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Theoretical Study of Transverse Offsets of Wide Span Tractor Working Implements and Their Influence on Damage to Row Crops

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Abstract: Wide span tractors have a wide transversal bar, on which different implements can be mounted, while the supporting wheels follow the set traffic-lanes. The stability of wide span tractor movement is influenced by unbroken small angular deviations and transversal displacements of the machine due to several factors. These deflections from the set trajectories affect the working implements, especially the peripheral ones, which can cut the plants if wide span tractors are used to manage row crops. In this context, it needs to consider a safeguard zone that allows to reduce the probability of contact between working implements and plants. The aim of this paper was to determine the quantitative effect of transverse displacements of the working implements and the suitable size of the aforesaid safeguard zone. The magnitude of the inner and outer displacements of the working implements depends significantly on their location in relation to the center of the wide span tractor. For working implements located outside the center of the tractor, the outer safeguard zone should be larger than the inner zone. The probability of crop damage by working implements can be reduced by automated control of wide span tractor movement.

Keywords: controlled traffic farming; wide span tractor; row crop damage; theoretical modeling

1. Introduction

In recent years, the aim to improve the efficiency of agricultural operations has increased the size and weight of agricultural machinery and in-field traffic [1], causing greater soil compaction [2–4]. Traffic-induced soil compaction can be avoided using controlled traffic farming (CTF), in which cropping areas are clearly and permanently separated from traffic-lanes [5–7]. With CTF, tractor wheels do not come into contact with the cultivation area, but increasingly compact the traffic-lanes, thus improving draught efficiency [8–11]. Wide span tractors are usually used in CTF because of their undeniable advantages over traditional tractors and machine-and-tractor aggregates [12–15]. This type of tractor can be used in operations from sowing to crop management (mechanical weeding, fertilization and so on); it has a wide transversal bar, on which different working implements can be mounted, while the supporting wheels follow the set traffic-lanes [16,17].

Several factors affect the stability of the movements of wide span tractors used in CTF, including the uneven resistance of the soil, the forward speed, and the resistance forces that develop during cornerings [18–20]. The magnitude of these factors changes constantly, causing continual small angular deviations and transversal displacements of the tractor [21]. Furthermore, the track is several times wider than the wheelbase of this type of tractor, so that the angular and transversal deviations cause considerable displacement of the working implements, especially the most peripheral ones, i.e., those farthest from the center of the machine [19,22]. When wide span tractors are used to manage row crops, these deflections from the set trajectories mean that the working implements, especially the more peripheral ones, can cut and damage the crop plants. In this case, the operative efficiency of wide span tractors is strictly correlated to the amount of crop plants damaged by the working implements [19,21]. Their transverse deflection must be reduced to a minimum in order to obtain better quality working conditions, although there is no doubt that the accidental non-alignment of plants along the rows also has a significant effect on the amount of the damage caused by these tractors. Therefore, the continual transverse displacements of the wide span tractor and the random non-alignment of the plants along the row increase the probability of working implements damaging the crop plants. In this context, there is a need for a safeguard zone large enough to reduce the probability of contact between tractor implements and crop plants. The aim of this paper was to establish the mathematical relationships concerning the quantitative effect of transverse displacements of the working implements and to evaluate the probability of such contacts within the safeguard zone. Furthermore, it used a statistical approach to assess the size of the safeguard zone that reduces the probability of working implement-plant contact below a set value.

2. Material and Methods

2.1. Kinematic Considerations

Kinematic analysis was performed on the transverse shifts of the working implements caused by the continuous small angular deviations and transversal displacements of a wide span tractor moving at constant speed along a technological track [23–25]. The wide span tractor system with six implements (coulters) mounted on its transversal bar is shown in Figure 1. The total displacement of each coulters consists of the displacement X_s of the center of the wide span tractor (i.e., S in Figure 1) from the set trajectory of motion and its own deflection due to the angular deviation φ of the tractor. Obviously, the intensity of total displacement increases together with the distance from the center of the tractor, so that the most peripheral coulters undergoes a more marked deflection (Figure 1).

As for the traditional tractor-implement aggregates, opposite angular deviations of the tractor of the same magnitude produce corresponding "outer" and "inner" deviations of the implement, with different magnitudes [26]. It is likely that the same occurs for wide-span tractors, so that every working implement attached to the wide span of the tractor will be subject to different "outer" and "inner" deviations corresponding to the equal but opposite angular deviations of the tractor.

Considering point A of the coulters (Figure 1), its kinematic "inner" displacement α_φ^i caused by the angular deviation of the wide span tractor can be evaluated with the following (Figure 1) [23,24]:

$$\alpha_\varphi^i = x \sin(\gamma + \beta) = x (\sin \gamma \cdot \cos \beta + \cos \gamma \cdot \sin \beta) \quad (1)$$

where $x = KA = AK_1$ (Figure 1) — deviation of the coulters; γ — angle, depending on the design parameters of wide span tractor (b , l); β — angle, depending on the magnitude of the angular deviation of the wide span tractor.

Similarly, the kinematic "outer" displacement α_φ^e of the coulters is evaluated with the following [23,24]:

$$\alpha_\varphi^e = x \cos(\gamma + \beta) = x (\cos \gamma \cdot \cos \beta - \sin \gamma \cdot \sin \beta) \quad (2)$$

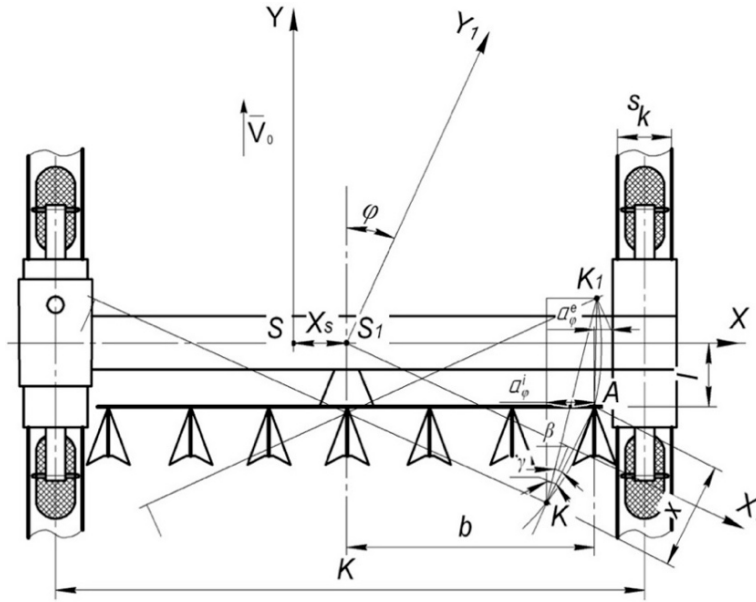


Figure 1. Transverse displacements of the wide span tractor and its working implements (coulters).

2.2. Statistical Approach

Considering the wide span tractor in Figure 1 and its uninterrupted small angular deviations and transversal shifts from the set direction during constant motion along a technological track, it is assumed that curves 1 and 2 in Figure 2 represent the respective probability densities of: i) the transverse displacements of an individual coulters from its set trajectory of movement $Y_d - Y_d$; ii) the placements of plants relative to the axis of the row $Y_r - Y_r$. Segment Z is the zone where there is the probability of the presence of the coulters $p(X_{oz})$ and the probability that plants will be in the coulters' trajectory of movement due to their non-alignment along the row $p(X_{rz})$.

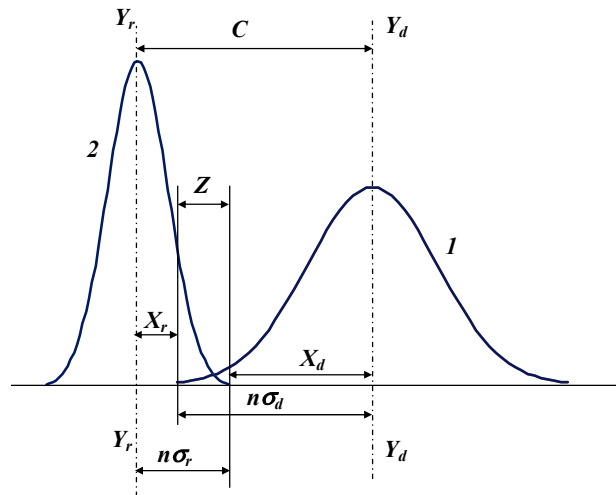


Figure 2. The probability density function of the transverse displacements from the given direction of coulters movement 1 and plant position 2.

Thus, the probability of plant damage $p(D_z)$ in zone Z can be evaluated according to the theorem that states the probability of the simultaneous occurrence of two independent events [27]:

$$p(D_z) = p(X_{oz} \cdot X_{rz}) = p(X_{oz}) \cdot p(X_{rz}) \tag{3}$$

If zone *C* is sufficiently wide, so that curves 1 and 2 in Figure 2 do not intersect (Figure 2), then zone *Z* is absent and the coulter causes no plant damage.

The value of the edges for X_r and X_d of zone *Z* can be evaluated with the following:

$$\begin{aligned} X_r &= C - n\sigma_d \\ X_d &= C - n\sigma_r \end{aligned} \tag{4}$$

where σ_d and σ_r , respectively, are the standard deviations of the transverse displacements of the coulter and standard deviations of the different non-aligned positions of plants in the row; $n\sigma_d$ and $n\sigma_r$ are the limits of deviations, where the value n can be 3 with sufficient accuracy; C is the value of the safeguard zone. The probability of finding the coulter $p(X_{oz})$ inside zone *Z* can be assessed with the distribution functions $F_{X_{oz}}(n\sigma_d)$ and $F_{X_{oz}}(X_d)$ and the probability density function $f_{X_{oz}}(u)$ [27]:

$$\begin{aligned} p(X_{oz}) &= p(X_d < X_{oz} < n\sigma_d) = F_{X_{oz}}(n\sigma_d) - F_{X_{oz}}(X_d) \\ &= \int_{-\infty}^{n\sigma_d} f_{X_{oz}}(u)du - \int_{-\infty}^{X_d} f_{X_{oz}}(u)du \end{aligned} \tag{5}$$

In a similar way, the probability of finding non-aligned plants in a row $p(X_{pz})$ inside the same zone *Z* can be evaluated with the distribution functions $F_{X_{pz}}(n\sigma_r)$ and $F_{X_{pz}}(X_r)$ and the probability density function $f_{X_{pz}}(u)$:

$$\begin{aligned} p(X_{pz}) &= p(-n\sigma_r < -X_{pz} < -X_r) = F_{X_{pz}}(-X_r) - F_{X_{pz}}(-n\sigma_r) \\ &= \int_{-\infty}^{X_r} f_{X_{pz}}(u)du - \int_{-\infty}^{n\sigma_r} f_{X_{pz}}(u)du \end{aligned} \tag{6}$$

Substitution of Equations (5) and (6), taking into account of Equation (4) into Equation (3) gives:

$$p(D_Z) = \left[\int_{-\infty}^{n\sigma_d} f_{X_{oz}}(u)du - \int_{-\infty}^{C-n\sigma_r} f_{X_{oz}}(u)du \right] \cdot \left[\int_{-\infty}^{-(C-n\sigma_d)} f_{X_{pz}}(u)du - \int_{-\infty}^{-n\sigma_r} f_{X_{pz}}(u)du \right] \tag{7}$$

For a Gaussian distribution, Equation (7) can be rearranged in the following form [27]:

$$p(D_Z) = \left[F_{X_{oz}}(n) - F_{X_{oz}}\left(\frac{C - n\sigma_r}{\sigma_d}\right) \right] \cdot \left[F_{X_{pz}}\left(-\frac{C - n\sigma_d}{\sigma_r}\right) - F_{X_{pz}}(-n) \right] \tag{8}$$

where:

$$F_{X_{oz}}(n) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^n e^{-\frac{u^2_{X_{oz}}}{2}} du_{X_{oz}};$$

$$F_{X_{pz}}(n) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^n e^{-\frac{u^2_{X_{pz}}}{2}} du_{X_{pz}};$$

$$F_{X_{oz}}\left(\frac{C-n\sigma_r}{\sigma_d}\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{C-n\sigma_r}{\sigma_d}} e^{-\frac{u^2_{X_{oz}}}{2}} du_{X_{oz}};$$

$$F_{X_{pz}}\left(\frac{C-n\sigma_d}{\sigma_r}\right) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\frac{C-n\sigma_d}{\sigma_r}} e^{-\frac{u^2_{X_{pz}}}{2}} du_{X_{pz}};$$

$$u_{X_{oz}} = \frac{X_{oz}}{\sigma_d}; \quad du_{X_{oz}} = \frac{dX_{oz}}{\sigma_d}; \quad u_{X_{pz}} = \frac{X_{pz}}{\sigma_r}; \quad du_{X_{pz}} = \frac{dX_{pz}}{\sigma_r}$$

Equation (8) is based on the hypothesis that distribution of the deviations of the coulter and of the position of the plants along the row occurs according to a Laplace-Gauss distribution.

Finally, considering a Laplace-Gauss distribution, the distribution functions $F(X)$ can be expressed with sufficient degree of accuracy by the following [27]:

$$F(X) = f(X) - \frac{r^3}{6} f^{(2)}(X) + \frac{r^4 - 3}{24} f^{(3)}(X) \tag{9}$$

where $f(X)$ is the probability density function; $f^{(j)}(X)$ is the j -th derivative of probability density function; r^3, r^4 are the main moments.

3. Results and Discussion

Expression of the values in the right-hand side of Equations (1) and (2) through design parameters b and l of the wide span tractor, as well as the heading angle φ , gives the following dependences of the transverse displacements of the coulter (working implement):

$$\begin{aligned} \alpha_{\varphi}^i &= l \sin \varphi + b(1 - \cos \varphi) \\ \alpha_{\varphi}^e &= l \sin \varphi - b(1 - \cos \varphi) \end{aligned} \tag{10}$$

where b and l , respectively, are the distances from the longitudinal and transverse axes of the wide span tractor, which pass through its center to the coulter.

Equation (10) show that the inner and outer displacements of the same coulter are not equal to each other ($\alpha_{\varphi}^i \neq \alpha_{\varphi}^e$) under the same angular deviation φ of the wide span tractor. According to the Equations (10), Figure 3 shows that the difference between the inner and outer displacements of the peripheral working implements increases with the angle of deviation φ and the design parameter l ; the difference between displacements is negligible with small values of these parameters.

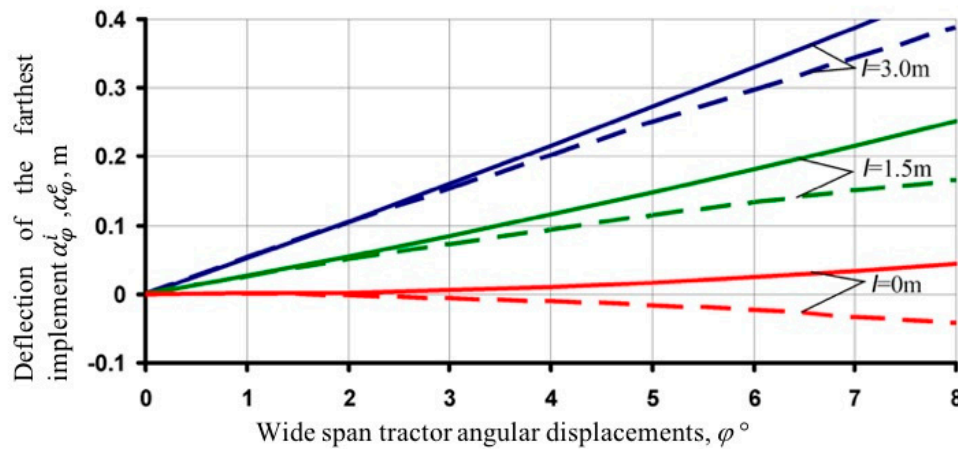


Figure 3. Inner α_{φ}^i (—) and outer α_{φ}^e (---) displacements of the peripheral working implement of the wide span tractor, depending on its angular deviation φ for different values l .

It is extremely unprofitable to remove the implements from the transverse axis passing through the center of the wide span tractor. As the absolute value of the displacements of the implements increases, especially the inner displacements, the probability of damage to the plants by the implements also increases. Furthermore, the difference in shifts of wide span tractor implements affects the asymmetry of the operation. Therefore, if the displacements of the implements in opposite directions from a set motion trajectory are unequal to each other, then displacements of their aggregates are also unequal. It is not difficult to verify this if the value of the angle φ is replaced by the standard deviation of the deflections in the right-hand member of the Equations (10). In this case, the standard deviation of implement displacements is obtained, which is determined by the standard angle deviations of the wide span tractor.

According to this, Equations (10) have the form:

$$\begin{aligned} \sigma_{\alpha_{\varphi}^i} &= l \sin \sigma_{\varphi} + b(1 - \cos \sigma_{\varphi}) \\ \sigma_{\alpha_{\varphi}^e} &= l \sin \sigma_{\varphi} - b(1 - \cos \sigma_{\varphi}) \end{aligned} \tag{11}$$

where:

$\sigma_{\alpha_{\varphi}^i}$, $\sigma_{\alpha_{\varphi}^e}$ —standard deviations of inner and outer displacements of the implement due to angular deviations of the wide span tractor;

σ_{φ} —standard deviation, pertinent to all angular deflections of the wide span tractor from the set trajectory of motion.

It is then possible to evaluate the absolute difference $\Delta\sigma_{\alpha_{\varphi}}$ between the standard deviations of the inner and outer displacements of the implement due to the corresponding standard deviations of the angular deflections of the wide span tractor:

$$\Delta\sigma_{\alpha_{\varphi}} = \sigma_{\alpha_{\varphi}^i} - \sigma_{\alpha_{\varphi}^e} = 2b(1 - \cos \sigma_{\varphi}), \quad (12)$$

Equation (12) indicates that the absolute difference between the standard deviations of the inner and outer displacements of the implement caused by the angular deflections of the wide span tractor is essentially dependent on design parameter b concerning its location on the tractor. The magnitude of $\Delta\sigma_{\alpha_{\varphi}}$ as a function of standard angular deviation of the wide span tractor for different values of b is reported in Figure 4.

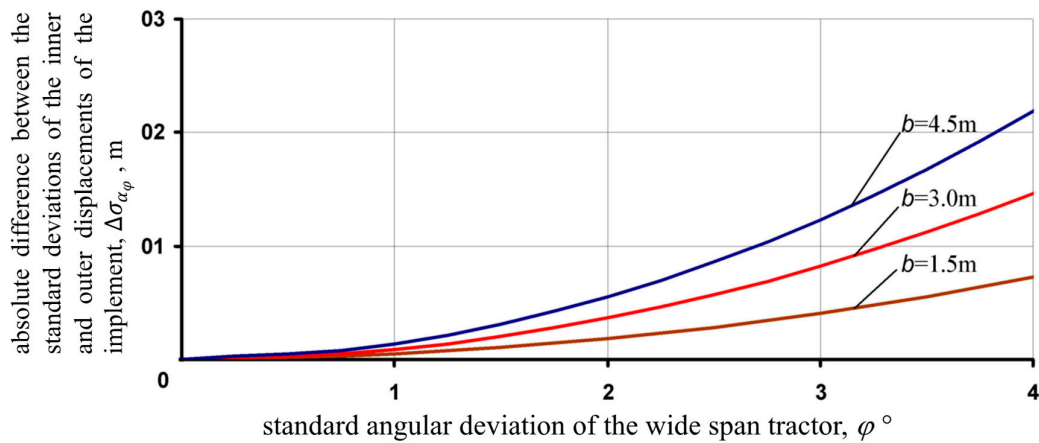


Figure 4. The absolute difference between the inner and outer standard deviations of displacements of the working implement depending on the standard deviations of the angular deflections of the wide span tractor, considering different values of b .

Figure 4 highlights that the design parameter b significantly affects the magnitude of $\Delta\sigma_{\alpha_{\varphi}}$ caused by the angular deflections of the wide span tractor. Therefore, the wider the track of the wide span tractor, and consequently, the greater the distance from the longitudinal axis passing through the tractor center to the implement, the greater is the absolute difference between the standard deviation $\Delta\sigma_{\alpha_{\varphi}}$ of its inner and outer displacements. This is more noticeable with an increase in the angular standard deviation σ_{φ} , which considers the combination of all angular deviations of the wide span tractor from a set trajectory of motion. Therefore, to reduce the probability of damage to row plants by working implements, especially the more peripheral ones, the automatic system controlling wide span tractor movement must be able to reduce the magnitude of the angular variations from the set trajectory of movement.

The asymmetry of distribution of the working implement displacements can be taken into account for statistical evaluation of the damage to row plants. It is supposed that curves 1 and 3 of Figure 5 represent the probability density functions of the transverse displacements from the set trajectory of movement of the working implements located, respectively, on the left and right sides of the row, whereas curve 2 represents the probability density function concerning the position deflections of the plants from the row axis.

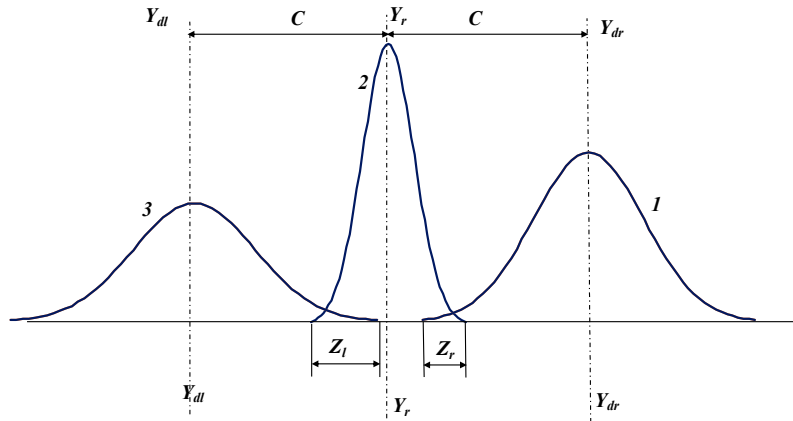


Figure 5. Probability density function of the transverse displacements from the set trajectory of movement of the right 1 and left 3 working implements located on both sides of the row and position deflections of the plants from the row axis 2.

The probabilities that the working implement to the left of the row is inside the Z_l zone and the probabilities concerning the position of the working implement to the right of the row inside zone Z_r differ from each other (zones Z_l and Z_r , respectively, are different in Figure 4), i.e.:

$$p(X_{ozl}) \neq p(X_{ozr}) \tag{13}$$

Identically for the placement deflections of the plants from the row axis inside the Z_l and Z_r zones, respectively:

$$p(X_{rzl}) \neq p(X_{rzr}) \tag{14}$$

Considering Equation (3), the probability of plant damage inside zones Z_l and Z_r , caused respectively by the left and right working implements, can be assessed by [27]:

$$\begin{aligned} p(D_{zl}) &= p(X_{ozl} \cdot X_{rzl}) = p(X_{ozl}) \cdot p(X_{rzl}) \\ p(D_{zr}) &= p(X_{ozr} \cdot X_{rzr}) = p(X_{ozr}) \cdot p(X_{rzr}) \end{aligned} \tag{15}$$

According to Equations (13) and (14), the right-hand sides of Equations (15) are unequal to each other, that is $p(D_{zl}) \neq p(D_{zr})$ and then C distance being equal, the probabilities of plant damage by cutting are dissimilar for the left and right working implements. This unlikeness increases with the increase in the asymmetry among the probability density functions pertinent/concerning to the transverse displacements of the working implements and the plant placement deviations from the row axis, respectively. The probability of plant damage by the working implements can be evaluated considering a Gaussian distribution [25]. Therefore, taking account of Equations (7), (8) and (9), Equations (15) can be rearranged to assess the probability of damage to row plants caused by the left (inner) and right (outer) working implements, respectively [27]:

$$\begin{aligned} p(D_{zl}) &= \left\{ \left[f_{X_{ozl}}(n) - \frac{r_3}{6} f_{X_{ozl}}^{(2)}(n) + \frac{r_4 - 3}{24} f_{X_{ozl}}^{(3)}(n) \right] \right. \\ &\quad - \left[f_{X_{ozl}} \left(\frac{C - n\sigma_{xr}}{\sigma_{xd}} \right) - \frac{r_3}{6} f_{X_{ozl}}^{(2)} \left(\frac{C - n\sigma_{xr}}{\sigma_{xd}} \right) + \frac{r_4 - 3}{24} f_{X_{ozl}}^{(3)} \left(\frac{C - n\sigma_{xr}}{\sigma_{xd}} \right) \right] \left. \right\} \\ &\quad \cdot \left\{ \left[f_{X_{pz}} \left(-\frac{C - n\sigma_{xd}}{\sigma_{xr}} \right) - \frac{r_3}{6} f_{X_{pz}}^{(2)} \left(-\frac{C - n\sigma_{xd}}{\sigma_{xr}} \right) \right. \right. \\ &\quad \left. \left. + \frac{r_4 - 3}{24} f_{X_{pz}}^{(3)} \left(-\frac{C - n\sigma_{xd}}{\sigma_{xr}} \right) \right] \right. \\ &\quad \left. - \left[f_{X_{pz}}(-n) - \frac{r_3}{6} f_{X_{pz}}^{(2)}(-n) + \frac{r_4 - 3}{24} f_{X_{pz}}^{(3)}(-n) \right] \right\} \end{aligned} \tag{16}$$

$$\begin{aligned}
 p(D_{Zr}) = & \left\{ \left[f_{X_{ozr}} \left(-\frac{C - n\sigma_{Xr}}{\sigma_{Xd}} \right) - \frac{r_3}{6} f_{X_{ozr}}^{(2)} \left(-\frac{C - n\sigma_{Xr}}{\sigma_{Xd}} \right) + \frac{r_4 - 3}{24} f_{X_{ozr}}^{(3)} \left(-\frac{C - n\sigma_{Xr}}{\sigma_{Xd}} \right) \right] \right. \\
 & \left. - \left[f_{X_{ozr}}(-n) - \frac{r_3}{6} f_{X_{ozr}}^{(2)}(-n) + \frac{r_4 - 3}{24} f_{X_{ozr}}^{(3)}(-n) \right] \right\} \\
 & \cdot \left\{ \left[f_{X_{pz}}(n) - \frac{r_3}{6} f_{X_{pz}}^{(2)}(n) + \frac{r_4 - 3}{24} f_{X_{pz}}^{(3)}(n) \right] \right. \\
 & \left. - \left[f_{X_{pz}} \left(\frac{C - n\sigma_{Xd}}{\sigma_{Xr}} \right) - \frac{r_3}{6} f_{X_{pz}}^{(2)} \left(\frac{C - n\sigma_{Xd}}{\sigma_{Xr}} \right) + \frac{r_4 - 3}{24} f_{X_{pz}}^{(3)} \left(\frac{C - n\sigma_{Xd}}{\sigma_{Xr}} \right) \right] \right\}
 \end{aligned} \tag{17}$$

In order to analyze the probability of plant damage as a function of the size of safeguard zone C, it is supposed that the standard deviations of the displacements of the tractor’s working implements and the plants’ placement deflections from the row axis placements are approximately equal to $\sigma_{Xd} \approx \sigma_{Xr}$. This hypothesis is fairly well-founded if the tractor’s technological and automated driving systems ensure its stability when in movement [21–23]. Figure 6 shows the probability of damage to plants as a function of the value of safeguard zone C for the inner and outer working implements, respectively. Figure 6 shows that with equal-sized safeguard zones C on both sides of the row, the probability of damage by the corresponding working implements is different (Graph 1 and Graph 2, respectively, in Figure 6). For example, the probability of damage is 11.5% by the outer implement and 4.5% by the inner implement, considering a safeguard zone C of 13 cm on each side of the row. This difference in the probability of plant damage is highly significant (greater than 150%). Accordingly, to obtain the same probability of damage to the plants on both sides of the row, the right-hand and left-hand working implements of the wide-span tractor must be situated at different distances from the row axis. For example, to obtain a probability of damage below 2% on both sides of the row, it is necessary to place the peripheral working implements at distances of 0.13 m (inner working implements) and 0.16 m (outer working implements) respectively from the row axis (Figure 6).

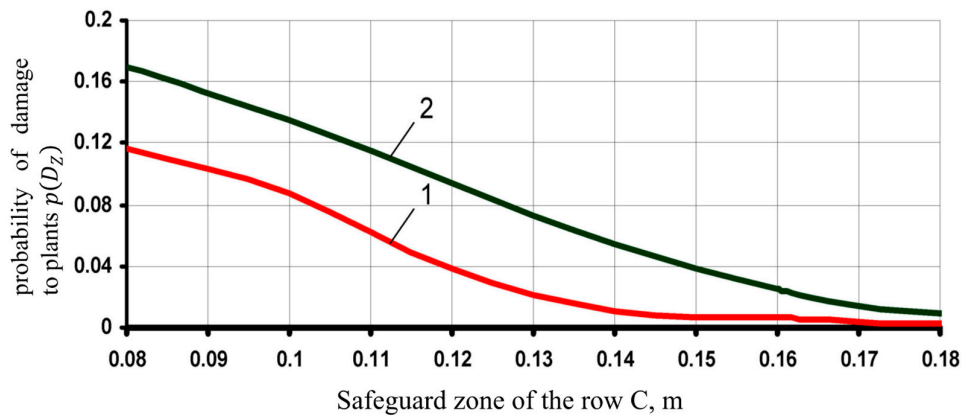


Figure 6. The probability of plant damage depending on the size of safeguard zone C: 1—inner working implement; 2—outer working implement.

4. Conclusions

1. Mathematical dependencies were developed, which make it possible to evaluate the transverse displacements of the working implements of a wide span tractor as a function of its design parameters, and the small angular deviations that unavoidably occur during operating conditions. In addition, a statistical methodology was developed for assessing the probability of damage to row plants and the suitable size of the safeguard zone to reduce this probability.

2. The magnitude of the inner and outer displacements of the working implements, as well as the absolute difference of the corresponding standard deviations, depends significantly on their longitudinal and transverse location relative to the center of the wide span tractor and is assessed by the magnitude of the angular deviations from the set trajectory of motion. For small values of these

parameters, the magnitude of the transverse displacements of the working implements, and the absolute difference of their standard deviations, is negligible.

3. When placing cultivators as working implements for wide span tractor, the difference of their displacements should be taken into account. For working implements located outside the geometrical axis of the tractor, the size of the outer safeguard zone should be greater than the inner one. The probability of damage to row plants by the working implements can be reduced by automated control of wide span tractor movement in order to reduce all its angular deviations from the set trajectory of movement.

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