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Justification of the parameters affecting the maneuverability of a four-wheeled tractor

Bakhtiyor Kambarov[1*], *Vosit* Ashirov[2], *Shavkat* Ravshanov[1], and *Najmiddin* Mirzayev[2]

[1]Scientific and Research Institute of Agricultural Mechanization, Yangiyul, Gulbahor, 110801, Uzbekistan
[2]Tashkent State Technical University named after Islam Karimov, University 2 str., Tashkent, 100095, Uzbekistan

Abstract. This paper presents the development and experimental design of an enhanced front driving axle for a new universal cotton cultivating tractor, designated as 4K4. The innovative axle design significantly increases the tractor's agrotechnical clearance, enabling improved performance in cotton cultivation. The 4K4 propulsion scheme enhances the tractor's traction capabilities by 15-18%, allowing it to efficiently operate machinery for cotton production across four or more rows simultaneously. A key advantage of the 4K4 configuration is the reduced vertical load on individual wheels, which contributes to superior directional stability and safer lateral static stability of the Machine Tractor Unit. This design feature not only optimizes the tractor's performance in cotton fields but also extends its utility, enabling year-round application in both transportation and various field operations. The research highlights the potential of this advanced tractor design to significantly improve efficiency and versatility in cotton cultivation, addressing the specific needs of the industry while offering broader agricultural applications.

1 Introduction

One of assessment criteria of wheeled tractors drivability is its minimum turning radius. Tractors cultivating the row spacings of crops should have the smaller turning radius as much as possible. Only in that case turning way and time will be shortened, the assembly operation productivity will be increased due to efficient shift operation.

The research and development works are implemented in the country and abroad show that transfer of agricultural energy to a conceptually new technical level, namely, the use of tractors with a 4K2 and 4K4 propulsion scheme, while increasing their traction potential for the possibility of aggregating agricultural machinery, will allow achieving new results [1-4]. However, the implementation of this concept is hindered due to large turning radius of tractors with a 4K2 and 4K4 propulsion scheme. In this regard, decision to minimize the tractors turning radius with a 4K2 and 4K4 propulsion scheme is of paramount importance in increasing the efficiency of using mechanization tools in the cultivation of agricultural crops. Therefore, in effort to minimize the turning radius, the improvement of tractor design

* Corresponding author: b_kambarov@rambler.ru

should be based on new technical solutions that increase the deflection angles of the external and internal steering wheels of the tractor.

2 Materials and methods

In accordance with the requirements of GOST 30752-2001 (State Standard) and many scientific studies, distance from tractor turning center *O* (Figure 1) to middle part of surface of the front steering external wheel in connection with the ground is taken as minimum turning radius of tractor R_{ou} [4]. Turning radius is set up by means of R_{ou} symbol on Figures 1 and 2.

For the case where minimum turning radius of tractors with four (4K4) or rear steering wheels (4K2) are performed directly around *O* point (Figure 1), turning radius R_{ou} on front steering external wheel is determined as in the following way:

$$R_{ou} = \frac{(L + a_p \cdot sin\beta_{ou})}{sin\beta_{ou}} \tag{1}$$

or

$$R_{ou} = \frac{L}{sin\beta_{ou}} + a_p, \tag{2}$$

in this case a_p=(B_l–M)/2, m; L–longitudinal base of tractor, m.

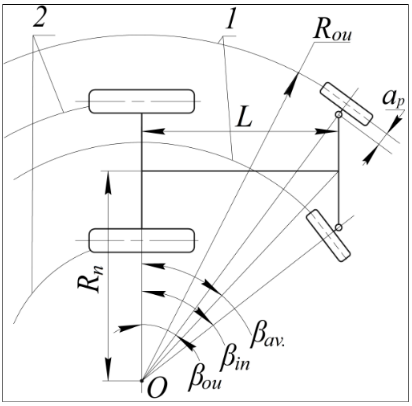

Fig. 1. Turning diagram of four-wheeled tractor: 1-front and 2-rear tracks of wheels, a_p –the shortest distance from pin axis of axle until wheel flatness, R_n–nominal turning radius.

In addition, in avoiding of that the front steering wheels of tractor do not slip and not deformed in turning process, the intersection point *O* of perpendiculars transferred to the axes of symmetry plane should theoretically lie along with the continued part of the rear steering axle geometric axis (Figure 1). For this reason, difference between the cotangents of turning angles of left and right steering wheels of the front axle must be constant quantity [5], as in the following:

$$ctg\beta_{ou} - ctg\beta_{in} = \frac{M}{L} = const. \tag{3}$$

Using this formula, it will be possible to determine turning angle β_{ou} of external wheel when the inner wheel of the front axle of the tractor is turned to a certain angle β_{in}:

$$\beta_{ou}^{th.} = arcctg\frac{M + Lctg\beta_{in}}{L}. \tag{4}$$

In highlighted type of turning, four non-overlapping traces are formed on field surface. Let's use the following formula for such situation where four-wheeled tractors turn by braking rear steering inner wheel around the point O_1 (Figure 2) [6]:

$$R_n = \frac{L}{[tg(\beta_{av} + \delta_c) + tg_{c2}]}, \tag{5}$$

in this case β_{av}– average turning angles of front guiding wheels, β_{av}=0.5(β_{ou}–β_{in}), °; δ_c and δ_{c2}– lateral thrusting angles of front and rear wheels, °.

V. V. Guskov and others [7] pointed out that if angle of side shift δ_c of tractor tires does not exceed 3–5°, their side slipping will not occur. On the basis of implemented tests, we can say that angle of tires lateral push of the front steering wheels does not exceed 3–5°. Considering that tractor moves only when the wheels of front axle are steered and rear wheels are not pushed to side, we assume that δ_{c2}=0 [7].

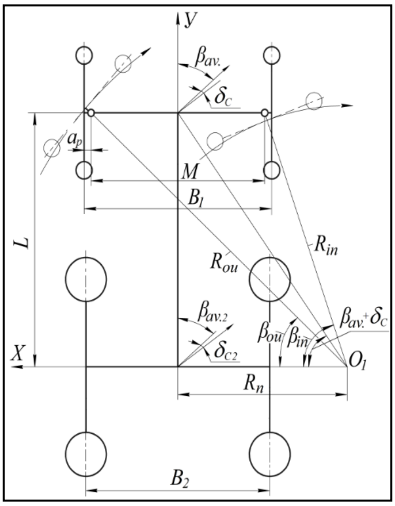

Fig. 2. Calculation scheme of turning radius: B_1 and B_2 – trace of front and rear wheels, M–distance between shafts of turning stub axle (distance between kingpin), R_{ou} –turning radiuses of external and R_{in} –inner wheels.

Considering all above, the formula (5) will be as in the following:

$$R_n = L \cdot ctg(\beta_{av.} + \delta_c). \tag{6}$$

From Figure 2 the minimum turning radius $R_{ou.min}$ of external guiding wheel of front axle will be as in the following:

$$R_{ou.min} = \sqrt{L^2 + (R_n + 0{,}5M)^2} + a_p \tag{7}$$

Test trials have shown that minimum turning radius $R_{ou.min}$ of four-wheel tractor can be ensured by braking the rear steering inner wheel.

Maneuverability of four-wheeled tractor directly depends on right selection of front guiding inner β_{in} and external β_{ou} wheel turning angles, shape, structure and parameters of steering trapezoid structures [8].

In order to study the maneuverability of four-wheeled tractors by use of different turning methods, let's determine their minimum turning radius. In effort to make above, let's consider the minimum turning radius of tractor equipped with symmetrically trimmed cross-pull steering trapezoid, the inner wheel of which can be turned up to 90° (Figure 3) [4].

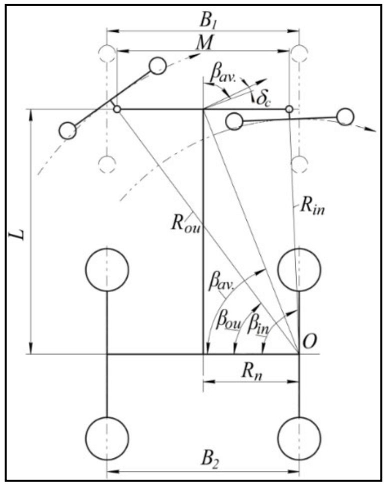

Fig. 3. Calculation scheme on turning radius of tractor equipped with transverse steering trapezoid.

In Figure 3, tractor equipped with new steering trapezoid is turned around point *O* by direct braking the rear steering internal wheel [4]. In this case, turning angles of front guiding internal β_{in} and external β_{ou} wheels are determined as in the following:

$$\beta_{in} = arctg\frac{L}{0{,}5B_2(1+k)}, \tag{8}$$

$$\beta_{ou} = arctg\frac{L}{0{,}5B_2(1-k)}, \tag{9}$$

in this case $k=M/B_2$ – distance between shaft axises *M* of turning pins rear steering wheel track to ratio B_2.

In that case average bending angle of guiding wheels will as below:

$$\beta_{av.} = 0{,}5\left[arctg\frac{L}{0{,}5B_2(1+k)} + arctg\frac{L}{0{,}5B_2(1-k)}\right]. \tag{10}$$

Based on Figure 3, tractor's nominal R_n and minimum turning radius R_{ou} are determined by formulas (2), (6) and (7).

In order to increase maneuverability of tractor, we will consider the case of turning its front axle on the «*Super Stir*» system (Figure 4) [8]. Front axle of tractor is connected by its steering trapezoid in accordance with on the «*Super Stir*», and it also turns front steering inner β_{in} and external β_{ou} wheels to maximum angles and ensures minimum turning radius of tractor.

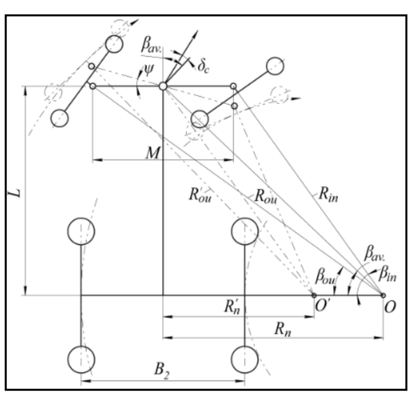

Fig. 4. Calculating scheme of tractor turning radius, front axle of which deviates on the «*Super Stir*» system.

In Figure 4, when tractor operating on the «*Super Stir*» system makes turn around O point, guiding inner β_{in} and external β_{ou} wheels are turned to maximum angles, its turning radius moves from O point to point O' [8]. In this case, minimum turning radius R_{ou} of tractor is reduced and R'_{ou} they are determined as in the following way:

$$R_{ou} = \frac{L}{sin\beta_{ou.max}} + a_p \ , \tag{11}$$

$$R'_{ou} = \frac{L+0.5Msin\psi}{\sin(\beta_{ou.max}+\psi)} + a_p \ . \tag{12}$$

It can be seen from formulas (11)–(12) and Table 4 that maneuverability of four-wheeled tractor whose front axle deviates on the «*Super Stir*» system the ψ angle depends on turning angles of front axle and steering wheels.

In effort to ensure minimum turning radius of 4K4 tractor and increase its maneuverability, let's consider the case where control method is similar to chain tractor, that can be by variation movement velocity of left or right side wheels (Figure 5).

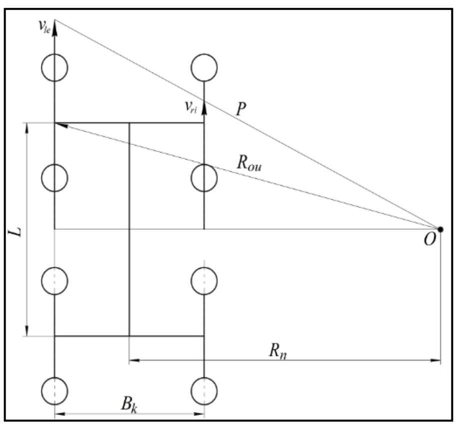

Fig. 5. Scheme for calculating the minimum turning radius of tractor in 4K4 wheel formula.

By using Figure 5, we can carry out the following actions. In the event if we denote by $P = R_n + 0{,}5B_k$, due to that right triangles are similar to each other we will formulate the following: $\frac{P}{v_{le}} = \frac{P-B_k}{v_{ri}}$. Here we will find out the following formula: $P = \frac{B_k v_{le}}{v_{le}-v_{ri}}$. Minimum turning radius of wheeled tractor by method of variating the amount of movement velocity of left or right-side wheels: $R_{ou} = \sqrt{P^2 + \left(\frac{L}{2}\right)^2}$, that means

$$R_{ou} = \sqrt{\left(\frac{B_k v_{le}}{v_{le}-v_{ri}}\right)^2 + \left(\frac{L}{2}\right)^2}, \tag{13}$$

in this case v_{le} and v_{ri} – velocity of left side and right-side wheels, m/s; B_k –track of front and rear wheels (the dimensions are the same), m.

3 Results and discussion

Thus, using the main parameters (L, B_1, M, a_p) of four-wheeled tractor according to Figure 2, the theoretical values of turning angle β_{ou} and turning radius R_{ou} of external wheels of front steering wheel (2), (4), let's determine by formulas (6) and (7). In the calculations, we accept the maximum turning angle of internal wheel of the front steering axle β_{in}=55° determined on base of testing results and technical specifications of tractors. As an example, let's take the remaining parameters of the experimental tractor: L=1310 mm, B_1=B_2=1400 mm, M=1086 mm, a_p=157 mm and δ_c=3–5°. Results of calculations are shown in Table 1.

Table 1. Main parameters of four-wheel tractor model (4K2).

Parameter values									
L, mm	B_1, mm	M, mm	a_p, mm	$\frac{\beta_{in}}{\beta_{ou}}$	β_{av}	δ_c,°	R_n, m	R_{ou}, m Unbraked	R_{ou}, m Braked
1310	1400	1086	157	$\frac{55°}{33°11'}$	44°05′	3	1.22	2.55	2.35
						4	1.18		2.32
						5	1.14		2.29

From results of calculations according to formulas (2), (4), (6) and (7) and the analysis of the data presented in Table 1, it can be seen that turning radius of four-wheeled tractors are values of R_{ou} of turning angles (β_{in} and β_{ou}) and main parameter depends on these ones - (L, B_1, a_{av}).

Let's determine the maneuverability indicators of tractor specified in Figure 3 based on formulas (2), (6) - (10). Let's take the following as initial data for calculation work: L=1310 mm, B_1=B_2=1400 mm, M=1086 mm, a_p=157 mm and δ_c=3–5°. Results of calculations are mentioned in Table 2.

Table 2. Main parameters of four-wheeled tractor, internal wheel of the front steering able to turn to 90°.

Tractor model	Parameters values									
	L, mm	B_2, mm	M, mm	a_p, mm	$\frac{\beta_{in}}{\beta_{ou}}$	β_{av}	k	δ_c, °	R_n, m	R_{ou}, m Unbraked	R_{ou}, m Braked
Trial tractor (4K2)	1310	1400	1086	157	$\frac{83°10'}{46°30'}$	64°50′	0.78	3	0.53	1.96	1.85
								4	0.51		1.84
								5	0.48		1.82

It can be seen from Figure 3, Table 2 and formulas (8)–(10) that nominal R_n and minimum R_{ou} turning radius of tractor depend on M distance between axes of its longitudinal base L, rear steering wheel track B_2, and axes of turning shafts.

According to Figure 4 and formulas (11), (12), let's determine indicators of the tractor minimum radius able to turning base on the «*Super Stir*» system. Let's take the following as initial data for calculation work: L=1310 mm, B_1=B_2=1400 mm, M=1086 mm, a_p=157 mm, β_{in}=55°, β_{in}=45° end ψ=12°. Calculations' results are specified in Table 3.

Table 3. Performance indicators of the tractor able to turning «*Super Stir*» system.

Tractor model	**Parameters values**							
	L, **mm**	B_2, **mm**	M, **mm**	a_p, **mm**	$\frac{\beta_{in}}{\beta_{ou}}$, °	ψ, °	R_{ou}, **m**	R'_{ou}, **m**
Trial tractor (4K2)	1310	1400	1086	157	$\frac{55}{45}$	12	2.01	1.85

It can be seen from Figure 4 the formulas (11)–(12) and Table 3 that maneuverability of four-wheeled tractor whose front axle able to turning «*Super Stir*» system depends on turning angles of front axle and steering wheels. It means, when the turning «*Super Stir*» system will result in decreasing the turning radius R_{ou}.

According to Figure 5 and (13), let's determine the parameters of tractor's minimum radius able to turn at its standing place (similar to chain tractor). Let's accept the following as initial data for calculation work: L=1310 mm, B_k =1400 mm, v_{le}=0.5 m/s, v_{ri}=0.2 m/s. Calculations' results are presented in Table 4.

Table 4. Performance indicators of the tractor able to turn at its standing place.

Tractor model	**Parameters values**				
	L, **mm**	B_k, **mm**	v_{le}, **m/s**	v_{ri}, **m/s**	R_{ou}, **m**
Trial tractor	1310	1400	0.5	0.2	2.42

From the Figure 5, formula (13) and Table 4, turning radius of four-wheeled tractor, which is performed by variating the velocity of left or right side wheels, is directly dependent on velocity of left or right side wheels. When four-wheel tractor performs such turn, two traces are formed on the field surface.

4 Conclusion

In effort to avoid slipping and deformation of front steering wheels when the tractor turns, it is desired that intersection point O of perpendiculars transferred to axes of symmetry plane theoretically lies along the geometric axis of the rear steering axle. Using the above-mentioned optimum turning methods of tractors, increasing their maneuverability depends on values of internal and external turning angles (β_{in} or β_{ou}) and the main parameters (L, B_1, a_p) of axles, which reduces the minimum turning radius R_{ou}. As the front axle of tractor deviates to angle ψ, it also ensures its minimum radius. In addition, as longitudinal base of tractor (distance between front and rear axles) and distance between the wheels (track) increases, values of minimum turning radius also increase. In effort to reduce minimum turning radius of velocity of tractor side wheels able to turn at its standing place depends on driver's skills.

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