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Original Article

Operational and energy performance of a powershift transmission tractor during tillage at different speeds[1]

Performance operacional e energética de trator powershift na operação de subsolagem em diferentes velocidades

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HIGHLIGHTS:
Slippage increased progressively as the gears shifted from A to E.
Hourly fuel consumption increased with higher gear settings.
Brake specific fuel consumption remained unchanged across the different gears.

ABSTRACT: Agricultural machinery plays a key role in optimizing crop yields. In tillage operations, it is essential to analyze both operational and energy performance variables. Continuous research is needed to quantify performance without compromising soil conservation, particularly with modern agricultural tractors, to update strategies, increase productivity and ensure the sustainability of mechanized operations. This study aimed to assess the energy and operational efficiency of an agricultural tractor (John Deere®, model 8400R), during subsoiling at different speeds, using five gear settings (A, B, C, D and E, corresponding to gears F5, F6, F7, F8 and F9), with a nominal engine speed of 2,100 rpm. The parameters evaluated were operating speed, wheel slip, engine speed, drawbar force, drawbar efficiency, hourly fuel consumption, fuel consumption per unit area, brake specific fuel consumption, brake thermal efficiency, and field capacity. The experiment followed a randomized block design. Analysis of variance indicated significant improvements in operating speed, wheel slippage, engine speed, drawbar force and drawbar efficiency as the gears shifted from A to E. Correlation analysis showed strong relationships between operating speed and parameters such as wheel slippage, drawback force and drawback efficiency, hourly fuel consumption and operational field capacity. Gear D was the most efficient for tillage. Although gear E improved operational performance, it reduced energy efficiency, indicating a trade-off between speed and fuel economy.

Key words: agricultural mechanization, fuel consumption, operational efficiency

RESUMO: As máquinas têm grande importância na produtividade agrícola. Na lavoura, é fundamental a análise das variáveis de desempenho operacional e energético. Estudos que quantifiquem o desempenho, sem comprometer a conservação do solo, devem ser constantes, principalmente com os novos tratores agrícolas, para atualização de estratégias, aumento da produtividade e sustentabilidade das operações mecanizadas. O objetivo foi avaliar a eficiência energética e operacional do trator agrícola (John Deere®, modelo 8400R), na subsolagem em diferentes velocidades, utilizando cinco marchas (A, B, C, D e E), correspondentes às marchas F5, F6, F7, F8 e F9, com rotação nominal de 2.100 rpm. Os parâmetros coletados foram a velocidade operacional, patinagem, rotação do motor, força na barra de tração, eficiência na barra de tração, consumo horário de combustível, consumo de combustível por área, consumo específico de combustível, eficiência térmica e capacidade de campo. O experimento foi realizado em delineamento de blocos casualizados. Após a análise de variância, verificou-se que a velocidade operacional, patinagem, rotação do motor, força na barra de tração e eficiência da barra de tração demonstraram uma melhoria significativa dos parâmetros à medida que ocorria a progressão de A para E. A análise de correlação da velocidade de funcionamento com os outros parâmetros indicou uma forte relação entre patinagem, força na barra de tração, eficiência na barra de tração, consumo horário de combustível e capacidade de campo. A marcha D foi a mais eficiente para a lavoura. A marcha E melhorou o desempenho operacional, mas reduziu a eficiência energética, indicando um trade-off.

Palavras-chave: mecanização agrícola, consumo de combustível, rendimento operacional

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Introduction

Global food productivity has increased substantially over the decades, primarily due to advances in agricultural technologies, contributing to continuous progress in the sector. A successful harvest requires a series of operations, each demanding specific techniques, inputs and appropriate equipment (Jaworski et al., 2024).

Among these operations, soil preparation remains a fundamental practice for many crops and is significant from an agronomic and economic standpoint, given its high energy consumption, often requiring high-powered tractors and large amounts of fuel (Zimmermann et al., 2023).

Agricultural tractors are important for tillage, providing traction, power and support. It is therefore essential that these machines are driven efficiently, with satisfactory operational and energy performance (Li et al., 2020).

Tractors offer different gear shift options, which are used to provide the necessary tractive force depending on operational and field conditions. Given the significant impact on performance, engine load and transmission efficiency, proper gear selection for each operation is crucial. Although several studies have addressed energy efficiency and soil-machine interaction parameters such as wheel slippage in tillage operations, there is a lack of research focused specifically on transmission technologies, including Powershift systems (Lou et al., 2021; Kim et al., 2023; Luo et al., 2023; Jensen et al., 2025).

This study aimed to assess the operational and energy performance of a tractor equipped with a Powershift transmission during subsoiling operations, using five gear ranges (A, B, C, D and E) at different operating speeds.

Material and Methods

The study was carried out in Candói, Paraná state, Brazil, located at 25° 34' 47.08" S and 52° 3' 8.42" W, at an altitude of 930 m. The soil at the experimental site is classified as Oxisol (Soil Survey Staff, 2022) (Latossolo, EMBRAPA, 2017), with desiccated winter crop cover of 8 Mg ha^{-1} and a maximum slope of 10% in the direction of tillage. The previous crop was corn, and the last tillage operation occurred 11 months before the experiment.

The experiment was conducted in a randomized block design, with five subsoiling gear treatments (A - 3.61 km h^{-1}, B - 4.05 km h^{-1}, C - 4.72 km h^{-1}, D - 5.46 km h^{-1} and E - 5.90 km h^{-1}), corresponding to gears F5, F6, F7, F8 and F9 of the John Deere® 8400R tractor, operated at a nominal engine speed of 2,100 rpm. Each treatment was replicated seven times in 300-meter-long strips, resulting in 35 experimental units and a total experimental area of 238 m^2.

Soil penetration resistance (SPR) was determined using a portable electronic penetrometer (Falker® model PLG 1020), set to record measurements every 0.01 m until a depth of 0.3 m. Concurrently, soil samples were collected at depths of 0.0-0.30 and 0.30-0.60 m. Soil water content (Uv) was determined according to EMBRAPA (2017) guidelines. The SPR values were 1.75 and 1.30 MPa and Uv 40.56 and 0.45 m^3 m^{-3}, for the respective depths.

The soil strips were tilled with a TERRUS DSR 10H subsoiler (GTS®), equipped with 10 shanks and a 24-inch diameter flat disc, spaced 0.68 m apart, providing an effective working width of 6.80 m. The operating depth was set to 0.45 m. The subsoiler was mounted on the drawbar of the John Deere® 8400R tractor, with 275 kW of effective power (DIN 70020), a 23 × 11 automatic PowerShift transmission, 1132 operating hours, and configured in accordance with ASABE standard D496.3 (2011). During tillage operations, the tractor operated with auxiliary front-wheel drive and differential lock engaged.

The tractor was fitted with dual Firestone® tires: 480/70R34 on the front and 800/70R38 on the rear, with both inner and outer tires inflated to 68.95 kPa (10 psi). The front and rear axle contact areas were 0.51 and 0.98 m^2, respectively, resulting in a 1.60% advance rate.

The 40% hydraulic ballast was added to the front and back axle wheels. The front axle was loaded with 22 plates (50 kg each) and 2 rings (72 kg each) and the rear with four 205 kg rings and two 625 kg rings, yielding a total mass of 19,574 kg distributed 38.5% over the front axle and 61.5% on the rear. Both axles were fitted with hydraulic ballast (Schlosser et al., 2020), and the mass-power ratio was 52.33 kg hp^{-1}.

A printed circuit board-based data acquisition system (DAS) was used in the experiment, operating at a sampling frequency of 1 hz. Data were recorded and stored on a hard drive for later tabulation and analysis. Engine speed and wheel slip were calculated based on operating speed under both loaded and unloaded conditions, according to Eq. 1.

$$SLP = \left(1 - \frac{OS_L \times ES_U}{OS_U \times ES_L}\right) \times 100 \quad (1)$$

where:

SLP - wheel slip, %;
OS_L - loaded operating speed, m s^{-1};
OS_U - unloaded operating speed, m s^{-1};
ES_L - loaded engine speed, rpm; and,
ES_U - unloaded engine speed, rpm.

Engine speed (ES) was determined by measuring the power take-off (PTO) using an Autonics® E100S encoder. A Victor® digital tachometer was used to determine the transmission ratio. Operating speed (OS) was measured with the SVA-60 speed antenna (Agrosystem®), which calculates displacement based on the number of pulses emitted.

Hourly fuel consumption (HFC) was measured using two Flowmate Oval M-II LSF 45 flow meters (TechMeter®) installed in the tractor's fuel supply system. Fuel consumption was determined by counting the pulses emitted by the flow meters, which were then converted into volume.

A calibrated Bermann® load cell (300 kN capacity, sensitivity 2.0 + 0.002 Mv V^{-1}, accuracy of 0.01 kN) was used to measure drawbar force (DF).

Drawback efficiency (DF) was calculated based on the power available at the tractor engine and the drawbar, as shown in Eq. 2.

$$DE = \left(\frac{DF}{EP}\right) \times 100 \quad (2)$$

where:

DE - drawbar effciency, %;
DF - drawbar force, kW; and,
EP - engine power, kW.

Diesel fuel density was determined by measuring temperatures using K-type thermocouples placed near the flow meter on the tractor's fuel return line. A density of 850 g L^{-1} was used, as established by Klanfar et al. (2016).

Hourly fuel consumption on a mass basis was determined using Eq. 3.

$$HFC = \left(\frac{HFC_V \times D}{1000}\right) \quad (3)$$

where:

HFC - hourly fuel consumption, g h^{-1};
HFC_V - volumetric hourly fuel consumption, L h^{-1}; and,
1000 - conversion factor.

Considering the mass-based hourly fuel consumption and drawbar power, brake specific fuel consumption was calculated according to Eq. 4.

$$BSFC = \left(\frac{HFC}{DF}\right) \quad (4)$$

where:

BSFC - brake specific fuel consumption, g kW h^{-1}.

Brake thermal efficiency (BTE) was determined according to Farias et al. (2017), using the BSFC and the fuel's lower calorific value (LCV), as shown in Eq. 5.

$$BTE = \left(\frac{3600}{BSFC \times LCV}\right) \quad (5)$$

where:

BTE - brake thermal efficiency, %; and,
LCV - lower calorific value, 42.295 MJ kg^{-1}.

Field capacity and fuel consumption per unit area were calculated using the theoretical efficiency parameter of 80% proposed by Levien et al. (2011).

The data collected was submitted to normality (Shapiro-Wilk) and homogeneity of variance (Brown-Forsythe) tests, and when significant, analysis of variance (ANOVA) was carried out using the R Software statistical program to evaluate the effect of the factor (gear) on each parameter.

Pearson's correlation was performed to evaluate the relationship between operating speed and the other variables. Correlation strength was categorized as follows: very weak (0.01 to 0.19), weak (0.20 to 0.39), moderate (0.40 to 0.69), strong (0.70 to 0.89) and very strong (0.90 to 1.00).

Results and Discussion

Table 1 presents the results of the ANOVA and mean comparison tests for the operational performance data. No transformation of the means was necessary for any of the variables studied, indicating homogeneity of variance (Shapiro-Wilk) and normality (Brown-Forsythe).

The coefficient of variation remained stable across all variables, except for wheel slip (SLP), which exhibited moderate dispersion according to the classification of Ferreira (2018). This variation is most likely a result of spatial variability in the field, which may have affected SLP, as reported by Kostić et al. (2021).

Operating speed increased progressively with each gear change, ranging from 3.61 to 5.90 km h^{-1}, as expected, given the transmission ratio (Li et al., 2018).

As the five gears progressed from A to E, SLP increased proportionally, from 9.16 to 18.50%. According to Shi et al. (2023), this suggests that speed influences SLP.

Gears A, B, C and D remained within the acceptable slip range (9-15%) defined by Janulevicius et al. (2019), which differed from gear E, with 18.50%. Excessive wheel slip above 15% indicates energy expenditure in the engine, thereby reducing operational efficiency (Battiato & Diserens, 2017).

ES was affected by gear changes, with gear C obtaining the highest value. However, given the low amplitude observed, ES remained stable throughout the experiment, likely due to the tractor´s torque reserve (Gritsuk et al., 2023). The low coefficient of variation in engine speed indicates that the operating speed of the mechanized unit remained stable.

DF also remained stable, but was slightly higher in gears D and E, possibly due to the higher SLP, indicating greater tire-soil interaction and, consequently, a higher load demand on the drawbar, as explained by Battiato & Diserens (2017).

Across the different gears, DE increased progressively. Gear E was superior due to the increases in OS and DF, which resulted in the observed gains. As reported by Regazzi et al. (2019), engine power is influenced by active traction and

Table 1. Analysis of variance and mean comparison tests OS, SLP, ES, DF, and DE

Tests	Parameters				
	OS (km h^{-1})	SLP (%)	ES (RPM)	DF (kN)	DE (%)
Normality					
SW	0.248	0.928	0.093	0.208	0.334
Homogeneity					
BF	0.486	0.960	0.060	0.527	0.777
Anova					
F test	116,110**	5,728**	32,015**	2,861*	69,326**
Engines					
A	3.61 e	9.16 a	2.006 b	109.52 b	37.40 e
B	4.05 d	9.86 b	1.990 d	111.03 b	42.45 d
C	4.72 c	13.00 c	2.016 a	111.66 b	49.86 c
D	5.46 b	14.10 d	2.000 c	114.65 a	59.09 b
E	5.90 a	18.50 e	1.992 d	116.16 a	64.73 a
CV (%)	4.92	32.02	0.24	3.78	7.10

SLP - Wheel slip; ES - Engine speed; DF - Drawbar force; DE - Drawbar efficiency; OS - Operating speed. In each column, factors sharing the same letter do not differ significantly according to the Scott-Knott test ($p \leq 0.05$). ANOVA F test; * - Significant ($p \leq 0.05$) and ** - Significant ($p \leq 0.01$). CV (%) - Coefficient of variation. Shapiro-Wilk Normality test: SW ≤ 0.05 - Brown-Forsythe Homogeneity test: BF ≤ 0.05

transmission efficiency, both of which are directly correlated with tire-ground contact. Consequently, the system's traction efficiency improved at higher gears. The results of ANOVA and mean comparison tests for the energy-related parameters are shown in Table 2. No transformations were necessary, indicating residual normality (Shapiro-Wilke) and homogeneity of variance (Brown-Forsythe). Furthermore, the coefficient of variation (CV) for all parameters was classified as stable.

Since higher gears are staggered, HFC rose as the gears were changed, increasing the effective operating speed and, as a result, the hourly fuel consumption (Martins et al., 2018). This is consistent with Damanauskas et al. (2019), who reported that HFC is proportional to rolling resistance and working speed. At higher speeds, the tractor requires more energy to counteract soil inertia.

Neither BSFC nor BTE differed across gear changes. This can be attributed to the maintenance of stable engine speed across gears, supported by the tractor's high torque reserve, which ensures consistent engine performance (Gao et al., 2019). FC increased with gear changes, due to the higher OS, which enables a greater area to be worked per unit of time. Nevertheless, the FCA did not differ significantly among the first four gears (A, B, C and D), as indicated by ANOVA. FCA was only higher in gear E, due to the increase in HFC associated with higher OS. Although gear E provided a higher FC, it also resulted in a greater FCA, indicating lower energy efficiency. By contrast, the progression from gears A to D did not increase in FCA, demonstrating the superiority of gear D in terms of energy efficiency

This suggests that gear E delivers the highest OS and HFC, it does not offer the best energy performance. Therefore, gear D is recommended as the most balanced option, combining optimal operating speed with reduced FCA under similar field conditions, according to Zhang et al. (2024).

Table 2. Analysis of variance and mean comparison tests of the data for parameters HFC, BSFC, BTE, FC and FCA

Tests	Parameters				
	HFC ($L\ h^{-1}$)	BSFC ($g\ kW\ h^{-1}$)	BTE (%)	FC ($ha\ h^{-1}$)	FCA ($L\ ha^{-1}$)
Normality					
SW	0.535	0.516	0.592	0.248	0.506
Homogeneity					
BF	0.165	0.800	0.857	0.486	0.898
Anova					
F test	75,592**	1,716^{ns}	1,503^{ns}	116,047**	4,173**
Engines					
A	31.89 a	246.35	34.66	1.96 e	16.26 a
B	36.51 b	248.51	34.37	2.20 d	16.63 a
C	41.66 c	241.38	35.36	2.57 c	16.21 a
D	51.09 d	249.77	34.26	2.97 b	17.25 a
E	61.46 e	274.29	31.21	3.21 a	19.20 b
CV (%)	8.10	10.12	10.47	4.92	9.36

HFC - Hourly fuel consumption; BSFC - Brake specific fuel consumption; BTE - Brake thermal efficiency; FC - Field capacity; FCA - Fuel consumption per unit area. In each column, factors sharing the same letter do not differ significantly according to the Scott-Knott test ($p \leq 0.05$). ANOVA F test: ns - Not significant; ** - Significant ($p \leq 0.01$). CV (%) - Coefficient of variation. Shapiro-Wilk Normality test: SW ≤ 0.05 - Brown-Forsythe Homogeneity test: BF ≤ 0.05

Table 3 shows the Pearson correlation coefficients between gear scaling, in this case operating speed, and the other factors studied to determine the strength of their relationships.

A very strong correlation was found between OS and SLP, DF, DE, HFC and FC. A strong correlation was observed for FCA, moderate associations for BSFC and BTE, and a very weak correlation between OS and ES.

These results indicate that OS significantly influenced most of the parameters evaluated, particularly showing very strong correlations with SLP, DF, DE, HFC, and FC. This suggests that increases in speed are closely associated with higher traction demands and fuel use. The strong correlation with FCA further underscores the relationship between speed and area-based fuel efficiency. By contrast, the moderate correlations for BSFC and BTE suggest that while OS affects engine efficiency, other factors may also influence these outcomes. The very weak correlation between OS and ES indicates that energy savings are not directly influenced by changes in speed alone, highlighting the complexity of optimizing operational efficiency under field conditions (Jensen et al., 2025; Kazenwadel et al., 2025).

From gear A to E, OS increased by 63.43%, effectively doubling the tractor's velocity, which is closely linked to the specific soil conditions described in the study, including soil texture, moisture content, and mechanical resistance. This significant variation in performance is also strongly influenced by the type of equipment used, particularly the arrangement, number, and shape of the shanks on the chassis, which differ from those of conventional subsoilers commonly used on farms. An increase of over 10% in operational efficiency under field conditions can translate into substantial reductions in fuel consumption and/or operational time, highlighting the economic impact of equipment-soil interaction (Zhu et al., 2022; Lopes et al., 2023; Alemanno et al., 2025).

Conclusions

1. Gear D proved to be the most suitable, in terms of energy and operational efficiency, for the tillage operation.

2. Gears A, B, and C resulted in energy expenditures that outweigh operational gains, indicating a less favorable balance between fuel consumption and field efficiency.

3. Gear E favored energy performance but compromised operational quality, indicating a trade-off between fuel economy and implement performance or soil disturbance efficacy.

Table 3. Pearson correlation matrix between SPL, ES, DF, DE, HFC, BSFC, BTE, FC and FCA

	SLP (%)	ES (rpm)	DF (kN)	DE (%)	HFC ($L\ h^{-1}$)	BSFC ($g\ kW\ h^{-1}$)	BTE (%)	FC ($ha\ h^{-1}$)	FCA ($L\ ha^{-1}$)
OS ($km\ h^{-1}$)	0.96	-0.18	0.98	1.00	0.98	0.67	-0.67	1.00	0.82

SLP - Wheel slip; ES - Engine speed; DF - Drawbar force; DE - Drawbar efficiency; HFC - Hourly fuel consumption; BSFC - Brake Specific Fuel Consumption; BTE - Brake thermal efficiency; FC - Field capacity; FCA - Fuel consumption per area; OS - Operating speed. Pearson correlation index: very weak (0.01 to 0.19), weak (0.20 to 0.39), moderate (0.40 to 0.69), strong (0.70 to 0.89) and very strong (0.90 to 1.00)

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