INVESTIGATION OF WIDE SPAN VEHICLE TECHNOLOGICAL PART SUSPENSION SYSTEM COMPACTING IMPACT ON SOIL

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Abstract. One of the most important tasks of Controlled Traffic Farming (CTF) was and remains elimination of the compacting effect on the soil in the fruit-bearing zone of the field of the supporting running systems of agricultural machines, acting as a technological part of Wide Span Vehicles. The problem is that if semi-mounted agricultural machines are incorrectly connected to them, there may not be a decrease but, on the contrary, an increase in the compacting effect of the support running systems of the technological part in the fruit-bearing zone of the field. The influence of the parameters of the mounted devices and the connection scheme of the technological part to the Wide Span Vehicle on the compacting effect of its running systems on the soil in the fruit-bearing zone of the field has not been sufficiently studied. The process of redistribution of vertical reactions on the support wheels of the running systems of the technological part of the Wide Span Vehicle from the angles of inclination of the rods of its hinged mechanism remains practically unstudied today. The purpose of the research is to study the compacting effect of the Wide Span Vehicle running systems in the fruit-bearing zone of the field in order to optimally configure its mounting mechanism. Theoretical studies, synthesis of the design diagrams and parameters of the Wide Span Vehicle were carried out by modelling on a PC the conditions of its operation, using the basic principles of theoretical mechanics and tractor theory. Experimental investigations were conducted, using both generally accepted and developed methods, and included the use of modern control and measuring equipment. Processing of experimental data was performed on a PC, using regression analysis. The physical object of the experimental research was Wide Span Vehicles with a track width of 3.5 m. As a result of the research it was established that, in order to ensure a minimum vertical load on the support wheel of the Wide Span Vehicle agricultural machine and, as a result, minimum soil compaction in the fruit-bearing zone of the CTF field, the adjustment of its mounted mechanism should be made with a positive angle of inclination of the central link, which in absolute value must be positive and less than the angle of inclination of the lower links. But, in addition, it is desirable to achieve negative angles of inclination of the lower links of the Wide Span Vehicles linkage mechanism. The installation height of the Wide Span Vehicle linkage also affects the amount of vertical reaction on the support wheel of the agricultural machine. Therefore, in practice the choice of a compromise solution between the values of these parameters should be made according to the proposed algorithm. The work proves that, when designing agricultural machines for their aggregation with Wide Span Vehicles, the longitudinal coordinate of the support wheel installation should be as small as possible. The conducted experimental investigations confirm the adequacy of the theoretical calculations, so they can be used in the design of Wide Span Vehicles or direct adjustment of their mounted mechanisms in production conditions.

Keywords: wide span vehicles, controlled traffic farming, suspension mechanism, soil compaction.

Introduction

Farming, using a permanent tramline, is separation of the movement zones from the plant processing zones [1; 2]. The idea of Controlled Traffic Farming (CTF) is determined by the consequences of resolving the fundamental contradiction in the “propulsion-soil” system the essence of which is that, in order an energy vehicle could achieve high traction properties, its wheels must be in contact with the dry and hard surface of the soil of the technological zone of the field, and for the normal growth of cultivated plants an optimally moist and loose environment is needed [3, 4]. Practically such requirements can be satisfied only when the zones of movement of the energy resources (the technological field zone) and the plant growth zones (the agrotechnical fruit-bearing zone of the field) are clearly demarcated on the field.

An analysis of the relevance and prospects for the implementation of CTF in the world has established that the use of the Wide Span Vehicles (WSV), specially created for this purpose, is characterized by their high potential technological properties [5; 6]. The technological properties of WSV, as a whole, are completely determined by the requirements of the technological process.

From a position of high versatility, any WSV should be aggregated with almost all trailed, semi-mounted and mounted agricultural machines. In addition, the technological part of the Wide Span Vehicle, regardless of the method of its aggregation, can have support wheels that are located in the fruit-bearing zone of the field. The problem is that, if the technological part of WSV is incorrectly connected, the vertical load on the support wheels of the agricultural machines, aggregated with it, located, as a rule, in the agrotechnical fruit-bearing zone of the field, can be significantly increased. Because of this, as a result of the excessive compaction effect of the suspension systems of the machines on the soil, the entire effect of CTF may be reduced to zero.

The existing world experience in aggregating WSVs has shown the possibility of using three-point mounted devices on them [7; 8]. The study of the design features of these mounted devices, when used on WSV, is practically not covered in the scientific literature. Besides, it is known that the inclination angles of the central and the lower links of its mounted mechanism have a significant impact upon the redistribution of normal reactions on the wheels of a traditional tractor [9; 10]. The very nature of the redistribution of normal reactions on the tractor wheels is determined by the design parameters of its mounted mechanism and the agricultural machine. aggregated with it. Using the existing scientific and practical experience of a traditional machine-tractor aggregate [11; 12] to analyze the nature of changes in vertical reactions on the wheels of WSV suspension systems is impossible due to its atypical layout. In this regard the issue of energy assessment [13] of these energy means during their design and operation, as well as the selection of parameters of their mechatronic systems [14], remain problematic.

Therefore, the issue of studying the impact of the parameters of the WSV suspension mechanism and the scheme of connection to the technological part to it upon the nature of the change in vertical loads on the wheels of its supporting suspension systems is relevant.

Materials and methods

To conduct experimental studies, a prototype Wide Span Vehicle (Fig. 1) with a wheelbase width of 3.5 m was used. The studies were carried out using both generally accepted and developed methods.

Fig. 1. **Experimental Wide Span Vehicle**

The pressure on the soil, which is created by the pneumatic support wheel of the suspension system of the WSV agricultural machine, was determined by expression:

$$\sigma = \frac{N_k}{F_k}, \tag{1}$$

where N_k – vertical load, acting upon the support wheel of the suspension system of the WSV agricultural machine;

F_k – area of the supporting surface of the wheel of the suspension system of an agricultural machine, aggregated with WSV, which can be determined with sufficient accuracy [15]:

$$F_k = \pi \cdot H_z \cdot \sqrt{(D - H_z) \cdot (B - H_z)}, \tag{2}$$

where D – static tire diameter;

B – tire profile width;

H_z – depth of penetration into the soil of the wheel of an agricultural machine, aggregated with WSV, which can be determined with sufficient accuracy from expression [15]:

$$H_z = \frac{N_k}{\pi \cdot \rho_w \cdot \sqrt{D \cdot B}}, \tag{3}$$

where ρ_w – wheel air pressure.

The physical and mechanical properties of the soil in the fruit-bearing zone of the field were measured in a layer thickness of 0-20 cm. Based on our observations, it was found that the soil density and hardness in the fertile zone of the field have a fairly high correlation, so the compaction effect was assessed by the hardness indicator in the wheel tracks of the technological part of the Wide Span Vehicle. To determine the hardness of the soil, a hardness tester of the Revyakin system was used. The experimental research was performed in the same seasonal short period of time, so the soil moisture was practically constant. The value of the soil moisture was measured using the standard thermostat-gravimetric method. The soil moisture content in the fertile zone of the field was 21.2 ± 1.5%. The error of the experimental measurements did not exceed 12%.

To draw up the equilibrium condition for the Wide Span Vehicle in the longitudinal-vertical plane, we will consider it as a solid physical body that has a longitudinal plane of symmetry, passing through its centre of mass. With an agricultural machine, aggregated with it, let us present it on the design diagram in the form of a flat equivalent model (Fig. 2). For further analysis we will accept the following assumptions.

1. Let us imagine the mounted agricultural implement of the WSV technological part as one “equivalent” working body. We will concentrate the horizontal (R_x) and vertical (R_z) components of its traction resistance in the “centre of resistance”, point π (Fig. 2).
2. The support wheels that the WSV technological part may have, are represented in the diagram by one “equivalent” support wheel (Fig. 2).
3. Changing the installation coordinate of the support wheel of a mounted agricultural implement (D_k) has little effect on the longitudinal coordinate a_T of its center of mass (Fig. 2).

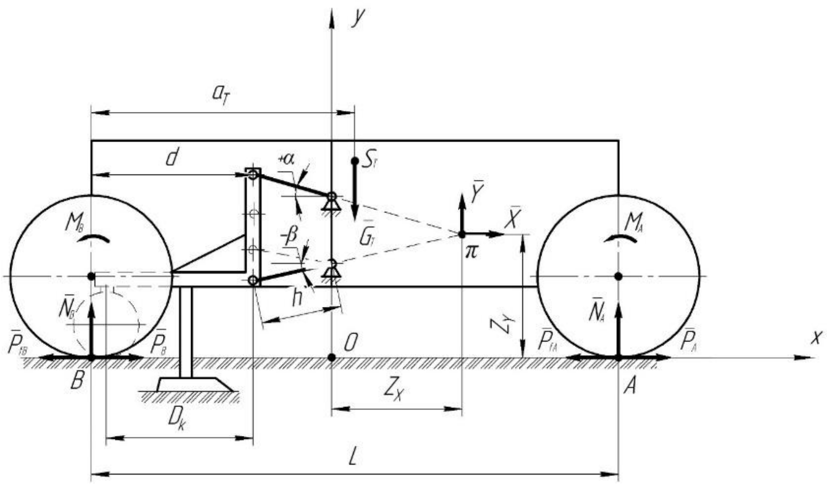

Fig. 2. **Diagram of forces and moments that act upon a Wide Span Vehicle in a longitudinal-vertical plane**

4. The coordinates of the instantaneous centre of rotation of the mounted WSV device (Z_X and Z_Y) (Fig. 2) during its movement change in time. But, since the trend of their oscillations is small, this practically does not affect the nature of the redistribution of vertical loads on the front and rear wheels of WSV; so they (the coordinates) are assumed to be constant.
5. The centre of resistance of the mounted agricultural machine and its centre of mass coincide.

From the results of studies of functioning of WSV, it follows that the placement of the mounted mechanism on it should be as close as possible to its centre of mass [16, 17]. Based on the analysis of the design diagrams of the mounted mechanisms and the parameters of their placement on WSV, it is advisable to consider all the possible options for attaching the mounted agricultural implements. Of the possible options for attaching machines and implements to WSV, the angles of inclination of the central (α) and lower (β) rods of its hinged mechanism can be either positive or negative, or equal to zero.

Therefore the WSV hitch, depending on the angles of inclination of its central and lower links, can have six options for its settings (Fig. 3).

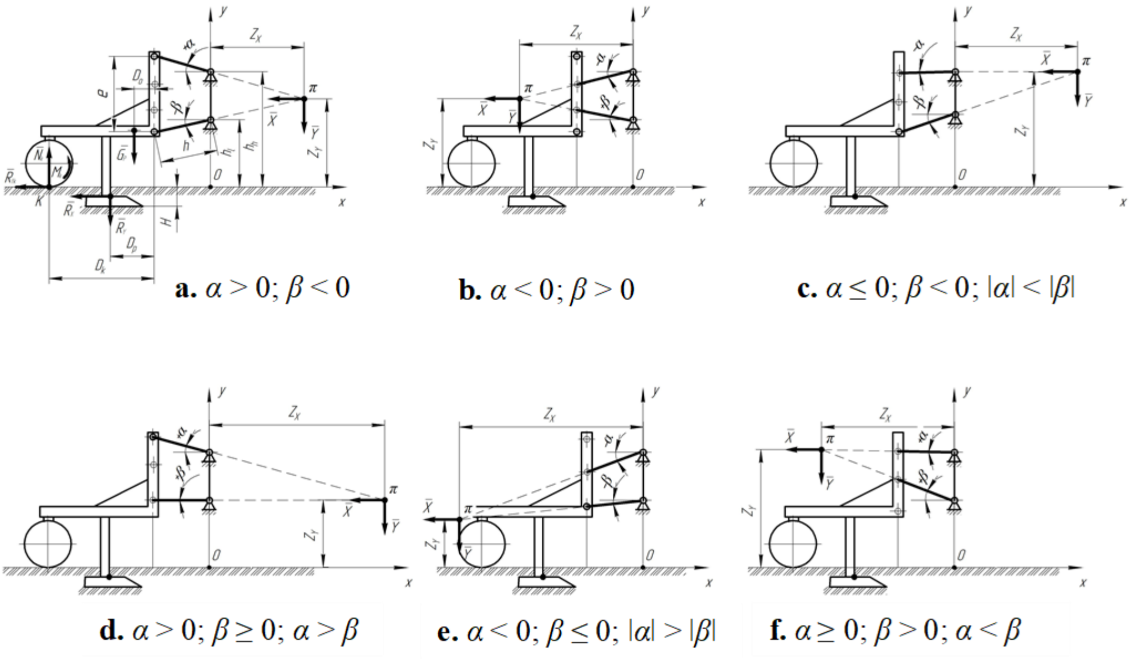

Fig. 3. **Wide Span Vehicle attachment setup diagrams**

Depending on the values of angles α and β of inclination, respectively, of the central and the lower link of the Wide Span Vehicle attachment, the coordinates of its instantaneous centre of rotation π (Z_X and Z_Y) from Fig. 3.a can be expressed through its design parameters:

$$Z_X = \frac{h_h - h_l}{\tan\alpha - \tan\beta}, \quad Z_Y = h_l - \frac{(h_h - h_l)\cdot\tan\beta}{\tan\alpha - \tan\beta}, \tag{4}$$

where Z_X, Z_Y – longitudinal and transverse coordinates of the instantaneous centre of rotation of the WSV hitch;

h_h, h_l – design parameters of WSV, the nature of which is clear from Fig. 3.a.

To determine the vertical reaction N_k on the equivalent support wheel of the technological part of WSV, three independent equations of its equilibrium are sufficient:

$$\begin{gathered} N_k - G_P - R_Y - Y = 0; \\ -P_{fk} - R_X + X = 0; \\ \pm G_P\cdot(D_0 + h\cdot\cos|\beta| + Z_X) \pm R_Y\cdot(D_P + h\cdot\cos|\beta| + Z_X) \pm \\ \pm N_k\cdot(D_k + h\cdot\cos|\beta| + Z_X) \pm P_{fk}\cdot Z_Y \pm R_X\cdot(Z_Y + 0.5H) - M_k = 0, \end{gathered} \tag{5}$$

where H – soil tillage depth;

G_P – weight of the agricultural machine;

R_X, R_Y – horizontal and vertical components of the traction resistance of an agricultural machine;

P_{fk}, M_k – force and moment of the rolling resistance of the support wheel of an agricultural machine;

D_0, D_P, D_k – design parameters of an agricultural machine, the nature of which is clear from Fig. 3.a.

The " + " sign in the third equation of system (5) is placed in the case when the acting forces form a moment relative to point π, the direction of which coincides with the clockwise direction, otherwise the "–" sign is placed.

To determine two unknown reactions X and Y of the WSV (Fig. 2), it is enough to create two equations of the system:

$$N_A + N_B - G_T + Y = 0;$$
$$-N_A \cdot L + G_T \cdot a_T - M_A - M_B \pm Y \cdot (Z_X + h \cdot \cos|\beta| + d) \pm X \cdot Z_Y = 0, \quad (6)$$

where G_T, a_T – weight of WSV and the horizontal coordinate of its centre of mass;
M_A, M_B – rolling resistance moments of the front and rear wheels, respectively;
L – wheelbase of WSV;
d – distance from the mounted mechanism of an agricultural machine to the axis of the rear wheels of WSV;
h – length of the lower link of the WSV hitch.

The choice of the “ + ” or “–” sign before the last two terms in the second equation of system (6) depends on the position of the instantaneous centre of rotation of the attachment (point π) WSV relative to point B (Fig. 2). If the moment, formed by the reactions X and Y is in a clockwise direction, then the “ + ” sign is placed, otherwise “–”.

After determination of reactions X and Y from system (6), you can determine the value of the unknown reaction N_k from system (5). Systems of equations (5) and (6) make it possible to determine the optimal values of both the inclination angles of the linkages of the mounted device and other design parameters of WSV from the position of the lowest value of the reaction N_k of its equivalent support wheel to the soil.

Results and discussion

Taking into account the possible ranges of inclination angles of the central α and the lower link β of the WSV mounted mechanism (Fig. 1), the results of theoretical studies show that, on the whole, with an increase in the angle α, the vertical reaction on the plough support wheel increases (Fig. 4).

The intensity of the compaction process upon the soil of an equivalent support wheel of the technological part of WSV practically does not depend on the angle of inclination of the lower links (β) of its mounted mechanisms (Fig. 4). At the same time, the value of this parameter quite significantly affects the magnitude of the force N_k. First, as β decreases, it increases linearly proportionally. Second, when the angle of inclination of the lower links of the WSV linkage mechanism is negative and is -20 deg, and the angle of inclination of the central link is also negative and is at the level of -30 deg, the equivalent support wheel of the agricultural machine is completely unloaded (Fig. 4).

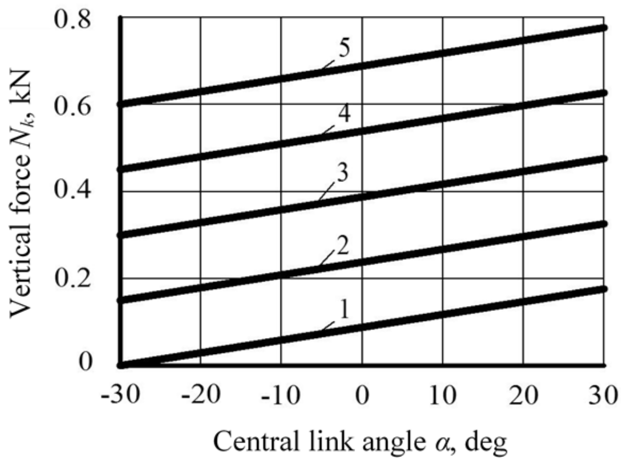

Fig. 4. **Dependence of the vertical reaction on the equivalent support wheel of the Wide Span Vehicle agricultural machine upon the angle of inclination of the central link (α) and various angles of inclination of the lower links (β) of its mounted mechanism:**
1. β = –20 deg; 2. β = –10 deg; 3. β = 0 deg; 4. β = 10 deg; 5. β = 20 deg

As it is evident from Fig. 4, to configure the Wide Span Vehicle attachment mechanism, the choice of the inclination angles of the central and lower links of its attachment mechanism should be carried out taking into account their negative values.

Now let us analyse how the vertical coordinates of the fastening of the central (h_h) and the lower (h_l) links of the mounted WSV mechanism affect the nature of the change force N_k. By calculating dependence (5) it has been established that this character significantly depends on the direction and magnitude of the inclination of the links of the mounted mechanism (Fig. 5). Thus, in the setting option of the WSV attached mechanism, where the angles of its links have values $\alpha \geq 0$; $\beta > 0$; $\alpha < \beta$, then in this case with an increase in the parameter h_l from 0.4 to 1.0 m, the value of the vertical reaction upon the plough support wheel decreases practically by the same number of times (Fig. 5). At the same time, increasing the coordinate h_h of the height of the central link of the WSV attached mechanism, we have an opposite result.

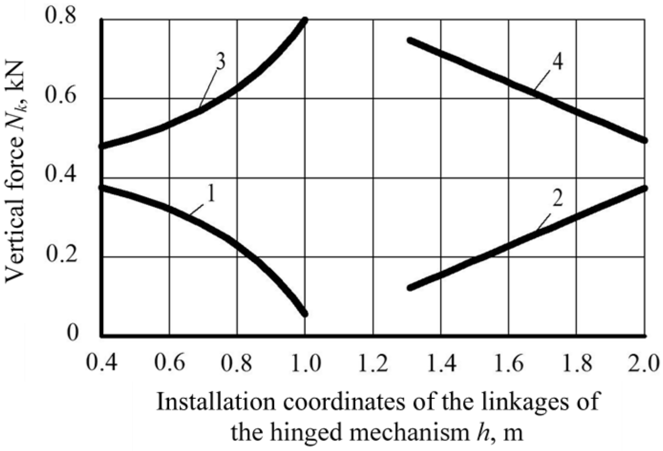

Рис. 5. **Dependence of the vertical reaction on the equivalent support wheel of the WSV agricultural machine on the height of the links of the attachment mechanism:**
1, 2 – $\alpha \geq 0, \beta > 0, \alpha < \beta$; 3, 4 – $\alpha < 0, \beta \leq 0, |\alpha| > |\beta|$; 1, 3 – h_l; 2, 4 – h_h

Installing the central link of the WSV linkage at a greater angle than the lower ones, i.e. in the case where $\alpha < 0$; $\beta \leq 0$; $|\alpha| > |\beta|$, shows the opposite nature of the dependences of the vertical load on the wheel of an agricultural machine depending on the vertical coordinates of the installation of the central (h_h) and lower (h_l) links of the mounted mechanism (Fig. 5).

In practice the choice of a compromise solution between the options for the parameters h_h and h_l of the Wide Span Vehicle mounted mechanism should be carried out as follows. First, for its mounted mechanism, select the h_h coordinate for fastening of the central link of its mounted mechanism. Next, from the dependence $N_k = f(h_h)$ (Fig. 5), we determine the vertical reaction on the support wheel of an agricultural machine at the accepted value of the installation coordinate of the central link of the mounted mechanism. Second, based on the obtained significance of the force N_k from the dependence $N_k = f(h_l)$ (Fig. 5), we determine the vertical coordinate of the installation of the lower links of the WSV mounted mechanism. Then with the selected values of h_h and h_l and the accepted angles of inclination of the links α и β of its mounted mechanism, we set the distance e between the fastening of the central and lower rods on the agricultural machine. Only in this case it is possible to ensure the least compacting effect of the support wheel of the WSV technological part on the soil in the fruit-bearing zone of the field.

Let us analyse how the dynamics of changes in the force N_k are affected by the placement of the support wheel of the Wide Span Vehicle agricultural machine, in particular, the longitudinal coordinate of the installation of the support wheel D_k (Fig. 6).

By the research it has been established that, changing the longitudinal coordinate D_k the vertical reaction N_k on the equivalent support wheel of a WSV agricultural machine, although not significantly, changes depending on the setting of the links of its mounted mechanism. In qualitative terms, an increase in the parameter D_k causes an increase in the force N_k in the option of setting the links of the mounted mechanism $\alpha \geq 0, \beta > 0, \alpha < \beta$. And vice versa, it decreases in the variant $\alpha < 0, \beta \leq 0, |\alpha| > |\beta|$. Therefore, with a positive inclination of the links of the WSV mounted mechanism, the longitudinal installation coordinate of the support wheel of its technological part should be as small as possible.

The obtained result should be taken into account when analysing the dynamics of WSV motion in a horizontal plane. Because with increasing the vertical load on the support wheel of a WSV agricultural machine, the rolling resistance force increases. At the same time, the characteristic lateral displacements of the WSV agricultural machine increase the area of the soil compaction in the fruit-bearing zone of the field and increase the wear rate of the tires of its support wheels. In any case, the smaller this load, the better it is in terms of the sealing effect of the suspension systems of the WSV technological part and their technical reliability.

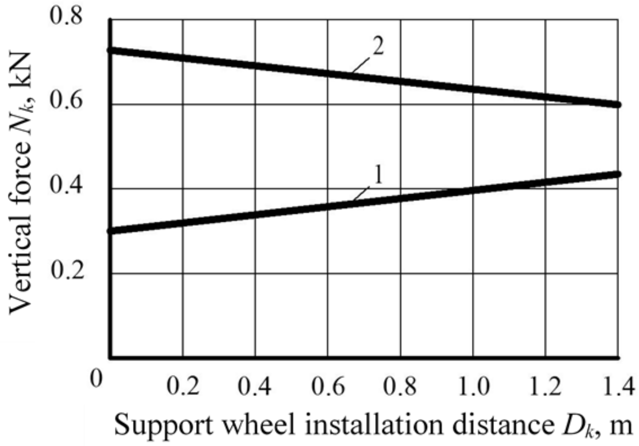

Fig. 6. **Dependence of the vertical reaction on the equivalent support wheel of the agricultural machine WSV on the installation coordinates of the support wheel of its technological part at various settings of the mounted mechanism:** 1 – $\alpha \geq 0$, $\beta > 0$, $\alpha < \beta$; 2 – $\alpha < 0$; $\beta \leq 0$, $|\alpha| > |\beta|$

The results of the theoretical research are confirmed by experimental studies. As a result of experimental investigations the soil hardness was measured in the fruit-bearing zone of the field after passing WSV with a semi-mounted tillage implement having various settings of the links of its mounted mechanism. Besides, after setting up the mounted mechanism, the angles of inclination of its central α and lower rods β were measured. Based on these values and other parameters of the soil tillage implement and WSV, according to dependence (5) the vertical reaction N_k on the support wheel of the agricultural machine was calculated. Based on the obtained value N_k, the pressure on the soil σ, which is created by its pneumatic support wheel, was calculated according to dependence (1). In addition, the hardness of the soil was experimentally measured after passage of the WSV. As a result, we have a dependence of the measurement of the soil hardness in the fruit-bearing zone of the field upon pressure σ , created by the pneumatic wheel of the Wide Span Vehicle agricultural machine (Fig. 7).

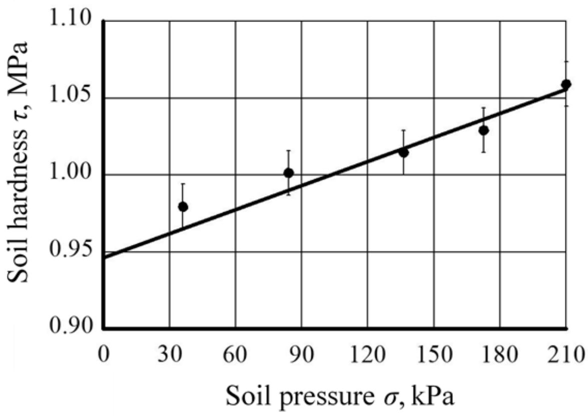

Fig. 7. **Dependence of experimental determination of the soil hardness in the range of absolute error on the pressure on it, created by the support wheel of the technological part of the Wide Span Vehicle**

From the analysis of Fig. 7 it follows that with an increase in pressure on the soil σ, created by the support wheel of the WSV agricultural machine, the hardness of the soil in its upper layer also increases. The obtained result confirms the adequacy of the study, and it may be used when designing WSV or directly setting up its mounted mechanism under production conditions.

In order to practically completely eliminate the compacting effect on the soil of the suspension systems of the technological part of the Wide Span Vehicles in the fruit-bearing (agrotechnical) zone of the field under operating conditions, it is recommended to use regulators to adjust the normal vertical load on the support wheels of the semi-mounted agricultural machines, aggregated with them.

Conclusions

1. To ensure minimal vertical load on the support wheel of the technological part of the Wide Span Vehicle and, as a consequence, minimal soil compaction in the fruit-bearing zone of the CTF field, the adjustment of its mounted mechanism should be performed with a positive angle of inclination of the central link, which by its absolute value should be less than the inclination angle of the lower links. The same result can be achieved with negative angles of inclination of the lower links of the Wide Span Vehicle linkage mechanism.
2. With an increase in the installation height of the lower links of the WSV mounted mechanism, the value of the vertical reaction on the support wheel of its technological part decreases proportionally. Increasing the coordinates of the installation height of the central link of the Wide Span Vehicle mounted mechanism, we have an opposite result. At the same time, at negative angles of inclination of the central and lower links of the WSV mounted mechanism, we have the opposite indicated nature of dependencies. Therefore, in practice the choice of a compromise solution to justify the coordinates of the heights of fastening the links on the WSV mounted mechanism is recommended to be carried out according to the algorithm, proposed in this work.
3. A comparative analysis of the schemes for connecting agricultural machines to WSV showed that with a change in the longitudinal coordinate of the installation of their support wheels, the vertical reaction on it, although not significantly, changes depending on the setting of the linkages of the mounted mechanism. In qualitative terms the removal of the support wheel of the technological part from the attachment points of the linkages of the WSV linkage mechanism causes an increase in this force in the option of setting the linkages of the linkage mechanism at positive angles. And vice versa, it decreases when it is configured at negative angles of inclination of its central and lower links. Therefore, when designing agricultural machines for their aggregation with WSV, the longitudinal coordinate of installation of their support wheels should be as small as possible.
4. The experimental studies carried out confirm the adequacy of the theoretical calculations. The results of measuring the soil hardness in the fruit-bearing zone of the field showed a decrease in this indicator from the decrease in the analytically obtained pressure on the soil, created by the support wheel of the WSV agricultural machine.
5. The results of the research can be used in the design of WSV or the direct adjustment of its mounted mechanisms under production conditions.

Author contributions

Conceptualization, V.B., A.R.; methodology, I.H. and V.A.; software, V.T.; validation, A.A., V.A., O.C, and V.B.; formal analysis, V.B., A.R., O.C. and V.Ku.; investigation, V.B., V.A., V.Ky, V.Ku. and V.T.; data curation, A.A., V.B. and A.R.; writing – original draft preparation, V.B.; writing – review and editing, A.A., A.R. and V.B.; visualization, V.T. and V.Ky.; project administration, V.B.; funding acquisition, A.R. and A.A. All authors have read and agreed to the published version of the manuscript.

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