

THEORETICAL RESEARCH ON IMPROVING THE PERFORMANCE OF A 65 HP AGRICULTURAL TRACTOR USED FOR HARROWING OPERATIONS

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In this paper a theoretical study is presented which, based on a dynamic model of the tractor-agricultural machine system, a mathematical model and a computational algorithm, makes an important contribution to the theoretical estimation of the traction performance and the increase of this performance (driving force, specific driving force, coefficient of adhesion weight utilization, rolling resistance force of the agricultural tractor, draft force) for a 4x2 tractor of 65 HP type, used in soil tillage with a mounted disc harrow rather than the semi-mounted version as is commonly used.

Keywords: disc harrow, tractor dynamics, soil, resistive force.

1. Introduction

It is well known that tillage for seedbed preparation is the most fuel-consuming of all agricultural works. Disc harrow tillage is one such tillage and can be used for soil fragmentation after ploughing or for conservation tillage, replacing ploughing under certain conditions.

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Numerous theoretical and experimental studies have been carried out over the years in order to identify the optimal operating conditions of the tractor and disk harrow aggregate used for processing soil after plowing for fragmenting. Such a study presents the results obtained from experimental field trials of a tractor-disk harrow system, which provide dependency relationships between operating conditions, tillage quality indices and energy indices, for two different soil types [1]. Compared to cultivators, the use of disc harrows is more advantageous, especially where the volume of plant residues is higher, because it is possible to cut the stems of plant residues and avoid clogging of the machine, with lower energy consumption [2]. In these conditions with higher volume of plant residues in the soil to be processed, it has been proved that disc harrows are more versatile and can be used in a wider variety of conditions compared to other soil tillage machines [3].

At the same time, the danger of artificial compaction of agricultural soil is present in tillage systems, which greatly affects plant growth, soil water infiltration and cultivation costs. Optimal exploitation of the tractor-disk harrow system for prevention of soil compaction and carrying out agricultural tillage with maximum quality indices under energy-efficient conditions is a continuous challenge of researchers in this field [4, 5].

Over the years, several researchers have tried to develop both theoretical and empirical computational models for estimating the power consumed for soil tillage in the harrowing operation, depending on the physical-mechanical properties of the soil, soil humidity, working depth and working speed [6, 7]. To this end, mathematical models based on regression equations have been developed to estimate the draft force and power consumed with working speed and depth as independent variables [8].

In order to increase the efficiency of soil tillage with disk harrows, experimental research has been carried out to develop technical solutions for harrow construction, more suitable for working at different soil moisture contents [9], more adapted for cutting plant residues [10], more adequate to ensure an efficient trajectory of soil particles in contact with the disk and the lowest energy consumed for transporting the soil furrow [11].

As the working parts of agricultural soil tillage machines, including disc harrows, are subject to a pronounced wear process as a result of interaction with the soil, great attention has been paid to the choice of materials from which these working parts are made, as well as to the special heat treatments they are subjected to, or to the deposits of wear-resistant materials in the area of the disc edge [12].

In recent years, there has been an increasing emphasis on the development of computational models for advanced assessment of tractor performance in aggregate with a towed disk harrow [13] and, in particular, of mechanical models that allow the calculation of the reactions on the tractor wheels and disk harrow so

that the draft force and the optimal redistribution of these reactions can be estimated and the tractor's draft performance can be increased [14].

The main objective of this study is to develop calculation algorithms for the front and rear wheel reactions of a 65 HP 4x2 tractor coupled with a disc harrow, in two coupling configurations: (1) semi-mounted and (2) fully-mounted, in order to identify and improve the tractor's draft performance under various soil and operating conditions.

2. Dynamics of the Tractor–Disc Harrow System

During operation, the 4x2 tractor (U-650) (Fig. 1), is subjected to the following forces: tractor's weight G , the rolling resistant force R_r , rolling resistant moments M_{r1} și M_{r2} , driving force F_m , components F_t și R_z of the resultant force R transmitted to the tractor by the implement, and the reaction forces Z_1 și Z_2 at the front and rear axles, respectively. It is assumed that the tractor's weight G acts at its center of mass, defined by the coordinates a_c și h . The action of the implement on the 4x2 tractor can be replaced with the draft force (parallel to the ground surface) F_t and the normal component R_z (perpendicular to the ground surface). The point of application of these two forces is defined by the coordinates l_t (relative to the rear axle axis) and h_t (relative to the ground surface).

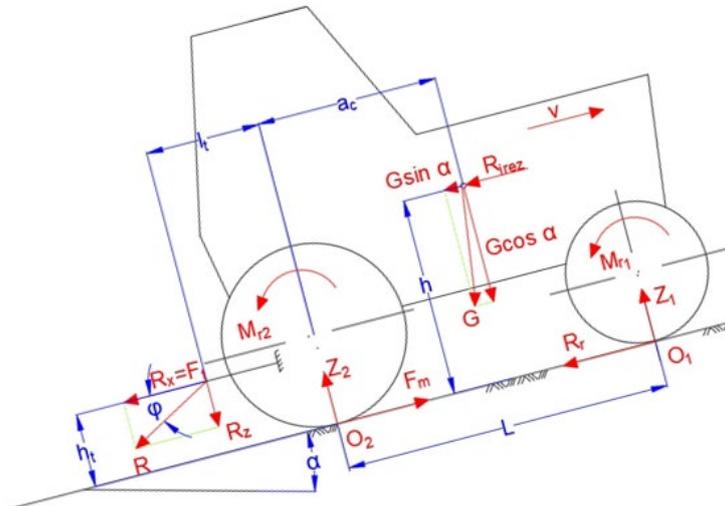


Fig. 1. Forces acting on a 4x2 tractor coupled with a trailed or semi-mounted implement [15]

In the case of the aggregate formed by a 4x2 tractor and a semi-mounted disc harrow (Fig. 2), the reactions Z_1 și Z_2 are determined based on the equilibrium equations of the tractor under the action of external forces, using the following relations [15]:

reactions on the tractor's two axles and the total load are calculated using the following relations:

$$Z_1 = \frac{G \cdot a_c}{L} - \frac{G_d \cdot l_m + F_z \cdot l_r - F_x \cdot h_r}{L} \quad (8)$$

$$Z_2 = \frac{G \cdot (L - a_c)}{L} + \frac{G_d \cdot (L + l_m) + F_z \cdot (L + l_r) - F_x \cdot h_r}{L} \quad (9)$$

$$Z_t = Z_1 + Z_2 = G + G_d + F_z \quad (10)$$

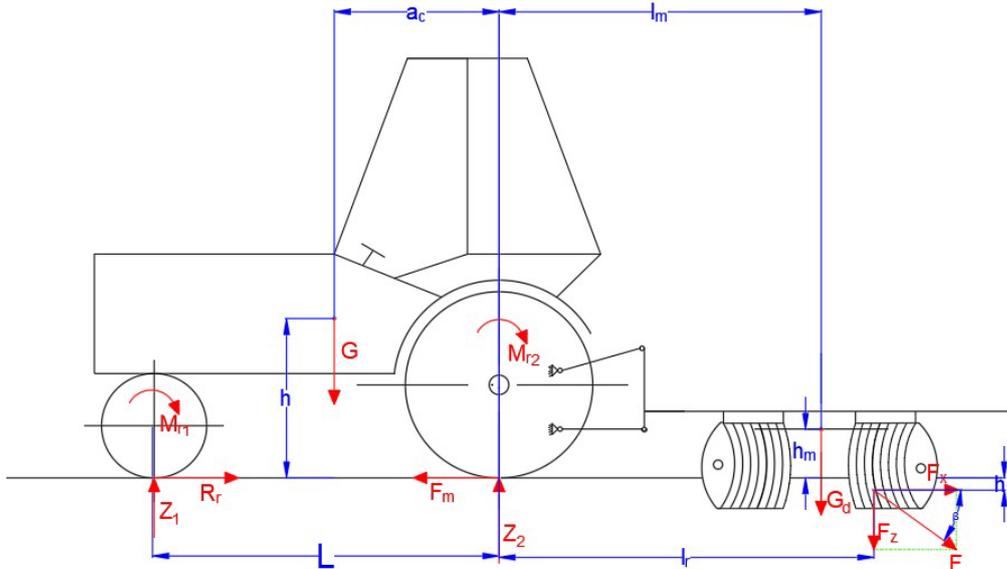


Fig. 3. Forces acting on a 4x2 tractor coupled with a fully-mounted disc harrow during operation

3. Calculation of the draft force of the U-650 tractor

The traction balance equation of a tractor operating in combination with an agricultural implement on level ground is [16]:

$$F_t = F_m - R_r \quad (11)$$

where F_m - represents the driving force (the tangential draft force), R_r - rolling resistant force, and F_t -draft force.

For any driving wheel operating on different soil types, the maximum tractive force and the maximum wheel efficiency are developed under specific vertical loads. The parameter that most accurately characterizes the slippage of tractor wheels is the specific driving force (φ_m) which represents the coefficient of utilization of the adhesive weight. It is defined as the ratio between the driving force F_m of the drive wheel (or drive axle) and the vertical reaction Z_m on the drive wheel (or axle):

$$\varphi_m = \frac{F_m}{Z_m} \quad (12)$$

For a firm plowed soil surface on which the tractor operates in combination with the disc harrow, the coefficient of utilization of the adhesive weight is $\varphi_m=0.4\div 0.6$. Therefore, the expression of the driving force as a function of the vertical load on the drive axle is:

$$F_m = \varphi_m \cdot Z_m \quad (13)$$

The rolling resistance force of the agricultural tractor is calculated using the following relation:

$$R_r = f \cdot (Z_1 + Z_2) \quad (14)$$

where: f - represents the rolling resistance coefficient of the tractor ($f=0.12-0.14$ - for a flat ploughed terrain), Z_1 and Z_2 - represents the reactions at the two axles (front and rear).

The reactions Z_1 and Z_2 are dependent on the tractor weight G , the weight of the disc harrow G_d , the coordinates of the tractor and disc harrow centers of gravity, the tractor wheelbase, and the draft force F_t , as shown in equations (5), (6), (8) and (9).

The slippage of the drive wheels depends on the magnitude of the draft force F_t , the load on the driving wheel Z_m , the type and condition of the ground surface, the shape and size of the tires. Figure 4 presents the slip characteristic of the U-650 tractor on the tilled soil, for which a regression equation was also derived by a second-degree interpolation function that expresses the relationship between tractive force and wheel slip. For optimal operation of the tractor–implement system, it is recommended that the wheel slip remain within the range of 10–20% [17]. Therefore, as shown in Fig. 4, or the U-650 tractor operating on tilled soil, the recommended tractive force values are in the range of 8.3-10.6 kN.

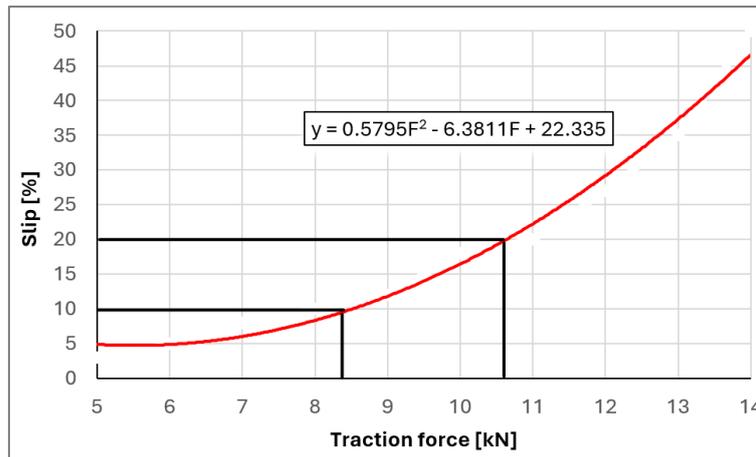


Fig. 4. Slip characteristic of the U-650 tractor on tilled soil [17]

In order to move the agricultural implement (in this case, the semi-mounted disc harrow), the tractor's tractive force must be greater than the resistance force

generated during the harrow's operation, which can be calculated using the following relation [15,16]:

$$R = K_s \cdot B_l \quad (15)$$

where: K_s - represents the specific resistance per unit working width during soil tillage using a disc harrow, (N/m); B_l - the working width of the disc harrow, (m). For smooth disc harrows, the specific resistance K_s typically ranges between 2÷3.25 kN/m [16]. In the case of fully-mounted disc harrows, the specific resistance K_s is 15–20% lower compared to that of trailed or semi-mounted implements [16].

4. Results and discussion

Given the importance of the specific resistance per unit working width in soil tillage using a semi-mounted disc harrow, and the fact that this resistance decreases by 20 % in the case of a fully-mounted harrow, Figure 5 presents a comparative view of the variation curves of the resistance force R , for the two disc harrow coupling configurations (semi-mounted – blue curve, and fully-mounted – orange curve), as a function of K_s .

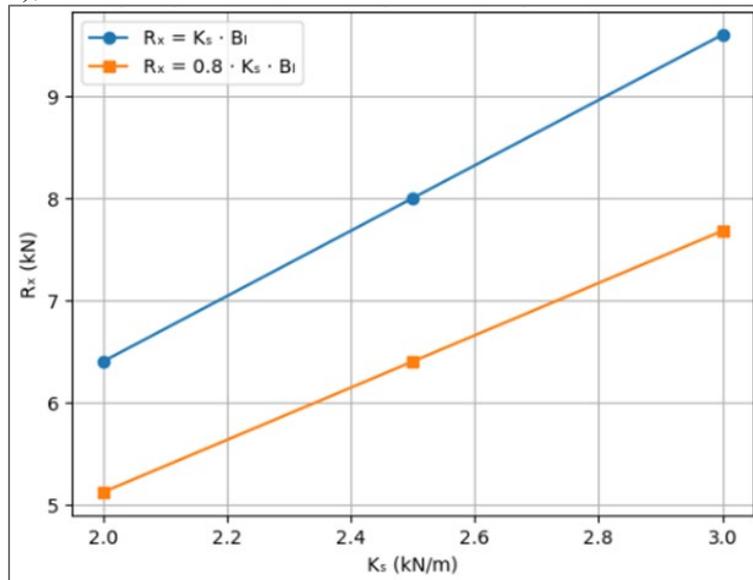


Fig. 5. Variation of the resistance force R as a function of K_s

Based on relations (5), (6), (8) and (9) a Python script was developed to calculate the normal reactions on the two axles of the U-650 tractor for the two coupling configurations of the disc harrow: semi-mounted (Z_{11} and Z_{12}), and fully-mounted (Z_{21} și Z_{22}). Figures 6 and 7 show the graphical variation of these reactions as a function of the specific resistance per unit working width K_s during soil tillage using the disc harrow.

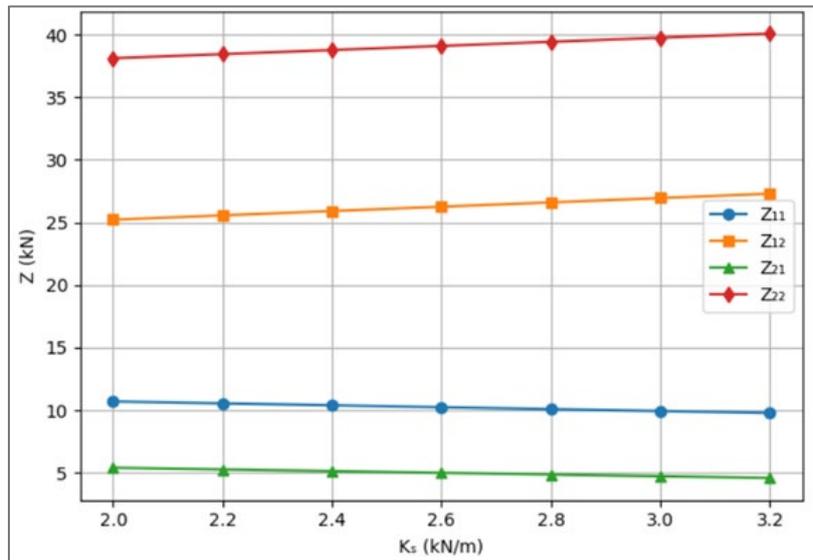


Fig. 6. Variation of the normal reactions on the two axles of the U-650 tractor as a function of K_s

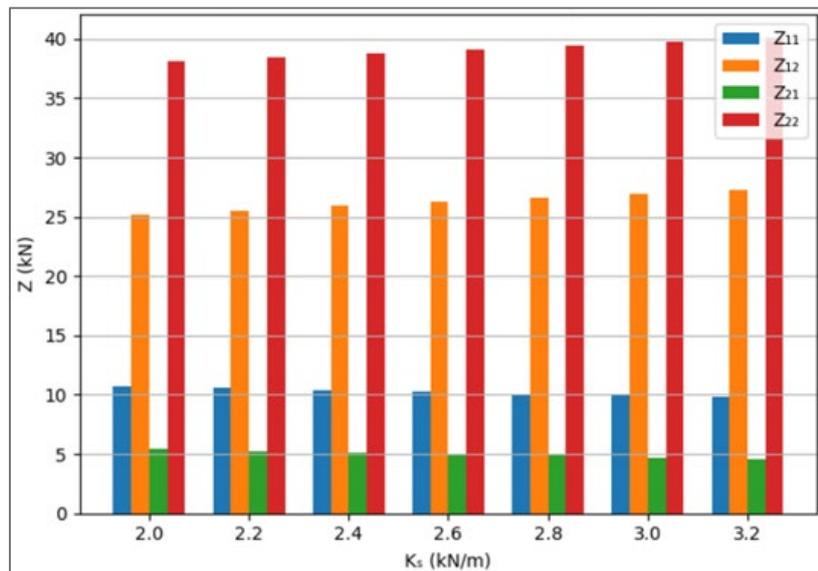


Fig. 7. Variation of the normal reactions on the axles of the U-650 tractor as a function of K_s

Taking into account the coefficient of utilization of the adhesive weight, which is calculated based on the vertical reaction on the drive axle according to relation (12), the driving force F_m was calculated using relation (13) for the U-650 tractor operating in combination with a semi-mounted and fully-mounted disc harrow on a firm plowed surface. The calculation results obtained using a Python script, along with the corresponding variation graphs, are presented in Figure 8.

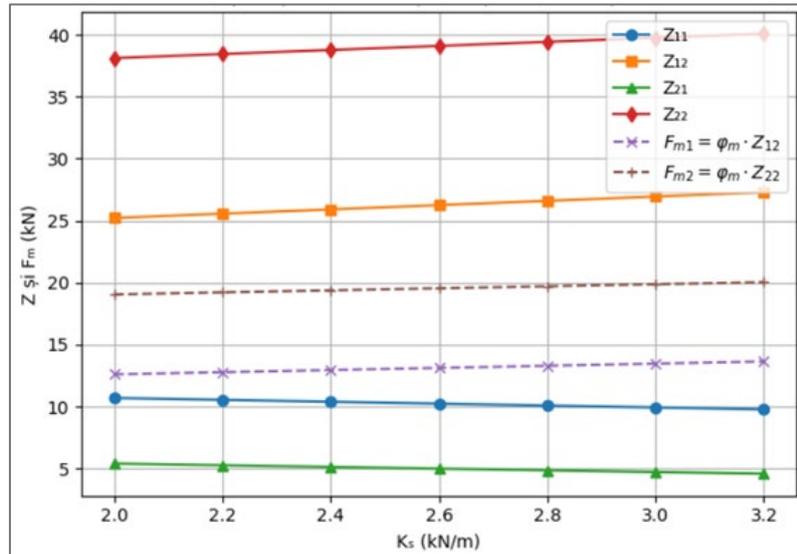


Fig. 8. Variation of the normal reactions and the driving force of the U-650 tractor as a function of K_s

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import matplotlib.pyplot as plt
import numpy as np
# Parametri constanti
G = 34 # kN
G_d = 7.6 # kN
L = 2.5 # m
B_l = 3.2 # m
a_c = 0.9 # m
l_t = 1.0 # m
l_r = 2.0 # m
l_m = 1.8 # m
h_t = 0.3 # m
h_r = 0.07 # m
fi_m = 0.5 # coeficient pentru F_m1 și F_m2
f = 0.13 # coeficient pentru R_r1 și R_r2
# Valorile lui K_s între 2 și 3.2 cu increment de 0.2
Ks = np.arange(2, 3.21, 0.2)
# Calculul funcțiilor Z
Z11 = (G * a_c - Ks * B_l * h_t - 0.3 * Ks * B_l * l_t) / L
Z12 = (G * (L - a_c) + Ks * B_l * h_t + 0.3 * Ks * B_l * (L + l_t)) / L
Z21 = (G * a_c - G_d * l_m - 0.3 * Ks * B_l * l_r + Ks * B_l * h_r) / L
Z22 = (G * (L - a_c) + G_d * (L + l_m) + 0.3 * Ks * B_l * (L + l_r) - Ks * B_l * h_r) / L
# Calcul F_m1 și F_m2
F_m1 = fi_m * Z12
F_m2 = fi_m * Z22
# Calcul R_r1 și R_r2
R_r1 = f * (Z11 + Z12)
R_r2 = f * (Z21 + Z22)
# Calcul F_t1 și F_t2
F_t1 = F_m1 - R_r1
F_t2 = F_m2 - R_r2
# Trasarea graficului comparativ
plt.plot(Ks, F_t1, marker='o', linestyle='-', label=r'$F_{t1} = F_{m1} - R_{r1}$')
plt.plot(Ks, F_t2, marker='s', linestyle='-', label=r'$F_{t2} = F_{m2} - R_{r2}$')
plt.xlabel('K, (kN/m)')
plt.ylabel('F_t (kN)')
plt.title('Comparație între funcțiile $F_{t1}$ și $F_{t2}$ în funcție de $K_s$')
plt.grid(True)
plt.legend()
plt.tight_layout()
plt.show()

```

Fig. 9. Python code for calculating the variation of the traction force of the U-650 tractor as a function of K_s for the two disc harrow coupling configurations (semi-mounted F_{t1} and fully-mounted F_{t2})

To calculate the traction force of the U-650 tractor in combination with a semi-mounted and a trailed disc harrow, depending on soil conditions and the cross-sectional area of the soil furrow processed in a single pass, as well as to generate a comparative graphical representation, a Python script was developed, as shown in Figure 9, and the graphical results are illustrated in Figure 10.

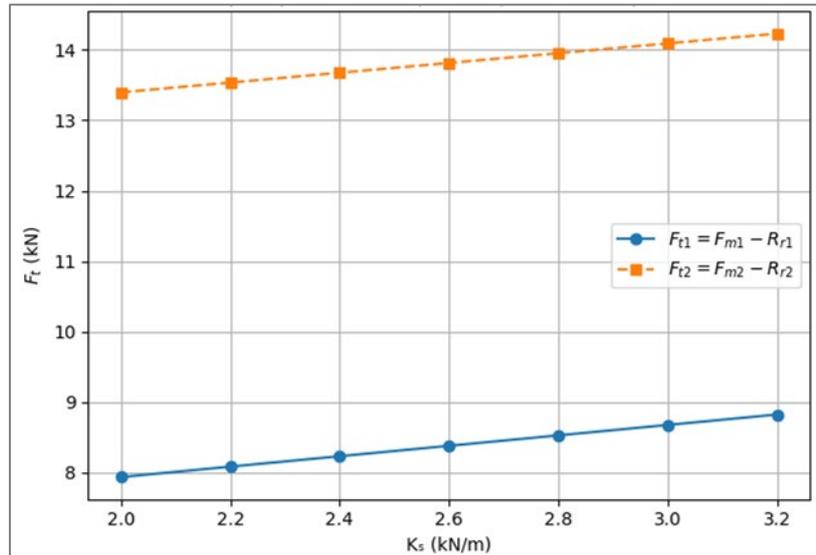


Fig. 10. Variation of the traction force of the U-650 tractor as a function of K_s for the two disc harrow coupling configurations (semi-mounted F_{t1} and fully-mounted F_{t2})

As can be seen in Figure 10, under the same working conditions, the draft force of the U-650 tractor increases significantly when the disc harrow is fully-suspended, due to the higher vertical reaction on the drive axle compared to the semi-suspended configuration, which also results in a considerable increase in the driving force. As shown in Figure 10, the draft force increases by approximately 25–35%.

5. Conclusions

Based on the dynamics of the technical system composed of a rear-wheel-drive tractor and two different types of disc harrows, one semi-mounted and one fully-mounted, a study can be developed to determine the axle reactions on the tractor for both coupling configurations. The mathematical models developed in this article are particularly important, as they allow for the theoretical estimation and improvement of the traction performance of a 4x2-type tractor when used in combination with a disc harrow in either a semi-mounted or fully-mounted configuration. These models enable the evaluation of the driving force, the specific

driving force, the coefficient of utilization of the adhesive weight, the rolling resistance force of the agricultural tractor, and the overall draft force.

In order to ensure the operation of the disc harrow during fieldwork, the tractor's traction force must exceed the resistance force generated by the harrow, which depends on the specific resistance per unit working width and the working width of the disc harrow. For smooth disc harrows coupled to the tractor in a semi-mounted configuration, the specific resistance per unit working width has values in the range of $K_s=2\div 3.25$ kN/m, and in the case of fully-mounted disc harrows, the specific resistance is 15–20% lower compared to that of trailed or semi-mounted implements. Since the vertical load on the drive axle of the tractor increases when the disc harrow is coupled in the fully-mounted configuration, the driving force also increases, leading to a rise in the tractor's draft force by approximately 25–35%, and consequently to a reduction in fuel consumption required for soil tillage under the same working conditions.

REFERENCES

- [1] P. Balsari, A. Biglia, L. Comba, D. Sacco, L. Eloi Alcatrão, M. Varani, M. Mattetti, P. Barge, C. Tortia, M. Manzone, P. Gay, D. Ricauda Aimonino, Performance analysis of a tractor - power harrow system under different working conditions, *Biosystems Engineering*, Vol. **202**, Pages 28-41, 2021, ISSN 1537-5110, <https://doi.org/10.1016/j.biosystemseng.2020.11.009>.
- [2] P. Lonkwic, I. Usydus, A. Tofil, T. Krakowski, H. Ruta, D. Pieniak, Case Study on Numerical Calculation of a Disc Bush in the Disc Harrow in the Welding Version, *Mechanika*. Vol. **27**, Iss. 6, Pages 513-520, 2021, DOI:10.5755/j02.mech.28233.
- [3] P.P. Nalavade, V.M. Salokhe, T. Niyamapa, P. Soni, Application of Powered Disc Implements for Efficient on-Farm Residue Management: A Review, *International Agricultural Engineering Journal*. Vol. **20**, Iss. 3, Pages 1-8, 2011.
- [4] G. Upadhyay, H. Raheman, Comparative assessment of energy requirement and tillage effectiveness of combined (active-passive) and conventional offset disc harrows, *Biosystems Engineering*, Vol. **198**, Pages 266-279, 2020, ISSN 1537-5110, <https://doi.org/10.1016/j.biosystemseng.2020.08.014>.
- [5] I. Ahmadi, A power estimator for an integrated active-passive tillage machine using the laws of classical mechanics, *Soil and Tillage Research*, Vol. **171**, Pages 1-8, 2017, ISSN 0167-1987, <https://doi.org/10.1016/j.still.2017.04.006>.
- [6] M. Rashidi, H. F. Lehmal, M.S. Beni, M. Malekshahi, S. Tabrizi Namin, Prediction of Disc Harrow Draft Force Based on Soil Moisture Content, Tillage Depth and Forward Speed, *Middle-East Journal of Scientific Research*, Vol. **15**, Iss. 2, Pages 260-265, 2013, ISSN 1990-9233, DOI: 10.5829/idosi.mejsr.2013.15.2.11674.
- [7] P. Okoko, E.A. Ajav, W.A. Olosunde, Draft and power requirements for some tillage implements operating in clay loam soil, *Agricultural Engineering International: CIGR Journal*, Vol. **20**, No. 1, Pages 95-102, 2018.
- [8] K. Acquah, Y. Chen, Soil Compaction from Wheel Traffic under Three Tillage Systems, *Agriculture*, Vol. **12**, No. 2, Iss. 219, 2022, <https://doi.org/10.3390/agriculture12020219>

- [9] *V.L. Astafyev, A.A. Kurach, M.A. Amantayev*, The influence of scheme and tillage tool parameters on the material consumption and performance of chain tooth harrow, *Journal of Water and Land Development*, No. 50 (VI-IX), Pages 69-73, 2021, DOI: 10.24425/jwld.2021.138162.
- [10] *M. Trevini, G. Tosti, P. Benincasa*, Agronomic performance of disc chain harrow as a conservation agriculture tool for a one-step cover crop termination and seedbed preparation, *Experimental Agriculture*, Vol. 60, Pages 1-11, 2024, DOI: 10.1017/S001447972400005X.
- [11] *O. Kozachenko, E. Aliiev, K. Sedykh*, Results of investigation of the spring shank disc harrow performance, *U.P.B. Sci. Bull., Series D*, Vol. 83, Iss. 4, 2021, ISSN 1454-2358.
- [12] *A. Shutkin, A. Ishkov, P. Shmykova, M. Kalimullin, A. Aksenov, R. Sakhapov, A. Yakushev*, Study of the wear resistance of hardened harrows of agricultural machines, *E3S Web of Conferences, GEOTECH-2024*, Vol. 525, No. 03018, 2024, <https://doi.org/10.1051/e3sconf/202452503018>.
- [13] *A. Kumar, A.K. Shrivastava, Y. Nandini, R. Namdeo*, Performance evaluation of trailed type disc harrow on vertisols field condition, *International Journal of Statistics and Applied Mathematics*, SP-8(6): 329-333, 2023, ISSN: 2456-1452.
- [14] *A.E. Slepnev, E.S. Polikutina, S.V. Shchitov, E.E. Kuznetsov, Z.F. Krivutsa*, Increasing the efficiency of use of wheeled harrow units in regions of risk farming, *E3S Web of Conferences, ITEEA 2021*, Vol. 262, No. 01003, 2021, <https://doi.org/10.1051/e3sconf/202126201003>.
- [15] *A. Șandru, S. Popescu, I. Cristea, V. Neculăiasa*, *Exploatarea utilajelor agricole (Operation of agricultural machinery)*, Editura Didactică și Pedagogică, București, 1983.
- [16] *S. Năstăsoiu, C. Andreescu, S. Popescu, Gh. Frățilă, D. Cristea*, *Tractoare și automobile (Tractors and automobiles)*, Editura Didactică și Pedagogică, București, 1983.
- [17] *N. Tecușan, E. Ionescu*, *Tractoare și automobile (Tractors and automobiles)*, Editura Didactică și Pedagogică, București, 1982.
- [18] *V. Scripnic, P. Babiciu*, *Mașini agricole (Agricultural machinery)*, Editura Ceres, București, 1979.