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RURAL ENGINNERING

Energy efficiency of four-wheel drive tractor in sowing operation

Samir Paulo Jasper[1] William Santiago de Mendonça[1*] Eduardo Affonso Jung[1] Gabriel Ganancini Zimmermann[1] Eduardo Alves Gracietti[1]

[1]Departamento de Solos e Engenharia Agrícola, Universidade Federal do Paraná (UFPR), 80035-050, Curitiba, PR, Brasil. E-mail: bilmendonca@gmail.com. *Corresponding author.

ABSTRACT: The breakthrough of articulated tractors has led to a significant increase in productivity and a cost reduction of agricultural operations. The performance of the tractor implement system depends on the understanding of the tractors' energy parameters. Fertilizer seeders operate between 6 and 9 km h^{-1}, while seed drills allow higher speeds. Increasing sowing speed improves operational efficiency. However, it is important to adequately set the machinery, to optimize the energy parameters, considering the balance between productivity and sustainability. This study evaluated the energy and operating parameters of a 398kW articulated agricultural tractor in a sowing operation at different speeds. The experiment was conducted in a complete randomized block design. Five theoretical speeds were chosen for the sowing operation (6, 7, 8, 9 and 10 km h^{-1}), with seven replications (35 units). The tractor operating parameters were measured: operational speed, slippage, engine speed, hourly fuel consumption, engine thermal efficiency, specific fuel consumption, drawbar force, drawbar efficiency, fuel consumption per area and field operating capacity. The data were subjected to normality test, when significant, variance analysis. Results showed high field capacity in the highest speed and low fuel consumption per area at the highest speed.
Key words: agricultural machinery, fuel consumption, operational efficiency.

Eficiência energética de um trator de tração integral na operação de semeadura

RESUMO: O advento de tratores articulados proporcionou aumento significativo da produtividade e redução dos custos das operações agrícolas. Para que o conjunto mecanizado seja eficiente é necessário que haja um entendimento do desempenho energético dos tratores nas operações. Semeadoras adubadoras operam entre 6 e 9 km/h, enquanto semeadoras permitem velocidades superiores. Aumentar a velocidade de semeadura favorece a eficiência operacional e reduz custos com mão de obra. No entanto, é importante ajustar o conjunto a fim de otimizar os parâmetros energéticos, buscando o equilíbrio entre produtividade e sustentabilidade. O objetivo deste estudo foi avaliar os parâmetros energéticos e operacionais de um trator agrícola articulado de 398kW em diferentes velocidades. O experimento foi conduzido em faixas, no delineamento de blocos casualizado. Foram empregadas cinco relações de velocidade teórica para operação de semeadura (6, 7, 8, 9 e 10 km h^{-1}), com sete repetições, totalizando 35 unidades experimentais. Sendo mensurados os parâmetros: velocidade operacional, patinagem, rotação do motor, consumo horário e específico de combustível, eficiência térmica do motor, força e rendimento na barra de tração, consumo de combustível por área e capacidade operacional de campo. Os dados coletados foram submetidos aos testes de normalidade, quando significativos, submetidos à análise de variância. Os resultados evidenciam elevada capacidade de campo, superior a 20 ha h^{-1}, para operação de semeadura com trator articulado, com consumo de combustível por área foi inferior 3,2 L ha^{-1} nas velocidades avaliadas, demonstrando vantagem em operar em maiores velocidades.
Palavras-chave: mecanização agrícola, consumo de combustível, rendimento operacional.

INTRODUCTION

Over the past century, significant productivity improvements, the availability of agricultural products, and cost savings have resulted from the development of agricultural machinery. Articulated tractors serve as an example, which offer excellent performance and high power (ZIMMERMANN et al., 2023). Therefore, energy and operational efficiency depends on the suitability of the machinery setup, which can favor lower fuel consumption and sustainability of the operation (ZHU et al., 2022). Nonetheless, limited research has investigated the parameters of specific operations, such as sowing (ASKARI et al., 2022).

In agricultural production, sowing is critical for crop establishment. Prioritizing the operational windows and the work speed is necessary for the operation to be successful. Given that travel speed grows with operational efficiency and labor expenses decreases with it, it is imperative to comprehend the operational speed on the efficiency parameters of each set (AIKINS et al., 2021).

Fertilizer seeders are used in more than 90% of sowing operations in Brazil (SPAGNOLO et al., 2020). However, the openers involved in fertilizer

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deposition intensify soil disturbance (CHEN et al., 2004). As soil disturbance increases, so does torque demand, and, consequently, the energy consumption (ZHAO et al., 2020), limiting operating speed between 6 and 9 km h^{-1} (BARR et al., 2016).

Seed drills, that only deposit seeds, allow higher operational speeds. Additionally, the absence of a fertilizer reservoir and metering mechanisms reduces the implement's weight, allowing more sowing rows to be added (SPAGNOLO et al., 2020). These features favor operational efficiency. However, changes in the equipment configurations require appropriate adjustments.

To investigate the performance relationships inherent in the sowing operation, this study o evaluated energy and operational parameters of a 398-kW articulated tractor at different speeds.

MATERIALS AND METHODS

The research study was conducted in the municipality of Primavera do Leste, Mato Grosso, Brazil, on a Red Yellow Latosol (sandy texture) with soybean cover (harvest) of less than 1 Mg ha^{-1} and a maximum slope of 2% in preparation direction.

The research was conducted in complete randomized bock and consisted of five theoretical speeds for the sowing operation (6, 7, 8, 9 and 10 km h^{-1}), obtained by automatic gear management (F4, F5, F6, F7 and F8). For each treatment, seven replications were conducted in 100-meter strips. Automatic management of the transmission and engine speed was conducted simultaneously by the APM software, according to the theoretical speed selected on the in-cab monitor.

A Fast Riser seed drill (Case IH®) was used, with 61 rows and a 20-inch diameter straw cutting disc, spaced 0.45 m apart, giving a total working width of 27.45 m. The seeding depth was 100 meters. The sowing depth was 0.04 m. The implement was attached to a Case IH® Steiger 540 articulated tractor, with 398 kW of power (ISO TR14396) and 4WD traction, fitted with a Full PowerShift 16 x 2 transmission and automatic productivity management (APM).

During the test, the set, with double wheels, was fitted with Michelin® 800/70R38 tires on the front and rear axles, with 82.74 kPa pressure on the inner and outer axles, respectively. The total mass of 27,745 kg was distributed 57.7% on the front axle and 42.3% on the rear axle, and the mass-to-power ratio was 69.61 kg kW^{-1}. Considering the setting of the operation, no ballast was not required.

The engine speed (ES) was measured using an Autonics® encoder, model E100S, attached to the power take-off of the tractor. The transmission ratio was measured with the relation between the engine speed and the wheel rotation, that was mesured with a Victor® digital tachometer, model DM6236P ($R^2 = 0.99$). The operating speed (OS) was measured using the GPS SVA-60 speed antenna (Agrosystem®), placed in the ceiling of the tractor.

Two flow meters (volumetric type - nutation disk) model RCDL25 (BadgerMeter®) were installed in the fuel supply system of the tractor (tank inlet and return), allowing the fuel hourly consumption (FHC) to be measured. Consumption was given by the difference in the number of pulses emitted by the flow meters, and then converted into volume.

The drawbar force (DF) was measured using a Bermann® load cell with a capacity of 300 kN, a sensitivity of 2.0 + 0.002 Mv V^{-1}, and an accuracy of 0.01 kN, which was calibrated and mounted on the tractor's drawbar.

During the experiment, a data acquisition system (DAS) with a printed circuit board (ARDUINO® Mega) was employed, consisting of the connection of the specified sensors in the board, with a programmed data acquisition frequency of 1 Hz (All the sensors being measured once every one second), which was then transmitted to a hard disk, by a usb cable, for tabulation and analysis.

The slippage rate was determined using the engine speed and the tractor's travel speed with and without load, according to Equation 1.

$$SLP=\left(1-\frac{V_C \text{ x } R_S}{V_S \text{ x } R_C}\right)\text{x}100 \quad (1)$$

SLP- slippage (%).
V_C - tractor operational speed with load (m s^{-1}).
V_S - tractor operational speed without load (m s^{-1}).
R_C - engine speed with load (RPM).
R_S - engine speed without load (RPM).
From the drawbar available power and the tractor engine, it was possible to determine the drawbar efficiency using Equation 2.

$$DY=\left(\frac{DBP}{EP}\right)\text{x}100 \quad (2)$$

DY - drawbar yield (%).
DBP - drawbar power (kW).
EP - engine power (kW).

The density of the diesel was obtained from the temperatures measured by K-type thermocouples installed next to the flow meter in the fuel return of the tractor. The density was determined according to KLANFAR et al. (2016), who employed a usual diesel fuel density of 850 g L^{-1}.

The fuel hourly consumption was determined with Equation 3.

$$FHC = \left(\frac{CHC \times D}{1000}\right) \quad (3)$$

FHC – fuel hourly consumption (g h^{-1}).
CHC – volume v hourly consumed L h^{-1}.
1000 – conversion factor.

The specific fuel consumption was determined by considering the hourly consumption on a mass basis, in relation to the drawbar power, according to Equation 4.

$$SFC = \left(\frac{FHC}{DP}\right) \quad (4)$$

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

The engine thermal efficiency was obtained from the specific consumption and the lower calorific value of the fuel using Equation 5, according to FARIAS et al. (2017).

$$ETE = \left(\frac{3600}{SFC \times PCI}\right) \quad (5)$$

ETE – engine thermal efficiency (%).
PCI – lower calorific power (42.295 MJ kg^{-1}).

The operational field capacity (OFC) and fuel consumption per area (FCA) were determined according to LEVIEN et al. (2011), adopting a theoretical value of 90% for the efficiency parameter, since the equipment only works with seeds.

The collected data was subjected to normality tests (Shapiro-Wilk) and, when significant, regression analysis using the R statistical program. The models were selected based on the criterion of significance ($P \leq 0.05$) of the equation parameters and the highest coefficient of determination (R^2).

RESULTS AND DISCUSSION

The results showed that the means were normal. In addition, the coefficient of variation was categorized as stable (Table 1), according to FERREIRA (2018). In relation to the analysis of variance, slippage and fuel consumption per area were not significant according to the treatments. However, the other parameters were significant at 1%.

Analyzing the effect of the speeds studied on the parameters OS, SLP, ES, FHC, ETE, SFC, DF, DY, FCA and OFC, linear regressions were drawn up showing the behavior as a function of the treatments (Figure 1).

Comparing the speed without load with the operational speed (Figure 1A), the loss of efficiency is evident, generating a disparity between the actual and programmed speeds. Slippage and losses due to mechanical action can be responsible for this energy expenditure. The observations made by GUPTA et al. (2023), which evaluated operational parameters in the performance of a tractor implement system, corroborate to the obtained results, demonstrating the relationship between slippage and operational speed.

In agricultural operations, there is a direct correlation between working speed, implement characteristics and slippage. The slippage (Figure 1B) did not differ due to the decrease in force on the drawbar as the speed increased. However, the slip values remained within the ideal range for articulated tractors (4 to 8%), according to ASABE (2011).

There was a linear increase in engine speed (Figure 1C). This phenomenon is influenced by the engine load. Which happens because, at higher speeds, the inertial forces of the surface are reduced. This results in an increase in engine speed (SERRANO et al., 2007), analogous to KUMARI & RAHEMAN (2023), who reported that subjecting the engine to higher loads generates stability in engine speed.

Increasing operational speed, simultaneously to the engine speed, led to higher hourly fuel consumption (Figure 1D). This observation is consistent with MARTINS et al. (2018), who showed that increasing engine speed, due to higher speeds, intensifies energy

Table 1 - Statistical summary of normality and coefficients of variation of the studied parameters.

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	OS (km h^{-1})	SLP (%)	SLP (RPM)	FHC (L h^{-1})	ETE (%)	SFC (g kW h^{-1})	DF (kN)	DY (%)	FCA (L ha^{-1})	OFC (ha h^{-1})
Normality										
SW	0.94	0.17	0.04	0.95	0.87	0.88	0.02	0.08	0.67	0.94
CV (%)	18.22	24.27	5.33	18.52	21.14	29.32	23.70	26.95	4.49	18.22

OS - operational speed; SLP - slippage; ES - engine speed; FHC - fuel hourly consumption; ETE - engine thermal efficiency; SFC - specific fuel consumption; DF - drawbar force; DY - drawbar yield; FCA - fuel consumption per area; OFC - operational field capacity. *Significant at $P \leq 0.05$ and **Significant at $P \leq 0.01$ by the F test; Vertical bar - Standard error.

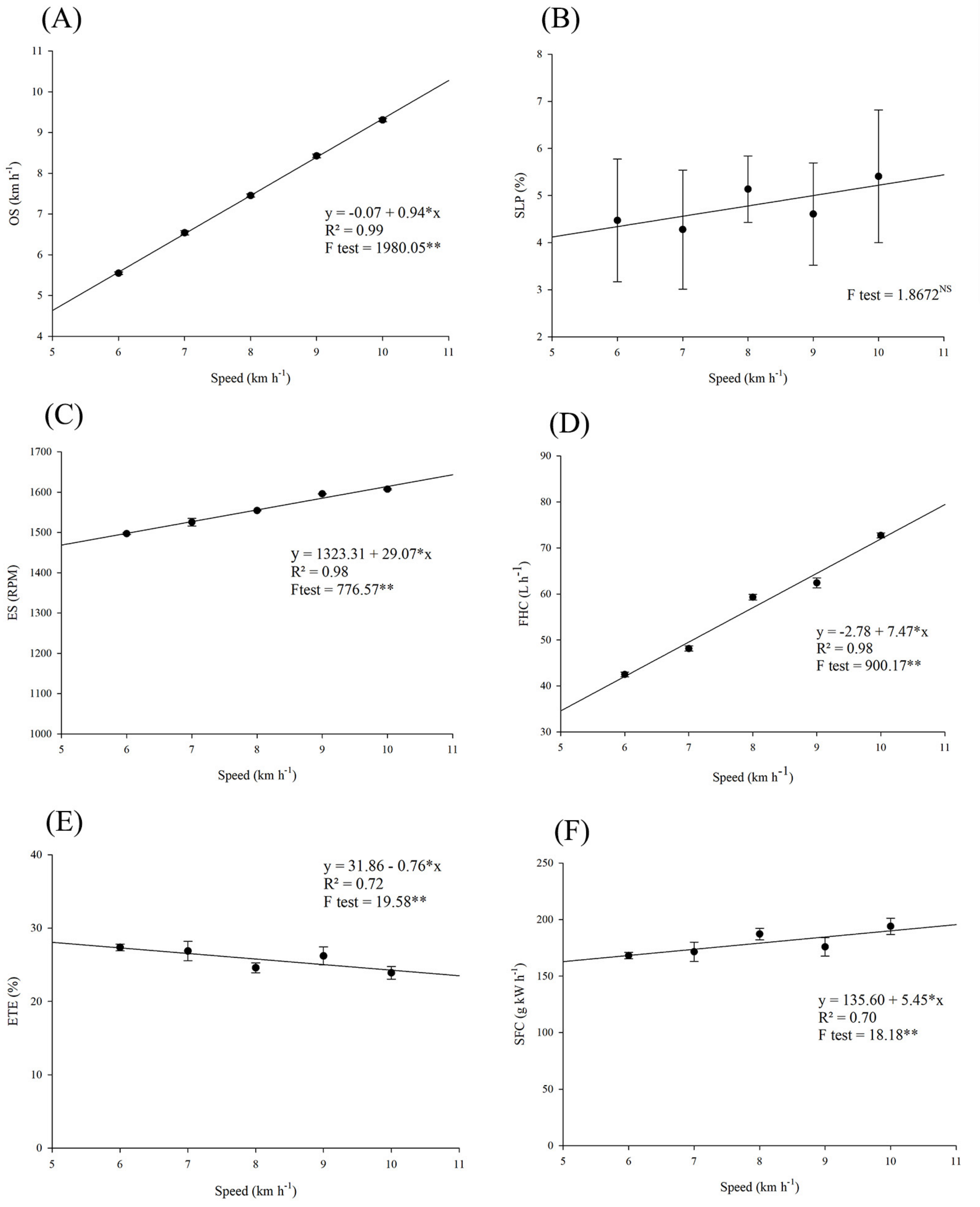

Figure 1 - Energy and operating parameters as a function of target speed.

expenditure. ZHANG et al. (2023) also showed that fuel consumption increases with working speed.

Figure 1E shows that there were losses in thermal efficiency at higher speeds. This can be attributed to the ratio between the stability of the engine load and the increase in speed. This result contrasted with AGARWAL et al. (2023), who found that there can be an increase in thermal efficiency as the engine load intensifies.

The decrease in thermal efficiency led to an increase in specific fuel consumption (Figure 1F). EMAISH et al. (2021) attributed variations in specific fuel consumption to engine speed. These authors found that consumption is linked to the engine load.

Regarding the force on the drawbar (Figure 2A), there was a decrease in this parameter at higher speeds. This is due to the overcome in the inertial soil resistance forces, as the torque decreases and the speed increases. As a result, less pulling force is needed from the tractor. (KUMARI & RAHEMAN, 2023).

Simultaneously with the increase in speed, there were higher yields on the drawbar (Figure 2-B). These findings are consistent with PENTOŚ et al. (2020), who pointed out that drawbar yield is related to operating speed. This is also in line with the findings of NKAKINI et al. (2020), who studied a predictive model that related drawbar force to operations. In this study, they showed that drawbar performance increases as the mobility of the mechanized unit increases.

Fuel consumption per area (Figure 2C) did not vary as speed increased. This can be attributed to the increase in operational field capacity at higher speeds, despite the increase in hourly consumption and decrease in the engine's thermal efficiency (ZIMMERMANN et al., 2023). According to MOINFAR et al. (2020), the tractor's energy performance has a significant effect on fuel consumption per area. Therefore, it can be concluded that speed increases up to 10 km/h^{-1} improve the automated system's performance.

It is not surprising that advances in mobility allow the worked area per time unit to rise, as shown by the impact of higher speeds in the operational field capacity (Figure 2D). DAS et al. (2016) also noted this when assessing field capacity and particular fuel consumption in various tractors. They discovered that field capacity increases with higher speeds, with the best results obtained at 10 km/h.

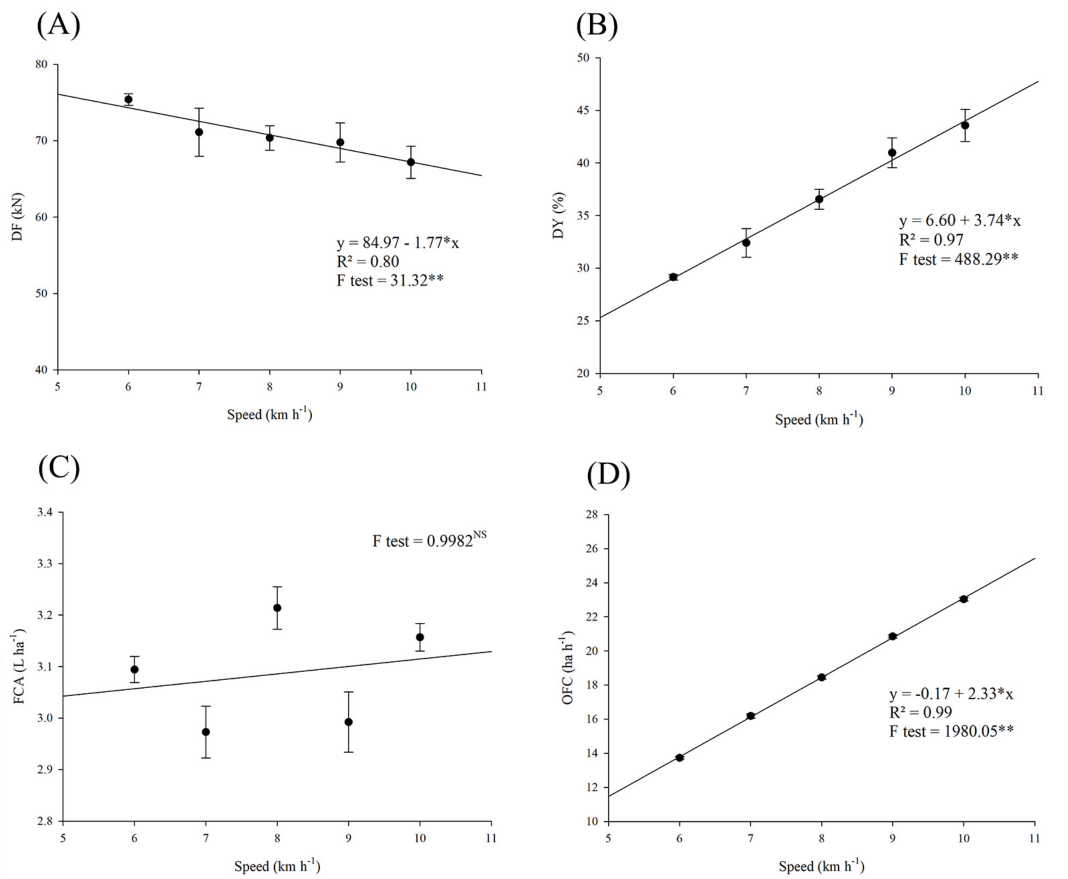

Figure 2 - Energy and operating parameters as a function of target speed.

CONCLUSION

The results showed high field capacity of the setup in the highest speed, more than 20 ha h^{-1}, and low fuel consumption per area, less than 3.2 L ha^{-1} at the evaluated speeds, demonstrating the advantage of sowing at higher speeds.

DECLARATION OF CONFLICT OF INTEREST

There are no conflicts of interest with this work, according to the authors.

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AUTHORS' CONTRIBUTIONS

Samir Paulo Jasper, William Santiago de Mendonça, Eduardo Affonso Jung, Gabriel Ganancini Zimmermann and Eduardo Alves Gracietti contributed equally to conceptualization,writing-original draft, and writing-review and editing.

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