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DETERMINATION OF THE CONTACT PATCH LENGTH IN TRACTOR TIRE-SOIL INTERACTION

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Abstract

Soil fertility is determined mainly by its level of compaction. For a single wheel, this level depends on the pressure, which is calculated by dividing the wheel's vertical load by its contact patch area. The latter is directly related to the length of the tire's contact patch with the soil (L_k). In this regard, this article aims to develop a strategy for selecting the parameters of a tractor chassis system based on the analysis of such an analytical dependence for determining the length of the wheel-soil contact line, which would contain the radius (R) and the tire width (b); the vertical load on the tire (G) and the air pressure in it (p_k); the soil characteristic in the form of the coefficient of volumetric compression (k). The results of theoretical and experimental studies of such a dependence have established that an increase in the contact line length of the wheel with the soil causes an increase in the values of the parameters R and G on the one hand, and a decrease in the values of b , p_k and k parameters on the other. However, to practically implement the functional link of increasing the L_k parameter and subsequently reduce the compaction effect of the wheel on the soil, it is necessary to increase the wheel radius and tire width, while reducing the tire air pressure and the vertical load on the wheel. From an agronomic perspective, it is necessary to create a soil structure with a lower coefficient of volumetric compression.

Key words: vertical load, wheel radius, tire air pressure, tire width, soil volumetric, compression

Introduction

One way to preserve soil fertility is to reduce the specific pressure (q , $N \cdot m^{-2}$) of tractor wheels on the soil [1-3]. For a single wheel, this pressure is the result of dividing its vertical load (G , N) by the supporting area (S , m^2), i.e., $q = G/S$.

In turn, the S parameter depends on the width (B) and the contact length (L_k) of the wheel with the supporting surface. However, while the value of the B parameter is primarily determined by the tire width (b), the situation with L_k it is more complex. As follows from an analysis of studies [4,5], the value of the L_k parameter is determined by many factors. These include the vertical load on the wheel, the tire's width and diameter, and the tire's air pressure. When the wheel moves over a compressible surface, the soil compaction

coefficient, along with its density and hardness, significantly influences the contact length between the wheel and the surface.

Several methods are known for determining the wheel's contact length with the supporting surface, including varying degrees of surface complexity [6]. However, most researchers interpret the contours of this contact as an ellipse [7,8]. The central axis of this ellipse is represented by the L_k parameter. According to Biderman L.V. [9], its value depends directly on the vertical load on the wheel and, conversely, on the tire width and air pressure. To account for tire elasticity and pressure redistribution across the contact patch, Biderman L.V. introduced an additional correction factor. However, it turned out that the complexity of determining the latter for modern tires significantly complicates the practical application of the formula proposed in⁹ for determining the value of the L_k parameter.

Quite often, researchers use the following formula to determine the contact length of a tire with a supporting base [10]:

$$l_{co} = 2 \cdot \sqrt{\Delta z \cdot (2R_o - \Delta z)}(1)$$

where l_{co} – length of the tire contact line with the supporting surface, m; R_o , Δz – rolling radius of the tire and its deflection under vertical load, m.

Since in practice the actual shape of the tire contact imprint with the soil often differs from an ellipse, the researchers modify formula (1) to the following form [11]:

$$l_{co} = K \cdot 2\sqrt{\Delta z \cdot (2R_o - \Delta z)}(2)$$

This equation introduces a K coefficient, which adjusts the l_{co} value to account for the deviation of the actual tire-soil contact shape from an ellipse. In paper [12], this coefficient is intended to account for the tire's ply rating. The use of a similar coefficient is also presented in papers [13-15].

Note that equation (1) can easily be transformed to the form:

$$l_{co} = 2\sqrt{2R_o \cdot \Delta z - \Delta z^2}(3)$$

Further, neglecting the sufficiently small value of Δz^2 , equation (3) is significantly simplified:

$$l_{co} = 2\sqrt{2R_o \cdot \Delta z} = 2\sqrt{D \cdot \Delta z}(4)$$

where D – wheel diameter, m.

This approach was used to determine the contact length between the tire and the soil in the study [16].

In general, the shortcomings of formulas (1)-(4), which significantly limit their application, are as follows. First, they are only suitable for the case of a wheel rolling on a rigid (non-deformable) surface. Second, these equations do not account for many of the parameters mentioned above for both the wheel and the soil. Third, each new tire type requires the determination of its own correction K factor. However, the practical solution to this problem is far from trivial.

Another approach to solving the problem under consideration is demonstrated in article [17]. The authors of this study considered twice the product of the wheel's free-rolling radius and the sine of the arc's central angle, which represents the tire-soil contact line. However, this methodological approach can only be used to solve the problem for a wheel that does not create a track (i.e., a stationary wheel). Moreover, the authors' equation considers only the vertical deformation of both the soil and the tire relative to each other. Other parameters that significantly affect the wheel-soil contact line length are not considered in the proposed analytical relationship.

In addition to analytical methods, experimental methods for determining the parameters of a tire's contact patch on both rigid and deformable (plastic) surfaces have been widely tested in practice [18-24]. Marusiak M. et al. [25] depicted the shape of this patch as a superellipse. The use of this methodological approach is complicated by the need for special gamma functions.

It should be noted, however, that along with their advantages, experimental methods for determining tire-to-base contact length have significant drawbacks. Firstly, conducting such experiments requires expensive equipment, materials, energy, and labor.

Secondly, experimental studies are conducted under specific conditions: soil type, moisture content, density, and hardness. Therefore, even when repeating an experiment, it is often very difficult to achieve identical conditions and good reproducibility of results.

Third, an experiment only records results for a specific range of parameters under study. Because of this, extrapolating data to other scales or conditions (for example, different soil types) is often impossible without a theoretical model. The absence of a latter usually turns experimental data into a "black box," that is, a set of empirical facts.

The most informative model for studying the problem under consideration is the one proposed in paper [26]. The author considers both the tire deflection of a given radius and soil deformation in the vertical direction. However, his proposed analytical expression lacks two crucial factors: the vertical load on the wheel and the tire's air pressure. Furthermore, the formula for determining the wheel-to-soil contact length does not include a single characteristic of the latter. This is a significant drawback.

In connection with the above, this article aim to develop a strategy for selecting the parameters of the tractor chassis system based on the analysis of such an analytical relationship for determining the length of the wheel-soil contact line, which would contain the following parameters: i) the radius and width of the tire; ii) the vertical load on the tire and the air pressure within it; iii) the soil characteristic reflecting its ability to deform (vertical compression).

Theoretical premises

Under the influence of a vertical load G , a wheel of radius R deforms the soil to a depth of h (Fig. 1). The tire's vertical deflection is equal to z .

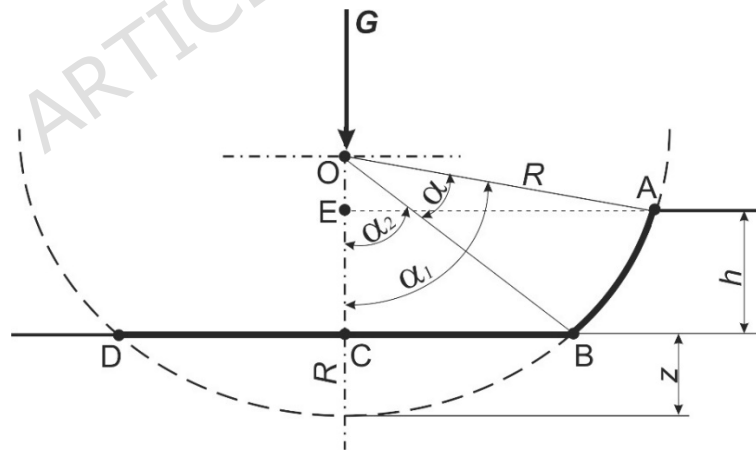


Fig. 1. Diagram for determining the length of the tire contact line with the soil

The contact length of the tire with the soil (L_k) can be presented as the sum of the arc AB and two approximately equal straight-line segments BC and CD :

$$L_k = \overset{\frown}{AB} + BC + CD = \overset{\frown}{AB} + 2BC. (5)$$

The length of the arc AB (see Fig. 1) can be determined by multiplying the tire radius (R) by the difference in central angles $\alpha_1 - \alpha_2$:

$$\overset{\frown}{AB} = R \cdot \alpha = R \cdot (\alpha_1 - \alpha_2). (6)$$

As for the segment BC, it is defined as follows:

$$BC = \sqrt{R^2 - (R - z)^2} = \sqrt{2Rz - z^2}. \quad (7)$$

From the analysis of Fig. 1, it follows that:

$$\left. \begin{aligned} \alpha_1 &= \arctan \frac{AE}{EO} = \arctan \frac{\sqrt{R^2 - (R - h - z)^2}}{R - h - z}; \\ \alpha_2 &= \arctan \frac{BC}{CO} = \arctan \frac{\sqrt{R^2 - (R - z)^2}}{R - z} = \arctan \frac{\sqrt{2Rz - z^2}}{R - z}. \end{aligned} \right\} (8)$$

Taking into account (6)-(8), equation (5) is transformed to the form:

$$L_k = R \cdot \left(\arctan \frac{\sqrt{R^2 - (R - h - z)^2}}{R - h - z} - \arctan \frac{\sqrt{2R \cdot z - z^2}}{R - z} \right) + 2\sqrt{2R \cdot z - z^2} \quad (9)$$

The parameters h and z included in equation (9) can be obtained as follows [27]:

$$h = \sqrt[3]{\frac{G^2}{k^2 \cdot b^2 \cdot 2R}}; \quad z = \frac{G}{2\pi \cdot \rho_k \cdot R} \quad (10)$$

where k – coefficient of volumetric soil compression, $N \cdot m^{-3}$; b – tire width, m; ρ_k – air pressure within tire, Pa.

Ultimately, the analytical relationship (9), taking into account the system of equations (10), represents a theoretical model for calculating and analyzing the length of the tire-soil contact line (L_k). In this model, the wheel, under a vertical load G , is represented by its rolling radius (R), tire width (b), and the air pressure within it (ρ_k). The soil backsoil is characterized by its volumetric compression coefficient (k). **In its physical essence, it is an integrated assessment of the soil's volumetric stiffness, which characterizes the soil mass's force response to a single reduction in its volume under external loading. This coefficient generally takes into account the initial structural state of the soil, changes in its porosity, and compressibility. In practice, its value can be determined using a cylindrical penetrometer.**

Materials and Methods

Methodology for conducting theoretical research

To conduct theoretical studies of model (9) using system of equations (10), the wheels of two physical objects were selected. These include the most common tractors in Ukraine: the KhTZ-16131 (Fig. 2) and KhTZ-17022 (Fig. 3), for which brief descriptions are provided in Table 1.



Fig. 2. Tractor KhTZ-16131



Fig. 3. Tractor KhTZ-17022

Table 1. Tractors' technical specifications

Index	KhTZ-16131	KhTZ-17022
Engine power (kW)	132	132
Weight (kg)	8260	8520
Vertical load on the front axle (kg)	5000	5350
Vertical load on the rear axle (kg)	3260	3170
Tires	16.9R38	23.1R26
Track (mm)	2100	1860
Wheelbase (mm)	2860	2860

As shown in Table 1, the front and rear axles of both tractors are equipped with tires of the same size. The studies measured the contact length of the front wheels (the heavier-load wheels) with the soil.

The fact that the vertical load on the front axles of these tractors differs only slightly allowed us to use the same range of vertical load variation (G parameter) on the wheel under study. The ranges of variation for the remaining parameters included in equations (9) and (10) are shown in Table 2.

The soil volumetric compression coefficient values varied from 3 to 7 $\text{MN}\cdot\text{m}^{-3}$. Variations in this parameter within this range are characteristic of soil conditions throughout virtually the entire territory of Ukraine.

Table 2. Nomenclature of the parameters studied

Parameter	Unit	Value
G	kN	25-27
R	m	0.70-0.80
b	m	0.40-0.61
ρ_k	MPa	0.08-0.16
k	$\text{MN}\cdot\text{m}^{-3}$	3-7

In the process of analyzing the modeling data, the following process chain was considered: " $P \rightarrow L_k \rightarrow S \rightarrow q \rightarrow \rho$ ". The following notations are used here: P is the value of the parameter included in equations (9) and/or (10); L_k is the length value of the tire contact line with the soil obtained from expression (9), m; S is the contact of the tire with the soil, m^2 ; q is the specific pressure of the wheel on the soil, Pa; ρ is the compaction of the soil in the tractor track, $\text{g}\cdot\text{cm}^{-3}$.

The values of the S and q parameters were not determined in this study. The following logical reasoning was used in analyzing the research results. An increase in the L_k parameter, while maintaining the tire width, unambiguously increases the S parameter, and vice versa. An increase/decrease in the S parameter, while maintaining the vertical load on the wheel, unambiguously leads to a decrease/increase in its specific pressure (q) on the soil. This, in turn, ensures a decrease/increase in soil compaction (ρ) in the track formed by the tractor wheel.

The logic of these assumptions has been proven in practice for a long time [28, 29]. This allowed us to abandon the procedure for calculating the values of the S and q

indicators, limiting ourselves to calculating the values of the L_k parameter. This approach fully aligns with the article's aim.

Theoretical calculations using equations (9) and (10) were performed in Mathcad 15.0.

Methodology for conducting experimental research

The KhTZ-16131 and KhTZ-17022 tractors (Kharkiv, Ukraine) were used as physical test subjects. Each was used with both standard tires (see Figs. 2 and 3) and dual tires, designated 23.1R26D (Figs. 4 and 5).



Fig. 4. Tractor KhTZ-16131 with dual tires 23.1R26D



Fig. 5. Tractor KhTZ-17022 with dual tires 23.1R26D

According to the adopted scheme, each of these tractors moved across the field sequentially on 16.9R38, 23.1R26, and 23.1R26D tires.

The field experiments were conducted in a field in the Zaporizhzhia region (Ukraine). The soil was dark chestnut, medium loamy, with a humus content of 2.8% in the 0-20 cm layer. This same layer contained 21.2 mg of total nitrogen, 38.5 mg of phosphorus, and 295.0 mg of potassium per kg of soil.

Soil density was measured at the center of the tracks left by the tractor's front wheels. When using 23.1R26D tires, measurements were taken at the center of the tracks created by one of the inner wheels. This parameter was recorded in duplicate in the 0-10 cm soil layer at 1 m intervals. At least 20 such measurements were taken for each tire type.

To record soil density, we used a measuring kit consisting of a Digital Scale Professional-Mini MS-2020 electronic scale (China), capable of measuring up to 200 grams with an accuracy of 0.01 g, and a density meter we developed (Fig. 6). Its measuring cup has a volume of $V = 28.35 \text{ cm}^3$.



Fig. 6. Kit for measuring soil bulk density

The scales used were set to measure in ounces, with a mass (weight) of 28.35 g. In the classical sense, soil density (ρ) is equal to:

$$\rho = \frac{M}{V}.$$

In our case, the mass of the soil sample collected by the density meter is $M = n \cdot 28.35 \text{ g}$, where n is the scale reading in ounces. The volume of the soil sample is $V = 28.35 \text{ cm}^3$. The result is:

$$\rho = \frac{M}{V} = \frac{n \cdot 28.35 \text{ [g]}}{28.35 \text{ [cm}^3\text{]}} = n \left[\frac{\text{g}}{\text{cm}^3} \right].$$

The resulting expression implies that when a single 28.35 cm³ soil sample is placed on a scale, it yields a reading (in ounces) that corresponds to the soil density (in g·cm⁻³). The resulting soil density data sets were used to calculate statistical characteristics, including the mean, confidence interval, and least significant difference (LSD05), at the 0.05 significance level.

Results and Discussion

Results of theoretical modeling

An analysis of theoretical calculation data shows that increasing the vertical wheel load (G parameter) leads to an increase in the L_k parameter (Fig. 7).

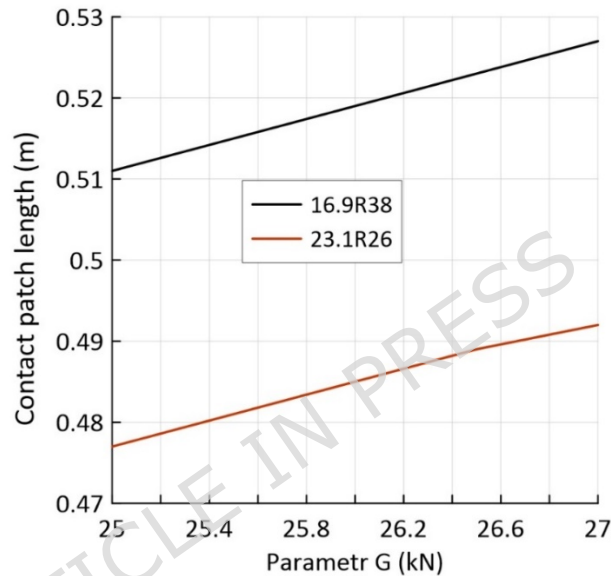


Fig. 7. Dependence of the tire contact line length on the vertical wheel load

Furthermore, the 16.9R38 tire has a 7.1% longer soil contact length than the 23.1R26 tire. This result is explained by the 7.7% larger rolling radius of the former compared to the latter. Note that the dependence $L_k = f(G)$ is practically linear. This result, both qualitatively and quantitatively, agrees with that presented in the study [30]. There, the authors determined the tire-to-soil contact length by digitally analyzing the footprint captured by video cameras.

It should be noted that increasing the L_k parameter leads to an increase in the tire-soil contact area (S parameter). However, there is no decrease in tire pressure (q parameter). On the contrary, the q parameter increases. This is due to the different rates of change (increasing) of the G and L_k parameters. The former has a higher pace than the latter. As follows from the analysis of Fig. 7, the G parameter increases by 8.0%, while the L_k one increases by only 3.1% for both tires: 16.9R38 and 23.1R26. As a result, we have the following: the faster increase in the vertical load on the wheel compared to the increase in the length of the tire-soil contact line causes an increase in pressure on the supporting surface, which is a logical fact.

The rolling radius of a wheel (R) depends on both the tire size and the air pressure (ρ_k). Our specialized research has established the following relationships: $R = f(\rho_k)$:

$$\left. \begin{aligned} R &= 3.40\rho_k^2 - 0.316\rho_k + 0.75 \rightarrow \text{KHz} - 16131; \\ R &= 3.39\rho_k^2 - 0.510\rho_k + 0.72 \rightarrow \text{KHz} - 17022. \end{aligned} \right\} (11)$$

With the value of the ρ_k parameter remaining constant, an increase in the value of the R parameter leads to an increase in the length of the contact line between the tire and the

soil (Fig. 8). Moreover, the intensity of this process is approximately the same for the 16.9R38 and 23.1R26 tires being compared. The former's larger radius leads to a higher L_k value, which is quite logical.

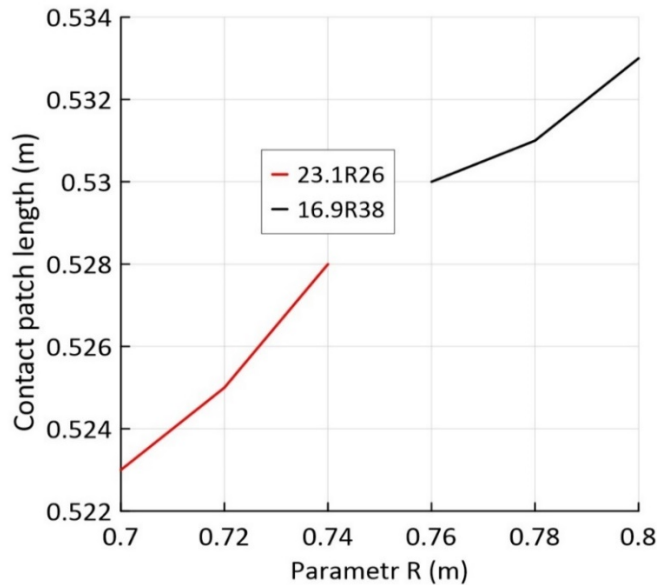


Fig. 8. Dependence of the tire-to-soil contact length on the wheel radius

Ultimately, we observe that an increase in the tire's contact patch length, accompanied by an increase in its rolling radius, results in a corresponding increase in the S parameter and a decrease in the tire's specific pressure q on the soil.

Increasing the tire width (b parameter) leads to a decrease in the value of L_k parameter (Fig. 9). This somewhat counterintuitive result is due to the following: increasing the value of the b parameter reduces the level of vertical soil deformation (h parameter, Fig. 1). This, in turn, leads to a decrease in the length of arc AB (see Fig. 1), and therefore to the reduction in the value of L_k parameter.

It's worth noting that the rate of increase in the b parameter is significantly higher than the rate of decrease in the tire-to-soil contact patch length. For example, for a 16.9R38 tire, a 22.5% increase in its width results in a reduction of the L_k parameter of only 3.8%. For a 23.1R26 tire, a 12.2% increase in the b parameter corresponds to a decrease in the L_k parameter of only 1.6%. Therefore, because the tire width increases faster than the length of its contact patch with the soil, the S parameter will increase. This will ultimately lead to a decrease in tire pressure on the soil.

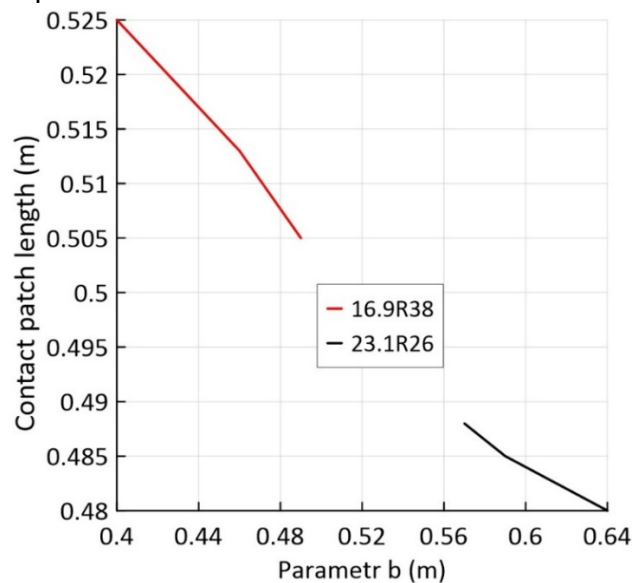


Fig. 9. The dependence of the tire's contact line length on its width

The results of theoretical modeling (black lines in Figs. 10 and 11) indicate that increasing tire air pressure decreases the length of tire-to-soil contact. According to the physics of the process, this effect occurs indirectly, but rather through a change in the wheel's rolling radius (R parameter). The functional dependencies of the latter on the ρ_k parameter are presented above by the system of equations (11). Analysis of these equations reveals that increasing tire air pressure increases the wheel's radius.

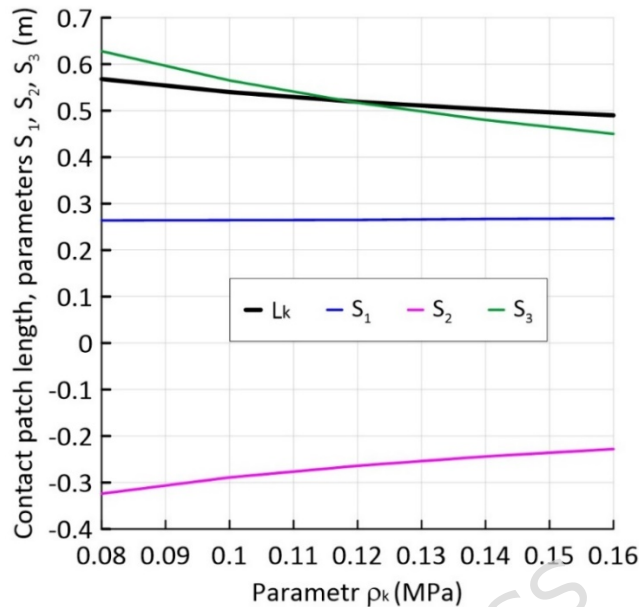


Fig. 10. The dependence of the 16.9R38 tire's contact line length on the air pressure within it

Above (see Fig. 8), we established that an increase in the value of the R parameter causes an increase in the value of L_k parameter. It follows that an increase in tire air pressure through a corresponding increase in its radius should lead to an increase, not a decrease, in the value of L_k parameter.

To analyze such a contradictory result, we divide equation (9) into three terms:

$$S_1 = R \cdot \operatorname{atan} \frac{\sqrt{R^2 - (R-h-z)^2}}{R-h-z}. \quad (12)$$

$$S_2 = R \cdot \operatorname{atan} \frac{\sqrt{2R \cdot z - z^2}}{R - z}. \quad (13)$$

$$S_3 = 2\sqrt{2R \cdot z - z^2}. \quad (14)$$

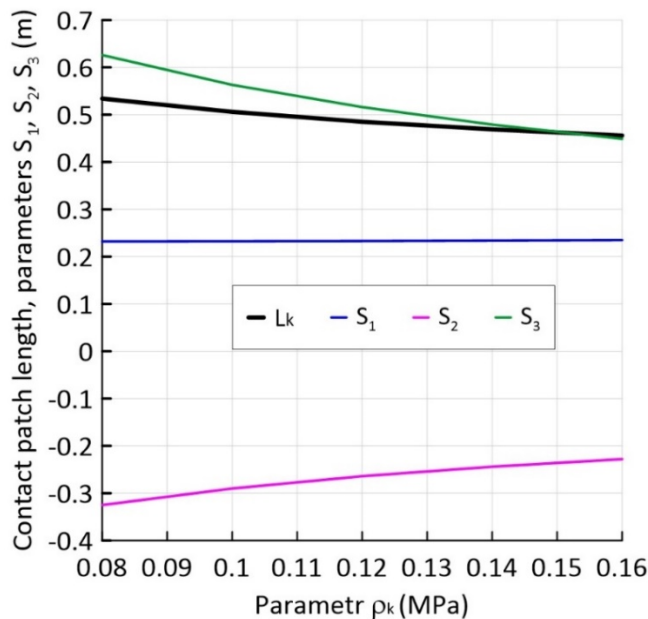


Fig. 11. The dependence of the 23.1R26 tire contact line length on the air pressure in it

Next, we analyze how each of these depends on the tire pressure. Analysis of the obtained results, taking into account dependencies (10), revealed (see Figs. 10 and 11) that term S_1 depends very weakly on changes in the ρ_k parameter. The value of term S_2 increases as the tire pressure increases. At the same time, term S_3 increases more rapidly as the ρ_k value increases over the negative term S_2 . The increase in term S_3 with a growing value for ρ_k parameter is due, as follows from the second equation of system (10), to a decrease in the tire vertical deflection (z parameter). The smaller the z value, the smaller (i.e., shorter) the straight line BD (Fig. 1). As a result, we have a smaller value for L_k parameter. Taking into account the above, we see that ultimately, increasing the air pressure in the tire leads to a decrease in the length of its contact patch with the soil. The pressure of the wheel on the supporting base increases.

It should be noted that a decrease in wheel-to-soil contact length with increasing tire pressure has been observed in studies [30] and [31]. However, these authors' studies do not explain their findings. Their presentation is limited to a summary of the findings.

It's logical to assume that the higher the soil's volumetric compression coefficient (k parameter), the harder the soil. As a result, as follows from the analysis of mathematical modeling data, the tire contact length decreases (Fig. 12).

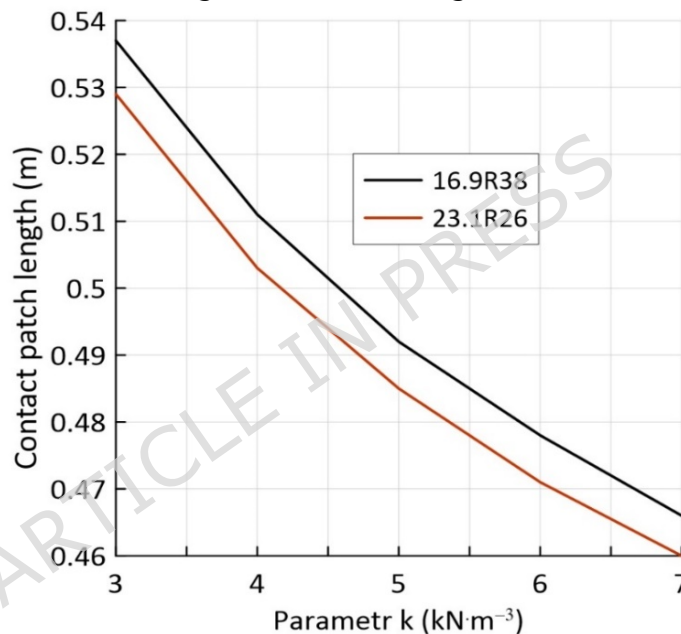


Fig. 12. The dependence of the tire's contact line length on its volumetric compression coefficient

With the same value of the k parameter, the value of the L_k parameter for the 23.1R26 tire is lower. This is explained by the greater width of this tire ($b = 0.59$ m) compared to the width of the 16.9R38 tire ($b = 0.43$ m). As Fig. 9 shows, a larger b parameter corresponds to a shorter tire-to-soil contact length.

In the analysis presented above, the functional link of the form: "change in $L_k \rightarrow$ change in $S \rightarrow$ decrease in q " is of particular scientific interest.

As the calculation results show (Table 3), the practical implementation of such a chain is feasible with varying degrees of variation in the parameters under consideration. To ultimately increase the length (L_k) and area (S) of tire-soil contact, thereby reducing soil compaction (q), the tire radius (R) should be increased and the air pressure inside it (ρ_k) should be reduced. From an agronomic perspective, it is necessary to reduce the soil compression coefficient (k).

Table 3. Results of mathematical modeling

Input parameter	L_k (m)	Output parameter:	
		S (m ²)	q (Pa)
b (m)	(+)	-	+
			-

G (kN)	(-)	-	-	-
R (m)	(+)	+	+	-
ρ_k (MPa)	(-)	+	+	-
k (N·m ⁻³)	(-)	+	+	-

«+» - increase; «-» - decrease

We established above (see Fig. 7) that increasing the vertical wheel load increases the tire-to-soil contact length and soil compaction. With the opposite direction of change in the G parameter (i.e., with its decrease), we will see an opposite trend (see Table 3).

The tire width (b parameter) plays a key role in the process we're studying. As this parameter increases, as established above, the tire-to-soil contact length decreases (see Fig. 9). Since the rate of increase in the b parameter is higher than the rate of decrease in L_k one, this leads to an increase in the S parameter and a corresponding decrease in the q parameter.

It should be noted that the "increase in b parameter \rightarrow decrease in q parameter" process chain will be accompanied by a decrease in soil density in the wheel track. Practical confirmation of this fact is presented below.

Results of experimental studies

Experimental studies were conducted in the Zaporizhzhia region (Ukraine) on an agrotechnical backsoil with a moisture content of 19.6% in the 0-15 cm layer and a bulk density of 1.17 g·cm⁻³. After passing the KhTZ-16131 tractor, the following was obtained (Fig. 13).

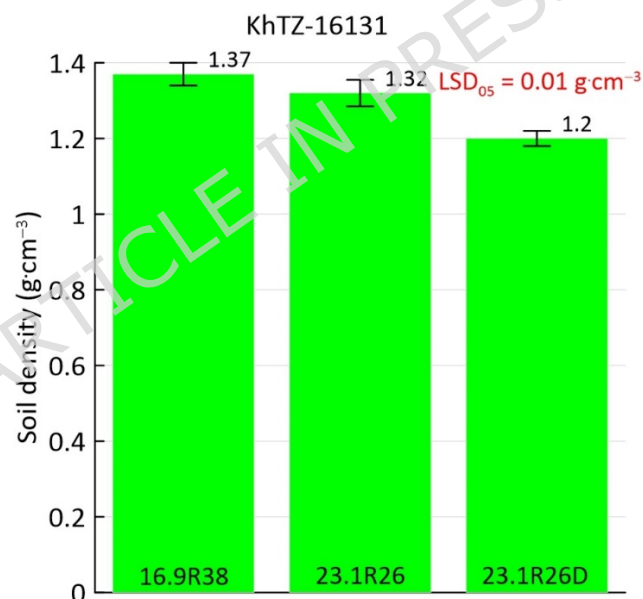


Fig. 13. The influence of the KhTZ-16131 tractor's front wheels on soil compaction

The highest soil density was found in the tracks created by the front axle wheels equipped with single 16.9R38 tires ($b = 0.43$ m). After switching to wider 23.1R26 tires ($b = 0.59$ m), soil compaction decreased by 0.05 g·cm⁻³. However, this is five times greater than the LSD₀₅ value of 0.01 g·cm⁻³. The confidence intervals for the soil density of these two variants partially overlap. However, given the LSD₀₅ value of 0.01 g·cm⁻³, it can be concluded at the 95% confidence level that replacing the standard tires on the KhTZ-16131 tractor with wider ones results in a predictable and significant reduction in soil compaction. It should be noted that partial overlap of the confidence intervals of the mean values does not negate the significance of the difference between them if it is greater than the least significant difference for a given statistical significance level [32-35].

Equipping the KhTZ-16131 tractor with 23.1R26D tires, for which $b = 1.18$ m, further reduces soil compaction in the track from 1.32 to 1.20 g·cm⁻³. This is 0.12 g·cm⁻³ (or 9%)

less than in the version with single 23.1R26 tires. Moreover, in this case, the confidence intervals of the mean soil density values do not overlap (see Fig. 13).

A comparison of the KhTZ-16131 tractor's performance with 16.9R38 and 23.1R26D tires reveals that a 2.74-fold increase in the b parameter (from 0.43 to 1.18 m) results in a $0.17 \text{ g}\cdot\text{cm}^{-3}$ reduction in soil compaction, equivalent to 12.4%. This difference is statistically significant and not due to chance. This conclusion is supported by both $\text{LSD}_{05} = 0.01 \text{ g}\cdot\text{cm}^{-3}$ and the absence of overlapping confidence intervals for the compared mean soil compaction values. **Similar results were obtained in [36].**

Using the KhTZ-17022 tractor yields qualitatively similar but slightly different quantitative results (Fig. 14). Installing narrower 16.9R38 tires on this tractor results in the highest soil compaction (under these study conditions). The mean value reaches $1.40 \text{ g}\cdot\text{cm}^{-3}$. This is $0.06 \text{ g}\cdot\text{cm}^{-3}$ (or 4.5%) greater than when using single standard 23.1R26 tires. Despite the partial overlap of the confidence intervals for the compared mean soil density values, the difference is significantly greater than the $\text{LSD}_{05} = 0.01 \text{ g}\cdot\text{cm}^{-3}$ and is therefore statistically significant.

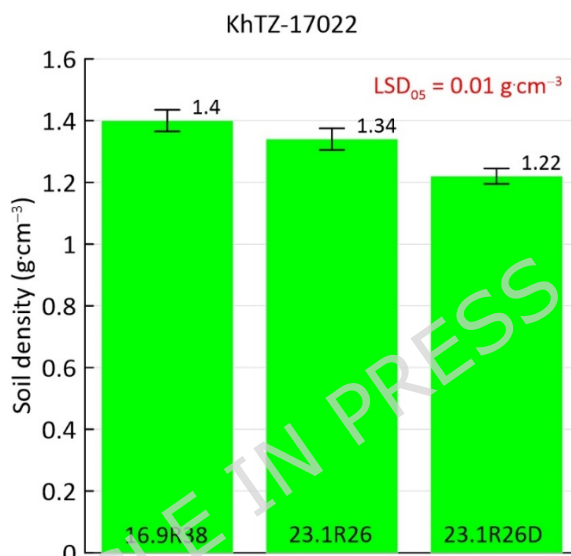


Fig. 14. The influence of the KhTZ-17022 tractor's front wheels on soil compaction

As with the previous variant, using the KhTZ-17022 tractor with dual standard tires resulted in the lowest soil compaction. Under experimental conditions, the density was $1.22 \text{ g}\cdot\text{cm}^{-3}$. This is 8.9% less than with single standard tires and 12.9% less than with relatively narrow 16.9R38 tires.

Research [33], in particular, found that wider tires created a wider but shallower zone with a lower mean compaction level. Subsequently, the compaction caused by wider tires is easier to remove without disturbing the soil layer.

Comparing the tractors yields the following results (see Figs. 13 and 14). When using 16.9R38 tires, the KhTZ-17022 compacts the soil more effectively than the KhTZ-16131. The resulting difference in mean soil compaction values in the tracks is $0.03 \text{ g}\cdot\text{cm}^{-3}$, which is three times greater than $\text{LSD}_{05} = 0.01 \text{ g}\cdot\text{cm}^{-3}$.

When using single and dual 23.1R26 tires, soil compaction by the front wheels of the KhTZ-17022 tractor is also higher than that of the KhTZ-16131 tractor equipped with the same tires. Although the difference between the compared mean compaction values in these cases decreases to $0.02 \text{ g}\cdot\text{cm}^{-3}$, it still exceeds the $\text{LSD}_{05} = 0.01 \text{ g}\cdot\text{cm}^{-3}$. This clearly indicates that the KhTZ-17022 tractor's wheels compact the soil consistently and significantly more than the KhTZ-16131.

The most obvious evidence of this result is that the KhTZ-17022 tractor has a higher vertical load on its front axle wheels. As shown in Table 1, it is 350 kg higher than that of the KhTZ-16131 tractor. As demonstrated above, a higher G value clearly leads to increased soil deformation. **This scientific fact is confirmed in research [37].**

Conclusions

An analytical relationship has been developed for determining the contact patch length of a tire with a supporting surface (L_k). The tire is represented by the vertical load (G), rolling radius (R), tire air pressure (p_k), and tire width (b). The soil volumetric compression coefficient (k) is the supporting surface parameter.

An increase in vertical wheel load increases the tire's contact length with the soil. However, due to the higher growth rate of the G parameter compared to the L_k parameter, the wheel's soil pressure will also increase.

Increasing the rolling radius of a wheel increases the length, and therefore the contact area, of the tire with the soil. As a result, the pressure exerted by the wheel on the soil decreases.

Increasing the tire width reduces the contact length with the soil. The wheel's contact surface area increases due to the faster increase in the b parameter. As a result, the wheel's specific pressure on the soil decreases. Experiments have shown that increasing the tire width of the same tractor by 37% reduces soil compaction by 3.7% to 4.3%. Conversely, doubling the tire width by using dual 23.1R26 tires instead of single ones reduced soil compaction by 8.9-9.1%.

Changing the tire pressure affects the L_k parameter through a corresponding change in the wheel's rolling radius. Therefore, increasing the p_k parameter decreases the L_k parameter, thereby reducing the wheel's contact area (S) and increasing its soil pressure (q).

The higher the soil compression coefficient (k parameter), the greater its hardness, and therefore the shorter the tire contact length (L_k). This results in increased tire-to-soil pressure (q). As the k parameter decreases, the opposite trend in L_k and q will occur.

To practically implement the functional link "increase $L_k \rightarrow$ increase $S \rightarrow$ decrease q ," the wheel radius and tire width should be increased, while the air pressure in the tire and the vertical load on the wheel should be reduced. From an agronomic perspective, a soil structure with a lower coefficient of volumetric compression should be formed.

The vertical load on a tractor's wheels (parameter G) depends significantly on the type and parameters of the agricultural machinery used. Establishing quantitative indicators for this relationship is of scientific interest and, therefore, the subject of further research.

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Conceptualization, V.N., T.H., and G.G.; methodology, V.N., S.G., and V.K.; software, V.N., I.H.; validation, I.H., S.G.; formal analysis, S.D., and V.K.; resources, T.H., W.T.; data curation, S.D., and G.G.; visualization, S.D., W.T.; project administration, V.N.; funding acquisition, S.G.; supervision, T.H. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement:

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Conflicts of Interest:

The authors declare that they have no conflict of interest.

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