ANALYSIS OF THE DEPENDENCE OF TRACTION RESISTANCE FORCE ON FORWARD SPEED FOR TRACTOR-CULTIVATOR AGGREGATES

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ANALIZA DEPENDENȚEI FORȚEI DE REZISTENȚĂ LA TRACȚIUNE DE VITEZA DE AVANS PENTRU AGREGATELE TRACTOR-CULTIVATOR

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ABSTRACT

The article presents results generated by research on the influence of forward speed on the traction resistance force for soil processing machines. Statistical estimators are proposed to highlight the intensity of the connection between the traction resistance force and the forward speed and an optimal evaluation method of an exponent of the work speed to explain as well as possible the behaviour of the traction resistance force. It is found that the variance and the standard deviation are the statistical estimators that highlight the most intensively the connection between the traction resistance force and the forward speed.

REZUMAT

Articolul prezintă rezultatele obținute în urma cercetărilor privind influența vitezei de înaintare asupra forței de rezistență la tracțiune pentru mașinile de prelucrat solul. Se propun estimatori statistici pentru a evidenția intensitatea legăturii dintre forța de rezistență la tracțiune și viteza de înaintare şi o metodă optimă de evaluare a unui exponent al vitezei de lucru pentru a explica cât mai bine comportamentul forței de rezistență la tracțiune. Se constată că varianța și abaterea standard sunt estimatorii statistici care evidențiază cel mai intens legătura dintre forța de rezistență la tracțiune și viteza de înaintare.

1. INTRODUCTION

In the last decades, numerous kinds of research in the field of working processes of agricultural machines intended for work have been methodically directed in the last decades towards experimental or theoretical-empirical research (*Moeenifar et al., 2014; Ranjbar et al., 2013; Naderloo et al., 2009; Singh et al., 2018; Al-Shamiry et al., 2020; Elsheikha et al., 2021; Kushwaka et al., 1996; Al-Suhaibani et al., 2010*). The classical literature until then was dominated by theoretical calculation supplemented by experiments for the calculation of model constants and validation *(Cârdei et al., 2023; Krasnicenko et al., 1964; McKyes E., 1985; Sandru et al., 1982; Sandru et al., 1983; Scripnic et al., 1979; Tecusan & Ionescu, 1982; Toma et al., 1978).*

However, there have been attempts at statistical modelling since the middle of the 20th century, *(Harrison & Reed, 1962)*. In particular, the experimental search for the dependence of the tillage draft force on the speed of advance of agricultural aggregates intended for soil processing began a few decades ago. Until then, the estimates of the traction force contained the contribution of the forward speed to the traction resistance force in simpler or more complicated analytical formulas, *(Cârdei et al., 2023; Damanauskas & Janulevicis, 2022; Cardei et al., 2020; Cardei et al., 2019; Krasnicenko et al., 1964; McKyes E., 1985; Sandru et al., 1982; Sandru et al., 1983; Scripnic et al., 1979; Tecusan & Ionescu, 1982; Toma et al., 1978),* purely theoretical or theoretical-empirical, (*American Society of Agricultural Engineers, 2023; Moeenifar et al., 2014)*, sometimes with complex theoretical relationships including the geometry of the machine and working parts, *(Al-Neama & Hertzilius, 2017)*.

The theoretical or theoretical-empirical formulas contain a number of "constants" or "coefficients", which also vary primarily with the parameters neglected in the model (soil moisture, soil cohesion and adhesion, the temperature in the soil layer in which work is being done, type of processed soil, etc.), but also with parameters contained in the model, but unknown variations. The experimental estimates of these "constants" or "coefficients" are few, and then engineering intuition is used in the design calculations. Although appreciable, this intuition also has its limits, especially in the context where experiments are increasingly limited in terms of time and activities. On the other hand, all theoretical formulas must be validated experimentally.

Therefore, the theoretical formulas are doubly conditioned by the experiment by finding the "constants" of the model and by validating them.

In the conditions in which the experimental research took a large scale, statistics was more and more involved in the process of extracting the essences from the experimental data, the authors emphasize, *Da Silva et al., (2020)* or *Gomez & Gomez, (1976)*, referring to modern agriculture. Intending to rationalize fuel consumption, *Mamkagh A.M., (2018)* reviews the main influencing factors: forward speed, tractor weight, and tire pressure. Finally, *Sadek et al., (2021),* determine a linear regression equation based on experimental data, in which, in addition to the forward speed, the gang angle, the inclination angle, the working depth and the disk diameter also appear. *Ahmed & Al-Sayed, (2022),* give results regarding the influence of working speed and soil type on the performance of the Massey Ferguson tractor (model 290). Statistical modelling has become a frequently used tool for formulating some predictions of tensile strength, having speed and working depth as predictors as well as others *(Afify et al., 2020; Kim et al., 2020; Rashidi et al., 2013; Rashidi et al., 2013; Saleh et al., 2021)*. Artificial neural networks began to be used in the last decade to predict physical quantities of interest in the field of agricultural soil processing *(Shafei et al., 2018; Çarman et al., 2021; El Wahed & Aboukarima, 2007; Al-Dosary et al., 2020; Çarman et al., 2019; Askari & Abbaspour-Gilandeh, 2020)*. Non-linear regression formulas for the problem of predicting the tensile strength are given or used, in the case of a disk plough *(Almaliki et al., 2019; Shafaei et al., 2018)*.

The relationship between tillage draft force and the forward speed has been investigated by many researchers, *(Moeenifar et al., 2014; Ranjbar et al., 2013; Naderloo et al., 2009; Singh et al., 2017; Al-Shamiry et al., 2020; Damanauskas & Janulevicis, 2022; Cardei et al., 2020; Cardei et al., 2019; Elsheikha et al., 2021; Kushwaka & Linke, 1996; Gatea A.A., 2013; Oprescu et al., 2021; Odero A.J., 2019; Salahloo et al., 2021; Afify et al., 2020; Kim et al., 2020; Rashidi et al., 2013; Rashidi et al., 2013; Saleh et al., 2021; Al-Neama & Hertzilius, 2017; Okoko & Ajav, 2020; Askari et al., 2017)* for example. Some of the authors note the efficiency with which the variance of the traction resistance force highlights the influence of the forward speed *(Naderloo et al., 2009)*. In general, in low working speed ranges, all authors agree that the traction resistance force increases with increasing feed speed. However, the statistical analysis of linear regression also leads to inverse dependencies between the traction resistance force and the forward speed *(Abbaspour-Gilandeh et al., 2020)*.

The problem of the dependence of the tillage draft force on the forward speed has been raised for a very long time. It was hoped that optimal values of the working speed would be found that would minimize the traction resistance force. The implications are very important: the reduction of energy consumption, the emission of polluting gases, and the possible increase in productivity. Even if theoretically and experimentally, the existence of these optimal points was not demonstrated, optimal points were obtained by putting additional conditions, among which, for example, the achievement of a desired productivity *(Cardei et al., 2019)*. Experimentally, it has been observed that the optimal values determined in this way, or critical values of the advance speed, are impossible to reach by the aggregates used or, if they can be reached, they negatively affect the quality of the work performed (it is lost from the programmed working depth, or there is inappropriate granulation, for example) *(Cardei et al., 2019; Kushwaka & Linke, 1996)*.

In some cases, reaching high forward speed values negatively affects the resistance structures of the agricultural machine *(Cardei et al., 2012)*. The attempt of *Zhang & Kushwaha, (1999),* to investigate the influence of the forward speed on the wave propagation length in front of the working body is interesting. The influence of the forward speed on the traction power transfer indices for agricultural tractors, to make energy consumption more efficient during soil processing and cultivation, was studied by the authors *Md-Tahir et al., (2021)*. An important study mainly addresses the influence of humidity together with that of the advanced speed on soil processing *(Okyere et al., 2018)*. Few works address the subject of the quality of soil processing works in relation to the speed of agricultural machinery *(Latypov & Kalimullin, 2020; Wang et al., 2021)*.

In the framework of the above research, those carried out by the authors of this article in the last five-six years are included. The obtained results are partially described in a series of works of which this article is the last *(Cârdei et al., 2023a; Cârdei et al., 2023b; Cârdei et al., 2021a; Cârdei et al., 2021b)*. The MCLS complex cultivator was conceived and designed to carry out a large number of research activities: the investigation of the parameters of the work regime on the output parameters of the system, those that give the quality of the work (from an agrotechnical and economic point of view); investigating the behaviour of different types of working bodies (it is possible to mount at least 8-10 types of working bodies on the structure); the research of soil processing in three variants of working width, being able to use traction capacities with different powers (the structure is modulated and can work in three variants, see fig. 1). Initially, a large experimental plan was designed. Later it was found that the designed experimental plan was much oversized for our capacities and financing possibilities. For this reason, many aspects remain to be researched with the structure itself, but also relative to the extremely diverse and complex problem of soil processing with agricultural machines intended for soil works that can be carried out with MCLS (complex machine for soil works).

2. MATERIALS AND METHODS

The subject of the research whose results are described in this article consists of the experimental recordings made with the MCLS complex tractor-cultivator aggregate, the version with a working width of 1m. One of the seven experiments has already been analysed in some works (*Cârdei et al., 2023a; Cârdei et al., 2023)*. The experiments carried out with the 1 m working width variant of the MCLS complex cultivator were described in *Cârdei et al., (2023)* and in more detail in *Cârdei et al., (2023)*. Digital recordings were made for each of the seven experiments. In fig. 1-4 the four basic configurations of MCLS can be seen: the folded form (for transport) and the working variants with widths of 4, 2 and 1 m, in fig. 2, 3 and 4.

Fig. 1 – Tractor unit 80 HP - MCLS, in the folded state

Fig. 2 – Variant with 4 m working width of MCLS with 80 HP tractor

Fig. 3 – The 2 m working width version of the MCLS with an 80 HP tractor

Fig. 1 - The 2 m working width version of the MCLS with a 45 HP tractor

Additional details about how the experiments were carried out can be found in *Cârdei et al., (2023a)* and *Cârdei et al., (2023b)*.

The recording of each experiment consisted of a file containing a matrix with variable dimensions from experiment to experiment: a variable number of rows and a fixed number of 13 columns. The first column corresponds to the time recording (equidistant steps in time, corresponding to the recording frequency of 100 Hz). The next twelve columns correspond to the recording of the signals from the deformation sensors mounted on each of the twelve supports of the working parts of the cultivator. As a result, the file (data structure) of an experiment will be symbolized with:

$$A_{j,k}^{i}, i = 1, \dots, 7, j = 1, \dots, n_i, k = 1, \dots, 13 \tag{1}$$

where the upper index $i = 1, \dots, 7$ corresponds to the experiment, in the order in which the seven experiments are listed in table 1 by their codes, $j = 1, \dots, n_i$ is the index of the rows of the data matrix and varies from 1 to n_i, the number of rows corresponding to the selection of the stable work sequence from each experiment, and k is the column index, for 1 the column of times is indicated, and from 2 to 13, are the columns that contain the records corresponding to the twelve supports of the working parts.

The forward speed is denoted by v, which is a vector with seven components, representing each forward speed considered constant in the respective experiment, on the stable work portion:

$$v_i, i = 1, \dots, 7. \tag{2}$$

With these notations, the vector of average values of the tillage draft force on the working body will be given by the formula:

$$F_i = \frac{\sum_{j=1}^{n_i} \sum_{k=2}^{13} A_{j,k}^{i}}{12 n_i}, i = 1, \dots, 7. \tag{3}$$

For the values of the average resistance forces on the entire cultivator, it is proposed to multiply the average force per working body, (3), by the number of parts of the structure (neglecting the friction of the working depth adjustment wheels with the soil):

$$R_i = 12F_i, i = 1, \dots, 7. \tag{4}$$

The study of the dependence of the deformation resistance forces on the forward speed includes the RMS (root mean square) calculation. The calculation formula is the following:

$$RMS_i = \sqrt{\frac{\sum_{j=1}^{n_i}\sum_{k=2}^{13}\left(A_{j,k}^i\right)^2}{12n_i}}, i = 1, \dots, 7. \tag{5}$$

The next stage of the study of the dependence of tillage traction forces on forward speed will use the variance of the data, that is, the RMS calculated with the recorded force values from which the average value per cultivator is subtracted, (3).

$$Var_i = \sqrt{\frac{\sum_{j=1}^{n_i}\sum_{k=2}^{13}\left(A_{j,k}^i - F_i\right)^2}{12n_i}}, i = 1, \dots, 7. \tag{6}$$

In the third stage of investigating the influence of the forward speed on the tensile strength exerted by the cultivator, records of equal size will be selected from the records (1) corresponding to the seven experiments. Obviously, for each of the seven selections that have been worked on so far, the number of lines will be reduced to the number corresponding to the smallest selection. The equalization of the dimensions of the records entered into the calculation is done to be able to calculate the correlations between the data of the seven experiments (records) and to estimate the influence of the speed of advance on the value of the correlation coefficients. In this way, the necessary tools for regression analysis are also prepared.

3. RESULTS

The results presented below include descriptive statistical estimators of the experimental data described in “Material and Methods”, obtained on the version of the initial selection of the stable sequence corresponding to each experiment and on the version of data files limited to the condition of the same recording length. For the last version, the correlations between the data files are also given, relative to all the twelve recording channels corresponding to all the supports of the working bodies of the MCLS with the working width version of 1 m. Results of inferential statistical analysis such as regression analysis to find the relationship between tensile strength and work speed are also presented in this chapter. Results are also given regarding the study of quartiles and experimental points designated as outliers, all investigated for a possible connection with the speed of advance. A final result presented is a method to establish a variant of determining the optimal exponent for the forward speed in the representation of the variance of the traction resistance force.

3.1. The average values of traction forces per working part, per experience

The statistical estimators defined in “Material and Methods” are calculated for the seven selections from field recordings. They contain electrical signals that are converted into strain values and which, in turn, are converted into stress values, accepting the hypothesis that the material of the supports behaves linearly elastic throughout the experiments.

The experiences are ordered in ascending order according to the forward speeds that characterize them as in Tables 1 and 2. The selected sequences were extracted from the total recordings based on the identification of a stable operating regime (no big shocks, or intense oscillations).

Table 1

The dimensions of the matrices that store the maximum data sequences selected from the total records

Experiment code	Rows	Cols	Forward speed, m/s
T2_R2_1500rpmtxt	4001	13	0.781
T1_R2_2400rpmtxt	4001	13	0.789
T1_R3_1500rpmtxt	2501	13	1.095
T2_R2_2700rpmtxt	1501	13	1.613

Experiment code	Rows	Cols	Forward speed, m/s
T2_R3_1500rpmtxt	2501	13	1.613
T3_R2_1500rpmtxt	2201	13	2.158
T2_R3_2000rpmtxt	1701	13	2.256

Some of the statistical estimators exposed in “Material and Methods” are listed in Table 2: the average value of the traction resistance force per working part, the average total tillage draft force corresponding to the entire cultivator, the average value of the RMS per working part, and the average variance on the working body. The last column of Table 2 identifies the experiment by its code. It must be specified that, in this article, when it is written forward speed, average resistance force on the working part or the entire cultivator, or RMS, it is meant the vectors containing the values of these quantities for each of the seven experiments.

It is found that, in this case, the RMS does not reflect new aspects compared to the average value. The Pearson correlation coefficient between the average tillage draft force on the working part and the RMS has a very high value, 0.954. The Pearson correlation coefficient between the average tillage draft force on the working body and the forward speed has an important but negative value, -0.684. The Pearson correlation coefficient between forward speed and RMS has a negative value, of -0.467.

Table 2

The average values of the tillage draft force per working body and cultivator, for the version with a working width of 1 m, working at a working depth of 10 cm. Entire selections of data files have been processed

The tillage draft force on the working body, N	Total tillage draft force, N	Average RMS per working body, N	The variance of tillage draft forces, N	experiment code
478.413	5740.954	509.552	175.398	T2_R2_1500rpmtxt
518.448	6221.375	541.368	155.857	T1_R2_2400rpmtxt
491.532	5898.387	518.961	166.483	T1_R3_1500rpmtxt
508.530	6102.357	544.803	195.469	T2_R2_2700rpmtxt
495.540	5946.479	526.732	178.569	T2_R3_1500rpmtxt
448.719	5384.632	500.626	221.985	T3_R2_1500rpmtxt
452.695	5432.344	500.985	214.600	T2_R3_2000rpmtxt

The Pearson correlation coefficient between the average value of the tillage draft force per working body and the variance has a large negative value, -0.801. A particularly important value is the Pearson correlation coefficient between forward speed and variance, 0.92.

3.2. Results obtained on data sequences of equal sizes

To facilitate the calculation of the correlation between the records corresponding to the seven experiments, the data files are all cut at a number of rows equal to that of the minimum length record. Results similar to those in Table 2, for data files of equal size, are given in Table 3. Between the results included in Tables 2 and 3, the differences are small, compared to the average values.

Table 3

The average values of the tillage draft force per working body and cultivator, for the version with a working width of 1 m, working at a working depth of 10 cm, for records of equal dimensions

The tillage draft force on the working body, N	Total tillage draft force, N	Average RMS per working body, N	The variance of tillage draft forces, N	Experiment cod
489.587	5875.039	518.864	171.828	T2_R2_1500rpmtxt
513.947	6167.359	536.168	152.758	T1_R2_2400rpmtxt
482.382	5788.590	508.670	161.407	T1_R3_1500rpmtxt
508.530	6102.357	544.803	195.469	T2_R2_2700rpmtxt
491.364	5896.373	520.502	171.708	T2_R3_1500rpmtxt
434.721	5216.651	488.809	223.500	T3_R2_1500rpmtxt
454.788	5457.452	501.457	211.253	T2_R3_2000rpmtxt

The Pearson correlation coefficients between the data matrices (except the time column), in the version with equal dimensions, are given in Table 4. It is found that the maximum value of the Pearson correlation coefficient (except the correlations of the matrices with themselves) is 0.384, in the case experiments T2_R2_1500rpmtxt and T2_R3_1500rpmtxt, which correspond to working speeds of 0.781 m/s and 1.613 m/s. The value of the correlation coefficient between experiments T2_R2_2700rpmtxt and T2_R3_1500rpmtxt, 0.127, which is one-third of the maximum value in table 4, although the two experiments were carried out with equal work speeds, brings a new argument to the randomness of the work process of the cultivator. This finding confirms the statements made in (*Cârdei et al., 2023a)* and (*Cârdei et al., 2023b)*.

In the case of processing data from files of equal size, the Pearson correlation coefficient between the average traction resistance forces on the working body and the forward speed has a negative value, of -0.734. And in this case, the average tensile strength of the working body and the RMS is highly correlated (0.951). The Pearson correlation coefficient between the forward speed and RMS is negative, -0.542. The correlation between the average value per working part of the traction resistance force and RMS is high, but negative, which implies inverse dependence. The correlation coefficient of variance with RMS is high, 0.897.

Table 4

Pearson correlation coefficients between the experimental data of the seven experiments

	T2_R2_ 1500rpmtxt	**T1_R2_ 2400rpmtxt**	**T1_R3_ 1500rpmtxt**	**T2_R2_ 2700rpmtxt**	**T2_R3_ 1500rpmtxt**	**T3_R2_ 1500rpmtxt**	**T2_R3_ 2000rpmtxt**
T2_R2_1500rpmtxt	1.000	0.264	0.268	0.163	0.384	0.180	0.144
T1_R2_2400rpmtxt	0.264	1.000	0.23	0.123	0.274	0.151	0.038
T1_R3_1500rpmtxt	0.268	0.230	1.000	0.168	0.165	0.136	0.013
T2_R2_2700rpmtxt	0.163	0.123	0.168	1.000	0.127	0.096	0.115
T2_R3_1500rpmtxt	0.384	0.274	0.165	0.127	1.000	0.238	0.043
T3_R2_1500rpmtxt	0.180	0.151	0.136	0.096	0.238	1.000	0.015
T2_R3_2000rpmtxt	0.144	0.038	0.013	0.115	0.043	0.015	1.000

3.3. Regression analyses

For the case where the data files with the original dimensions are analysed (after separating the work sequences with a stable regime), the main results appear in Table 2. The importance of the forward speed parameter using regression approximation of the other parameters will be tested. The multilinear regression calculator, free online, (*www.statskingdom.com*) is used as a calculation tool. For additional explanations regarding the regression analysis, you can consult the literature (*Clocotici V.; Anghel et al., 2020)*.

For the dependence of the average tillage draft force on the working body on the forward speed, the regression is obtained:

$$F = 528.893602 - 29.925106v \tag{7}$$

with the coefficient of determination R^2 =0.468179, which shows that the work speed explains 46.8% of the variation of the average tillage draft force on the working part. The adjusted determination coefficient has a value of 0.361814, and the multiple correlation coefficient is 0.684236. The rejection probabilities of the regression coefficients (6) are, for the free term 0.00000258053 less than 0.05 and 0.08998, greater than 0.05. As a result, the linear regression (7) is weaker than the model that does not contain the independent variable v.

For the RMS dependence on the forward speed, the regression is obtained:

$$RMS = 540.895831 - 13.900419v \tag{8}$$

with the coefficient of determination R^2=0.217649, which shows that the work speed explains 21.88% of the RMS of the average tillage draft force on the working part. The adjusted determination coefficient has a value of 0.0611788, and the multiple correlation coefficient is 0.919695. The rejection probabilities of the regression coefficients (6) are, for the free term 0.00000089 less than 0.05 and 0.21294, greater than 0.05. As a result, the linear regression (8) is weaker than the model that does not contain the independent variable v.

For the dependence of the variance of the average tillage draft force on the tensile strength of the working body on the forward speed, the regression is obtained:

$$Var = 131.870213 + 37.386658v \tag{9}$$

with the coefficient of determination R^2=0.845839, which shows that the forward speed explains 84.58% of the variance of the average resistance force on the working part. In relation (8), by Var, it was noted the variance of the average traction resistance force on the working body. The adjusted determination coefficient has a value of 0.815007, and the multiple correlation coefficient is 0.919695.

The rejection probabilities of the regression coefficients (6) are, for the free term 0.00000793687 less than 0.05 and 0.00336019, also less than 0.05. As a result, the linear regression (9) is better than the model that does not contain the independent variable v.

For the case where data files with equal sizes are analysed (after reducing the work sequences with the stable regime to the number of rows of the smallest data file), the main results appear in Table 3. The tests are similar to those made for the results obtained in the case of the original data files, using the same processing tool (*www.statskingdom.com/410multi_linear_regression.html*).

For the dependence of the average tillage draft resistance force on the working body on the forward speed, the regression is obtained:

$$F = 532.730864 - 34.332562v \tag{10}$$

with the coefficient of determination R^2 =0.537891, which shows that the forward speed explains 53.8% of the variation of the average tillage draft force on the working body. The adjusted determination coefficient has a value of 0.445469, and the multiple correlation coefficient is 0.733411.

The rejection probabilities of the regression coefficients (6) are, for the free term 0.00000246185 less than 0.05 and 0.0606795, greater than 0.05. As a result, the linear regression (10) is weaker than the model that does not contain the independent variable v.

For the RMS dependence, the regression is obtained:

$$RMS = 542.572238 - 17.344266v \tag{11}$$

with the coefficient of determination R^2=0.294075, which shows that the forward speed explains 29.4% of the variance of the average tillage draft force on the working body. The adjusted determination coefficient has a value of 0.15289, and the multiple correlation coefficient is 0.542287. The rejection probabilities of the regression coefficients (6) are, for the free term 0.00000097 less than 0.05 and 0.208549, greater than 0.05.

As a result, the linear regression (11) is weaker than the model that does not contain the independent variable v.

For the dependence of the variance of the average tillage draft force on the working body on the work speed, the regression is obtained:

$$Var = 126.322016 + 39.172138v \tag{12}$$

with the coefficient of determination R^2=0.803943, which shows that the forward speed explains 80.39% of the variance of the average tillage draft force on the working body. The adjusted determination coefficient has a value of 0.764732, and the multiple correlation coefficient is 0.896629.

The rejection probabilities of the regression coefficients (11) are, for the free term 0.000246048 less than 0.05 and 0.00623692 also less than 0.05.

As a result, the linear regression (12) is better than the model that does not contain the independent variable v.

3.4. The intensity of the correlation between the variance of the tillage draft force and the forward speed

Starting from the relationship found between the variance of the average resistance force on the working body and the forward speed, the problem arises of the existence of an exponent of the working speed that maximizes the intensity of this relationship. By the optimal value of the speed exponent, it is understood the value of the power of the forward speed, which maximizes the coefficient of determination of the vectors of the forward speed (raised to the respective power) and the average resistance force on the working body. A regression study for values of the speed exponent between 1 and 4.5, performed both for the initial data and for the dimensionally equalized data, followed by an ordinary polynomial interpolation, leads to the curves in fig. 5. The curves in fig. 5 are the dependences of the determination coefficient R^2 to the forward speed exponent. You can graphically observe the existence of a maximum point of the coefficient of determination, both for the initial data and for those of equal size. In the case of the curve corresponding to the initial data (of different sizes), the coordinates of the optimal point are α_{opt}=2.368, R^2_{opt}=0.878, and in the case of data of equal sizes, α_{opt}=2.454, R^2_{opt}=0.839.

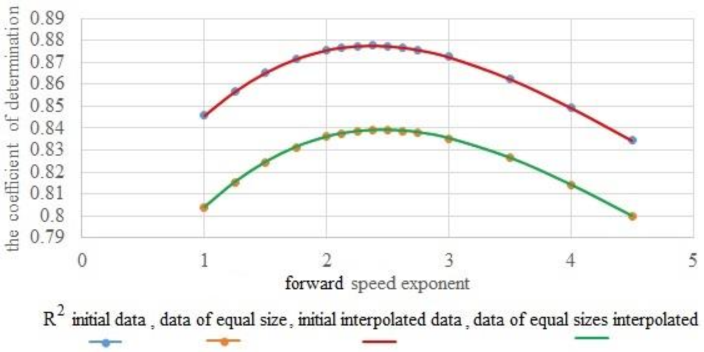

Fig. 5 - Interpolation data and interpolation curves used to calculate the optimal work speed, exponent

The speed exponents, determined in this way, cannot be entered into the formula for calculating the tensile strength because, from a dimensional point of view, the speed at a power that is not an integer has no dimensional meaning. For this reason, the use of the above result is conditioned by the reconsideration of the calculation formula by introducing the speed as a dimensionless factor (speed divided by an important speed in the work process, for example, a critical speed of propagation of waves in soil).

3.5. The analysis of the Quartiles, boxplot graphical representations

According to *Clocotici V. and https://en.wikipedia.org/wiki/Box_plot*, in descriptive statistics, a boxplot or boxplot is a method for graphically demonstrating the local properties of data distribution, spread groups and asymmetry of numerical data through their quartiles. In this sub-chapter, the possible connection between the distribution of the quartiles of the experiments and their other characteristics is studied, in comparison with the speed of progress of each experiment. This analysis was done to find new estimators significantly related to the aggregate advance speed. Finding such estimators contributes to the widening of the range of statistical tools for investigating the involvement of the speed of advance in the quantities of energetic and economic nature of the work process, but also to the creation of new directions in the modelling, of the soil processing phenomenon. Finding such estimators contributes to the widening of the range of statistical tools for investigating the influence of the working speed in the quantities of energetic and economic nature of the work process, but also to the creation of new directions in the statistical modelling, of the soil processing phenomenon. The box plot graphic representation is given in fig. 6.

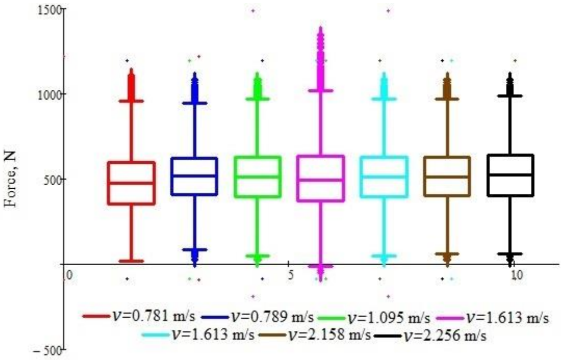

Fig. 6 - Boxplot graphical representations for each of the seven experiments performed for the aggregate consisting of the 45 HP tractor and the 1 m wide version of the MCLS

Table 5

Important statistical estimators involved in the investigation of the relationships between the parameters of the MCLS work process and the aggregate advance speed

Experiment code	Average of outliers per experiment, N	Number of outliers	The variance of outliers	Average of the original data, N	The standard deviation of the original data, N	The variance of the original data
T2_R2_1500rpmtxt	1012.533	148	0.558	478.413	175.400	30764.988
T1_R2_2400rpmtxt	818.985	211	6.377	518.448	155.859	24291.887
T1_R3_1500rpmtxt	930.699	99	2.85	491.532	166.486	27717.492
T2_R2_2700rpmtxt	1086.370	197	2.30	508.530	195.475	38210.409
T2_R3_1500rpmtxt	930.699	99	2.85	495.540	178.572	31887.955
T3_R2_1500rpmtxt	930.699	103	3.361	448.719	221.989	49279.026
T2_R3_2000rpmtxt	883.709	71	3.267	452.695	214.605	46055.503

The Pearson correlation coefficient between the three characteristics of the box-plot analysis, which are given in table 5, are listed in table 6. In addition, the correlation is also made with the velocity vector of the seven experiments. It was also introduced in the table the Pearson correlation coefficients and the main statistical characteristics calculated using the data files with the original selection: the average value, the standard deviation and the variance. It is found that the standard deviation and the variance of the original data are highly correlated with the forward speed.

As a result, it can be concluded that with the increase in the working speed, the parasitic vibration energy of the entire MCLS structure will also increase, with all the negative consequences, including affecting the quality of soil processing. The variance of the original data is strongly and positively related to the speed of advance (correlation coefficient 0.919). The linear regression study shows that the forward speed explains 84.42% of the behaviour of the variance of the traction resistance force. Even more intense and positive is the connection between the standard deviation of the original data and the speed of advancement (correlation coefficient 0.92). The variation of the forward speed, according to the linear regression analysis, explains 84.58% of the behaviour of the standard deviation of the original data.

Table 6

Pearson correlation coefficients between the main estimators from the study of quartiles and box plot diagrams, together with other estimators of descriptive statistics

	Average of outliers per experiment	Number of outliers	The variance of outliers	Average of the original data	The standard deviation of the original data, N	The variance of the original data	Forward speed
Average of outliers per experiment	1	0.194	-0.784	0.067	0.200	0.163	0.015
Number of outliers	0.194	1	0.294	0.759	-0.481	-0.477	-0.589
The variance of outliers	-0.784	0.294	1	0.320	-0.227	-0.191	-0.036
Average of the original data	0.067	0.759	0.320	1	-0.801	-0.808	-0.684
The standard deviation of the original data, N	0.200	-0.481	-0.227	-0.801	1	0.999	0.92
The variance of the original data	0.163	-0.477	-0.191	-0.808	0.999	1	0.919
Forward speed	0.015	-0.589	-0.036	-0.684	0.92	0.919	1

4. Comments

After calculating the average value of the tillage draft force on the active body, the linear regression analysis between the vector of these average values and the vector of forward speeds (the first column in Table 2 and the last in Table 1), leads to a coefficient of determination $R^2=0.468$, the Pearson correlation coefficient between the two vectors being -0.684. Therefore, the working speed can explain at most 46.8% of the behaviour of the average value of the traction resistance force on the working body. In addition, these vectors are highly (according to (*www.umfcv.ro*) for example) correlated but vary inversely or are negatively correlated. The statistical analysis of the regression gives the values of the probabilities of rejection of the regression relationship coefficients, approximately 0.0 for the constant term and 0.057 for the term of the first degree. The last value being greater than 0.05, the hypothesis of the correctness of the linear regression is rejected. Therefore, this type of connection is unlikely between the two vectors.

The results in table 7 show that the most significant estimator for the dependence of tillage draft force on the forward speed is the variance. The same result is obtained by the linear regression study carried out in subchapter 3.3. Variance is the statistical estimator of tillage draft force most strongly related to forward speed.

The intensity of the link between the variant of the average tillage draft force on the working part and the speed of advancement is also of interest for the suggestion that the coefficient of determination (taken as an objective function) can be optimized, in this case, maximized. More interesting is that the exponent of the speed that achieves the maximization is quite close to 2, as it was shown in chapter 3.4. It should be mentioned that the value of 2 of the forward speed exponents is very common in the calculation formulas proposed for the tillage draft force generated by agricultural machines intended for soil processing (*Letosnev M.N., 1959; American Society of Agricultural Engineers, 2003; Ranjbar et al., 2013; Singh et al., 2018*). In *Moeenifar et al., (2014*), a formula with an exponent, generally non-integer, is used for the forward speed. Significant effects of the working speed of some agricultural machines intended for soil processing were also found experimentally using the variance of the tillage draft force, by the authors *Naderloo et al., (2009*) for example. From the study in subchapter 3.4, it can also be found, which was to be expected, that using longer experimental sequences, the intensity of the found link increases.

Table 7

Correlations between the main parameters of the work process. The hatched cells correspond to the processing of the original data, and the non-hatched cells correspond to data files of equal size

	The average tillage draft force on the working body	Variance	Forward speed	RMS
The average tillage draft force on the working body	1	-0.801	-0.684	0.954
Variance	-0.801	1	0.92	-0.587
Forward speed	-0.684	0.92	1	-0.467
RMS	0.954	-0.587	-0.467	1
The average tillage draft force on the working body	1	-0.778	-0.733	0.951
Variance	-0.778	1	0.897	-0.548
Forward speed	-0.733	0.897	1	-0.542
RMS	0.951	-0.548	-0.542	1

Almost linear and increasing dependences of tensile strength on feed rate, over narrow speed ranges, have been found by numerous researchers (*Elsheikha et al., 2021; Al-Suhaibani & Ghaly, 2010*), and our article confirms this finding. The authors *Kushwaka & Linke, (1996*) conclude that the working speed influences the resistance force of an agricultural aggregate for processing the soil. The study ok *Kushwaka & Linke, (1996*) reaches interesting conclusions related to the existence of a critical value of the forward speed (specificity of each soil), above which the energy consumption of the tractor becomes lower. Some of these conclusions were also reached in *Cardei et al., (2019*) starting from the theoretical formula of tensile strength proposed by Goriacikin *(Letosnev M.N., 1959*). The conclusions in the present paper confirm most of the results found in *Cardei et al., (2019*) or *Letosnev M.N., (1959*) but do not disprove any of them.

The use of quartile analysis and boxplot graphic representation was tried in this article to find some statistical estimators strongly related to the speed of advance. The results were weak, in the sense that in subchapter 3.5 insignificant correlations were found between the forward speed and the main estimators chosen from the quartile analysis (the number of outliers, the average and the variance of the resistance forces per working part). A single couple attracts attention, having a correlation coefficient of -0.784, a value recorded between the variance of the outliers and the average value of the tillage draft force per experiment. As for our purpose, first of all, the maxima of correlation with the speed of advance were interesting, it can be stated that the analysis of quartiles and box plot diagrams does not bring new elements to the study.

The experimenters have found, not only in the experiments analysed in this article but also in other experiments, that, at least apparently, there are situations in which the increase in the forward speed of the aggregate leads to a decrease in the tillage draft force. This aspect can be related to a hypothetical critical speed (specificity of soil type, humidity and other environmental conditions) described in *Kushwaka & Linke, (1996*) or in *Cardei et al., (2019*), but, often, as shown in *Gatea A.A., (2013*), the phenomenon happens due to the decrease of the working depth, practically the partial exit of the active body from the furrow.

In subchapter 3.5 it was showed that the standard deviation and the variance of the tillage draft force are well or even very well correlated. Other authors have also found such results. For example, *Odero A.J., (2019*) (table 4.2), for the disc plough, makes a number nine experiments for three forward speeds and three working depths. The correlation coefficient of tensile strength with working depth has a value of 0.597, and with speed, 0.773. The bilinear regression analysis gives for the predictors working depth and forward speed the coefficient of determination R^2=0.95 with the adjusted value 0.94. Therefore, the two predictors together explain 95% of the behaviour of the dependent variable, tillage draft force. In the same conditions, for a tiller plough, the correlations of force with depth and forward speed have values of 0.439 and 0.884, respectively. The regression analysis provides R^2=0.97 with an adjusted value of 0.97. Both for the disc plough and for the plough with the tiller, both predictors (depth and forward speed) are considered to be very significant collective predictors. Obviously, to complete the remaining 5% or 3% of the behaviour of the traction resistance force, the frictional forces can be studied. In the case of the tiller plough, if instead of the speed it is considered the square of it, it reaches R^2=0.98 with the adjusted value 0.97, and for the disk plough, at R^2=0.96 with the adjusted value 0.94. This is just a suggestion for the dependence on the square of the speed. However, it is possible to follow the path of numerical optimization introduced in subchapter 3.4.

5. CONCLUSIONS

The results presented in this article, compared to the results of other researchers who have investigated in a similar way the problem of the influence of the speed of advance of agricultural machines intended for soil processing on the tensile strength, allow us to express some useful conclusions for those who try to highlight this connection in experimental data.

C1) The forward speed influences the intensity of the tillage draft force on the entire machine and the working part. The influence becomes clearer if the variance and standard deviation of the tillage draft force are used.

C2) It cannot be certain that conclusion C1) is valid for all soils and different humidity levels of the same soil. Therefore, conclusion C1) must also be studied to other environmental conditions, working depths, etc.

C3) Evidence of the intensity of the connection (correlation) between the tillage draft force and the forward speed is made difficult by two phenomena: the first consists in the fact that the component of the traction resistance force given by the forward speed is usually small in the usual range of speeds advancement, and its increase must be done with caution because it negatively affects the quality of the work; the second reason consists in the fact that with the increase in the speed of advance, there are also losses of the working depth which can lead to the erroneous conclusion that the increase in the working speed leads (perhaps starting from certain values) to the decrease of the tillage draft force or the growth rate of the same force.

C4) It is possible that starting from certain forward speeds, the increasing speed of the tillage draft force decreases (so the derivative of the tillage draft force to the working speed) and not the traction force itself.

C5) The use of non-linear regression analysis allows finding indicative powers for the dependence of the variance of the tillage draft force, powers that can then be used in theoretical or theoretical-empirical modelling of the tillage draft force.

C6) Although the analysis of quartiles and outliers did not indicate significant links between forward speed and tillage draft force or its statistical estimators, the subject is not considered closed and can be further addressed for cultivators but also for other agricultural machines to be processed on the ground.

C7) Continuation of research aimed at agricultural machines of the type of working variants of the MCLS, are conditioned by: direct measurements of the tillage draft force, accelerometry measurements, control measurements or monitoring of the working depth, measurements of the working width and monitoring, estimation productivity, consumption and work qualities (working depth, granulation or granulation ratio). These are just a few directions to continue, but next to them there are others equally important: the introduction of soil qualities into the soil, namely moisture, cohesion, adhesion, degree levelling, density, compactness, resistance to penetration, other mechanical properties, etc. Time and money will solve them all, in a positive or negative sense.

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