residuals. Additionally, the coefficient of variation for all variables was categorized as stable, as reported by FERREIRA (2018).

In table 2, only the engine thermal efficiency (ETE) variable showed no significant difference in relation to the surface factor, while for the tire technology factor, only specific fuel consumption (SFC) presented a significant difference. Regarding the interaction between factors, hourly fuel consumption (HFC) was the only parameter that showed significant variation.

When analyzing the drawbar power (DBP) and drawbar efficiency (DBE) parameters, values were 51 kW and 30% higher, respectively, on the concrete surface. This outcome can be attributed to the higher DP and operating speed (OS) associated with the concrete surface when compared to firm soil.

The higher hourly fuel consumption observed on the concrete surface is associated with a greater capacity to transfer available energy (DBE), which reflects a more efficient use of fuel and results in lower SFC values. It is worth highlighting that with DP being 40% higher on the concrete surface, SFC was 142 g (47.40%) lower, indicating a greater efficiency in fuel-to-work conversion, as supported by EMAISH et al. (2021).

In the second factor, the VF tire showed greater efficiency in the SFC, with a fuel consumption 17.85% lower compared to the STD tire, although no significant difference was observed in relation to the IF tire. This performance can be attributed to the lower WS and higher OS achieved by the VF tire. The high energy efficiency of the VF tire compared to the STD reflects a more effective use of the calorific value of fossil fuels, which is a key factor in advancing sustainable agriculture (AL-SAGER et al., 2024).

Table 3 contains the results of the statistical analysis of the interaction between factors for no-load operating speed, wheel slip, operating speed and hourly fuel consumption.

Table 2 - Analysis of variance and mean tests for energy performance data.

Tests	----DBP (kW)----	----DBE (%)----	---HFC ($L\ h^{-1}$)---	--SFC ($g\ kW\ h^{-1}$)--	-----ETE (%)-----
Normality					
SW	0.184	0.184	0.570	0.484	0.581
Homogeneity					
BF	0.970	0.970	0.470	0.875	0.845
Anova					
Surface (F1)	204.18^{**}	204.18^{**}	182.53^{**}	68.114^{**}	89.09^{**}
Tire Technology (F2)	1.835^{NS}	1.835^{NS}	3.316^{NS}	5.27^{*}	2.549^{NS}
F1 x F2	0.003^{NS}	0.003^{NS}	15.226^{**}	3.78^{NS}	1.590^{NS}
Surface (F1)					
Concrete	123.27 A	71.63 A	42.62 A	298.84 B	29.00
Firm soil	71.94 B	41.80 B	36.99 B	440.51 A	19.59
Tire Technology (F2)					
STD	93.29	54.20	40.91	407.95 A	22.70
IF	96.92	56.32	39.51	365.92 AB	24.23
VF	102.61	59.62	39.00	335.16 B	25.97
CV (%)					
F1	10.08	10.08	2.86	12.72	11.24
F2	11.24	11.24	4.32	13.62	13.31
F1 x F2	9.71	9.71	3.16	10.05	9.98

DBP - drawbar power; DBE - drawbar efficiency; HFC - hourly fuel consumption; SFC - specific fuel consumption; ETE - engine thermal efficiency. Shapiro-Wilk normality test: SW ≤ 0.05 - Data abnormality; SW > 0.05 - Data normality. Brown-Forsythe homogeneity of variances test: BF ≤ 0.05 - Heterogeneous variances; BF > 0.05 - Homogeneous variances. F test of analysis of variance (ANOVA): NS - Not significant; *(P < 0.05) and **(P < 0.01). In each column, for each factor, means followed by the same uppercase letter do not differ from each other by the "Tukey test" (P < 0.05). CV %: Coefficient of variation.

Table 3 - Statistical analysis of the interaction between factors.

Tire Technology (F2)	Surface (F1) Concrete	Surface (F1) Firm soil	Average
OS WL (km h^{-1})			
STD	7.01 Ab	6.94 Bb	6.98
IF	6.97 Ac	6.94 Bb	6.96
VF	7.07 Aa	6.83 Ba	6.95
Average	7.02 A	6.90 B	6.96
WS (%)			
STD	5.50 Ba	9.01 Aa	7.26 A
IF	5.00 Bb	7.99 Ab	6.49 B
VF	3.99 Bc	7.00 Ac	5.49 C
Average	4.83 B	8.00 A	6.41
OS (km h^{-1})			
STD	6.52 Aa	5.63 Bb	6.08 B
IF	6.22 Aa	6.42 Aa	6.32 AB
VF	6.51 Aa	6.38 Aa	6.45 A
Average	6.42 A	6.15 B	6.28
HFC (L h^{-1})			
STD	42.24 Aa	39.58 Bb	40.91
IF	42.19 Aa	36.82 Ba	39.51
VF	43.42 Aa	34.58 Ba	39.00
Average	42.62 A	36.99 B	39.80

OS WL - operating speed without load; WS - wheel slip; OS - operating speed; HFC - hourly fuel consumption. Different uppercase letters in the columns indicate statistical difference by Tukey's test ($P < 0.05$); Different lowercase letters in the rows indicate statistical difference by Tukey's test ($P < 0.05$); The same letters do not differ significantly from each other.

The OS WL results (Table 3) indicate that the concrete surface provided the highest average speed (7.02 km h^{-1}) compared to firm soil (6.90 km h^{-1}), a difference attributed to the lower rolling resistance and surface roughness of the concrete, which favor higher operational speeds (FARHADI et al., 2019). The VF tire stood out on concrete, reaching 7.07 km h^{-1}, while on firm soil its performance was slightly lower, likely due to its structural design, which provides a larger contact area. The STD tire exhibited a balanced performance across both surfaces, whereas the IF tire did not show significant differences between concrete and firm soil.

The concrete surface resulted in lower WS values (4.83%) compared to firm soil (8.0%), indicating greater traction on the more uniform and rigid surface. The VF tire recorded the lowest WS values across surfaces. As previously discussed, the suboptimal mass/power ratio on firm soil reinforces the dependence of tire technology performance on proper ballasting, particularly under firmer ground conditions. The STD tire showed the highest slippage on firm soil, while the IF tire also experienced increased WS on this surface, though to a lesser extent than the STD.

The OS results showed that the concrete surface provided an average speed 4.20% higher than that on firm soil. The STD tire stood out on concrete, reaching 6.52 km h^{-1}, while on firm soil its speed dropped to 5.63 km h^{-1}. In contrast, the IF and VF tires showed no significant differences between surfaces, indicating more consistent performance regardless of the rolling conditions, as also reported by NAGAOKA et al. (2024).

The HFC results indicate higher consumption on the concrete surface, averaging

42.62 L h^{-1}, compared to 36.99 L h^{-1} on firm soil. All tires demonstrated lower fuel consumption on firm soil, with the VF tire showing the most pronounced reduction: from 43.42 L h^{-1} on concrete to 34.58 L h^{-1} on firm soil. It is important to highlight that the ground surface was operating 15% below the ideal load, which contributes to the reduced consumption and reinforces the importance of adequate ballasting for optimizing the performance of VF tire technology.

Table 4 presents the results of the analysis of variance and mean comparisons for the tire contact area data. No transformation of the means was necessary, indicating normality and homogeneity of variance in the residuals.

The OS results showed that the concrete surface provided an average speed 4.20% higher than that on firm soil. The STD tire stood out on concrete, reaching 6.52 km h^{-1}, while on firm soil its speed dropped to 5.63 km h^{-1}. In contrast, the IF and VF tires showed no significant differences between surfaces, indicating more consistent performance regardless of the rolling conditions, as also reported by NAGAOKA et al. (2024).

The HFC results indicated higher consumption on the concrete surface, averaging 42.62 L h^{-1}, compared to 36.99 L h^{-1} on firm soil. All tires demonstrated lower fuel consumption on firm soil, with the VF tire showing the most pronounced reduction: from 43.42 L h^{-1} on concrete to 34.58 L h^{-1} on firm soil. It is important to highlight that the ground surface was operating 15% below the ideal load, which contributes to the reduced consumption and reinforces the importance of adequate ballasting for optimizing the performance of VF tire technology.

Table 4 presents the results of the analysis of variance and mean comparisons for the tire contact area data. No transformation of the means was necessary, indicating normality and homogeneity of variance in the residuals.

In table 4, the average contact area for the front tire was 0.266 m², with the STD tire showing the smallest area (0.227 m²) and the VF tire the largest (0.300 m²). These findings indicate that tire construction technology influences the contact area even on the front axle, which typically exhibits a smaller footprint. As noted by SCHJØNNING et al. (2015), VF technology enhances flotation and load distribution on the front axle, improving traction control, grip, and steerability during field operations.

For the rear tire, the average contact area was 0.375 m² – substantially greater than that of the front tire. The VF tire once again exhibited the largest area (0.449 m²), followed by the IF (0.352 m²) and STD (0.324 m²). According to VANDERHASSELT et al. (2024), VF tires are designed to operate at lower inflation pressures, which increases the contact area relative to IF and STD technologies, thereby enhancing traction and load distribution, particularly under high-load conditions on the rear axle.

CONCLUSION

The concrete surface exhibited lower rolling resistance, which contributed to higher operating speed and reduced specific fuel consumption. In contrast, the firm soil surface required greater engine power, as indicated by increased ES and WS.

VF tires demonstrated superior performance in terms of energy efficiency and traction, achieving higher OS, larger CA, and lower WS compared to STD tires. However, under firm soil conditions, the effectiveness of VF technology was dependent on adequate ballasting to reach optimal performance.

The IF tire technology showed intermediate results between VF and STD, delivering a balanced

Table 4 - Analysis of variance and tests of means for tire contact patch data.

Contact Area (m²)			
Tire Technology (F2)	Tire (F1)		Average
	Front	Rear	
STD	0.227 Cb	0.324 Ca	0.276 C
IF	0.271 Bb	0.352 Ba	0.311 B
VF	0.300 Ab	0.449 Aa	0.374 A
Average	0.266 B	0.375 A	0.320

By ANOVA, the F-Test values were: F1 = 729.75; F2 = 220.76**; F1 x F2 = 28.063**. Shapiro-Wilk Normality Test = 0.119. Different uppercase letters in the columns indicate statistical difference by Tukey's test ($P < 0.05$); Different lowercase letters in the rows indicate statistical difference by Tukey's test ($P < 0.05$); The same letters do not differ significantly from each other.

compromise between operational efficiency and traction capability.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest. The funding sponsors were not involved in the study design, data collection, analysis, or interpretation, nor in the writing of the manuscript or the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors equally contributed to the conception and writing of the manuscript. They also critically reviewed the content and approved the final version for publication.

DATA AVAILABILITY STATEMENT

Research data is only available upon request.

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE

During the preparation of the article, artificial intelligence was not use.

REFERENCES

ALKHALIFA, N. et al. Effects of vertical load and inflation pressure on tire-soil interaction on artificial soil. **Journal of Terramechanics**, v.112, p.19-34, 2024. Available from: <http://doi.org/10.1016/j.jterra.2023.11.002>. Accessed: Jan. 14, 2025. doi: 10.1016/j.jterra.2023.11.002.

AL-SAGER, S. M. et al. Prediction of specific fuel consumption of a tractor during the tillage process using an artificial neural network method. **Agronomy**, v.14, n.3, e492, 2024. Available from: <https://www.mdpi.com/2073-4395/14/3/492>. Accessed: Jan. 14, 2025. doi: 10.3390/agronomy14030492.

ANIFANTIS, A. S. et al. An experimental–numerical approach for modelling the mechanical behaviour of a pneumatic tyre for agricultural machines. **Applied Sciences**, v.10, n.10, p.3481, 2020. Available from: <https://www.mdpi.com/2076-3417/10/10/3481>. Accessed: Jan. 11, 2025. doi: 10.3390/app10103481.

ASABE - American Society of Agricultural Biological Engineer. **ASABE EP 496.3**. Agricultural machinery management data. ASABE Standards, 2011.

BATTIATO, A.; DISERENS, E. Tractor traction and performance simulation on differently textures soils and validation: A basic study to make traction and energy requirements accessible to the practice. **Soil & Tillage Research**, v.166, p.18-32, 2017. Available from: <https://doi.org/10.1016/j.still.2016.09.005>. Accessed: Jan. 10, 2025. doi: 10.1016/j.still.2016.09.005.

BOTTA, G. F. et al. Agricultural traffic: Motion resistance and soil compaction in relation to tractor design and different soil conditions. **Soil and Tillage Research**, v.120, p.92-98, 2012. Available from: <https://www.sciencedirect.com/science/article/pii/S0167198711002078?via%3Dihub>. Accessed: Jan. 12, 2025. doi: 10.1016/j.still.2011.11.008.

CHANDRAKAR, H.; RAHEMAN, H. Effect of contact length of bias ply tractor tire on its tractive performance. **Journal of Terramechanics**, v.113, p.100969, 2024. Available from: <https://www.sciencedirect.com/science/article/pii/S0022489824000119?via%3Dihub>. Accessed: Jan. 12, 2025. doi: 10.1016/j.jterra.2024.100969.

DEUTSCHES INSTITUT FÜR NORMUNG – DIN. **DIN 70020**: Automotive engineering, maximum speed, acceleration and other terms, definitions, and tests. Berlin, 1986.

EMAISH, H. et al. Evaluation of the performance and gas emissions of a tractor diesel engine using blended fuel diesel and biodiesel to determine the best loading stages. **Scientific Reports**, v.11, e9811, 2021. Available from: <https://www.nature.com/articles/s41598-021-89287-0>. Accessed: Jan. 12, 2025. doi: 10.1038/s41598-021-89287-0.

FARHADI, P. et al. Prediction of the tractor tire contact area, contact volume and rolling resistance using regression model and artificial neural network. **Agricultural Engineering International**, v.21, n.3, p.26-38, 2019. Available from: <https://cigrjournal.org/index.php/Ejounral/article/view/5438>. Accessed: Jan. 12, 2025.

FARIAS, M. S. D. et al. Air and fuel supercharge in the performance of a diesel cycle engine. **Ciência Rural**, v.47, n.6, p.1-7, 2017. Available from: <https://www.scielo.br/j/cr/a/wJDhBcQFsBdgbbhGw3kLNxD/>. Accessed: Jan. 12, 2025. doi: 10.1590/0103-8478cr20161117.

FERREIRA, P. V. **Experimental statistics applied to agricultural sciences**. Viçosa: UFV, 2018. 126p.

JASPER, S. P. et al. Energy efficiency of four-wheel drive tractor in sowing operation. **Ciência Rural**, v.55, n.1, e20240141, 2025. Available from: <https://www.scielo.br/j/cr/a/jVpWGYcLGydk4FfYwQwTRhd/?format=html&lang=en>. Accessed: Jan. 12, 2025. doi: 10.1590/0103-8478cr20240141.

KLANFAR, M. et al. Fuel consumption and engine load factors of equipment in quarrying of crushed stone. **Tehnički vjesnik**, v.23, n.1, p.163-169, 2016. Available from: <https://doi.org/10.17559/TV-20141027115647>. Accessed: Jan. 02, 2025. doi: 10.17559/TV-20141027115647.

KMIECIK, L. L. et al. Agricultural tractor with different mass distributions between axles. **Ciência Rural**, v.53, n.3, e20210604, 2022. Available from: <https://www.scielo.br/j/cr/a/rhkgQ6BwBsC4Sd6dY6XJcZp/?lang=en>. Accessed: Jan. 02, 2025. doi: 10.1590/0103-8478cr20210604.

MAZETTO, F. R. et al. Avaliação do contato pneu-solo em três modelos de pneus agrícolas. **Engenharia Agrícola**, v.24, p.750-757, 2004. Available from: <https://www.scielo.br/j/eagri/a/8SdmYkqyFfrwS955WqKqFmJ/?lang=pt&format=html>. Accessed: Jan. 02, 2025. doi: 10.1590/S0100-69162004000300028.

NAGAOKA, A. K. et al. Agricultural Tire Test: Straw Cover Effect on Reducing Soil Compaction by Cargo Vehicles. **AgroEngenharia**, v.6, n.3, p.3016-3029, 2024. Available from: <https://www.mdpi.com/2624-7402/6/3/173>. Accessed: Jan. 02, 2025. doi: 10.3390/agriengineering6030173.

ROŞCA, R. et al. The improvement of a traction model for agricultural tire–soil interaction. **Agriculture**, v.12, n.12, p.2035, 2022. Available from: <https://www.mdpi.com/2077-0472/12/12/2035>. Accessed: Jan. 02, 2025. doi: 10.3390/agriculture12122035.

SCHJØNNING, P. et al. Driver-pressure-state-impact-response (DPSIR) analysis and risk assessment for soil compaction – a European perspective. **Advances in agronomy**, v.133, p.183-237, 2015. Available from: <https://www.sciencedirect.com/science/article/abs/pii/S0065211315001108>. Accessed: Jan. 02, 2025. doi: 10.1016/bs.agron.2015.06.001.

SERRANO, J. M. et al. Tractor energy requirements in disc harrow systems. **Biosystems Engineering**, v.98, n.3, p.286-296, 2007. Available from: <https://doi.org/10.1016/j.biosystemseng.2007.08.002>. Accessed: Jan. 02, 2025. doi: 10.1016/j.biosystemseng.2007.08.002.

TEKESTE, M. Z. et al. Effect of increased deflection tire technology on soil compaction. **Journal of the ASABE**, v.66, n.1, p.75-84, 2023. Available from: <https://doi.org/10.13031/ja.14794>. Accessed: Jan. 02, 2025. doi: 10.13031/ja.14794.

VANDERHASSELT, A. et al. Effects of road-vs. field-recommended tyre inflation pressures and small variations in soil moisture content on traffic-induced soil compaction during seedbed preparation. **Soil and Tillage Research**, v.241, p.106109, 2024. Available from: <https://www.sciencedirect.com/science/article/pii/S0167198724001107?via%3Dihub>. Accessed: Jan. 02, 2025. doi: 10.1016/j.still.2024.106109.

ZIMMERMANN, G. G. et al. Effect of hydraulic and solid ballast on agricultural tractor performance. **Revista Ciência Agronômica**, v.53, e20217963, 2022. Available from: <https://www.scielo.br/j/rca/a/JcwmtBBKKTxYxwDQcH3mrvL/?format=html&lang=en>. Accessed: Jan. 02, 2025. doi: 10.5935/1806-6690.20220059.

ZIMMERMANN, G. G. et al. Full-powershift energy behavior tractor in soil tillage operation. **Engenharia Agrícola**, v.43, n.6, e20230054, 2023. Available from: <https://www.scielo.br/j/eagri/a/FFpfgdcVjKTZTSDG9MxqTNy/?lang=en>. Accessed: Jan. 12, 2025. doi: 10.1590/1809-4430-Eng.Agric.v43n6e20230054/2023.