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Modeling the performance of an agricultural tractor with radial and diagonal tires on a firm soil

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Abstract: The tractive capacity and, consequently, the operational performance of the agricultural tractor depends on the characteristics of the tires. This study aimed to model the drawbar performance of an agricultural tractor equipped with radial and diagonal tires on a firm soil track with different force demands on the drawbar. An experiment was set up using a completely randomized statistical design in a split-plot scheme. The plots were made up of two types of tires (radial and diagonal), and the subplots were made up of six different forces, to which the tractor was subjected on the drawbar (1.4, 4.5, 10.5, 15.6, 19.9, and 23.3 kN), with three replications per treatment. A load cell was used to measure traction force, a flow meter for fuel consumption, and magnetic sensors for slippage. The results showed that the type of tire did not influence the hourly fuel consumption. Higher average values for specific fuel consumption, travel speed, and power available at the tractor drawbar were obtained with radial tires, while higher slippage values were obtained with diagonal tires. The modeling of the agricultural tractor performance allowed us to infer that the evaluated tractor behaved more efficiently, in terms of energy expenditure, on firm soil when equipped with radial tires than with diagonal tires.

Keywords: Dynamometer car. Fuel consumption. Power at the drawbar. Slippage.

Introduction

The efficiency of a tractor in achieving traction in real operating conditions is a consequence of the interaction between the wheelset and the road surface. This means that it depends on the interaction between the characteristics of the tires, such as the type of construction, and the physical-mechanical characteristics of the soil (Janulevičius et al., 2014).

The agricultural tire is a crucial factor in the tractor operational performance, as it ensures the machine balance and support, providing displacement, guides it in the desired direction, and cushions any impacts (Montanha et al., 2012). According to Jesuíno et al. (2011) and Montanha et al. (2011), the type of tire construction, among others, is also correlated with the tractor traction capacity, energy efficiency, and fuel consumption.

The radial construction tire has its plies forming an angle of 90º with the axis of rotation, while the diagonal tire has the plies at an angle of 45º (Neujahr and Schlosser, 2001). In Brazil, radial tires began to be introduced in agricultural machinery in 1994, due to changes in the import policy, given that Brazilian factories did not produce this type of tire at the time (Neujahr and Schlosser, 2001).

More than 30 years after the first imports, there is still a need for comparative studies that analyze the performance of agricultural tractors equipped with radial and diagonal tires, in Brazilian soil conditions.

Therefore, modeling the performance of agricultural tractors equipped with radial and bias-ply tires can explain and predict significant differences in specific fuel consumption, travel speed, drawbar power availability, and wheel slip. This approach enables the identification of the most energy-efficient tire type.

The performance of a tractor on surfaces such as agricultural soil, concrete or asphalt can be evaluated through variables such as specific fuel consumption, power available at the drawbar, travel speed and wheel slip (Fiorese et al., 2015). Therefore, modeling the performance of agricultural tractors with radial and bias tires can explain and predict significant differences in these variables, allowing the identification of the most efficient type of tire in terms of energy expenditure.

Because of the applicability of testing tractors in field situations, this work aimed to model the performance of an agricultural tractor equipped with radial and diagonal tires on firm soil with different forces on the drawbar.

Results and Discussion

According to the analysis of variance shown in Table 1, the interaction between drawbar load and the type of tire evaluated significantly influenced specific fuel consumption, set speed, drawbar power, and wheel slippage. However, hourly fuel consumption was only significantly influenced when the forces on the drawbar changed. Therefore, as these are quantitative factors, all the variables were evaluated using regression, and the mean comparison test was also applied to better visualize the results.

According to the average drawbar force, the hourly fuel consumption curve was fitted using the linear model (Fig 1). As there was no significant difference between the plot levels, the types of tires, or the interaction between the factors, the model was adjusted using the average fuel consumption at each level of the subplot, i.e., at each average value of force on the drawbar.

Despite the low coefficient of determination (R^2), the linear model shown in Fig 1 was significant, which corroborates the model presented by Fiorese, et al. (2015), who evaluated the performance of the drawbar of three agricultural tractors and concluded that the hourly fuel consumption behaves linearly according to the forces on the drawbar.

Specific fuel consumption according to the average tractive force was adjusted according to a quadratic model (Fig 2), corroborating the specific fuel consumption models presented by Ortiz et al. (2012).

It can be seen in the curves shown in Fig 2 that the specific fuel consumption of both types of tires decreased up to a certain limit as the traction force on the bar increased. After this inflection point, consumption reversed its trend, where similar results were found by Fiorese et al. (2015), Gomes et al. (2016) and Paula et al. (2016).

The Specific Consumption (SC) measures the efficiency with which the engine converts the fuel mass into mechanical energy, with lower SC values indicating higher efficiency. The parabolic behavior of SC is influenced by two regions, separated by the inflection point at the minimum SC value, which represents the engine's maximum efficiency. In Fig. 2, within the traction bar force range below the inflection point, a reduction in SC values is observed due to the low energy demand. As the force increases, the engine operates within a higher efficiency range. After reaching the minimum SC value, the engine requires a greater amount of fuel to maintain the same performance due to the increased energy demand.

The inflection points of the curves were shown in Fig 2. It represented by the forces 16.8 and 16.4 kN, respectively, for radial and diagonal tires. The tractor performance enters the range with the best performance in terms of specific fuel consumption on firm soil, optimizing the performance of the transmission system and wheels in terms of converting the chemical energy of the fuel into force on the drawbar.

The specific fuel consumption for the tractor equipped with diagonal tires, on average, was lower than that of radial tires (Fig 3). This differs from the results found by Monteiro et al. (2011), who, when evaluating diagonal and radial tires in different ballasting conditions and types of surfaces, concluded that diagonal tires have, on average, higher specific fuel consumption on firm soil with 40% and 75% ballasting.

This divergence is related to the variation in force on the drawbar carried out in this study, as changing the loads imposed on the drawbar (1.4, 4.5, 10.5, 15.6, 19.9, and 23.3 kN) resulting in different force values for calculating the specific consumption averages (Fig 3). This shows that specific fuel consumption cannot be analyzed using averages for the different forces imposed on the drawbar.

At the same time the point of intersection between the curves (which occurs at the force imposed on the drawbar of 12.6 kN), the specific fuel consumption of the tractor with radial tires is lower than when equipped with diagonal tires (Fig 2). Only before this intersection point the specific consumption with radial tires showed higher values.

This can also be seen by analyzing Fig 4 and Fig 5, where the averages presented that the specific fuel consumption of the tractor equipped with radial tires is lower for forces on the drawbar greater than 12.6 kN (Fig 4). The specific fuel consumption of the tractor equipped with diagonal tires is lower for forces on the drawbar below 12.6 kN (Fig 5).

After the intersection of the curves represented by force on the drawbar of 12.6 kN, i.e., approximately after the inflection point, at which the tractor enters the optimum performance range on firm soil (Fig. 2). The specific fuel consumption model in this work corroborated with Monteiro, et al. (2011), who used a continuous, high performance force on the drawbar during their study, possibly a force that generates higher specific consumption for diagonal tires because it is within the optimum performance range on firm ground. This study used forces in all work categories, both within and outside the optimum performance range.

The radial tires exhibit lower SC, which may occur under working conditions with low traction bar force or on firmer soil, where the radial tire design better distributes the weight and reduces rolling resistance (Fig. 4).

The diagonal tires exhibit lower SC, which may occur under conditions of high traction bar force or less compacted soils, where the more rigid design of diagonal tires provides greater traction and reduced slippage (Fig. 5).

This demonstrates that the choice of tire type depends on the operational conditions, to which the tractor will be subjected during its working cycles. The tractor travel speed was adjusted according to the average tractive forces using a polynomial model (Fig. 6). The tractor's average travel speed decreases as the force imposed on the drawbar increases, regardless of the type of tire construction that the tractor is equipped with.

The average speeds for the different types of tire construction were different; the tractor with the radial tire had a higher average travel speed (Fig. 7), which led to variations in the operational capacity of the units.

The results presented by the travel speed of the combination, together with the results of the specific fuel consumption and the greater slippage of the drive wheels of the diagonal tire, allow us to infer that the radial tire is the most advisable choice on firm soil, corroborating with Monteiro et al. (2011) and Ribas et al. (2014), where they stated that the constructive characteristics of the radial tire allowed for greater traction advantages over the diagonal tire.

Table 1. Summary of the analysis of variance for hourly fuel consumption (HC; L h^{-1}), specific fuel consumption (SC; g(kW $h)^{-1}$), average travel speed (Spd; km h^{-1}), drawbar power (Pb; kW), and wheel slippage (Slp; %).

Source of Variation	DF	Mean square				
		HC	SC	Spd	Pb	Slp
Tire (T)	1	0.3	2454309.6*	0.0478*	0.82*	83.6
Residue 1	4	0.1	8188.7	0.0030	0.07	19.8
Force on the drawbar (Df)	5	7.2**	212462331.2**	0.5329**	124.16**	1585.1**
(T) x (Df)	5	1.0	1933428.0**	0.0083*	0.85**	42.6**
Residue 2	20	0.5	131569.1	0.0027	0.09	9.4
Total	35					
CV1 =		1.59	1.91	2.35	3.50	34.37
CV2 =		3.45	7.68	2.24	3.99	23.71
Mean =		19.72	4725.50	2.31	7.49	12.93

**Significant at 1% probability by the F test. *Significant at 0.05 probability by the F test. DF: Degree of freedom. CV1: Coefficient of variation of the plot (%). CV2: Coefficient of variation of the subplot (%). According to the average force on the drawbar, the hourly fuel consumption curve was adjusted

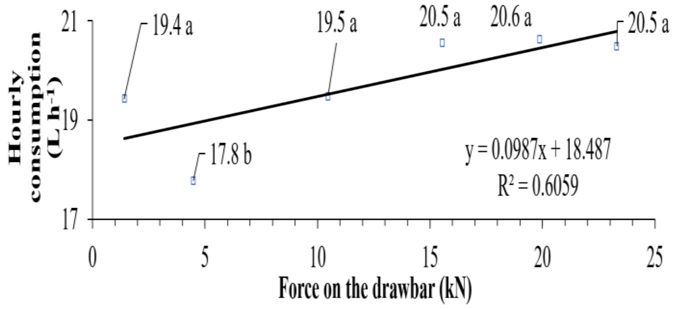

Fig 1. Linear regression model of average hourly fuel consumption (HC) for the different average forces imposed on the drawbar (Fm). When followed by the same letters, the hourly consumption averages shown in the graph do not differ according to the Tukey test (P > 0.05) and coefficient of determination (R^2) em decimal.

Table 2. Characterization of the tires used in the experiments.

Characteristic	Diagonal fronts	Radial rear	Diagonal rear
Measure	14.9-24 R1	18.4R34 R1	18.4 34
Load capacity (Ply Rating)	6	8	10
Perimeter (m)	3.9	5.25	5.18
Section width (m)	0.36	0.46	0,44
Liquid ballasting (liters)	180	210	350
Solid ballasting (kgf)	0	300	300
Inflation pressure (psi)	20	23	26
Static axle load (kgf)	2680	3550	3690

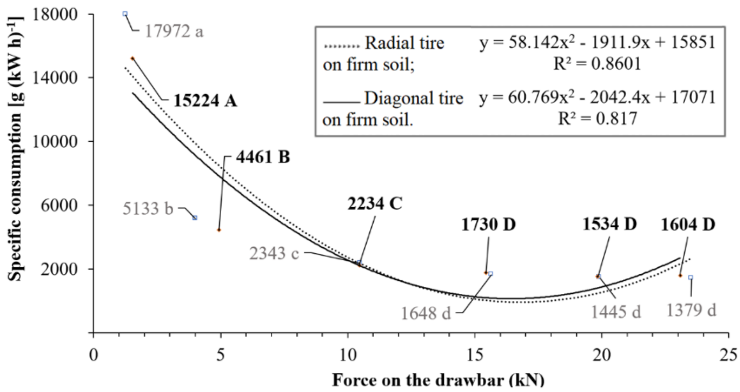

Fig 2. Polynomial regression model of the tractor specific fuel consumption (SC) for the types of tires tested [SC (D) - specific consumption with diagonal tires and SC (R) - specific consumption with radial tires] for the different average forces imposed on the drawbar (Fm). When followed by the same letters, the specific consumption averages shown in the graph do not differ according to the Tukey test (P > 0.05).

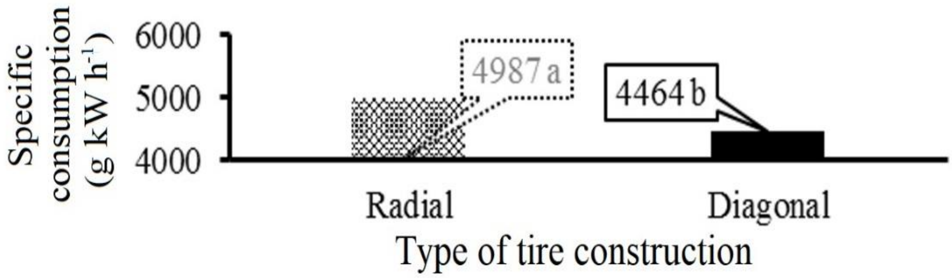

Fig 3. Average values of specific fuel consumption (SC) for the different tire construction types. When followed by the same letter, the specific consumption averages shown in the graph do not differ using the Tukey test (P > 0.05).

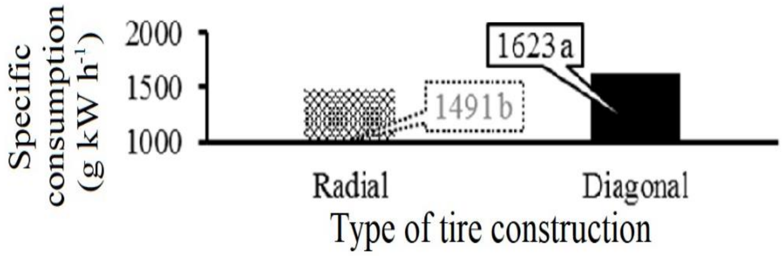

Fig 4. Average values of specific fuel consumption (SC) for forces on the drawbar higher than 12.6 kN for the different tire types. The averages of specific fuel consumption shown in the graph, when followed by the same letter, do not differ using the Tukey test (P > 0.05).

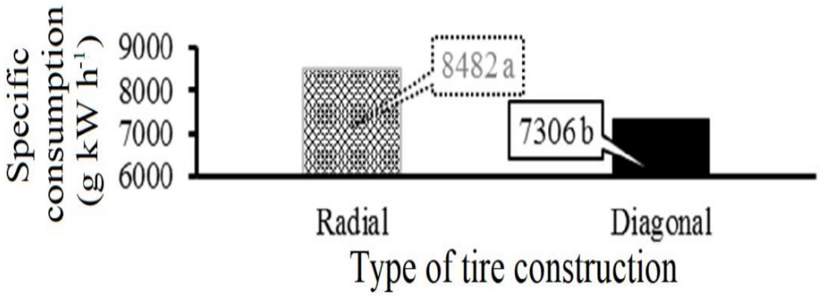

Fig 5. Average values of specific fuel consumption (SC) for forces on the drawbar lower than 12.6 kN for the different tire types. The averages of specific fuel consumption shown in the graph, when followed by the same letter, do not differ using the Tukey test (P > 0.05).

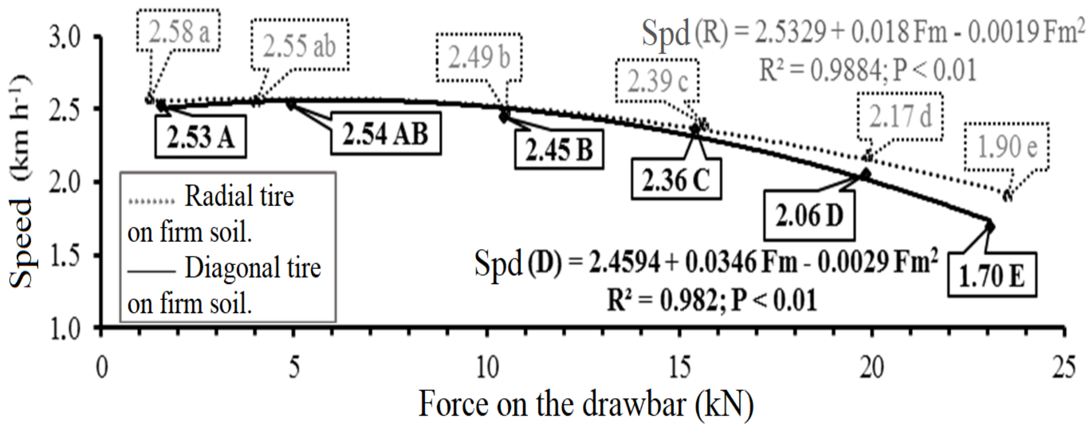

Fig 6. Polynomial regression model of tractor travel speed (Spd) with the types of tires tested [Spd (D) - speed with diagonal tires and Spd (R) - speed with radial tires] for the different average forces imposed on the drawbar (Fm). The travel speed averages shown in the graph, followed by the same lowercase letters for the radial tire and uppercase letters for the diagonal tire, do not differ according to the Tukey test (P > 0.05).

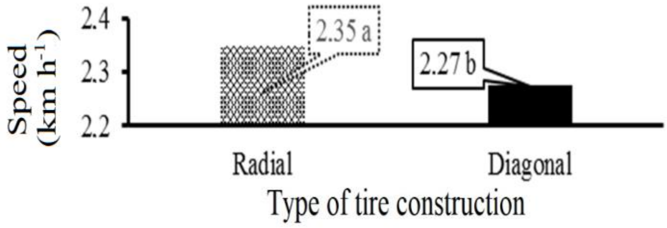

Fig 7. Average tractor travel speed values (Spd) for the different tire construction types. The average travel speeds shown in the graph, when followed by the same letter, do not differ according to the Tukey test (P > 0.05).

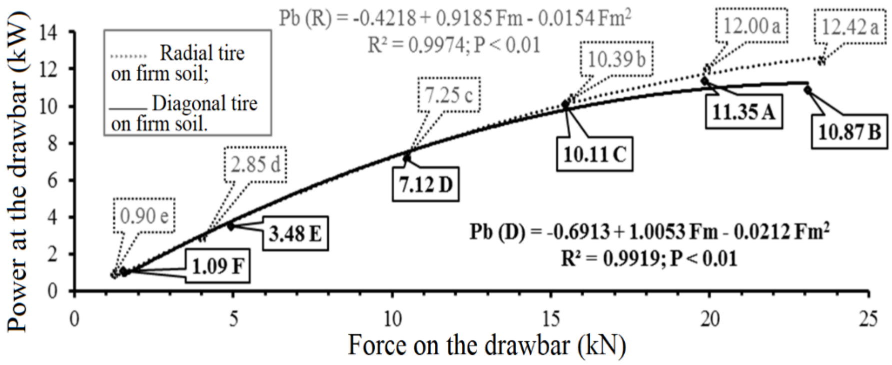

Fig 8. Polynomial regression model of the power available at the drawbar (Pb) for the types of tires tested [Pb (D) - power available with diagonal tires and Pb (R) - power available with radial tires], for the different average forces imposed on the drawbar (Fm). The power averages on the drawbar shown in the graph, followed by the same lowercase letters for the radial tire and uppercase letters for the diagonal tire, do not differ by Tukey test (P > 0.05).

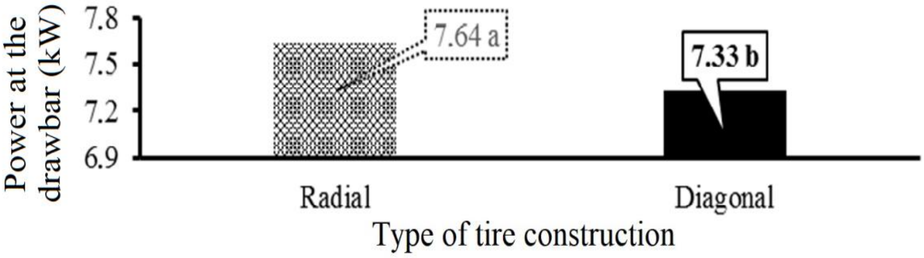

Fig 9. Average power available at the drawbar (Pb) for the different tire types. When followed by the same letter, the power averages available at the drawbar shown in the graph do not differ using the Tukey test (P > 0.05).

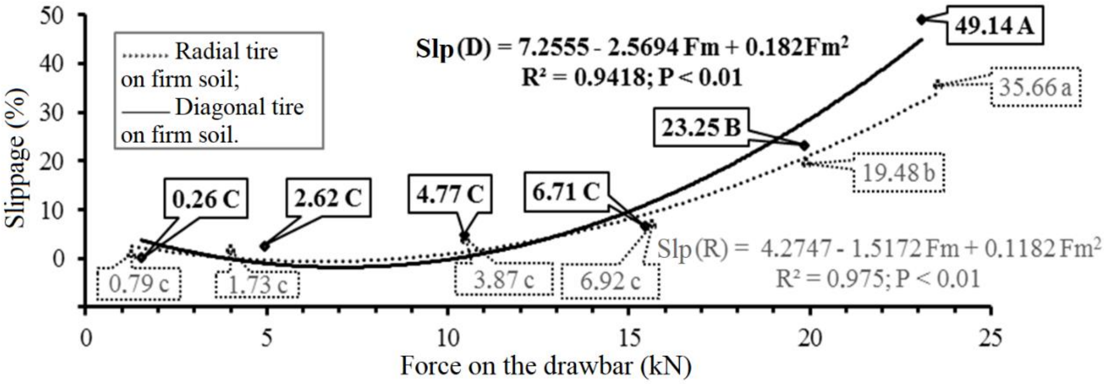

Fig 10. Polynomial regression model of the slippage of the drive wheels (Slp) on the types of tires tested [Slp (D) - slippage of diagonal tires and Slp (R) - slippage of radial tires] for the different average forces imposed on the drawbar (Fm). The slippage averages shown in the graph, followed by the same lowercase letters for the radial tire and uppercase letters for the diagonal tire, do not differ by Tukey test (P > 0.05).

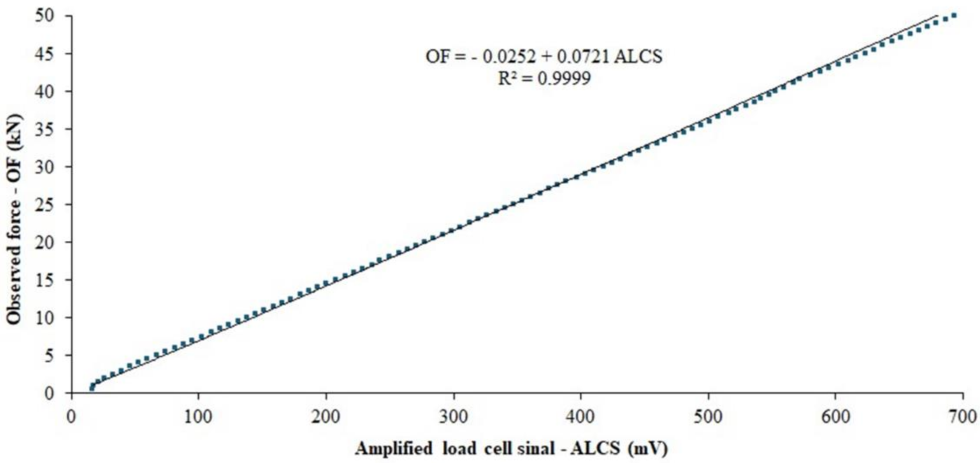

Fig 11. Load cell calibration model in the laboratory.

The behavior of the power at the drawbar on firm soil according to the average force was adjusted by a quadratic model (Fig. 8), in which the radial tire again proved superior to the diagonal tire (Monteiro et al., 2011).
In an experiment by Fiorese et al. (2015), the power available at the drawbar was adjusted with a linear model, diverging from the quadratic model found in this work. Fiorese et al. (2015) attributed this divergence to the range of power values, in which the drawbar performance was lower than recommended.
In addition, Ortiz et al. (2012) and Paula et al. (2016) adjusted the power available at the drawbar with a nonlinear model, in which the yield of the available power increases as the force on the drawbar increases up to a certain upper limit. After this inflection point, the authors state that the fractions of the tractor total power related to wheel friction, slippage, transmission, acceleration, and inclination increase substantially, inferring a decrease in the power available at the drawbar, thus again explaining the polynomial model fitted (Fig. 8).
When equipped with radial tires, the tractor on firm soil made an average of 4.05% more power available at the drawbar than when equipped with diagonal tires (Fig. 9). Similar results were found by Monteiro et al. (2011), that evaluated diagonal and radial tires in different ballasting conditions and types of surfaces. They concluded that the tractor evaluated when equipped with radial tires had more power available at the drawbar than when equipped with diagonal tires.
Fig. 10 shows the slippage of the drive wheels was adjusted according to the average tractive force following a quadratic model, corroborating the models proposed by Barger et al. (1963). Similar modeling was also carried out by Gomes et al. (2016), but they adjusted the slippage following a linear model while evaluating the performance of a tractor by varying the engine intake airflow and the forces imposed on the drawbar.
This result (Fig. 10) demonstrates that although diagonal tires are more robust and suitable for supporting heavy loads under certain conditions, they exhibit greater slippage due to their lower adaptability to the soil and reduced contact area. Radial tires, on the other hand (Fig. 10), are designed to maximize ground adherence, reducing slippage and increasing operational efficiency.
It can be inferred from the slippage values (Fig. 10) that diagonal tires slippage is more than radial tires. This influences travel speed and the operational capacity of the combination and, consequently, the operational performance of the tractor Mialhe (1996). This further confirms the advantage of choosing radial tires over diagonal tires (Barbosa et al., 2005).

Materials and Methods

The tests were carried out on a test track with firm soil characteristics, with dimensions of 12 m wide and 120 m long, effectively using 100 m, with the rest of the track being used for acceleration and deceleration. The test track had no slope in the width direction but a 1% slope in the length direction. The track is located at 16º22'48.4'' S, 48º56'48.5'' W, and an average altitude of 1109 m. An instrumented dynamometer was used to apply the force to the tractor drawbar, capable of imposing forces on the drawbar during the test and monitoring and acquiring the variables automatically.
The tests were carried out using a completely randomized design, in a split-plot scheme, consisting of twelve treatments with three replicates per treatment, for a total of thirty-six trials. The plots were made up of two types of tires (radial and diagonal), and the subplots were made up of six constant forces applied utilizing a dynamometric car attached to the tractor drawbar (1.4, 4.5, 10.5, 15.6, 19.9, and 23.3 kN). The tractor performance was modeled using hourly fuel consumption, specific fuel consumption, tractor and dynamometer travel speed, drawbar power, traction coefficient, and wheel slippage.
An agricultural tractor was evaluated, with auxiliary front-wheel drive switched off, a diesel cycle engine, turbocharged with intercooler, injection system with rotary pump, four cylinders, total displacement of 4485 cm^3, nominal power of 82.4 kW (110.5 hp). Diagonal tires (size 14.9-24) were used on the tractor front wheels; radial tires (size 18.4R34) and diagonal tires (size 18.4 34) were used on the rear drive wheels. Table 2 shows the detailed characteristics of the tires used. The wheelbase

of the tractor was 2.668 m. The static weight of the tractor rear axle, when fitted with radial tires, was 34,790 kN and 36,162 kN when fitted with diagonal tires. The height of the tractor drawbar was 0.465 m above the road surface.
The diesel oil used was obtained from the local supply network, classified by the Brazilian National Agency for Petroleum (ANP) as interior automotive diesel or type B, suitable for use in diesel cycle engines, with a specific mass of 842.5 g L^{-1}.
To acquire the average force on the drawbar, an Excel RS-5000 tensile/compression load cell was used, made of low alloy steel, with heat treatment and controlled mechanical properties, with an "S" shape, operating temperatures between -5ºC and 60ºC and a power supply between 6 and 10 Vcc, with a nominal capacity of 50 kN, and with the possibility of permissible overload for sporadic and occasional actions of up to 150% of the nominal load.
The load cell signal was amplified using an INA 125P amplifier, following the signal amplification methodology proposed by Martins Jr et al. (2013). The amplified signal was converted into observed force values in Newton (kN) according to the calibration curve shown in Fig 11 and processed using an Arduino micro controller.
After conversion, the data was averaged and transmitted to be stored on a computer with an Intel® Core™ i7-4510U 2GHz processor, 8GB of RAM, and 500 GB HD and Windows 10 64bit Operating System inside the tractor cab.
The average force on the drawbar was calculated by averaging the forces applied to the tractor drawbar over the effective length of the track in each test.
Hourly fuel consumption was calculated according to Equation 1, adapted from (Reis et al., 2013), in which the electrical pulses generated by the flow meter used were converted into volume, considering a flow rate of 1 mL $pulse^{-1}$ and the time spent on the plot.

$$HC = \frac{N_p \times 3.6}{T} \quad (1)$$

Where:
HC - hourly fuel consumption, (L h^{-1});
N_p - number of pulses of the fuel gauge, (mL); and
T - time spent on the parcel route, (s).
Equation 2 was used to determine specific consumption, adapted from Ortiz et al. (2012), where hourly consumption is transformed into specific consumption according to the power available at the drawbar.

$$SC = \frac{HC \times \rho}{P_b} \quad (2)$$

Where:
SC - specific fuel consumption, [g (kW h)$^{-1}$];
HC - hourly fuel consumption, (L h^{-1});
ρ - specific mass of the fuel used (g L^{-1}); and
P_b - power at the drawbar (kW).
The tractor travel speed was determined using the ratio between the distance (D) covered by the tractor and the time taken to do so (t), according to Equation 3:

$$S = \frac{D}{T} \quad (3)$$

Where:
S - average tractor travel speed (km h^{-1});
D - distance traveled by the tractor during the test (km); and
T - time taken to travel distance D, (h).
The power at the drawbar was determined according to Gomes et al. (2016) in function of the average force at the drawbar and the tractor travel speed (Equation 4). The power at the drawbar was then calculated according to Equation 4:

$$P_b = \frac{F_m \times Spd}{3.6} \quad (4)$$

Where:
P_b - power at the drawbar, (kW);
F_m - average force on the drawbar, (kN); and
Spd - travel speed (km h^{-1}).
The slippage of the tractor drive wheels was determined by comparing the number of laps with the tractor unladen with the number of laps with the tractor laden (Alves and Reis, 2018) over the 100 m course of the test track (Equation 5).

$$Slp = \frac{(NL_{UL} - NL_{WL})}{NL_{UL}} \times 100 \quad (5)$$

Where:
Slp - slippage of the drive wheels, (%);
NLwl - number of laps without load; and
NLul - number of laps under load.
The variables obtained were subjected to analysis of variance using the F test at 5% probability, and when there was a significant difference between the treatments, their means were compared using the Tukey test at 5% probability and also

subjected to regression analysis. The SISVAR 5.3 software Ferreira (2016) was used for all the statistical procedures described.

Conclusions

Changing the type of tractor tire did not influence the hourly fuel consumption and the traction coefficient. The increased loads on the tractor drawbar increased hourly fuel consumption and the traction coefficient. The tractor with radial tires had higher specific fuel consumption, average travel speed, and power available at the tractor drawbar and lower wheel slippage.

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