COMPARATIVE ANALYSIS OF THE HEADLAND WIDTH WHEN MAKING T-TURNS BY A MOUNTED MACHINE-TRACTOR UNIT ON AN IRREGULARLY-SHAPED FIELD
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СРАВНИТЕЛЕН АНАЛИЗ НА ШИРИНАТА НА ИВИЦАТА ЗА ЗАВИВАНЕ ПРИ ИЗВЪРШВАНЕ НА ГЪБОВИДНИ ЗАВОИ ОТ НАВЕСЕН МАШИННО-ТРАКТОРЕН АГРЕГАТ В ПОЛЕ С НЕПРАВИЛНА ФОРМА

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ABSTRACT
Analytical relations for determining the headland width when making T-turns by a machine-tractor unit with a mounted machine on an irregularly-shaped field have been specified. Five types of T-turns are described in two variants – open turn and closed turn. Each of these is done in two directions of movement. A total of 20 variants of the turns are described. The method for determining the headland width of a specific machine-tractor unit consisting of a tractor and mounted row seeder is demonstrated. For each type of turn the headland width is determined according to the angle between the direction of movement of the agricultural unit and the field border. A range of angle modification from 10° to 90° is adopted. The analysis shows that for obtaining minimum headland width closed turns in the left to right direction of movement should not be made. The smallest theoretical headland width is when making a closed T-turn with arch-shaped backward movement and left-to-right direction of movement on the field. When using T-turns with an arch-shaped backward movement and T-turns with straight-ahead movement when entering the headland, the actual headland width is the same (6 m) regardless of the type and direction of the turn.

РЕЗЮМЕ
Посочени са аналитични зависимости за определяне на широчината на ивицата за завиване при извършване на гъбовидни завои от машинно-тракторен агрегат с навесна машина в поле с неправилна форма. Разгледани са пет вида гъбовидни завои в два варианта – отворен завой и затворен завой. Всеки от тях се извършва в две направления на движение. Общо са описани 20 варианта на завои. Демонстрирана е методиката за определяне на широчината на ивицата за завиване за конкретен машинно-тракторен агрегат съставен от трактор и навесна редова сеялка. За всеки вид завой е определена широчината на ивицата за завиване в зависимост от ъгъла между посоката на движение на земеделския агрегат и границата на полето. Приет е диапазон на изменение на ъгъла от 10° до 90°. Анализът показва, че за получаване на минимална широчина на ивицата за завиване трябва да се извършват затворени завои с направление на движение отляво надясно. Най-малка теоретична широчина на ивицата за завиване има при извършване на затворен гъбовиден завой с дъгообразен заден ход и направление на движение по полето отляво надясно. При използване на гъбовидни завои с дъгообразен заден ход и гъбовидни завои с праволинеен ход при навлизане в ивицата за завиване, действителната широчина на ивицата за завиване е еднаква (6 m) независимо от видът и посоката на извършване на завоя.

INTRODUCTION
The turns made by the machine-tractor units in the field are a determining factor for the efficiency of the performed technological operation (*Trendafilov, 2021*). They have the greatest share among the non-working moves of the machine-tractor unit (*Sabelhaus et al., 2013*). In a study by Bochtis and Sorensen, it has been established that turns represent 5.27 % and 6.48 % of the total distance covered by the machine-tractor unit (*Bochtis et al., 2009*).

The way of movement of the machine-tractor units and the type of turns made depends on the shape of the field as well. It is usually accepted that the field has a rectangular shape and in great part of the literature, the shape of turns is presented in fields with rectangular (regular) shape (*Trendafilov, 2021*). In practice, great part of the fields is with shapes different from rectangular. Thus results in change of the shape of turns and their lengths as well as the width of the headland needed for making turns at the ends of the field.

Most often machine-tractor units with mounted machines make T-turns in the headland. According to some authors reversing turns reduce the headland width (*Cariou et al., 2010*). The headland width depends on the type of machine and its geometrical and kinematic properties. Due to that reason, the use of different machines with the same working width may require different headland widths (*Hameed et al, 2010*). The shape and length of turns in the headland change depending on the angle between the direction of movement of the machine-tractor unit when doing the working move and the field border. With a different value of that angle turns will have different lengths and will require different headland widths (*Trendafilov, 2020*; *Trendafilov 2021 a, b*; *Trendafilov, 2022 a, b*). These sources give dependencies for determining the headland width and the length of the non-working move when making various T-turns.

In order to minimize the time for making turns and servicing the machine on the field (loading and unloading materials and yield), orientation (the angle) of moves, the sequence of making the moves and the types of turns between them have to be optimized. The angle between the direction of the working moves and the field border influence the number and length of moves of the machine-tractor unit, the number of turns and the positions where the unit can be serviced (*Spekken de Bruin, 2013*).

Trajectory optimization in the headland can be made by using calculation methods. The minimum needed headland width when making turns is calculated. The needed headland width for the minimum time to make the turn is determined (*Tu, 2013*).

Existing navigation systems and automatic turning systems make it possible for the unit to follow various optimal models of movement. Various algorithms for optimizing the way of movement and planning the route of the units can be added to modern navigation systems (*Bochtis and Vougioukas, 2008*). The type of turn can be selected automatically and its parameters can be determined depending on the information about the headland obtained from the navigation system and the type of unit (*Freyberger and Jahns, 2000*). Such a system of movement in the headland can be successfully connected to a device that performs repetitive actions on the machine-tractor unit (for example, towbar control, power take-off shaft, hydraulic valves), which allows fully automated turns of the units (*Cariou et al, 2010*). Making automatic turns will allow the operator to focus more on the operation itself (*Freyberger and Jahns, 2000*). When making a turn at the end of the field, wheels slip, which impairs the ability to follow a predetermined trajectory. The incorporation of a slip assessment mechanism leads to an increase in the accuracy of the control system (*Bayar et al., 2016*).

The objective of the present article is to make a comparative analysis of the headland width when making various T-turns in an irregularly shaped field and to justify the choice of a type of turn and its direction in the field to ensure a minimum headland width.

MATERIALS AND METHODS

Five types of T-turns made by the machine-tractor unit are discussed:

- T-turns with straight reverse movement parallel to the field border;
- T-turns with straight reverse movement not parallel to the field border;
- T-turns with arcuate reverse movement;
- T-turns with straight movement upon entering the headland;
- T-turns with straight movement upon exiting the headland.

Each of the turns is in two variants – open and closed and is made in two directions – left to right and right to left. Table 1 contains the analytical dependencies for calculating each of the turns (*Trendafilov, 2020*; *Trendafilov 2021 a, b*; *Trendafilov, 2022 a, b)*. Designations in the formulas are given in Fig. 1 and mean the following:

α is the angle between the direction of movement and the field border;

H – the longitudinal base of the tractor;

l_a – the kinematic length of the unit;

M – the tractor track;

B – the working width of the unit;

R – the radius of the turn for the unit;

O – the centre of the respective curvilinear movement within the turn;

β – the central angle of the respective curvilinear movement;

E – the minimum headland width;

E' – the headland width limited by the tractor wheels.

When working conditions do not allow the unit to enter the field when making a turn in order not to damage the plants, for example when working in perennials and row crops, the headland width is *E'*. If there are no such restrictions, the headland has minimum width *E*. Headland width *E'* is in some types of turns only.

To compare the headland width in various turns, calculations have been made for the specific machine-tractor unit consisting of *Lamborghini Sprint 674-75* tractor and *Gaspardo M300* seeder (Figure 2). The unit has the following parameters: working width *B* = 3 m; kinematic length *la* = 3.1 m; radius of the turn *R* = 2 m; longitudinal base of the tractor *H* = 2.25 m and track *M* = 1.34 m. Some authors agree that the field has a headland when the angle between the direction of movement and the field border is greater than 10° (*Aurbacher and Dabbert, 2009*). According to other authors a headland is not needed when the angle is less than 15° (*Oksanen, 2007*). For the experiment, a range of change for the *α* angle from 10° to 90° has been adopted. Since there are no restrictions for entering the field about the specific unit, calculations have been made for headland width *E*. The results are presented through diagrams.

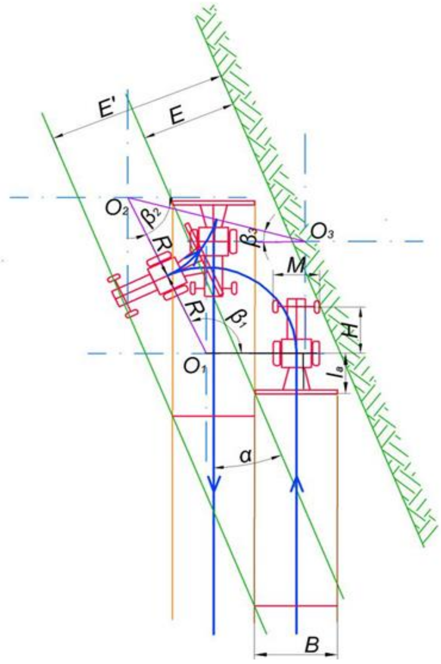


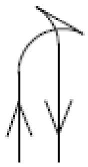
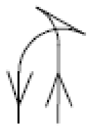
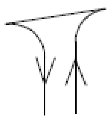
Fig. 1 – Scheme of turn in the headland of an irregularly-shaped field

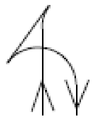
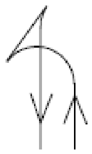
Fig. 2 – Machine-tractor unit with mounted row seeder

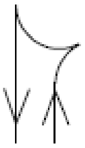
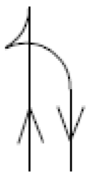
Table 1

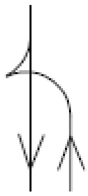
Analytical dependencies for determining the headland width when making T-turns in an irregularly-shaped field

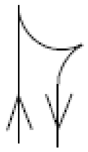
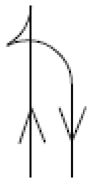
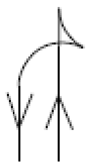
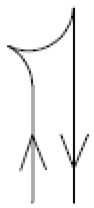
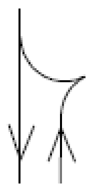
(*Trendafilov, 2020*; *Trendafilov 2021 a, b*; *Trendafilov, 2022 a, b)*

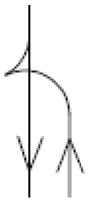
Name of the turn	Direction of execution	Dependence for determining the headland width
1	2	3
T-turns with straight reverse movement parallel to the field border		
open turns	left to right 	$E=(R+0.5B)\cos\alpha - l_a\cdot\sin\alpha + R + 0.5M$ (1)
	right to left 	$E=(R+0.5B)\cos\alpha + l_a\cdot\sin\alpha + R + 0.5M$ (2)
closed turns	left to right 	*E* is determined by dependence (2)
	right to left 	*E* is determined by dependence (1)
T-turns with straight reverse movement not parallel to the field border		
open turns	left to right 	$E=(R+0.5B)\cos\alpha+(R+0.5M)\cos(\beta_1-\alpha)-l_a\cdot\sin\alpha$ (3) where $\beta_1=\tan^{-1}\left(\frac{2R+B}{\frac{B}{\tan\alpha}+2l_a}\right)$ (4) when $\alpha>\tan^{-1}\left(\frac{2R+H\cdot\sin\beta_1}{H\cdot\cos\beta_1+2l_a}\right)$ (5) $E=(0.5M+R)\cos(\alpha-\beta_1)+H\cdot\sin(\alpha-\beta_1)+(0.5B-R)\cdot\cos\alpha+l_a\cdot\sin\alpha$ (6)
	right to left 	$E=(R+0.5B)\cos\alpha+(R+0.5M)\cos(\beta_2-\alpha)+H\cdot\sin(\beta_2-\alpha)+l_a\cdot\sin\alpha$ (7) where $\beta_2=\tan^{-1}\left(\frac{2R+B}{\frac{B}{\tan\alpha}-2l_a}\right)$ (8) and when $\alpha>\tan^{-1}\left(\frac{B}{2l_a}\right)$ (9) $\beta_2=180+\tan^{-1}\left(\frac{2R+B}{\frac{B}{\tan\alpha}-2l_a}\right)$ (10)
		$E'=M\cdot\cos(\beta_2-\alpha)+H\cdot\sin(\beta_2-\alpha)+2R\cdot\cos\alpha+2l_a\cdot\sin\alpha$ (11)

closed turns	left to right 	$E=(0.5M-R)\cos(\alpha+\beta_1)+H\cdot\sin(\alpha+\beta_1)+l_a\cdot\sin\alpha+(0.5B+R)\cos\alpha$	(12)
		where $\beta_1=\tan^{-1}\left(\frac{2R-B}{\frac{B}{\tan\alpha}+2l_a}\right)$	(13)
		when $\alpha>\tan^{-1}\left(\frac{l_a+\sqrt{l_a^2+(2R-B)B}}{2R-B}\right)$	(14)
		$E=H\cdot\sin(\alpha+\beta_1)+l_a\cdot\sin\alpha+(0.5B+R)\cos\alpha-(0.5M+R)\cdot\cos(\alpha+\beta_1)$	(15)
		$E^{'}=M\cdot\cos(\alpha+\beta_1)+H\cdot\sin(\alpha+\beta_1)+\frac{(2R-B)\sin(\alpha+\beta_1)}{\sin\beta_1}$	(16)
		when condition (14) is fulfilled for angle *α*	
		$E^{'}=H\cdot\sin(\alpha+\beta_1)+\frac{(2R-B)\sin(\alpha+\beta_1)}{\sin\beta_1}-M\cdot\cos(\alpha+\beta_1)$	(17)
	right to left 	$E=0.5(M+B)\cos\alpha+(H+l_a)\sin\alpha$	(18)
		with increasing angle *α*	
		$E=(R+0.5B)\cos\alpha-l_a\cdot\sin\alpha-(R+0.5M)\cos(\alpha+\beta_2)$	(19)
		where $\beta_2=\tan^{-1}\left(\frac{2R-B}{\frac{B}{\tan\alpha}+2l_a}\right)$	(20)
		when condition (9) is fulfilled for angle *α*	
		$\beta_2=180+\tan^{-1}\left(\frac{2R-B}{\frac{B}{\tan\alpha}-2l_a}\right)$	(21)
		when $\alpha>\tan^{-1}\left(\frac{R}{l_a}\right)$	(22)
		$E=(0.5B-R)\cos\alpha+l_a\cdot\sin\alpha-(0.5B+R)\cos(\alpha+\beta_2)-H\cdot\sin(\alpha+\beta_2)$	(23)
		$E=(R+0.5B)\cos\alpha+H\cdot\sin\alpha+(R+0.5M)\cos(\alpha+\beta_1)+H\cdot\sin(\alpha+\beta_2)$	(24)
		with increasing angle *α*	
		$E=2R\cdot\cos\alpha-2l_a\cdot\sin\alpha-M\cdot\cos(\alpha+\beta_2)+H\cdot\sin(\alpha+\beta_2)$	(25)
T-turns with arcuate reverse movement			
open turns	left to right 	$E=(R+0.5M)\cos(\alpha+\beta_2)+(0.5B+R)\cos\alpha+l_a\cdot\sin\alpha$	(26)
		where $\beta_2=\cos^{-1}\left(\frac{B}{2R}\right)$	(27)
		when $\alpha>\tan^{-1}\left(\frac{B}{\sqrt{4R^2-B^2}}\right)$	(28)
		$E=\left(B+R-\frac{M\cdot B}{4R}\right)\cos\alpha+\left(l_a+\left(\frac{M}{4R}-0.5\right)\sqrt{4R^2-B^2}\right)\sin\alpha$	(29)

		when $\alpha > \tan^{-1}\left(\dfrac{0.5B+R-0.5M-\dfrac{M\cdot B}{4R}}{H-\left(\dfrac{M}{4R}-0.5\right)\sqrt{4R^2-B^2}}\right)$	(30)
		E is determined by dependence (18)	
		when $\alpha > \tan^{-1}\left(\dfrac{B}{\sqrt{4R^2-B^2}-2l_a}\right)$	(31)
		E is determined by dependence (6)	
		where $\beta_1 = \cos^{-1}\left(\dfrac{2R+B}{4R\cos\left(\tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}+2l_a}{2R+B}\right)\right)}\right) - \tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}+2l_a}{2R+B}\right)$	(32)
	right to left 	$E = 0.5M\cdot\cos(\alpha+\beta_1)+H\cdot\sin(\alpha+\beta_1)+(1.5B+R)\cos\alpha - l_a\cdot\sin\alpha - R\cdot\cos(\beta_1-\alpha)$	(33)
		where $\beta_1 = \cos^{-1}\left(\dfrac{B}{2R}\right)$	(34)
		when angle $\alpha > \tan^{-1}\left(\dfrac{B}{\sqrt{4R^2-B^2}+2l_a}\right)$	(35)
		E is determined by dependence (12)	
		where $\beta_1 = \cos^{-1}\left(\dfrac{2R+B}{4R\cdot\cos\left(\tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}-2l_a}{2R+B}\right)\right)}\right) + \tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}-2l_a}{2R+B}\right)$	(36)
		when $\alpha > 90-\beta_1$ *E* is determined by dependence (15)	(37)
closed turns	left to right 	$E = (R+0.5M)(\cos\alpha+\cos(\alpha+\beta_1))$ where β_1 is determined by dependence (34)	(38)
		when $\alpha > \tan^{-1}\left(\dfrac{B}{\sqrt{4R^2-B^2}+H}\right)$	(39)
		$E = (R+0.5M)\cos\alpha + H\cdot\sin\alpha - (R-0.5M)\cos(\alpha+\beta_1)$	(40)
		when condition (37) is fulfilled for angle *α*	
		$E = (R+0.5M)\cos\alpha + H\cdot\sin\alpha - (R+0.5M)\cos(\alpha+\beta_1)$	(41)
		when condition (31) is fulfilled for angle *α*	
		$E = \dfrac{R+0.5M}{R}(R\cdot\cos\alpha + l_a\cdot\sin\alpha) + H\cdot\sin(\alpha+\beta_1)$	(42)

		where $\beta_1 = \cos^{-1}\left(\dfrac{2R-B}{4R\cdot\cos\left(\tan^{-1}\left(\dfrac{\dfrac{B}{\tan\alpha}+2l_a}{2R-B}\right)\right)}\right) - \tan^{-1}\left(\dfrac{\dfrac{B}{\tan\alpha}+2l_a}{2R-B}\right)$	(43)
		when $\alpha > \tan^{-1}\left(\dfrac{(R+0.5M)\cos\beta_1 + \dfrac{M-B}{2}}{(R+0.5M)\sin\beta_1 - \dfrac{M\cdot l_a}{2R}}\right)$	(44)
		E is determined by dependence (15)	
	right to left 	*E* is determined by dependence (18) when $\alpha > \tan^{-1}\left(\dfrac{(R-0.5M-(R+0.5M)\cos\beta_3)}{H+2l_a-(R+0.5M)\sin\beta_3}\right)$	(45)
		$E = (R+0.5B)\cos\alpha - (R+0.5M)\cos(\alpha+\beta_3) - l_a\cdot\sin\alpha$	(46)
		where $\beta_3 = \cos^{-1}\left(\dfrac{2R-B}{4R\cdot\cos\left(\tan^{-1}\left(\dfrac{\dfrac{B}{\tan\alpha}-2l_a}{2R-B}\right)\right)}\right)' - \tan^{-1}\left(\dfrac{\dfrac{B}{\tan\alpha}-2l_a}{2R-B}\right)$	(47)
		when $\alpha > \tan^{-1}\left(\dfrac{R-0.5M+H\cdot\sin\beta_1}{l_a-\dfrac{0.5M\cdot l_a}{R}+H\cdot\cos\beta_1}\right)$	(48)
		E is determined by dependence (6)	
		where $\beta_1 = \cos^{-1}\left(\dfrac{2R-B}{4R\cdot\cos\left(\tan^{-1}\left(\dfrac{\dfrac{B}{\tan\alpha}-2l_a}{2R-B}\right)\right)}\right) + \tan^{-1}\left(\dfrac{\dfrac{B}{\tan\alpha}-2l_a}{2R-B}\right)$	(49)
		$E' = (R+0.5M)(\cos\alpha+\cos(\alpha+\beta_2)) + H(\sin\alpha+\sin(\alpha+\beta_2))$ where β_2 is determined by dependence (27) when α for angle a condition is met (35)	(50)
		$E' = (R+0.5M)(\cos\alpha-\cos(\beta_1-\alpha)) + H(\sin\alpha+\sin(\beta_1-\alpha))$ where β_1 is determined by dependence (49)	(51)
T-turns with straight movement upon entering the headland			
open turns	left	E is determined by dependence (26) where β_2 is determined by dependence (27) when condition (28) is fulfilled for angle *α*	

	to right 	$E^{'} = \left(B + R - \frac{M \cdot B}{4R}\right)\cos\alpha + \left(l_a + \frac{(0.5M - R)\sqrt{4R^2 - B^2}}{2R}\right)\sin\alpha$	(52)
		when $\alpha > \tan^{-1}\left(\frac{0.5M - 1.5B - R + \frac{M \cdot B}{4R}}{2l_a - H + \frac{\sqrt{4R^2 - B^2}(0.5M - 2R)}{2R}}\right)$	(53)
		$E = \left(\sqrt{4R^2 - B^2} + H - l_a\right)\sin\alpha + 0.5(M - B)\cos\alpha$	(54)
	right to left 	$E = \left(\sqrt{4R^2 - B^2} + H - l_a\right)\sin\alpha + (0.5M + 1.5B)\cos\alpha$	(55)
		$E^{'} = \left(0.5B + \frac{M \cdot B}{4R} + R + 0.5M\right)\cos\alpha + \left(H + \left(0.5 + \frac{M}{4R}\right)\sqrt{4R^2 - B^2}\right)\sin\alpha$	(56)
closed turns	left to right 	E is determined by dependence (38), (39), (40) and (41)	
		when $\alpha > \tan^{-1}\left(\frac{R - \frac{M \cdot B}{4R}}{\left(0.5 - \frac{M}{4R}\right)\sqrt{4R^2 - B^2} - l_a}\right)$	(57)
		E is determined by dependence (54)	
	right to left 	$E = \left(R + B + \frac{M \cdot B}{4R}\right)\cos\alpha + \left(\sqrt{4R^2 - B^2}\left(0.5 + \frac{M}{4R}\right) - l_a\right)\sin\alpha$	(58)
		when $\alpha > \tan^{-1}\left(\frac{R - 0.5B - 0.5M + \frac{M \cdot B}{4R}}{\left(0.5 - \frac{M}{4R}\right)\sqrt{4R^2 - B^2} + H}\right)$	(59)
		E is determined by dependence (55)	
T-turns with straight movement upon exiting the headland			
open turns	left to right 	$E = \left(R + 0.5M + 0.5B + \frac{M \cdot B}{4R} + \frac{H\sqrt{4R^2 - B^2}}{2R}\right)\cos\alpha + \left(\left(\frac{M}{4R} + 0.5\right)\sqrt{4R^2 - B^2} - \frac{H \cdot B}{2R}\right)\sin\alpha$	(60)
		when $\alpha > \tan^{-1}\left(\frac{R - B + \frac{M \cdot B}{4R} + \frac{H\sqrt{4R^2 - B^2}}{2R}}{\frac{H \cdot B}{2R} + l_a - \left(\frac{M}{4R} - 0.5M\right)\sqrt{4R^2 - B^2}}\right)$	(61)
		$E = \left(\sqrt{4R^2 - B^2} + l_a\right)\sin\alpha + (1.5B + 0.5M)\cos\alpha$	(62)
	right to left 	$E = \left(\frac{M \cdot B}{4R} + R + \frac{H\sqrt{4R^2 - B^2}}{2R}\right)\cos\alpha + \left(\frac{H \cdot B}{2R} + l_a - \left(\frac{M}{4R} - 0.5\right)\sqrt{4R^2 - B^2}\right)\sin\alpha$	(63)
		when condition (37) is fulfilled for angle α (β_1 is determined by dependence (34))	
		$E = \left(R - \frac{M \cdot B}{4R} + \frac{H\sqrt{4R^2 - B^2}}{2R}\right)\cos\alpha + \left(\frac{H \cdot B}{2R} + l_a + \left(\frac{M}{4R} + 0.5\right)\sqrt{4R^2 - B^2}\right)\sin a$	(64)

		when $\alpha > \tan^{-1}\left(\dfrac{R-\dfrac{M\cdot B}{4R}+\dfrac{H\sqrt{4R^2-B^2}}{2R}-0.5M+0.5B}{\left(0.5-\dfrac{M}{4R}\right)\sqrt{4R^2-B^2}-\dfrac{H\cdot B}{2R}}\right)$	(65)
		$E=\left(\sqrt{4R^2-B^2}+l_a\right)\sin\alpha+0.5(M-B)\cos\alpha$	(66)
closed turns	left to right 	$E=\left(\dfrac{H\sqrt{4R^2-B^2}}{2R}+B+R+\dfrac{M\cdot B}{4R}\right)\cos\alpha+\left(\left(0.5+\dfrac{M}{4R}\right)\sqrt{4R^2-B^2}+l_a-\dfrac{H\cdot B}{2R}\right)\sin a$	(67)
		when $\alpha > \tan^{-1}\left(\dfrac{H\dfrac{\sqrt{4R^2-B^2}}{2R}+\dfrac{M\cdot B}{4R}+R-0.5B-0.5M}{\dfrac{H\cdot B}{2R}+\left(0.5-\dfrac{M}{4R}\right)\sqrt{4R^2-B^2}}\right)$ *E* is determined by dependence (62)	(68)
	right to left 	*E* is determined by dependence (18) when $\alpha > \tan^{-1}\left(\dfrac{B}{\sqrt{4R^2-B^2}-H}\right)$	(69)
		$E=\left(\sqrt{4R^2-B^2}+l_a\right)\sin\alpha-0.5(B-M)\cos\alpha$	(70)
		E ' is determined by dependence (50) when $\alpha > 90-\beta_2$	(71)
		$E'=\left(R+0.5M+0.5B+\dfrac{H\sqrt{4R^2-B^2}}{2R}-\dfrac{M\cdot B}{4R}\right)\cos\alpha+\left(H+\dfrac{H\cdot B}{2.R}-\left(0.5-\dfrac{M}{4R}\right)\sqrt{4R^2-B^2}\right)\sin\alpha$	(72)
		when condition (69) is fulfilled for angle *α* $E'=\left(R+0.5M-0.5B+\dfrac{H\sqrt{4R^2-B^2}}{2R}-\dfrac{M\cdot B}{4R}\right)\cos\alpha+\left(\dfrac{H\cdot B}{2R}+\left(0.5+\dfrac{M}{4R}\right)\sqrt{4R^2-B^2}\right)\sin\alpha$	(73)

RESULTS

The studied machine-tractor unit has greater kinematic length and a smaller turning radius compared to the unit for which the formulas in Table 1 have been derived. Therefore, not all of the stated dependencies are used to determine the headland width for some of the turns, and for some it is necessary to introduce new dependencies, listed below.

- *For „Open T-turn with straight reverse movement parallel to the field border – left-to-right movement" and „Closed T-turn with straight reverse turn parallel to the field border – right-to-left movement"*

In an angle determined by dependence (22) the headland is limited on the left side of the machine upon its entering the headland.

The headland width in this case is determined by the dependence:

$$E=(0.5B-R)\cos\alpha+l_a\cdot\sin\alpha+R+0.5M \tag{74}$$

- *For „Open T-turn with arcuate reverse movement – left to right movement"*

Dependence (29) is not used. In case of small *α* angle dependence (26) is used and in angle:

$$\alpha > \tan^{-1}\left(\frac{0.5B+R-0.5M+\dfrac{M\cdot B}{4R}}{H+\left(\dfrac{M}{4R}+0.5\right)\sqrt{4R^2-B^2}}\right) \tag{75}$$

The headland width is determined by dependence (18).

- *For „Open T-turn with arcuate reverse movement – right to left movement"*

The result by formula (36) is $\beta_1 = 0^\circ$ with angle:

$$\alpha = \tan^{-1}\left(\frac{-B}{\sqrt{4R^2 - B^2} - 2l_a}\right) \quad (76)$$

In case of a bigger angle the headland width is determined again by dependence (12), in which $\beta_1 = 0^\circ$. Dependence (15) is not used.

- *For „Open T-turn with straight movement upon entering the headland – left to right movement"*

In this case there is no straight movement upon the unit's entering the headland and its width is determined by dependence (18). In case of an angle determined by dependence (75) the headland width is determined by dependence (54).

- *For „Open T-turn with straight movement upon entering the headland – right to left movement"*

The length of the straight movement before the turn becomes 0 in an angle determined by dependence (76). In greater values for the angle, the headland is restricted from the side of the field to the left side of the unit entering the headland, while the headland width is determined by dependence (18).

The actual headland width should be greater than the theoretical width calculated according to the stated dependences, and it should be a multiple of the working width of the machine (3 m), i.e. it can be 3, 6, 9 and 12 m.

Fig. 3 and fig. 4 present the results from calculations about the different types of turns.

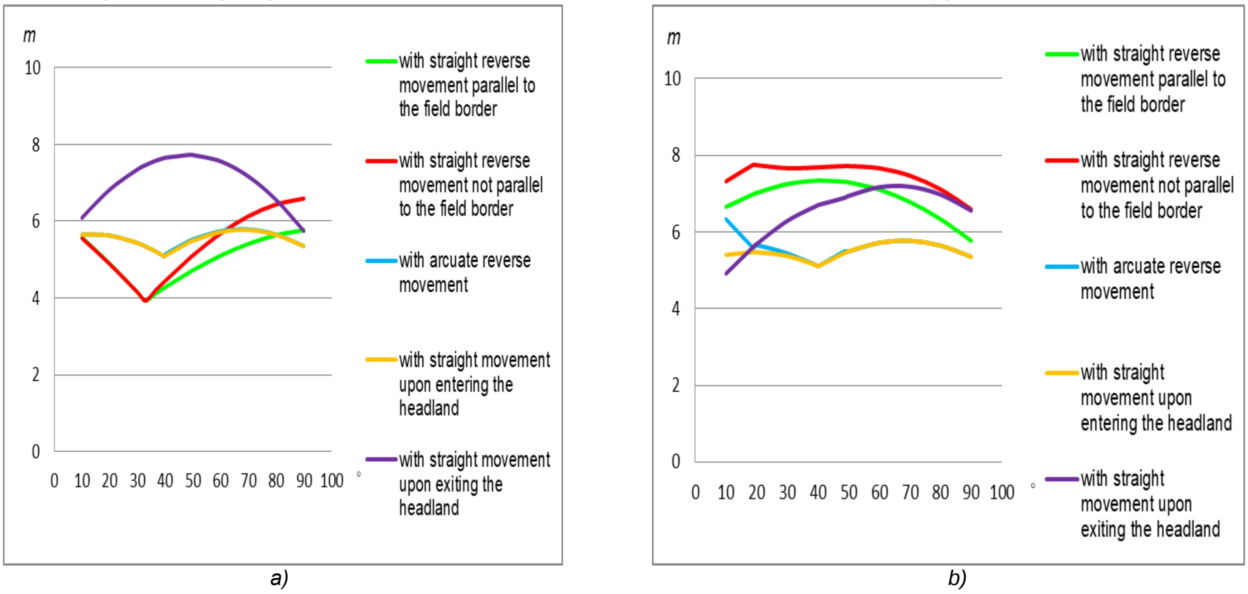


Fig. 3 – Headland width depending on the angle between the direction of movement of the machine-tractor unit and the field border when making open T-turns and movement in the field:
a) left to right; b) right to left

The following is seen through them:

- *T-turn with straight reverse movement parallel to the field border*

The headland has the smallest and equal width when making an open turn with left-to-right movement and a closed turn with right to left movement. In these cases the actual headland width will be equal to two working widths of the unit, i.e. at 6 *m*, whilst in the other two cases it will be greater – 9 m.

- *T-turns with straight reverse movement not parallel to the field border*

With these turns, the headland width is smaller when making an open turn with left-to-right movement and a closed turn with right-to-left movement. Both variants should only be used at a smaller angle between the direction of movement and the field border to ensure an actual headland width of 6 m for the specific unit.

- *T-turns with arcuate reverse movement*

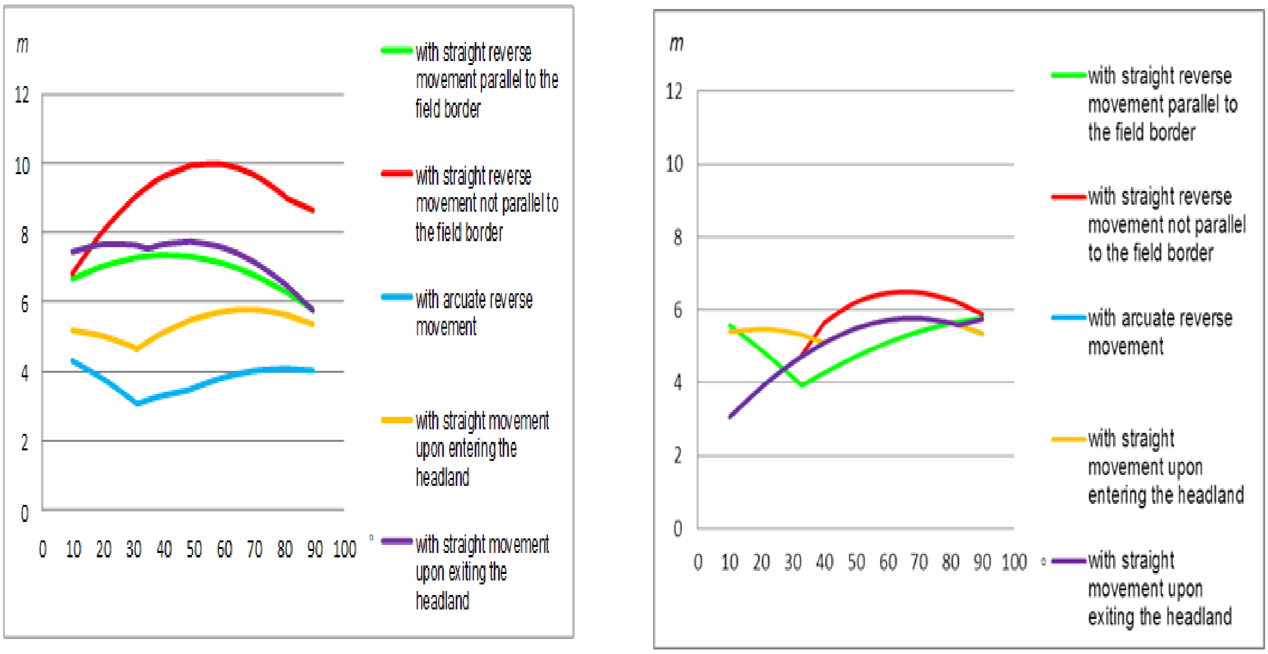
With this turn the theoretical headland width is the smallest compared to all others when it is closed and the movement in the field is from left to right. For the specific unit, the actual headland width is 6 m, regardless of the type and direction of this turn.

- *T-turns with straight movement upon entering the headland*

The same applies to this type of turns as to the T-turn with arcuate movement. The figures show that in many cases the headland width in both turns is the same.

- *T-turns with straight movement upon exiting the headland*

The headland width is the smallest when making a closed turn from right to left. Only in this case the actual headland width is 6 m for the entire range of change of the angle between the direction of movement and the field border. In the other three cases, such a headland width will be present either in very small or very large values of the angle.



a) *b)*

Fig. 4 – Headland width depending on the angle between the direction of movement of the machine-tractor unit and the field border when making closed T-turns and movement in the field:
a) left to right; b) right to left

CONCLUSIONS

New dependencies have been derived and the theory for determining the headland width in an irregularly-shaped field when making T-turns by a machine-tractor unit is supplemented.

It has been established that in order to obtain the minimum headland width, closed turns with a direction of movement from left to right should be made.

It has been proven that the theoretical headland width is the smallest when making a closed T-turn with arcuate reverse movement and direction of movement in the field from left to right.

When using T-turns with arcuate reverse movement and T-turns with straight movement upon entering the headland, the actual headland width is the same (6 m) regardless of the type and direction of the turn.

Further work plans include determining the length of the studied turns and experimental verification of the theoretical model. The obtained dependencies can be used for creating an algorithm for choice of a turn with minimum length and headland at given parameters of the unit depending on the angle between the direction of movement and the field border.

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