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# POWER PERFORMANCE OF FARM TRACTOR IN FIELD OPERATIONS

# WYKORZYSTANIE MOCY CIĄGNIKA ROLNICZEGO W PRACACH POLOWYCH

*Many studies have examined the effects of agriculture tractor engine energy performance. This paper presents an evaluation method of such engine actual power use during plowing operations. It includes results of a comparative study of power perform-ance of a 230 kW tractor model John Deere 8330 subject to soil plowing operations as a function of field size: A (26 ha), B (12.74 ha), C (3.22 ha). Statistical data clustering, a relatively novel approach in studies on actual utilization of engine power, was used. A positive correlation was observed between field size and the active state of the engine: 75.2% field A; 68.8% field B; 46.8% field C. The actual power utilization of agriculture tractor engine as a function of field size was 0.62, 0.58 and 0.39 respectively for the three fields used in this study. With this evaluation approach, performance indexes of operational power performance in various conditions were obtained for possible use in optimization of plowing operations.*

*Keywords*: *agriculture tractor, plowing, power performance, engine operation clusters.*

*Ocena stanu obciążenia silnika spalinowego w pojeździe podczas eksploatacji jest przedmiotem wielu prac badawczych. W ar-tykule przedstawiono nową metodę oceny wykorzystania mocy silnika ciągnika rolniczego eksploatowanego podczas orki. Za-prezentowano wyniki badań porównawczych nad wykorzystaniem mocy ciągnika John Deere 8330 (230 kW) w odniesieniu do powierzchni uprawianych pól: A (26 ha), B (12,74 ha) i C (3,22 ha). Do analizy danych pomiarowych zastosowano po raz pierw-szy statystyczną metodę grupowania punktów pomiarowych. Na podstawie wyników badań stwierdzono silną korelację dodatnią pomiędzy powierzchnią pól a stanem obciążenia silnika: 75,2% pole A; 68,8% pole B; 46,8% pole C. Opracowany wskaźnik efektywnego wykorzystania mocy silnika ciągnika rolniczego wyniósł odpowiednio: 0,62, 0,58 i 0,39. Stwierdzono, że uzyskane wartości wskaźnika efektywności wykorzystania mocy silnika mogą być przydatne do optymalizacji pracy ciągnika w pracach polowych.*

*Słowa kluczowe*: *ciągnik rolniczy, orka, wykorzystanie mocy, czas pracy silnika.*

## 1. Introduction

Tractors play a fundamental role in agriculture as the main power resource for operation with various add-on agriculture machinery. The most energy and labor intensive among agro-technological operations is soil plowing. The trend in a plow design favors tractors with substantial power [24, 26], but ultimately it is determined by the size and construction of the machinery satisfy-ing the needs of smaller farms [19].

Optimal tractor and machinery parameter selection, as a func-tion of various field operations, not only improves the economics of such activities, but also reduces exhaust pollution and other nega-tive environmental effects. The power requirements and energy con-sumption may be reduced through optimizing power characteristics and engine parameters [2, 3, 11, 31].

The $CO_2$ emissions may be reduced by minimizing idling states of the engine and maximizing the engine work load. The operational engine parameters are engine speed, transmission gear ratios and engine torque [1, 14]. The experience and reaction time of the tractor operator also play an important role in maintaining these parameters in optimal range [4, 18, 23, 28, 29] and optimal engine utilization [4, 12, 21].

Monitoring the performance indexes of operational power in various conditions provides data of engine modes of opera-tion and fuel consumption. Not many methods and mathemati-cal power performance models as a function of field parameters exist.

In this paper we present our evaluation method and introduce the performance indexes of operational power performance obtained in various conditions. It includes the evaluation of power use of an agri-culture tractor engine in various plowing operations and the results of a comparative study of power performance as a function of field size. Other studies [9, 10, 20] focus more on fuel and energy consumption efficiency and toxic exhaust emission characteristics.

## 2. Methodology

The study took place during the 2012 plowing season on the Agrofirma agricultural farm (Witkowo, Poland) for rapeseed sowing. The experimental setup included three fields (Fig. 1). The physical parameters of the three fields' soils were measured at the time of the plowing operations and are included in Table 1 [17].

This paper presents a comparative study of power performance of a 230 kW tractor model John Deere 8330 subject to soil plowing operations on the three fields. The tractor was pulling a Lemken semi-mounted reversible, full moldboard 7-furrows EuroDiamant plow unit combined with a Campbell soil compaction roller tiller. All operations involved the same one tractor operator reducing any comparative dis-crepancy in experiment results.

Table 1. Soil Parameters

| Soil | | Soil Layer | Field | | |
|---|---|---|---|---|---|
| | | | A | B | C |
| Soil Granulation, % | 2 ≥ d >1 | Tillage Layer | 2.7 | 1.5 | 1.7 |
| | 1 ≥ d > 0.5 | | 7.9 | 6.2 | 6.4 |
| | 0.5 ≥ d > 0.25 | | 15.1 | 11.0 | 12.5 |
| | 0.25 ≥ d > 0.1 | | 33.2 | 31.6 | 31.1 |
| | 0.1≥ d > 0.05 | | 17.1 | 17.7 | 19.3 |
| | 0.05 ≥ d > 0.02 | | 8 | 14 | 10 |
| | 0.02 ≥ d > 0.002 | | 11 | 13 | 14 |
| | d ≤ 0.002 | | 5 | 5 | 5 |
| | | | LFS | FSL | FSL |
| Soil Organic Matter Content, % | | | 2.1 | 1.9 | 2.0 |
| Soil Moisture (by weight), % | 0 - 10 cm 10 - 20 cm 20 - 30 cm | | 15.0  s=2.0 15.0  s=2.3 14.3  s=2.0 | 13.7  s=1.0 13.5  s=0.5 13.1  s=0.3 | 13.3  s=1.3 13.9  s=1.2 13.9  s=1.9 |
| Soil Volume Density, g/cm³ | 0 - 10 cm 10 - 20 cm 20 - 30 cm | | 1.35  s=0.10 1.57  s=0.14 1.57  s=0.10 | 1.31  s=0.15 1.57  s=0.04 1.52  s=0.03 | 1.44  s=0.15 1.62  s=0.06 1.65  s=0.07 |
| Soil Compactness, kPa | 0 - 10 cm 10 - 20 cm 20 - 30 cm | | 538  s=258 1183  s=463 2212  s=588 | 535  s=192 1539  s=348 2423  s=533 | 758  s=439 2459  s=683 3257  s=373 |
| Soil Shear Stress, kPa | 0 - 10 cm 10 - 20 cm 20 - 30 cm | | 24  s=10 50  s=16 56  s=11 | 18  s=6 35  s=6 53  s=10 | 18  s=4 49  s=19 67  s=15 |
| Plow Operation Velocity, m/s | | | 2.53  s=0.23 | 2.58  s=0.46 | 2.61  s=0.48 |
| Operating Plow Depth, cm | | | 25  s=2 | 22  s=2 | 25  s=3 |
| Operating Plow Width, m | | | 3.34  s=0.05 | 3.36  s=0.04 | 3.27  s=0.03 |

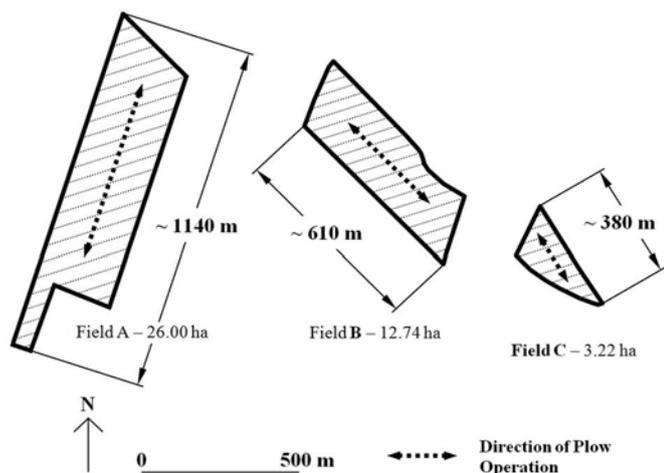LFS - loamy fine sand, FSL - fine sandy loam, s-standard deviation, d - particle size



Fig. 1. Experimental Setup of three fields (based on Agrofirma geographical map)

## 2. Analysis method

The operational parameters (the engine speed, torque and power, fuel consumption and GPS position) were monitored with digital sensors with 1 Hz frequency using Siemens VDO -EDM 1404.01 measuring system [7]. The readings were used to calculate nominal and operational power of the engine. There are many methods of finding engine torque $M_o$ indirectly [5, 8, 16, 22, 27, 32-34]. In our study, a method patented by the West Pomeranian University of Technology in Szczecin was utilized. In our view this method is unique and quite suitable for practical use in field operations [15, 16]. Other known methods focus more on theoretical analysis or represent laboratory experimental findings. In this study, the engine torque $M_o$ parameter was evaluated indirectly based on the measurement of fuel consumption and engine crankshaft rotations:

$$M_o = a \cdot g_{1000}^3 + b \cdot g_{1000}^2 + c \cdot g_{1000} + d, \quad (1)$$

where:

$$g_{1000} = \frac{V_{fuel}}{n_s} \cdot 1000, \quad (2)$$

$M_o$ – engine torque in Nm,
$g_{1000}$ – fuel consumption in dm³ per 1000 crankshaft revolutions,
$a, b, c, d$ – coefficients subject to the engine type and rpm (Table 2),
$V_{fuel}$ – fuel consumption, dm³/min,
$n_s$ – engine speed, rpm.

The values of torque were obtained indirectly with appropriate coefficient units to satisfy equation (2).

Engine utilization was evaluated with:

$$E_N = \frac{N_u}{N_{nom}} \cdot \frac{U_t}{100\%}, \quad (3)$$

where:

$E_N$ – engine utilization,
$N_u$ – plowing operation engine power, kW,
$N_{nom}$ – nominal engine power, kW,
$U_t$ – engine plowing operation time in relation to total engine operation time, %.

Table 2. Engine coefficients a, b, c, d – dyno test bench verified [16]

| Engine speed range $n_s$, rpm | Coefficient values | | | |
|---|---|---|---|---|
| | $a$, Nm/dm⁹ | $b$, Nm/dm⁶ | $c$, Nm/dm³ | $d$, Nm |
| < 950 | −7·10⁻⁶ | 0.0042 | 1.3992 | −1.1506 |
| 950–1250 | −6·10⁻⁶ | 0.0040 | 1.3193 | 14.087 |
| 1250–1550 | −8·10⁻⁶ | 0.0063 | 0.8354 | 37.374 |
| 1550–1850 | −1·10⁻⁵ | 0.0070 | 0.9304 | 20.479 |
| 1850–2150 | −1·10⁻⁵ | 0.0094 | 0.3923 | 50.361 |
| > 2150 | −7·10⁻⁶ | 0.0068 | 0.5357 | 59.126 |

The engine actual torque values were obtained from (1) and (2).

The measurements of relative time of engine operation are presented in Fig. 2, 3, 4 relative to total time of engine operation [6] and based on (4):

$$TD_{(i,j)} = \frac{t_{(i,j)}}{t_c} \cdot 100\% , \qquad (4)$$

where:

$TD_{(i,j)}$ – Relative time of engine operation (Time Density), %,
$i$ – Index of the engine speed coordinate with $\Delta n_s$ = 100 rpm,
$j$ – Index of the engine torque with $\Delta M_o$ = 50 Nm,
$t_{(i,j)}$ – time of operation at $(i,j)$,
$t_c$ – total time of engine operation.

Since the comparison and interpretation of the *TD* distribution plots (Fig. 2, 3, 4) may not be straightforward, a statistical data clustering (*k-means full binding*) method was used to obtain parameters for better quantitative comparison of effective utilization of the engine power at selected points $(n_s, M_o)$. A program *Statistica* [30] with 67450 measurement points was used to generate the results.

## 3. Results

The measurements of relative time of engine operation as a function of engine torque and engine speed are presented in Fig. 2, 3 and 4. For better visualization of the relative time of engine operation, the plots for fields A, B and C are normalized to show the measurements within 1% range of *TD*.

Two engine operative states were considered: idle and field operation. A quantitative comparison of the time duration of the engine states was ob-
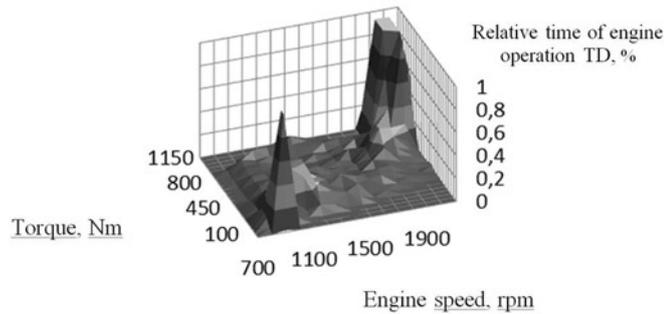


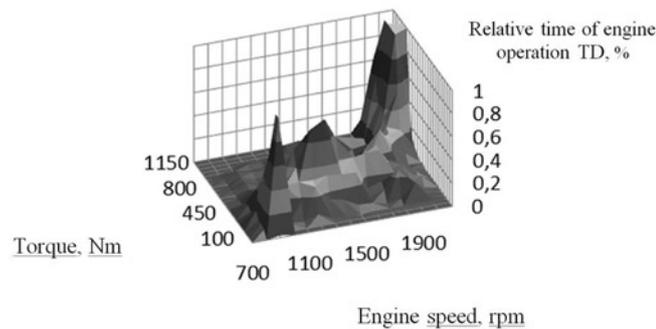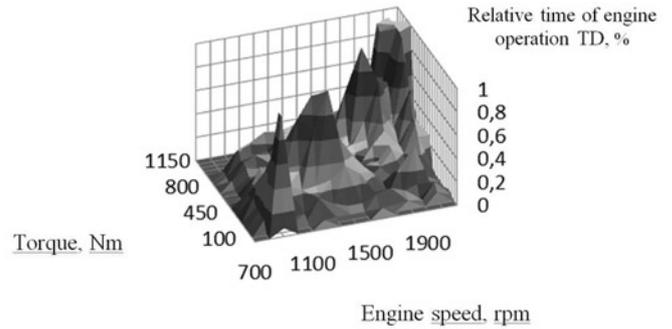*Fig. 4. Relative time of engine operation on field C*

tained also using the statistical data clustering approach, with results shown in Fig. 5. Four clusters were obtained as a function of engine speed $n_s$ and torque $M_o$, as well as field size and the corresponding engine state of operation.

For fields A and B, the resulting clusters were comparatively close to each other, as opposed to the cluster locations of field C (Fig. 5). The A and B cluster location coordinates (associated with engine speed and torque) correspond to the engine plowing operation. For clusters variance analysis was performed. It showed strong difference between clusters (Table 3).

*Table 3. Variance analysis for the clusters*

| Effect | Field A | | Field B | | Field C | |
|---|---|---|---|---|---|---|
| | F | p-Value | F | p-Value | F | p-Value |
| $n_s$ | 143565,8 | 0,00 | 41483,20 | 0,00 | 14324,31 | 0,00 |
| $M_o$ | 140147,9 | 0,00 | 77110,79 | 0,00 | 14324,31 | 0,00 |
| Number of cases | 39833 | | 20535 | | 7082 | |



*Fig. 2. Relative time of engine operation on field A*



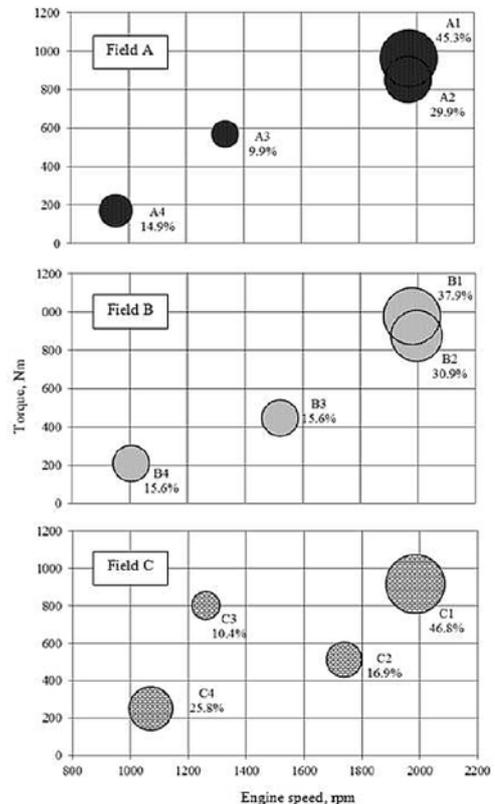*Fig. 3. Relative time of engine operation on field B*



*Fig. 5. Engine operation clusters for fields A, B and C; A1, ... C4 – cluster name, % – relative time of engine operation in a cluster*
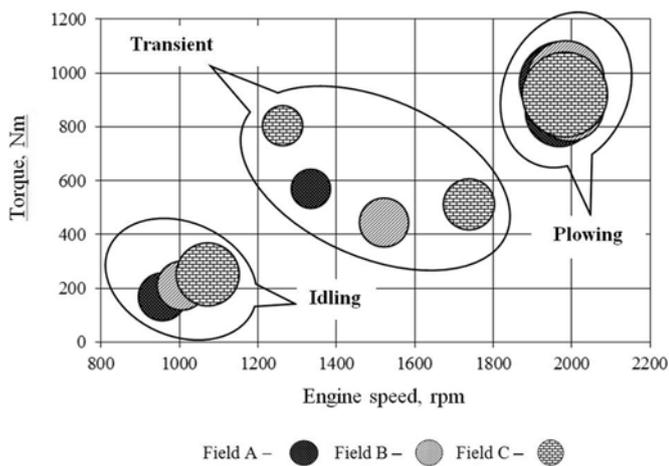
Fig. 6. Engine operationnal state clusters

minimization of energy usage [25]. Engine torque monitoring represents one of the key parameters in such analysis. Since its measurement requires specialized instrumentation setup, various indirect approaches have been explored [5]. Many such studies have presented their results in a general matrix form and fuel consumption profiles. In the evaluation approach here, performance indexes of operational power performance in various conditions have been presented. Implemented, they can contribute to optimal gear selection through visual display of actual engine power and to "gear up and throttle down" driving approach in transient engine states, possibly resulting in up to 20% fuel savings [4]. The actual engine utilization parameter may also be helpful in optimal tractor selection in terms of cost, as well as match of its engine power to target farm.

Our study, based on a theoretical model of engine optimal points of operation [4], implements a novel statistical data clustering and modern measurement technology approach. The time distributions of engine operation presented here confirm other studies [9, 10] validating our methodological approach. They may also help in modelling agriculture tractor engine load cycles [6], which in turn are used in evaluation of engine emissions.

During the plowing state interval, the engine was generating 190-195 kW, i.e. about 85% of nominal engine power. For fields A, B and C, the engine was generating 190-195 kW of power 75.2%, 68.8% and 46.8% of total time of engine operation respectively. In the case of engine idling state interval, the corresponding values were 14.9%, 15.6% and 25.8% (Fig. 5). The effective engine utilization $E_N$ obtained from (3) were accordingly for field A = 0.62, for B = 0.58 and for C = 0.39.

The coordinates of engine for both plowing and idling state intervals for each field clustered within 200 rpm and 100 Nm ranges of engine speed and torque (Fig. 6). The interoperation or transient states spread over 600 rpm and 350 Nm ranges.

A Pearson correlation coefficient was obtained to evaluate the functional relation of plowing vs. idling state share to the field size. Positive correlation (0.92) at $R^2 = 0,85$ was attained for plowing state and strongly negative (−0.85) at $R^2 = 0,72$ for idling.

## 4. Discussion

The plowing operations comprise 30% of tractor engine operation while its power is not fully utilized [13, 18]. Continuous monitoring and analysis of economy of agriculture activities contributes to the

## Conclusions:

- The statistical data clustering approach to quantitative comparison of the effective time duration of the various engine modes of operation and fields used in this study enabled more precise evaluation of the actual power utilization of agriculture tractor engine, as a function of field size, than theoretical and simulation approaches.
- The presented statistical approach may have practical applications as an optimization tool in a more effective utilization of various add-on agriculture machinery through a visualization driver support system for optimal gear selection.
- A strong positive correlation was observed between the field size and engine plowing state, while a negative correlation was observed in the case of idling engine state of operation.
- The actual power utilization of agriculture tractor engine as a function of field size was 0.62, 0.58 and 0.39 respectively for the three fields used in this study.

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