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Agricultural tractor with different mass distributions between axles

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ABSTRACT: *An adjustment of the agricultural tractor is necessary to achieve energy efficiency, which can be done through the correct distribution of mass between the axles for each operating surface. This research evaluated different distributions of mass between axles in a 93 kW tractor equipped with auxiliary front-wheel drive, on two soil surfaces. The experiment was carried out in strip design, with a double factorial scheme (2 x 3), with two soil surfaces (mobilized and firm) and three mass distributions between axes (35/65%, 40/60% and 45/55%), with five repetitions, totaling 30 parcels. The slippage parameters of the front and rear wheelset, engine rotation, hourly and specific fuel consumption, force, power and yield on the drawbar, displacement speed, engine thermal efficiency, traction coefficient, rolling resistance, and yield in traction. On firm soil, the energy performance of the tractor was superior in relation to the mobilized one, which allowed greater tractor and drawbar performance with lower specific fuel consumption. The use of a 35/65% between-axle mass distribution provided maximum traction for the mechanized set, resulting from the reduction in energy expenditure generated by skating and; consequently, the maximum use of the energy made available by the mechanized set. However, the maximum conversion of energy contained in the working fuel is obtained with the 45/55% setting.*
Key words: *energy efficiency, ballasting, fuel consumption.*

Desempenho do trator agrícola com diferentes distribuições de massa entre eixos

RESUMO: *A assertiva adequação do trator agrícola é necessária para atingir máxima eficiência energética, podendo ser feita através da correta distribuição de massa entre eixos para cada superfície de operação. O objetivo deste trabalho foi avaliar diferentes distribuições de massa entre eixos em um trator de 93 kW equipado com tração dianteira auxiliar, em duas superfícies de solo. O experimento foi realizado em delineamento de faixas, com esquema fatorial duplo (2 x 3), sendo duas superfícies de solo (mobilizado e firme) e três distribuições de massa entre eixos (35/65%, 40/60% e 45/55%), com cinco repetições, totalizando 30 parcelas. Foram determinados os parâmetros de patinamento dos rodados dianteiros e traseiros, rotação do motor, consumo horário e específico de combustível, força, potência e rendimento na barra de tração, velocidade de deslocamento, eficiência térmica do motor, coeficiente de tração, resistência ao rolamento e rendimento em tração. Em solo firme, o desempenho energético do trator foi superior em relação ao mobilizado, o qual possibilitou maior rendimento tratoreo e na barra de tração com menor consumo específico de combustível. O uso da distribuição de massa entre eixo de 35/65% proporcionou a maximização na tração do conjunto ~~moto~~mecanizado, decorrente da redução do dispêndio energético gerado pelo patinamento e consequentemente o máximo aproveitamento da energia disponibilizada pelo conjunto mecanizado. Entretanto, a máxima conversão da energia contida no combustível em trabalho é obtida com a configuração 45/55%.*
Palavras-chave: *eficiência energética, lastragem, consumo de combustível.*

INTRODUCTION

Given the need to maximize the operational and energy performance of agricultural tractors, combined with the optimization of the adjustment of the configurations of the mechanized set, several studies interpreted the interaction of the determining factors on the efficiency of the agricultural operation. In conjunction with obtaining good levels of efficiency, the aim is to make the parameters of adaptation of agricultural tractors more flexible. Thus, it is essential to evaluate the behavior of agricultural machines and implements under the most diverse conditions, due to the heterogeneity of situations reported in the field, seeking to optimize the field efficiency of operations (JASPER et al., 2017; MARTINS et al., 2018).

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Different variables affect the operational performance of the agricultural tractor, including the soil surface condition, type of tire used, total mass of the tractor and its distribution on the wheels, load pulled and travel speed (LEITE et al., 2017). Emphasizing the weight distribution between the front and rear axles, which determines the maximum available traction and the slip level under a given traction load, in view of current studies, maximum performance is obtained with ballast distribution with 40 a 45% of the total static load on the front axle. However, tractors do not always operate under constant working conditions, so an ideal ballast level that fits all conditions is unachievable (VARANI et al., 2020).

To achieve maximum efficiency of the mechanized set, the wheel-to-ground ratio must be optimized because 20 to 55% of the tractor's available energy can be lost in this interaction (KUMAR et al., 2019), resulting in energy expenditure, unnecessary costs, and emission greenhouse gases. In addition to harmful effects on the soil, such as its compaction, which causes difficulties for the root growth of crops (JÁNULEVICIUS et al., 2018). Traction of drive wheels is evaluated based on the traction capacity, slip of these wheels and rolling resistance (SCHREIBER & KUTZBACH, 2008).

Studies such as that conducted by BATTIATO & DISERENS (2017), with simulations of the soil-machine interaction under different traction forces, point out that improvements in traction efficiency can be achieved by increasing the load on the wheel or reducing the inflation pressure depending on the characteristics of the soil to be considered. Correct adjustment results in lower fuel consumption and reduction of polluting gases, leading to maximum field efficiency of the set (LEE et al., 2016).

This evaluated the operational and energetic performance of a 93 kW tractor operating with different mass distributions between axles, on two soil surfaces.

MATERIALS AND METHODS

The experiment located in the municipality of Pinhais, PR, Brazil, was carried out under two distinct surface conditions: mobilized soil and firm soil, which together had dimensions of 900 x 15 meters, totaling 13,500 m² and slope of 1%. Both strips were classified by SUGAMOSTO (2002) as *Latossolo Vermelho-Amarelo Distrófico típico* (Oxisol). The experimental design adopted was in strips, in a 2 x 3 factorial scheme, corresponding to two travel surfaces (mobilized soil and firm soil) and three mass distributions between axles (35/65%, 40/60% e 45/55%), with five replicates, totaling 30 plots.

The mobilized soil strip was prepared using a harrow with 14 discs, width of 2.34 m and approximate mass of 3,150 kg, performing two passes~~,~~ and mobilizing the soil to the depth of 0.20 m. The firm soil strip, in turn, was established through the controlled traffic of a tractor with a mass of 6,725 kg, without an attached ~~no~~ implement, passing in parallel three times over the same path as the experimental strip. Whereas, according to WEBER et al. (2021) the consecutive passage of agricultural equipment over the same strip provides a reduction in total porosity and an increase in soil penetration resistance. In this way, providing a simulated condition of firm ground.

The average soil penetration resistance (SPR) was determined with a handheld electronic penetrometer, Falker - PLG 1020 model, measuring the SPR through the conical rod from 0 to 0.4 m depth, with internal storage of the average values every 0.1 m. At the time of SPR evaluation, the gravimetric moisture (U_G) of the soil was determined according to the standard methodology (KLEIN, 2014). The values obtained for the two strips of the experiment are shown in table 1.

The tractor used in the experiment was a New Holland® T6050 Plus, rated power of 93 kW (ISO TR14396), rated velocity (2,200 RPM), maximum torque 560 Nm at 1,400 RPM, Semi Powershift 16 x 16 transmission, equipped with auxiliary front-wheel drive (FWD), which remained activated along with the entire experiment. The distance between axles was 2.6 m and the drawbar height from the soil was 0.5 m. This tractor was equipped with radial tires, Continental 380/85R28 at the front and Continental 460/85R38 at the rear, both with an inflation pressure of 68.94 kPa (10 PSI), providing 3.80% advance of the front wheel in comparison to the rear wheel when the FWD is activated. The fuel used during the experiment was diesel oil with a maximum sulfur content of 10 ppm and rotation of 1,970 RPM in the engine (establishing 540 RPM at the power take off), in the B6 gear corresponding to the theoretical velocity of 1.94 m s^{-1} (7 km h^{-1}).

The mass/power ratio of the tractor was 75 kg kW^{-1} (55 kg hp^{-1}), based on the engine power and pulled load (SCHLOSSER et al., 2005), resulting in 6,930 kg of the total mass. The ballasting procedure was performed using 40% hydraulic ballast in the tires, varying the amount of solid ballast (cast iron), until the desired mass distribution between axles was reached, which was checked using the Celmi CM-102 model pad scales, as presented in table 2.

Table 1 - Characterization of Firm Soil (FS) and Mobilized Soil (MS) strips for Gravimetric Moisture (U_G) and Soil Penetration Resistance (SPR).

Characteristic	FS	MS
----------U_G ($g.g^{-1}$)----------		
0 – 0.1 m	26.66	27.90
0.1 – 0.2 m	33.94	31.58
0.2 – 0.3 m	34.00	30.56
0.3 – 0.4 m	36.52	31.66
----------SPR (MPa)----------		
0 – 0.1 m	1.172	0.138
0.1 – 0.2 m	2.501	0.749
0.2 – 0.3 m	2.104	2.173
0.3 – 0.4 m	1.708	1.855

In order to generate resistance to the tractor of the experiment, a brake tractor was attached to the drawbar, a New Holland® T8 385 model with a rated power of 250 kW and 18 x 4 Full Powershift transmission with activated FWD. The set was in tandem, providing 30 kN of traction force reflecting 100% engine load on the tractor of the experiment, selected according to ASABE 497.7 (2011), which can be achieved by the change of gears and rotation of the tractor brake engine, assuming oscillations of up to 5% in the pulled load.

The tractor used in the experiment was equipped with the sensors described below, connected to a printed circuit board data acquisition system (DAS), a with data acquisition frequency of 1 Hertz and values being transferred and stored on a hard disk.

Autonics E100S encoders were used to determine the slip of the four driving wheels (WS), obtained through the rotations of the wheels with and without load, determined by Eq. 1.

$$WS = \left(\frac{NPwL - NPw/oL}{NPw/oL}\right) x\ 100 \qquad (1)$$

where,

WS – wheel slip in %;

NPwL – number of pulses of wheel with load;

NPw/oL – number of pulses of wheel without load.

Engine rotation (ER) was measured using an E100S Autonics encoder positioned at the tractor power take off (PTO). The PTO-engine transmission ratio was obtained by means of a Victor DM623P model digital tachometer.

Hourly fuel consumption (HFC) was determined using Flowmate OVAL MIII LSF 41 model flowmeters in the system of fuel supply and return to the tank, and the difference in the number of pulses emitted was converted into volume (1 pulse is equivalent to 1 mL), as described by OIOLE et al. (2019).

A load cell (Bermann®) with a capacity of 100 kN, the sensitivity of 2.0+0.002 Mv V^{-1} and accuracy of 0.01 kN properly checked, installed on the tractor drawbar, was used to determine the traction force (DBF) parallel to the ground.

Travel speed (TS) was determined, in m s^{-1}, with Agrosystem SVA-60 speed sensor, using the number of pulses emitted by the sensor during the test.

The value of available power on the drawbar (DBP) was calculated based on the pulled force (PF) and the travel speed, according to Eq. 2.

$$DBP = PF \text{ x } TS \qquad (2)$$

where,

DBP – available drawbar power, kW.

Drawbar efficiency (DBE) was calculated according to the available drawbar power and engine power, according to Eq. 3.

$$DBE = \left(\frac{DBP}{EP}\right) x\ 100 \qquad (3)$$

where,

DBE – drawbar efficiency, %;

EP – engine power, kW.

Type-K thermocouples were installed close to the fuel inlet and return flowmeters and, through the temperatures obtained, it was possible to correct the diesel oil density (D) through Eq. 4.

$$D = 844.14 - (0.53 \text{ x } T) \qquad (4)$$

where,

D – Diesel oil density, g L^{-1};

T – Diesel oil temperature, °C;

844.14 and 0.53 – density regression parameters.

Table 2 - Specifications of the three mass distributions between axles, with values presented in kg and, within parentheses, as a percentage of the total.

Static load on the axle	----------Distribution----------		
	35/65	40/60	45/55
Front	2,446 (35)	2,794 (40)	3,142 (45)
Rear	4,617 (65)	4,216 (60)	3,823 (55)
Total	7,063 (100)	7,010 (100)	6,965 (100)

With the corrected value of density (D), the specific fuel consumption (SFC) was calculated as a function of the drawbar power and hourly fuel consumption (HFC), according to Eq. 5.

$$SFC = \frac{HFC \text{ x } D}{DBP} \quad (5)$$

where,
SFC – specific fuel consumption, g (kW h)$^{-1}$.

Engine thermal efficiency (ETE) was calculated through the specific fuel consumption and lower calorific power of diesel oil, according to FARIAS et al. (2017), as described in Eq 6.

$$ETE = \left(\frac{3{,}600}{SFC \text{ x } LCV}\right) \text{x } 100 \quad (6)$$

where,
ETE – Engine thermal efficiency, %;
LCV – Lower Calorific value of the fuel (42.295 kcal kg^{-1});

Dynamic load (DL) values were obtained according to the mass on the rear wheels in each of the treatments and the load transfer, according to Eq. 7 (GABRIEL FILHO et al., 2010).

$$DL = \left(\frac{M \text{ x } 9.807}{1000}\right) + \left(\frac{DBF \text{ x } y}{Da}\right) \quad (7)$$

where,
DL – Dynamic load on the wheel, kN;
M – Mass on the rear wheel, kg;
y – drawbar height, m;
Da – distance between axles, m.

Rolling resistance (RR) was determined using Eq. 8 (ZOZ & GRISSO, 2003; ASAE D497.7, 2011).

$$RR = DL \times \left[(1/Bn) + 0.032 + \left(\frac{0.5 \times WS}{\sqrt{Bn}}\right)\right] \quad (8)$$

where,
RR – Rolling resistance, kN;
WS – Wheel slip, decimal;
Bn – Dimensionless index.

The Bn index used in the experiment was interpolated from the values proposed by the ASABE D497.7 (2011) standard, according to the average of the cone index of each soil condition at 0-0.2 m depth. Bn value of 52.51 was adopted for the soil strip called Firm and Bn value of 19.71 was adopted for the soil strip called Mobilized.

Tractive efficiency (TE) was defined by Eq. 9, according to ZOZ & GRISSO (2003), using the coefficients for radial tires.

$$TE = (1\text{-}WS) \times \left(\frac{NT}{GT}\right) \quad (9)$$

where,
TE – Tractive efficiency, %;
NT – Net traction, kN (Eq. 10);
GT – Gross traction, kN (Eq. 11).
where,

$$NT = DL \times \left[\left(0.88 \times (1\text{-}e^{-0.1\times Bn}) \times (1\text{-}e^{-9.5\times WS})\right) - \left(\frac{1}{Bn}\right) - \left(\frac{0.5\times WS}{\sqrt{Bn}}\right)\right] \quad (10)$$

$$GT = DL \times [0.88 \times (1\text{-}e^{-0.1\times Bn}) \times (1\text{-}e^{-9.5\times WS}) + 0.032] \quad (11)$$

where,
e – Base of Napierian logarithms.

The collected data were submitted to the Shapiro-Wilk normality test and the brown-forsythe variance homogeneity test and, when necessary, transformed with the Johnson tool. The data were then submitted to variance analysis (ANOVA) and, if significant, to the Tukey test, together with the analysis of the loitering coefficient using the SigmaPlot 12 program (Systat Software Inc., CA, USA).

RESULTS AND DISCUSSION

Tables 3 and 4 show the results of the analysis of variance and mean comparison test for the variables analyzed under the different mass distributions between axles and surfaces studied, while table 5 shows the results of the means comparison test for factors with a significant interaction. The coefficients of variation for all variables analyzed were classified as stable, according to the FERREIRA classification (2018), demonstrating the reliability of the data.

The increase in mass on the front axle provided a marked reduction in slip levels,

Table 3 - Summary of analysis of variance and means comparison test for the analyzed variables.

Factors	FWS	RWS	ER	HFC	DBF	TS
	(%)	(%)	(RPM)	(L h^{-1})	(kN)	(m s^{-1})
---Distributions (D)---						
35/65%	12.23 B	12.35 B	1.907 A	21.53 A	29.28	1.89 A
40/60%	14.27 A	14.20 A	1.879 AB	21.26 A	29.14	1.83 B
45/55%	14.38 A	14.50 A	1.834 B	20.26 B	29.91	1.82 B
---Surfaces (S)---						
Firm	14.38 A	14.38 A	1.922 A	21.14	29.50	1.89 A
Mobilized	12.88 B	12.99 B	1.825 B	20.89	29.40	1.81 B
---F test---						
D	7.90*	7.27*	10.95**	33.47**	3.55NS	11.46**
S	49.94**	38.26**	231.88**	0.41NS	0.21NS	233.67**
D x S	6.33*	6.57*	36.80**	3.96NS	7.56*	82.61**
---CV (%)---						
D	9.99	9.96	1.86	1.88	2.33	1.82
S	4.27	4.50	0.93	4.06	2.06	0.76
D x S	8.85	9.08	1.26	2.41	3.14	1.06
---Normality---						
SW	0.90	0.67	0.77	0.79	0.97	0.33
---Homogeneity---						
BF	0.71	0.80	0.57	0.14	0.90	0.89

Parameters: Front wheel slip (FWS), Rear wheel slip (RWS), Engine rotation (ER), Hourly fuel consumption (HFC), Drawbar force (DBF) and Travel speed (TS). In each column, for each factor, means followed by the same uppercase letter do not differ by Tukey test ($P < 0.05$). F test of the analysis of variance (ANOVA): NS – Not significant; * ($P < 0.05$) and ** ($P < 0.01$). CV %: Coefficient of variation. Shapiro-Wilk normality test: SW ≤ 0.05 – Data abnormality; SW > 0.05 – Data normality. Brown-Forsythe variance homogeneity test: BF ≤ 0.05 – Heterogeneous variances; BF > 0.05 – Homogeneous variances.

corroborating KUMAR et al. (2019) who reported that the increase wheel mass through the addition of ballast reduces its slippage. Demonstrating a greater mass balance in the 35/45 configuration, which provided the highest levels of tire-to-ground interaction. The results expressed in RWS, indicate less slip under higher mass on the wheel. However, in the front wheels the lowest value of slip is achieved with the lowest mass on the axle, proving that the 35/65% distribution promotes better utilization of the tractor mass for wheel grip on the ground.

For the surfaces evaluated, the slip value on firm soil was higher than on mobilized soil, but the recommendation of the ASABE 496.3 standard (ASABE, 2011) is 8 to 10% for firm surfaces and 11 to 13% for mobilized surfaces, and in the present experiment only the values on the mobilized surface were within the recommended range. Possibly due to surface compaction of the soil, thus impairing tire adhesion; however, even with excessive skating on firm ground, the tractor provides an adequate ration condition, which was not observed in the mobilized ground and consequently, corroborating with the reduction in engine speed.

With all distributions, it is noted that the firm soil led to greater slippage compared to the mobilized soil, since under this surface condition, the soil did not offer sufficient resistance to the tangential force produced by the wheels, corroborating the results reported by MONTEIRO et al. (2011).

The engine speed was higher, remaining close to that initially established, when there was greater mass on the rear axle, which in turn has more traction capacity. On the different surfaces, there was a reduction in engine rotation when the test tractor traveled on a mobilized surface, due to the greater sinking and deformation of the tires under this surface condition (MIALHE, 1991).

Hourly fuel consumption was lower with mass distribution of 45/55%, following the decrease in engine rotation, as evidenced by FARIAS et al. (2017), who relate lower rotation regimes in diesel engines to lower hourly consumption, due to the greater capacity to admit oxygen. For the different surfaces, there was no statistical difference, being similar to the results reported by LOPES et al. (2019) in a study using mobilized soil and firm soil with straw cover.

Drawbar force did not vary significantly in the different mass distributions between axles and surfaces studied, maintaining its stability within the range recommended by the OECD (2019) standard

Table 4 - Summary of the analysis of variance and means comparison test for the evaluated parameters.

Factors	DBP	DBE	SFC	ETE	RR	TE
	(kW)	(%)	(g (kW h^{-1}))	(%)	(kN)	(%)
---Distributions (D)---						
35/65%	55.41	59.83	321 A	26.50 B	4.30	75.73 A
40/60%	53.55	57.82	328 A	25.94 B	4.24	74.76 B
45/55%	54.55	58.91	308 B	27.73 A	4.32	74.40 B
---Surfaces (S)---						
Firm	55.72 A	60.17 A	314 B	27.19 A	3.40 B	77.95 A
Mobilized	53.28 B	57.53 B	325 A	26.26 B	5.18 A	71.98 B
---F test---						
D	3.86^{NS}	3.86^{NS}	36.26^{**}	32.13^{**}	0.68^{NS}	7.07^{*}
S	40.07^{**}	40.07^{**}	8.96^{*}	9.65^{*}	6.747^{**}	3.382^{**}
D x S	1.58^{NS}	1.58^{NS}	1.55^{NS}	2.11^{NS}	0.44^{NS}	3.24^{NS}
---CV (%)---						
D	2.75	2.75	1.75	1.92	3.67	1.09
S	1.94	1.94	3.08	3.07	1.39	0.37
D x S	2.52	2.52	3.21	2.98	4.14	1.13
---Normality---						
SW	0.54	0.54	0.02	0.03	0.89	0.99
---Homogeneity---						
BF	0.39	0.39	0.78	0.72	0.14	0.96

Parameters: Drawbar power (DBP), Drawbar efficiency (DBE), Specific fuel consumption (SFC), Engine thermal efficiency (ETE), Rolling resistance (RR) and Tractive efficiency (TE). In each column, for each factor, means followed by the same uppercase letter do not differ by Tukey test ($P < 0.05$). F test of the analysis of variance (ANOVA): NS – Not significant; * ($P < 0.05$) and ** ($P < 0.01$). CV %: Coefficient of variation. Shapiro-Wilk normality test: SW ≤ 0.05 – Data abnormality; SW > 0.05 – Data normality. Brown-Forsythe variance homogeneity test: BF ≤ 0.05 – Heterogeneous variances; BF > 0.05 – Homogeneous variances.

for conducting tests on the drawbar. The travel speed of the tractor was higher under the condition of higher mass on the rear axle, a result related to the lower slippage of the tires in this treatment. On the different surfaces, the higher speed on firm soil compared to the mobilized soil corroborates the results found by JADOSKI et al. (2016) and SHAFAEI et al. (2019), resulting from the change in soil resistance to rolling (Table 4).

In table 4, the results were significant in the different mass distributions between axles for the parameters SFC, ETE and TE, and for the studied surfaces for the variables DBP, DBE, SFC, ETE and RR.

Although, the 35/65% treatment reached higher OS, it was not enough to generate statistical difference in the power developed, and all mass distributions between axles were statistically equal with respect to this parameter, the same occurring for the DBE. Conversely, the increase in speed on firm soil, as observed in table 3, promoted a significant increase in DBP and consequently a higher DBE, corroborating the results reported by JASPER et al. (2017).

The lower specific fuel consumption observed in the 45/55% distribution represents an average reduction of 16.5 g of fuel required to generate a kW h^{-1}, 5% lower than the other configurations, this result is explained by the lower HFC and the lowest ER observed (Table 3), which is explained by MARTINS et al. (2018). According to these authors, due to the reduction in ER, the engine worked closer to the maximum torque range, reducing fuel injection due to the greater force provided by it. Under the condition of firm soil, lower SFC was obtained due to the better traction condition of the wheels, resulting from the higher DBP and lower HFC in this treatment.

Engine thermal efficiency (ETE) represents the perfection of its thermodynamic cycle, that is, it reflects the level of the energy conversion performed by it, as explained by AGRAWAL et al. (2019). The configuration with lower mass on the rear axle promoted higher ETE, due to the lower specific fuel consumption, demonstrating the greater energy efficiency of the set when operating with a mass distribution between axles of 45/55%. Similar results

Table 5 - Summary of the means comparison test for the interaction in the evaluated parameters.

---------------------------------FWS (%)---------------------------------			----------------------------------RWS (%)----------------------------------		
Distributions (D)	Surfaces (S)		Distributions (D)	Surfaces (S)	
	Firm	Mobilized		Firm	Mobilized
35/65%	13.04 Ab	11.42 Ab	35/65%	13.17 Ab	11.54 Ab
40/60%	14.04 Aab	12.70 Aab	40/60%	13.83 Ab	14.57 Aa
45/55%	16.06 Aa	14.51 Ba	45/55%	16.14 Aa	12.86 Bab
---------------------------------ER (RPM)------------------------------			----------------------------------DBF (kN)-----------------------------------		
Distributions (D)	Surfaces (S)		Distributions (D)	Surfaces (S)	
	Firm	Mobilized		Firm	Mobilized
35/65%	1,949 Aa	1,865 Ba	35/65%	28.99 Ab	29.58 Aa
40/60%	1,975 Aa	1,782 Bb	40/60%	28.62 Ab	29.67 Aa
45/55%	1,841 Ab	1,827 Aa	45/55%	30.88 Aa	28.94 Ba
-----------------------------------TS (m s^{-1})-----------------------------					
Distributions (D)	Surfaces (S)				
	Firm	Mobilized			
35/65%	1.93 Aa	1.85 Ba			
40/60%	1.93 Aa	1.74 Bb			
45/55%	1.81 Ab	1.84 Ba			

Parameters: Front wheel slip (FWS), Rear wheel slip (RWS), Engine rotation (ER), Drawbar force (DBF) and Travel speed (TS). Means followed by different letters, uppercase in rows and lowercase in columns, differ by Tukey test ($P < 0.05$).

were reported on firm soil, due to its greater capacity to promote traction.

The rolling resistance did not show significant variation with the different mass distributions between axles; conversely, the travel surface interfered significantly, and the mobilized soil had higher RR value. Similar result reported by RINALDI et al. (2016), who justify that higher RR in loose soil is due to machine-soil interaction, because power losses are greater under this condition.

However, the 35/65% configuration provided an increase on the tractive efficiency of the set, due to the increased load on the rear axle, which has greater traction capacity, and by the pre-compaction of the ground by the front axle, thus reducing the resistance to bearing and increasing the ability to promote traction during the passage of the rear axle. On firm soil, it is possible to achieve higher efficiencies, due to best soil-wheel interaction, similar results was reported by BATTIATO & DISERENS (2017).

Table 5 presents the decomposition of FWS, RWS, ER, DBF and OS values whose interaction between mass distribution and surface were significant in the analysis of variance. The wheel slip values of both front and rear axles were lower in the 35/65% distribution, proving that with the use of this configuration it is possible to minimize the energy losses caused by wheel slip (RANJBARIAN et al., 2017). This fact is associated with the lower dynamic load on the front wheel combined with kinematic advance, and greater dynamic load on the rear axle, assisting in the tractor's capacity to remain aligned and optimize traction (VIDAL et al., 2016). In general, wheel slip should be between 8 and 12% and should not exceed 15% (MAMKAGH, 2019).

In the mass distributions on the axles, there is lower engine rotation on firm soil in the 45/55% treatment, caused by the higher DBF, which led to lower OS. On the mobilized surface, there is no difference between DBF values, but the lower ER leads to reduction in displacement.

CONCLUSION

The firm soil strip promoted higher operational performance compared to the mobilized soil strip, enabling higher tractive efficiency and drawbar efficiency, with lower specific fuel consumption.

The 35/65% inter-axle mass distribution, when associated with different travel surfaces, reduces the energy expenditure generated by slipping and; consequently, provides an increase in the operating speed and tractive performance of the tractor. However, the lowest hourly and specific fuel consumption values were obtained in the 45/55% distribution.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript. All authors critically revised the manuscript and approved of the final version.

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