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Effects of Tractor and Soil Parameters on the Depth of the Permanent Traffic Lanes in Controlled Traffic Farming Systems

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Abstract: One of the basic requirements for controlled traffic farming (CTF) is the precise motion of all agricultural equipment on permanent traffic lanes (PTL). Tractors of machine-tractor units are then equipped with a GNSS (global navigation satellite) RTK (real-time kinematic) system, even though in many parts of the world, and Europe as well, satellite navigation is not yet used. In this case, for implementation of the CTF system, it needs to lay such PTL tracks that would be sufficiently visible, especially when using the CTF system in multi-year agricultural crop cultivation. The PTL track depth is influenced by both tractor and soil parameters and, in this paper, this influence is studied considering the dimensionless π -terms of the similarity theory. To obtain a greater depth of PTL tracks (h), the soil cone index must be low. The low density of the soil is important, even if its effect on the parameter h is less than that of the soil cone index. A greater depth of PTL tracks is also obtained by increasing the inflation pressure in the tractor tires. Ballasted wheels are the least effective for increasing the value of the parameter h .

Keywords: controlled traffic farming; soil bulk density; soil cone index; depth; Buckingham's π -theorem



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1. Introduction

The consistent use of heavy machinery in agricultural fields in past decades caused an increased risk of soil compaction [1–4]. According to various authors, this phenomenon is accentuated by the intensity of transits [5–7], the increase in the axle load of agricultural machinery [8,9], and the rise in power and traction capacity of tractors [10–13]. The row crop systems, in which agricultural machinery frequently transits between rows during the entire growth cycle, also lead to a high risk of soil compaction [14–16]. Soil compaction results in several and variously interconnected detrimental outcomes, such as air reduction, increased water reserve and nutrient absorption by plant lowering, and crop yield diminution [17–20].

In this context, controlled traffic farming (CTF) systems represent an excellent solution to this phenomenon, whereby traffic-induced soil compaction is minor, as the cultivation area is separated from the permanent traffic lanes (PTL) [21–23]. The crop area is thus not touched by the machinery wheels, which instead run only on the PTL [24,25]. In this way, it is possible to optimize the performance of both the cultivation zone and PTL [26].

The effectiveness of controlled traffic farming (CTF) in agricultural production has long been proven and its basic requirements have been formulated [27–30]. One of the requirements is the precise motion of all equipment on permanent traffic lanes (PTL). For this purpose, it is recommended to equip the technical means with a rather expensive GNSS (global navigation satellite) RTK (real-time kinematic) system [31,32]. Moreover, the accuracy and reliability of the GNSS-RTK system depend on weather conditions and the terrain [33]. In this regard, the scheme of the machine-tractor unit has a certain influence on the efficiency of the GNSS-RTK system [34].

However, the CTF method is still implemented without using satellite navigation systems in many countries, including Ukraine [35,36]. In these contexts, the PTL tracks are arranged earlier so that they will be detectable during the full crop growing cycle and then be used by the wheels or tracks of all implements and tractors for cultivation works. Furthermore, existing CTF systems are mainly used in a single field [37]. At the same time, the long-term use of the same PTL in the appropriate crop rotation is of interest. In Ukraine, the following variant is very promising: «sunflower» – «black fallow» – «winter wheat».

To implement CTF in such a crop rotation, it is desirable that the PTL are highly visible and deep enough. Otherwise, they may become almost undetectable after the first year of use. This problem has been solved by using a special machine-tractor unit, which the authors have developed [38]. This machine used a special front device, equipped with two plow bodies spaced as wide as the tractor gauge, to plow the PTL at a given depth.

However, the question arises: “Is it possible to form PTL tracks of a given depth without using a special machine, but with solely a wheeled tractor?”

PTL depth (h) depends on some tractor and soil parameters, and it is obvious that the greater the value of the parameter h , the greater the soil compaction.

The influence of many of the tractor’s design parameters on soil compaction has been studied in some detail. For example, soil compaction has been estimated as a function of the inflation pressure of the tire and the vertical load on it [39]. Furthermore, in studying this problem, the bearing capacity of the soil has been proposed to be evaluated by a special index, the field compaction capacity (FCC) [40].

The sealing effect of the tractor undercarriage system type has also been examined [41]. In addition, the effectiveness of changing the inflation pressure in twin traction vehicle tires has been analyzed [42].

The effects on soil compaction caused by tractor ballasting have been outlined in [43], in which study the equation for determining the track depth after the tractor wheels have passed is given, even if this equation only includes tractor manufacturing parameters (operating vertical load on the wheel, tire inflation pressure, tire diameter, and tire width) and does not contain soil parameters.

For laying PTL of a given depth, it is necessary to have information about the complex influence of both tractor and soil parameters on the depth. For the latter, the most important are density and soil cone index. Unfortunately, at present such information is scarce.

With the final objective of using solely a wheeled tractor to make PTL of a given depth h , this paper reports the results of research aiming at analyzing the complex interactions of the parameters concerning the characteristics of both the tractor and the soil on the depth of PTL (Figure 1). The above influences, experimentally evaluated, allowed for the setup of an ad hoc mathematical model, based on Buckingham’s π -theorem, which can be useful to support CTF users in obtaining PTL of suitable depth. According to our scientific hypothesis, this problem can be solved if we take into account not a separate (as was performed earlier), but a complex effect on the process of PTL formation of the tractor and soil parameters.

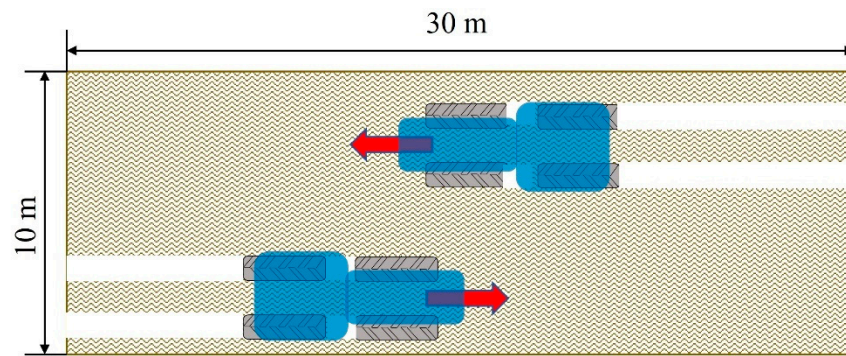


Figure 1. Single plot sizes with tracks made by the tractor.

2. Materials and Methods

2.1. Theoretical Premises

The relationship that makes it possible to evaluate the influence of both tractor and soil parameters on the depth of the PTL has been studied using dimensional analysis and Buckingham's π -theorem [44,45]. As is known, Buckingham's π -theorem states that the original number n_v of independent variables in a relationship between dimensional physical quantities is reduced to n_π (called π -terms) if the same relationship is expressed in a dimensionless form, according to the following equation [46]:

$$n_\pi = n_v - n_b \quad (1)$$

where n_b is the maximum number of dimensionally independent quantities that can be identified within the n_v ones. $n_b = 3$ if the phenomenon is dynamic, and the corresponding parameters are called basic variables [47].

The design parameters (variables) of a wheeled tractor and the physical–mechanical characteristics of the soil, which significantly affect the process of PTL track-making, and their corresponding dimensions and units with respect to the International System of Units (SI Units) are reported in Table 1. Considering that soil deformation moves its mass, these parameters are supplemented by a constant characteristic of the earth's gravitational field, i.e., the acceleration of gravity (Table 1).

Table 1. Variable influencing the depth of PTL.

Symbol	Variable	Dimension	Unit
Dependent variable			
h	PTL track depth	L	m
Independent variable			
N_w	vertical wheel load	MLT^{-2}	N
P_w	tyre inflation pressure	$ML^{-1} T^{-2}$	Pa
H	soil cone index	$ML^{-1} T^{-2}$	Pa
ρ	bulk soil density	ML^{-3}	$kg\ m^{-3}$
Constant			
g	gravity	LT^{-2}	$m\ s^{-2}$

The functional dependence of PTL track depth (h) on the above-mentioned parameters is given by:

$$h = f(N_w; P_w; H; \rho; g). \quad (2)$$

The following are the basic variables: (i) the tire pressure P_w ; (ii) the soil density ρ ; (iii) and gravity g .

To check the correctness of the parameters selected as the basic variables, we need to verify that the following monomial is dimensionless:

$$P_w^A \cdot \rho^B \cdot g^C \quad (3)$$

Thus, the dimension of expression (3) gives:

$$[P_w^A \cdot \rho^B \cdot g^C] = M^A \cdot L^{-A} \cdot T^{-2A} \cdot M^B \cdot L^{-3B} \cdot L^C \cdot T^{-2C}$$

The monomial (3) is thus dimensionless if and only if the determinant of the coefficients of the following homogeneous system is nonzero:

$$\begin{cases} A + B = 0 \\ -A - 3B + C = 0 \\ -2A - 2C = 0 \end{cases} \quad (4)$$

The determinant of the coefficients is given by:

$$D = \begin{vmatrix} 1 & 1 & 0 \\ -1 & -3 & 1 \\ -2 & 0 & -2 \end{vmatrix} = 2 \quad (5)$$

Since the determinant D of the coefficients of the system (4) is nonzero, the parameters P_w , ρ and g are indeed mutually independent.

The dimensionless π -terms are given, respectively, by the following equations:

$$\pi_0 = \frac{h}{P_w^{A_0} \cdot \rho^{B_0} \cdot g^{C_0}}; \quad (6)$$

$$\pi_1 = \frac{H}{P_w^{A_1} \cdot \rho^{B_1} \cdot g^{C_1}}; \quad (7)$$

$$\pi_2 = \frac{N_w}{P_w^{A_2} \cdot \rho^{B_2} \cdot g^{C_2}}. \quad (8)$$

The monomial placed as the denominator in Equation (6) must have the same dimension as the numerator h in the same equation thus:

$$[M^{A_0} \cdot L^{-A_0} \cdot T^{-2A_0} \cdot M^{B_0} \cdot L^{-3B_0} \cdot L^{C_0} \cdot T^{-2C_0}] = [L] \quad (9)$$

Equation (9) gives rise to the following system of equations:

$$\begin{cases} A_0 + B_0 = 0 \\ -A_0 - 3B_0 + C_0 = 1 \\ -2A_0 - 2C_0 = 0 \end{cases} \quad (10)$$

which makes it possible to calculate the coefficients A_0 , B_0 , and C_0 . Therefore, $A_0 = 1$, $B_0 = -1$, and $C_0 = -1$

Considering these results, Equation (6) gives:

$$\pi_0 = h\rho g / P_w \quad (11)$$

Similarly, the coefficients A_1 , B_1 , and C_1 have been assessed for Equation (7) and A_2 , B_2 , and C_1 for Equation (8), obtaining, respectively:

$$\pi_1 = \frac{H}{P_w} \quad (12)$$

$$\pi_2 = \frac{N_w \cdot \rho^2 \cdot g^2}{P_w^3} \quad (13)$$

Finally, in agreement with the π -theorem, we get:

$$\pi_o = f(\pi_1; \pi_2) \quad (14)$$

or, considering expression (11), we get:

$$h\rho g/P_w = f(\pi_1; \pi_2) \quad (15)$$

2.2. Mathematical Model

To build a mathematical model corresponding to Equation (14), we use the well-known technique of planning a full factorial experiment according to scheme 2^2 , (i.e., 2 factors at 2 levels of values) at a statistical significance level of 0.05 [48]. In this case, the factors are represented by the p-terms π_1 and π_2 , which in turn are functions, represented by the Equations (12) and (13), respectively. The experiment planning matrix is shown in Table 2. As follows from Equation (12), the lower level (−1, Table 2) of the p-term π_1 is obtained at the minimum value of parameter H and the maximum value of parameter P_w . Conversely, at the maximum value of H and the minimum value of P_w , we obtain the upper level (+1) of the p-term π_1 .

Table 2. Levels and interval variation of parameters and p-terms.

Parameter	Measurement			
	Min			Max
P_w (MPa)	0.10			0.16
ρ (kg m ^{−3})	1020			1260
H (MPa)	0.48			0.90
N_w (N)	8100			10,100
p-terms	Variation level			Variation range
	−1	0	+1	
π_1	3	6	9	3
π_2	0.0002	0.00085	0.0015	0.00065

The lower level (−1) of the p-term π_2 is obtained, as the analysis of Equation (13) shows, at the minimum value of the parameters N and ρ and the maximum value of the parameter P_w . On the other hand, at the maximal values of the parameters N and ρ and the minimal value of P_w , we obtain the upper (+1) level of the p-term π_2 (Table 2).

2.3. Field Tests

To perform the aforesaid full factorial experiment, tests were carried out in spring (March) in an agricultural field, which had been plowed with a chisel to 25 cm depth the previous autumn (September). Place of the field experiments: Ukraine, Melitopol (46°50′56″ north latitude, 35°21′55″ east longitude, altitude: 37 m).

A BELARUS model MTZ-1221.2 wheel tractor was used, whose main technical characteristics were: (i) rate power, 95.6 kW; (ii) total weight, 54.6 kN; (iii) front wheels, 420/70R24; (iv) rear wheels, 18.4R38; (v) weight on front wheels, 16.2 kN.

In the chosen agricultural field 4 plots of 10 × 30 m each were considered. In each plot the MTZ-1221.2 tractor formed the PTL tracks of depth h , moving in the forward and reverse directions with the same gear to ensure the double repetition of the experiments (Figure 1). The average speed of the tractor during the experimental studies was constant and equal to 2.1 m s^{−1}.

The minimum and maximum values of the parameters H and ρ of Table 2 were assessed as follows. The values of the soil density (ρ) and soil cone index (H) of all plots

were measured in the spring (March) before the experiment tests and were considered the maximum values for these parameters. Both the soil density and the soil cone index were measured in 50 points within each plot. The values of all these measurements performed in all the plots were used to assess the average values of soil density (ρ) and soil cone index (H), respectively, reported in Table 2.

Furthermore, the soil on 2 plots of the field (plot 2 and plot 4) was then tilled with a disc harrow to a depth of 15 cm. After the tillage, through the same method described above the average values of the soil density (ρ) and soil cone index (H) of these two plots were measured and considered as the minimum values for these parameters (Table 2). The test plan reported in Table 3 was then implemented.

Table 3. Plan summary of test performed in March.

Plot	Repetitions	Context	π -Level	
			π_1	π_2
1	2	no tillage performed	+1	+1
2	2	disc harrow to a depth of 15 cm	−1	−1
3	2	no tillage performed	+1	−1
4	2	disc harrow to a depth of 15 cm	−1	+1

The PTL trace depth was measured on each site as follows. The left track depth made by the MTZ-1221.2 tractor was measured in duplicate with a ruler-depth meter with an error of ± 0.005 m. Measurements were carried out at the center of the wheel track, as shown by the white points along the red line in Figure 2. The measurement points were 100, with a measurement step of 0.1 m [35].



Figure 2. Measures of the PTL trace depth formed by the tractor front wheel.

The soil cone index H was assessed using a Model Lan-M penetrometer (VP Dilis, Kyiv, Ukraine) with the following main technical characteristics: 0 to 7.8 MPa soil cone index measure range and 0.05 MPa accuracy.

The soil bulk density ρ was evaluated as follows [49,50]. The soil sample was taken with a 28.35 cm³ cylinder (height—1.7 cm; diameter—4.6 cm) and weighed on the scales, which were configured to measure in ounces. As 1 oz. = 28.35 g, the scales showed the soil mass value that was equal to its density in g cm^{−3}.

In addition to soil cone index H and soil bulk density ρ , soil moisture M_s was measured during field studies. Measurements of these parameters were carried out in the same zone where the depth of the wheels was determined after the passage of the tractor (see Figure 2). The depth of the soil layer for measuring soil moisture and soil density was 0–15 cm. The average soil moisture content M_s value was determined using soil samples dried at 105 °C for 3 h in an ARGOLAB model TCF 200 forced air oven (Argolab-XS Instruments s.r.l. Industry, Carpi, Modena district, Italy). Soil samples were weighed before and after drying using an electronic ABT model 220-5DM analytical balance (KERN & SOHN GmbH

Industry, Balingen, Germany) with the following technical characteristics: 0.22 kg max. capacity and 10^{-8} kg readability.

The minimum and maximum tractor tire inflation pressures P_w were 0.100 MPa and 0.160 MPa, respectively, (Table 2) in two-fold repetition. The pressure was measured using an Intertool model RT-0500 manometer (Intertool Ltd., Kyiv, Ukraine) with a measurement accuracy of ± 10 kPa.

The max value of vertical load N_w on the tractor's front axle was obtained with the help of 8 metal weights. Half of them loaded the left and half the right front wheels. The weight of each ballast was in the range of 50 ± 0.1 kg.

The methodology of processing the experimental data was performed as follows [51]:

- Evaluation of the arithmetic mean and variance for each series of parallel experiments;
- Assessment of the reproducibility of experiments and homogeneity of dispersions by the Cochran criterion;
- Calculation and evaluation of the significance of the regression equation coefficients using Student's test;
- Checking the adequacy of the obtained regression equation using Fisher's criterion.

All these procedures were performed in Microsoft Excel.

In conclusion, the research steps performed to obtain the mathematical model corresponding to Equation (14) can be summarized in the algorithm of Figure 3.

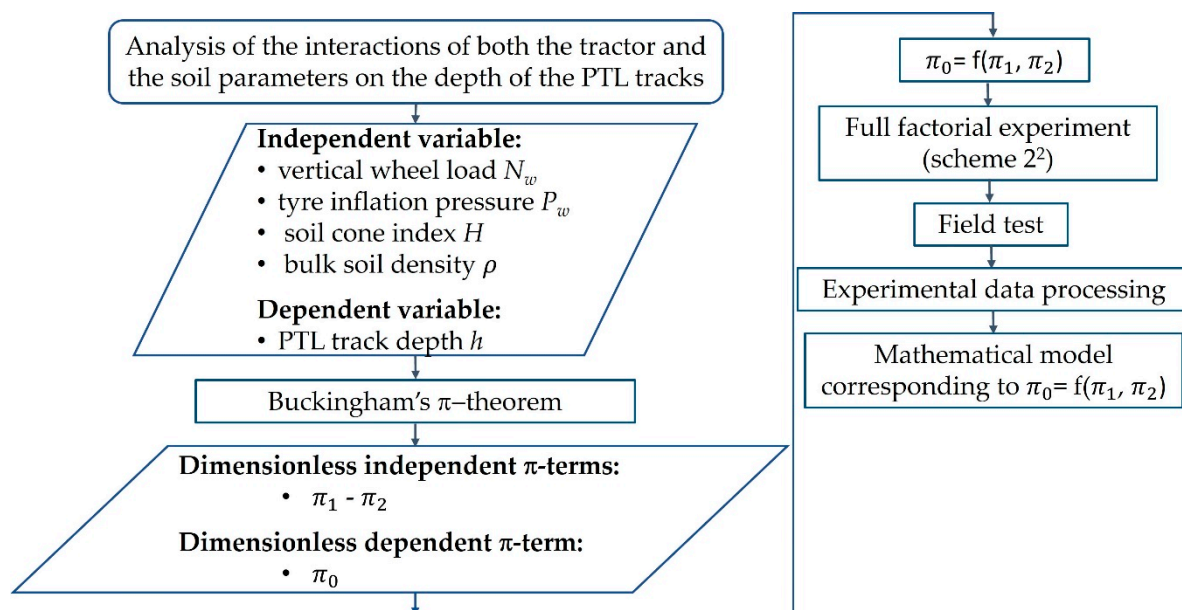


Figure 3. Research algorithm.

3. Results and Discussion

Experimental studies were carried out on the soil, which was dark chestnut chernozem with a humus content of up to 4.5%.

Before the experiment, the soil moisture content M_s was 20.9%, the soil cone index H was 0.90 MPa and density ρ was 1260 kg m^{-3} . After the tillage with a disc harrow, the soil cone index in the range from 0 to 5 cm layer decreased to 0.48 MPa and density to 1020 kg m^{-3} .

Processing of the experimental data shows that the functional dependence (15) can be approximated by a linear polynomial:

$$\frac{h\rho g}{P_w} = 0.01 - 0.001\pi_1 + 3.7\pi_2. \quad (16)$$

If we substitute Equations (12) and (13), Equation (16) takes the following final form:

$$h = 0.01 \frac{P_w}{\rho g} - 0.001 \frac{H}{\rho g} + 3.7 \frac{N_w \rho g}{P_w^2} \quad (17)$$

Analysis of Equation (17) shows that as the tractor front tires inflation pressures P_w increases, and the track depth increases (Figure 4). In principle, this occurs according to a nonlinear law.

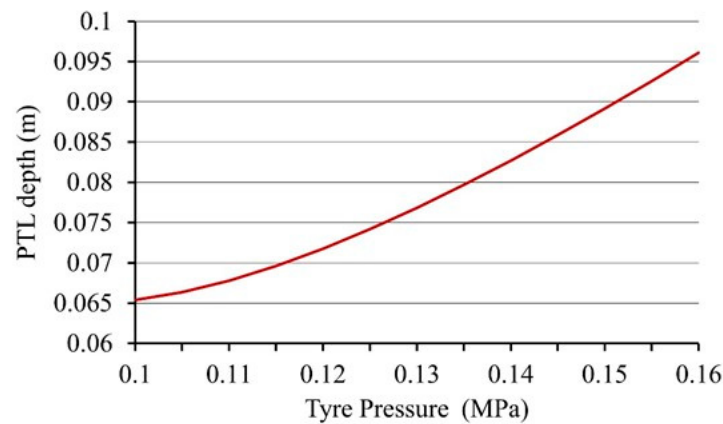


Figure 4. Dependence of the track depth PTL (h) on the tractor tire inflation pressure (P_w).

As the vertical load N_w on the wheel increases, the parameter h changes in direct proportion, and therefore according to the straight-line law (Figure 5).

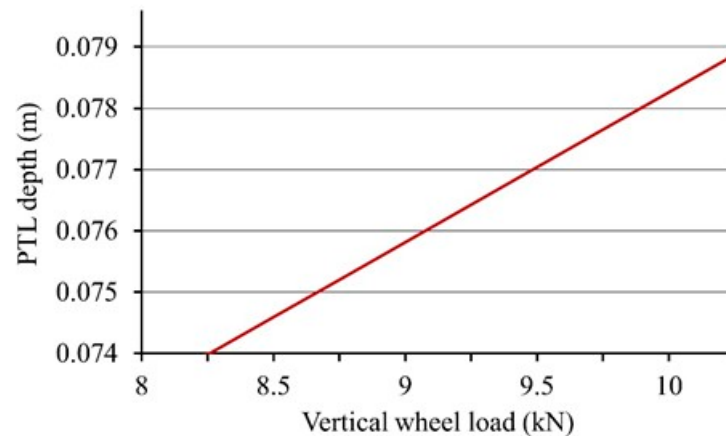


Figure 5. Dependence of the PTL track depth (h) on the vertical load on the tractor wheel (N_w).

According to scientific logic, the regularities shown in Figures 4–6 are quite natural and understandable. In qualitative terms, the influence of the parameters P_w , N_w , ρ and H on the value of h are known to researchers [52,53].

Of interest is their quantitative influence. At the same time, their quantitative and qualitative influence are not separate, but joint, i.e., complex. As follows from Table 2, the parameters P_w , N_w , ρ and H had different limits of variation. The inflation pressure in the wheel tire P_w was considered from 0.10 to 0.16 MPa, i.e., increased by 60%. The soil cone index H increased even more: from 0.48 to 0.90 MPa, i.e., by 88%. As for the values of the soil density ρ and vertical load N_w on the tractor wheel, their changes were almost the same and approximately equal to 25%.

With increasing soil density ρ , the depth h of the PTL trace naturally decreases (Figure 6). The same occurs with increasing soil cone index (Figure 7).

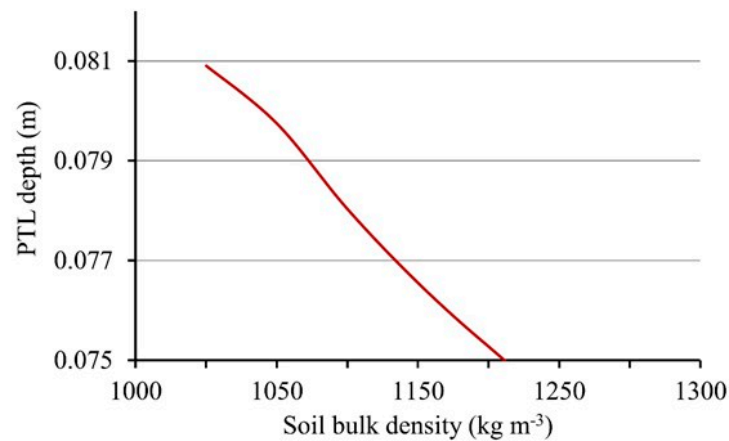


Figure 6. Dependence of the PTL track depth (h) on the soil density (ρ).

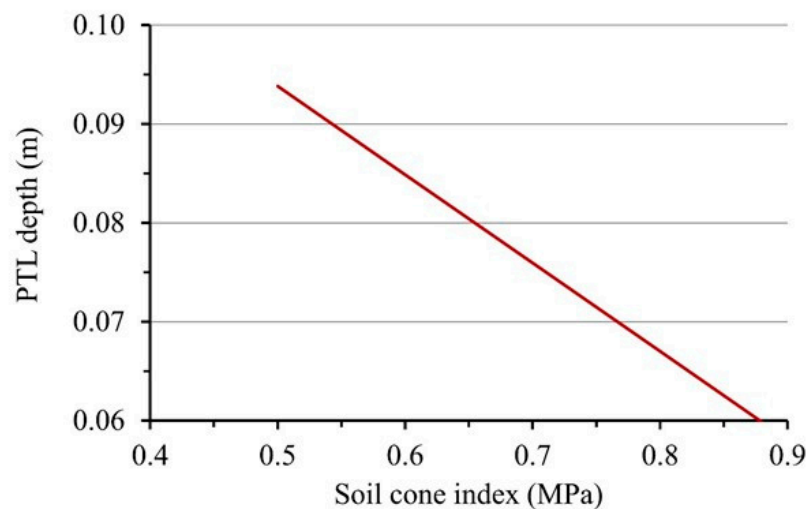


Figure 7. Dependence of the PTL track depth (h) on the soil cone index (H).

On this basis, it has been estimated the degree of change in the PTL track depth if the parameters P_w , N_w , ρ and H are increased by the same amount: 25%. It makes no sense to take a larger value because N_w and H increased by no more than 25% during the study of the mathematical model (17).

The analysis of the experimental data obtained considering such restrictions showed that the greatest contribution to the change in the parameter h is made by the soil cone index H (Figure 8). In this case, this contribution has been 24.0%.

The contribution of the tractor front tires inflation pressures P_w to the change in the PTL track depth h has been less and is 15%. Soil density ρ and vertical wheel load N_w had approximately the same effect on the change in the parameter h , namely 9 and 7%, respectively.

It follows from this analysis that to obtain PTL tracks of acceptable (specified) depth h , the initial soil background should have a low cone index.

The lesser degree of influence of the ρ parameter on the PTL depth (h) can be explained by the following. Although there is a direct correlation between soil density ρ and soil cone index H , it is not directly proportional. According to our studies of about 300 soil samples with 12–20% moisture content, a decrease in soil cone index H by 0.5 MPa led to a decrease in soil density ρ by only 50–80 g m^{-3} . Approximately the same data with a difference of no more than 5% were obtained by other authors [54]. In principle, at relatively low moisture content M_s , a highly porous soil is characterized by low density ρ but sufficiently high cone index H .

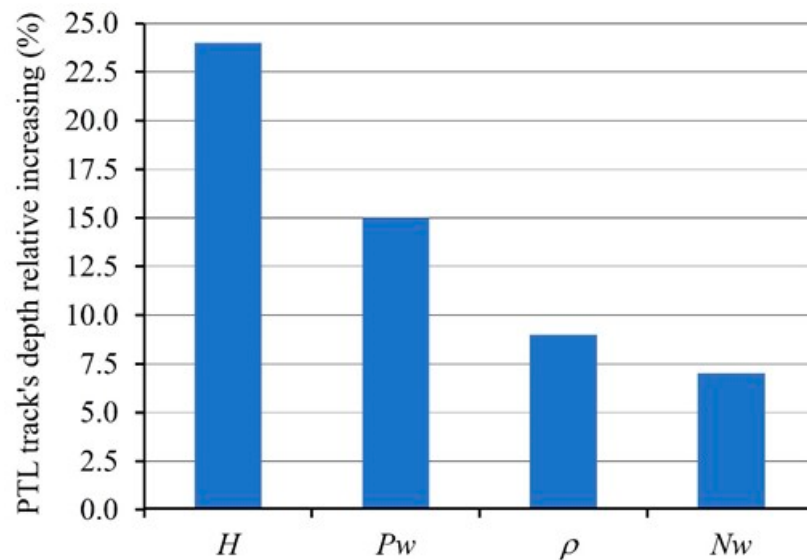


Figure 8. Degree of influence on the PTL track depth of parameters P_w , N_w , ρ and H when changing their values by 25%.

A reduction in soil density ρ is a desirable condition for obtaining a PTL track depth h that will provide good visibility without the use of a GPS. The coordinates (X ; Y) of the machine-tractor unit (MTU) in the field (Figure 9) in this case can easily be determined from the expression:

$$X = \frac{S \cdot (2n - 1)}{2}; Y, \quad (18)$$

where S is the PTL's step and n is the PTL's number where the MTU is located.

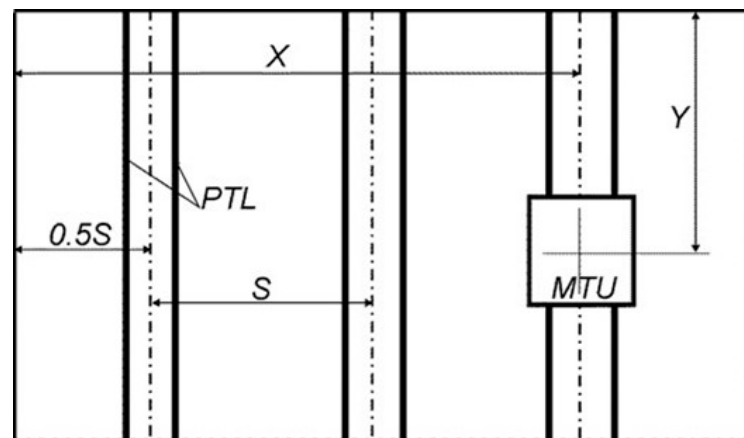


Figure 9. Diagram for determining MTU coordinates on a field with PTL.

To determine the Y coordinate, it is enough to equip the tractor with a simple displacement sensor.

4. Conclusions

The authors of the article are aware of numerous studies by other scientists on the effects on soil caused by the air pressure in tractor tires (P_w) and the vertical load (N_w), as well as of the studies focused on the effect of P_w and N_w on the depth of the furrow after the passage of the tractor wheels. However, the impact of each of these parameters on the soil was considered separately over time.

The undoubted novelty of this research is that the influence of the parameters P_w and N_w on the depth of the furrow traced by the tractor wheels is considered in their overall

effect and in combination with other important parameters of the soil such as its density (ρ) and cone index (H). In the experimental study, the authors of the article did not operate separately on each of the parameters ρ , H , P_w , and N_w (as all the researchers did), but on the parametric functions π_1 and π_2 . Under the field conditions, modifying π_1 and π_2 with the method of a full factorial 2^2 experiment is anything but a trivial task. However, its solution allowed us to obtain new and useful results both for the scientific community and for practical users.

In conclusion, to obtain a greater depth of PTL tracks (h), the soil must have a low cone index. The soil's low-density ρ is important, but its influence on the parameter h is less than the influence of the cone index H .

The second step in obtaining a greater depth of PTL tracks is to increase tractor front tires inflation pressures P_w . Ballasting, (i.e., placing ballast weights on the wheels) of the wheels to solve this problem is the least effective, since increasing the vertical load N_w , on them has the least effect on the value of the parameter h .

The obtained results of the research can be used in practice when choosing tractor parameters (P_w , N_w) and taking into account soil parameters (ρ , H) in order to obtain sufficiently visible (moreover, in a long-term crop rotation of agricultural crops) traces of the PTL without the use of navigation systems.

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