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TECHNICAL ARTICLE

ENERGY PERFORMANCE IN DISC HARROWING OPERATION IN DIFFERENT GRADIENTS AND GAUGES

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KEYWORDS

Fuel consumption, operating yield, controlled trafic.

ABSTRACT

The operational performance of the agricultural tractor can be increased by adjusting parameters such as tire inflation pressure, axle mass distribution and gauge opening, which is a very divergent factor in controlled-traffic production. The objective of the experiment was to measure the energy performance of a 93 kW agricultural tractor in intermediate grading operation in two slopes (flat and sloping) and three gauge configurations (closed, intermediate and open) in mobilized soil. Energy performance was determined from the following parameters: slip, engine speed, actual effective speed, hourly and specific fuel consumption; strength, power and performance on the drawbar. Turbo pressure and temperature monitoring was also performed at six different engine points. The experiment was conducted in double factorial arrangement (2 slopes and 3 gauges), with four replications, totaling 24 plots. Data were analyzed for normality and homoscedasticity of the residues, after ANOVA and when significant, the means test. Tilts and tire gauges did not differ statistically, so it can be concluded that depending on the operation do not interfere with operating performance.

INTRODUCTION

The modernization of agriculture in recent years allowed using mechanized assemblies in many agricultural operations. Therefore, validations under laboratory and field conditions are necessary to reproduce the worst operating conditions of these machines, ensuring maximum operational performance (Jasper et al., 2016, Beckmann & Santana, 2019).

Gomes et al. (2016) assessed operational performance by applying 15.4 and 20.5 kN of force to the drawbar and obtained the best fuel efficiency when the tractor dragged a load of 20.5 kN, confirming the importance of the correct dimensioning of the assembly.

During tractor traffic, mechanical stresses by the action of the tires on the soil depend on several factors, including axle load, tire pressure, ballasting, tire characteristics, and soil conditions (Mion et al., 2016).

Adjustments in tractor tread widths have been used mainly in traffic control, as reported by Michelazzo (2018), in which traffic was reduced using tractors with larger tread widths, allowing matching the traffic lanes between tractors and increasing the working range. Girardello et al. (2017) evaluated soil resistance to penetration, root development, and soybean yield using traffic-controlled farming and concluded that several passes of the machines on the same traffic lane reduced the length of the crop root system. However, this result was more evident on permanent traffic lanes, enabling localized corrections.

Another factor that affects the energy performance of the agricultural tractor is terrain slope, and this geomorphological feature directly limits the mechanization potential in agricultural areas. The slope classes of the terrain were classified according to the mechanization potential into a) extremely fit (0–3.0%), b) very fit (3.1–6.0%), c) fit (6.1–12.0%), d) moderately fit (12.1–20.0%), e) unfit (20.1–40.0%), and f) not recommended (>40%) (Ramalho & Beek, 1995).

The present study evaluated the energy performance of a 93 kW agricultural tractor with an offset disk harrow using three tread widths in two terrain slopes in soil without vegetation cover.

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MATERIAL AND METHODS

The study was conducted in the Laboratory of Adequacy of Agricultural Tractors (Laboratório de Adequação de Tratores Agrícolas–LATA) in the Agricultural Sciences Sector of the Federal University of Paraná (Universidade Federal do Paraná–UFPR), and the experiments were conducted at the Cangüiri Experimental Farm (Fazenda Experimental Cangüiri–FEC).

The experimental design was a 2 x 3 factorial arrangement (two terrain slopes × three tread widths of the tractor wheelset) with four repetitions, totalling 24 experimental plots. The evaluated parameters were wheel slip (WS), motor rotation (MR), actual travel speed (ATS), drawbar force (DF), hourly fuel consumption (HFC), drawbar power (DP), drawbar performance (DPF), and specific fuel consumption (SFC).

Soil samples from the experimental site were analyzed in the Soil Physics Laboratory and classified as a typical Dystrophic Red-Yellow Latosol (sand, 23.37%; silt, 9.76%, clay, 66.87%). During the study period, the gravimetric humidity of soil samples was measured in the laboratory, and the obtained values were U_G of 24.2% at the 0.0-0.20 m depth and 39.4% at the 0.20-0.40 m depth.

Penetration resistance was measured using a Falker® digital penetrometer, and the obtained values were 1.17 MPa at 0.0–0.10 m, 2.50 MPa at 0.10–0.20 m, 2.10 MPa at 0.20–0.30 m, and 1.71 MPa at 0.30–0.40 m.

The tractor used in the experiments was model T6050 (New Holland®) with a nominal power of 93 kW (ISO 14396), 4 x 2 traction with auxiliary front-wheel drive (AFWD), fitted with radial tires (Continental Contract Ac85®) in the front wheels (type 380/ 85R28-R1) and rear wheels (type 460/85R38-R1), and pressure of 12 psi (83 kPa) in all tires. Liquid ballast (water) corresponded to 40% of the volume of all tires. Solid ballasts comprised ten 45-kg cases (total of 450 kg) in the front wheels and three 65-kg rings in each rear wheel, totalling 390 kg. The tractor's fuel tank was kept full during the experiment, and the AFWD was engaged.

The test was conducted in two soil strips with a length of 500 meters and a width of 10 meters, with a total area of 5,000 m² in each plot. The first strip had a slope of less than 1% in both directions (designated "flat"), and the second strip had a width-wise slope of 5% (designated "inclined").

The tread widths were chosen according to the operation manual. The configurations comprised three widths: small (1.57 m), intermediate (1.97 m), and large (2.26 m). In this study, the same width was maintained for the front and rear axle, and the width was determined using a measuring tape.

The tractor weight was measured using a tractor scale model CM 1002 (Celmi®) with four platforms, each with a capacity of 8 tons, and a CSP-10ª electronic indicator. The total weight was measured in all tread width configurations, corresponding to 6,740 Kg, and there were no significant differences in tractor mass distribution between these configurations, with 44% of the weight in the front and 56% in the rear.

The dislocation was determined in all tread width configurations using an advance meter (Finger®) with two sensors, each attached to the front and rear wheelset of the tractor, and this parameter remained unchanged at 3.36%. The selected gear (range B gear 7) corresponded to a speed of 2.22 m s^{-1} (8 km h^{-1}) at a MR of 1970 rpm.

To provide the desired resistance in the drawbar system, an offset disk harrow model CRI (Baldan®) containing eighteen 26-inch discs with an inter-disc space of 270 mm and a total weight of 2,061 kg was used.

WS was measured using encoders model E100S (Autonics®), which generate 100 pulses per revolution (Equation 1), and was generated by rotating the wheels.

$$WS = \left(\frac{NLWT - NUWT}{NUWT}\right) x\ 100 \tag{1}$$

Where:

WS is the wheel slip in %;

NLWT is the number of loaded wheel turns,

NUWT is the number of unloaded wheel turns.

MR was determined by measuring the tractor power take-off (PTO) using an encoder model E100S (Autonics®) capable of generating 100 pulses per revolution. The transmission ratio between engine rotation and PTO was obtained using a digital tachometer model DM6236P (Victor®). These data were used to calculate MR according to [eq. (2)].

$$MR = \left(\frac{\sum NR}{t\ x\ 100}\right) x\ 60\ x\ RT \tag{2}$$

Where:

MR is motor rotation (in rpm);

NPS is the number of pulses per second in the PTO encoder;

ETPR is the engine transmission to PTO ratio (3.6611) (dimensionless),

t is the travel time of each revolution (in seconds).

The ATS of the tractor was determined using a radar model 740030A (Vansco®) mounted on the tractor chassis and previously measured with the tractor moving at a known distance and travel time. The speed was determined by the number of pulses emitted by the radar according to [eq. (3)].

$$ATS = \left(\frac{\sum NR}{t}\right) x\ C \tag{3}$$

Where:

ATS is the actual travel speed (km h^{-1});

C is a radar constant (0.0264) (dimensionless),

NP is the number of pulses emitted by the radar (dimensionless).

DP was measured using a laboratory-calibrated load cell (Bermann®) installed on the tractor drawbar, with a capacity of 100 kN, sensitivity of 2.0 ± 0.002 mV/V, and precision of 0.01 kN. The average traction force was obtained using [eq. (4)].

$$TF = C\ x\ NP - CF \tag{4}$$

Where:

TF is the traction force (kN);

C is a conversion constant (0.303 kN $mV^{-1)}$;

NP is the number of pulses emitted by the load cell (mV),

CF is the load cell calibration factor (1.22) (dimensionless).

The average DF was determined using [eq. (5)].

$$ATF = \frac{\sum_{i=1}^{n} ITF}{n} \quad (5)$$

Where:

ATF is the average traction force (kN);

ITF is the instantaneous traction force (kN),

n is the number of measurements.

HFC was measured using two flow meters model LSF 41L0-M2 (Flowmate OVAL MIII®) installed on the fuel inlet and outlet. Fuel consumption was determined by the difference between the number of pulses emitted by the flowmeter converted to volume, with a frequency of 1 pulse/mL according to [eq. (6)].

$$HFC = \left(\frac{V_{FET} - V_{FRT}}{t}\right) x\ 3.6 \quad (6)$$

Where:

HFC is the hourly fuel consumption (L h^{-1});

V_{FET} is the fuel volume in the inlet flowmeter (mL s^{-1}),

V_{FRT} is the fuel volume in the outlet flowmeter (mL s^{-1}).

DP was determined from the DF and the travel speed according to [eq. (7)].

$$DP = \left(\frac{ATF\ x\ ATS}{3.6}\right) \quad (7)$$

Where:

DP is the drawbar power (kW);

ATF is the average traction force (kN),

ATS is the actual travel speed (km h^{-1}).

Drawbar performance was determined as a function of the DP and engine power according to [eq. (8)].

$$DPF = \left(\frac{DP}{EP}\right) \times 100 \quad (8)$$

Where:

DPF is the drawbar performance (%);

DP is the drawbar power (kW),

EP is the engine power (kW).

Diesel oil density was measured in the laboratory by the fuel temperature correlated with the oil density curve according to the NBR 7148 standard of June 2014. Temperatures were measured using a previously calibrated type K thermocouple according to [eq. (9)].

$$D = (844.14 - 0.53)\ x\ T \quad (9)$$

Where:

D is the diesel oil density (g/L);

T is the diesel oil temperature (°C),

844.14 and 0.53 are density regression parameters.

Mass-based HFC (MHFC) was determined using [eq. (10)].

$$MHFC = \left(\frac{VHFC\ (844.14 - 0.53\ x\ T)}{100}\right) \quad (10)$$

Where:

MHFC is the mass-based hourly fuel consumption (kg h^{-1});

VHFC is the volume-based hourly fuel consumption (L h^{-1}),

1000 is the conversion factor.

SFC was calculated using [eq. (11)].

$$SFC = \left(\frac{MHFC}{DP}\right) \quad (11)$$

Where:

SFC is the specific fuel consumption (g kW h^{-1}),

DP is the drawbar power (kW).

Turbo pressure was measured using a piezoresistive pressure transducer model MPX 5700DP (Motorola Inc.) to assess the pressure at the tractor engine intake manifold during the test.

The temperatures of the intake air, radiator coolant, engine oil, exhaust gas, and fuel inlet and outlet were measured during the test using type K thermocouples placed at the air filter inlet, radiator, engine oil filter, exhaust, inlet flowmeter, and outlet flowmeter, respectively.

The sensors were connected to a data acquisition system made in an LPKF Protomat 93s milling machine with a microprocessor model Atmega 2560 (Atmel®) with a 16-MHz clock, and a 10-bit digital-analogue converter with a power of 12 V and data acquisition frequency of 1 Hz.

The data were subjected to the Shapiro-Wilk normality test ($P<0.05$) and Bartlett's homogeneity test ($P<0.05$). Normal data were analyzed by analysis of variance (ANOVA), and the means were compared using Tukey's test ($P<0.05$). All statistical analyses were performed using Sigmaplot® software version 12.

RESULTS AND DISCUSSION

The results of ANOVA and the means test for WS, MR, ATS, DF, HFC, DP, DPF, and SFC are shown in Table 1.

TABLE 1. Analysis of variance for different terrain slopes and tractor tread widths.

Factors	WS (%)	MR (RPM)	ATS (km h^{-1})	HFC (L h^{-1})	DF (kN)	DP (kW)	DPF (%)	SFC (g kW h^{-1})
Terrain slope (S)								
Flat	6.50	2,006	7.53	20.35	21.55	45.06	48.39	373
Inclined	6.31	1,991	7.58	19.75	21.12	44.47	47.71	366
Tread width (TW)								
Large	6.23	1,993	7.50	20.11	20.58 B	42.84 B	46.58 B	385 A
Intermediate	6.42	1,995	7.56	20.11	21.40 AB	44.92 AB	48.20 AB	369 AB
Small	6.52	2,007	7.61	19.93	22.03 A	46.52 A	49.91 A	353 B
F-test								
S	0.01^{NS}	1.08^{NS}	0.56^{NS}	0.76^{NS}	5.59^{NS}	0.63^{NS}	0.63^{NS}	0.15^{NS}
TW	0.44^{NS}	0.48^{NS}	1.25^{NS}	0.18^{NS}	5.78^{S}	6.68^{S}	6.68^{S}	12.43^{SS}
S x TW	0.67^{NS}	6.02^{S}	2.15^{NS}	1.52^{NS}	1.51^{NS}	1.53^{NS}	1.53^{NS}	1.02^{NS}
CV (%)								
S	15.79	1.58	1.92	8.39	4.72	3.98	3.98	11.13
TW	17.42	1.49	1.56	5.06	4.98	4.91	4.91	2.69
S x TW	14.29	0.41	0.51	7.34	1.92	2.21	2.21	3.15
Normality								
SW	0.17^{N}	0.52^{N}	0.08^{N}	0.35^{N}	0.09^{N}	0.19^{N}	0.19^{N}	0.72^{N}
Homogeneity								
Bartlett	3.93^{HO}	6.92^{HO}	7.03^{HO}	3.53^{HO}	6.43^{HO}	10.73^{HO}	10.73^{HO}	1.91^{HO}

The means followed by the same uppercase letter in each column were not significantly different from each other using the Tukey's test at $P<0.05$. F-test of the analysis of variance: NS, not significant; S, significant at $P<0.05$; SS, significant at $P<0.01$. CV (%), coefficient of variation. SW, Shapiro-Wilk normality test ($P<0.05$): N, normal; NN, non-normal. Bartlett test for homogeneity of variances ($P<0.05$): HO, homogeneous; HEV, heterogeneous.

WS, wheel slip; MR, motor rotation; ATS, actual travel speed; DF drawbar force; HFC, hourly fuel consumption; DP, drawbar power; DPF, drawbar performance; and SFC, specific fuel consumption.

WS, MR, ATS, PADF, HFC, DP, DPF, and SFC were not significantly different between the two terrain slopes evaluated. DF, DP, DPF, and SFC were significantly different between the different tread widths analyzed, whereas WS, MR, ATS, and HFC were not affected by this parameter.

The obtained WS values were within those recommended by Battiato & Diserens (2014) and lower than those established by ASAE (2005), which can be explained by the higher cohesion of clay soil in low humidity conditions, resulting in higher traction force and lower rolling resistance (Damanauskas, et al., 2015) (Table 1).

MR and ATS were not affected by these two analyzed variables. Rinaldi (2016) found that travel speed was directly related to WS, corroborating the results found in this study.

Li et al. (2019) reported that MR decreased and torque increased, which corroborates the present study because, given the non-significance of MR, there was no change in the generated torque, and consequently no change in HFC and SFC. Similar results were obtained by Estrada et al. (2016) when evaluating the performance of a diesel engine using different hydrated ethanol mixtures.

Martins et al. (2018) measured the energy performance of an agricultural tractor using an offset disk harrow and found no significant differences in DF, corroborating the present study. Tabile et al. (2009) evaluated fuel consumption with different castor bean biodiesel mixtures and found that SFC was 358 g kW h^{-1} and DF was 23 kN, which are similar to the results of the present study.

Given that the tractor transforms the fuel energy into power and makes it available to the drawbar, PTO, and wheelsets (Gabriel Filho et al., 2010), the smaller tread width affected DP, which reached 46.52 kW, and this width yielded the highest DPF (50%), corroborating the findings of Monteiro et al. (2013) and Siqueira et al. (2013). The analysis of the temperature variables that affect engine performance indicated that the interaction of tread width with different travel speeds only affected intake air temperature (Table 2), and the average temperature was higher using the smaller tread width, whereas terrain slope did not significantly affect intake air temperature.

TABLE 2. Results of the analysis of variance and means test for turbo pressure (TBP) (kPa) inlet air temperature (IAT) (°C), radiator coolant temperature (RCT) (°C), engine oil temperature (EOT) (°C), exhaust gas temperature (EGT) (°C), fuel inlet temperature (FIT) (°C), and fuel outlet temperature (FOT) (°C). Pinhais, Paraná, Brazil, 2018.

Factors	TBP (kPa)	IAT (°C)	RCT (°C)	EOT (°C)	EGT (°C)	FIT (°C)	FOT (°C)
Terrain slope (S)							
Flat	73 A	26.08 A	76.10	95.19 A	212.86	39.08 B	40.67 B
Inclined	63 B	25.07 B	74.57	89.43 B	215.60	41.84 A	44.96 A
Tread width (TW)							
Large	65 B	26.16 B	74.81 B	94.09	200.27	39.64 B	46.00 A
Intermediate	65 B	23.51 C	74.10 B	91.72	219.43	39.56 B	40.70 B
Small	74 A	27.05 A	77.10 A	91.12	222.99	42.14 A	40.24 B
F-test							
S	10.20^{S}	22.41^{S}	7.92^{NS}	10.83^{S}	4.98^{NS}	11.85^{S}	198.80^{SS}
TW	51.57^{SS}	143.36^{SS}	12.99^{SS}	0.59^{NS}	13.89^{SS}	10.67^{SS}	127.58^{SS}
S x TW	35.79^{SS}	30.90^{SS}	0.81^{NS}	0.55^{NS}	10.90^{SS}	0.52^{NS}	38.69^{SS}
CV (%)							
S	13.44	0.98	2.26	5.02	1.41	5.00	3.74
TW	6.16	0.96	1.53	4.88	4.34	2.23	3.55
S x TW	7.19	0.62	1.64	5.65	4.06	5.65	4.12
Normality							
SW	0.46^{N}	0.14^{N}	0.10^{N}	0.86^{N}	0.06^{N}	0.40^{N}	0.70^{N}
Homogeneity							
Bartlett	4.24^{HO}	2.94^{HO}	1.49^{HO}	6.90^{HO}	0.58^{HO}	6.39^{HO}	2.43^{HO}

The means followed by the same uppercase letter in each column were not significantly different from each other using the Tukey's test at P<0.05. F-test of the analysis of variance: NS, not significant; S, significant at P<0.05; SS, significant at P<0.01. CV, coefficient of variation. SW, Shapiro-Wilk normality test (P<0.05): N, normal; NN, non-normal. Bartlett test for homogeneity of variances (P<0.05): HO, homogeneous; HEV, heterogeneous.

TBP had the highest variability between treatments and was 74 kPa with a small tread width in flat terrain. TBP increases the torque and power of agricultural engines by enriching the fuel-air mixture with more oxygen, improving engine performance (Farias, et al., 2017).

It is critical to determine the IAT of the engine because this variable creates flow turbulence inside the cylinder, which triggers combustion and, consequently, crankshaft rotation. There was a significant interaction of ITA with terrain slope and tread width, and the highest average IAT (27.05 ºC) was obtained using a small tread width in flat soil.

Ramadhas et al. (2017) found that hot inlet air in the engine increased fuel vaporization and combustion efficiency. Therefore, the engine start-up period and fuel consumption decreased dramatically by heating the inlet air, consequently reducing hydrocarbon emissions.

Jung et al. (2013) and Adler & Bandhauer (2017) evaluated the performance of diesel engines at high temperatures and have shown that the RCT controlled engine temperature. In contrast, there were no significant differences in this variable in the present study; however, the values were within the limits established in the tractor operation manual, and the highest value obtained with the small tread width was directly related to IAT because the increase in ambient temperature throughout the day decreased the efficiency of heat exchange in the radiator.

EOT and EGT were not significantly affected by these two variables. However, Siqueira et al. (2011) have shown that engine performance can be improved by heating the oil to reduce viscosity and improve engine lubrication, which corroborates the present results and the study by Reis et al. (2013), who evaluated the performance and emissions of a diesel-cycle engine generator and found that gas temperature was useful for assessing combustion efficiency. Furthermore, Castellanelli et al. (2008) observed that the power requirement increased as the engine load and EGT increased.

FIT and FOT values were within the range considered normal by the NBR ISO1585 standard, and these values were used to calculate maximum fuel consumption and SFC.

TABLE 3. Interaction between motor rotation (MR), turbo boost pressure (TBP), inlet air temperature (IAT), exhaust gas temperature (EGT), and fuel outlet temperature (FOT). Pinhais, Paraná, Brazil, 2018.

Factors	MR (rpm)		
	Large	**Intermediate**	**Small**
Flat	1,992 Ab	1,999 Ab	2,024 Aa
Inclined	1,995 Aa	1,990 Aa	1,990 Ba
Factors	**Turbo boost pressure (kPa)**		
	Large	**Intermediate**	**Small**
Flat	68 Ba	66 Ba	86 Aa
Inclined	63 Aa	64 Aa	62 Ab
Factors	**Inlet air temperature (^{0}C)**		
	Large	**Intermediate**	**Small**
Flat	27.45 Aa	24.59 Ba	26.19 Ab
Inclined	24.87 Bb	22.43 Cb	27.90 Aa
Factors	**Exhaust gas temperature (^{0}C)**		
	Large	**Intermediate**	**Small**
Flat	196.45 Cb	209.34 Bb	232.79 Aa
Inclined	204.08 Ca	229.53 Aa	213.19 Bb
Factors	**Fuel outlet temperature (^{0}C)**		
	Large	**Intermediate**	**Small**
Flat	44.94 Ab	39.11 Bb	37.95 Bb
Inclined	47.06 Aa	42.29 Ba	42.52 Ba

The means followed by different uppercase letters in each line and lowercase letters in each column were significantly different using the Tukey's test (P<0.05).

MR was higher using the smaller tread width in flat soil, corroborating the higher TBP, consequently increasing EGT.

There were remarkable differences in IAT between treatments; however, this variable did not increase efficiency, and the value was within the NBR ISO3040 standard.

In diesel engines, which are controlled by the injection pump, part of the fuel is not consumed and returns to the fuel tank. The returning fraction absorbs heat as it passes through the engine and reaches the tank with a temperature higher than that of the outlet. Siqueira et al. (2011) assessed the use of diesel and vegetable oil in diesel engines and found that the temperature of the fuel supply system varied depending on the required traction, tractor PTO, and engine type.

DF varied between treatments, and the value was lower using a larger tread width in steep terrain because the ATS was lower using a larger tread width due to the higher total weight distribution and the steeper slope, causing the tractor to slip sideways, consequently reducing DF in this condition.

TBP was not significantly different between tread widths, resulting in higher averages using a smaller tread width in flat terrain. Higher TBP values resulted in higher air intake and thermodynamic yield, as observed by Ghazikhani et al. (2008).

IAT varied in all treatments. IAT was higher using a smaller tread width in steep terrain and lower using a larger tread width in flat terrain (29.9 °C and 27.18 °C, respectively), and this difference was directly related to the time of the tests due to changes in atmospheric air temperature throughout the day.

CONCLUSIONS

The smaller tread width resulted in higher drawbar power and performance regardless of the slope of the terrain.

Drawbar force was lower using a larger tread width in steep terrain, whereas turbo boost pressure was higher using a smaller tread width in flat terrain.

Inlet air temperature was higher using a smaller tread width in steep terrain and lower using an intermediate tread width in flat terrain.

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