COMPARATIVE ANALYSIS OF THE IDLE MOVE LENGTH WHEN MAKING T-TURNS BY A MOUNTED MACHINE TRACTOR UNIT IN A FIELD OF IRREGULAR SHAPE
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СРАВНИТЕЛЕН АНАЛИЗ НА ДЪЛЖИНАТА НА НЕРАБОТНИЯ ХОД ПРИ ИЗВЪРШВАНЕ НА ГЪБОВИДНИ ЗАВОИ ОТ НАВЕСЕН МАШИННО-ТРАКТОРЕН АГРЕГАТ В ПОЛЕ С НЕПРАВИЛНА ФОРМА

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DOI: https://doi.org/10.35633/inmateh-68-45

Keywords: *T-turns, idle move length, motion of a machine-tractor unit, field of irregular shape*

ABSTRACT
The productivity of machine-tractor units depends on the length of the idle move performed in the headland. Analytical dependences for determining the length of the idle move when making T-turns by a machine-tractor unit with a mounted machine in a field of irregular shape have been specified in the article. Five types of T-turns have been considered in two variants – open turn and closed turn. Each of them is carried out in two directions of motion. A total of 20 variants of turns have been described. The methodology for determining the idle move length for a specific machine-tractor unit consisting of a tractor and a mounted row seeder has been demonstrated. It has been established that the idle move of the machine-tractor unit had the smallest length when the direction of making the turn is from right to left. For three of the studied turns, the idle move length in open and closed turns is the same when travelling from right to left. Right-to-left open and closed T-turns have been shown to provide the same idle move length of the unit in the headland, which is the smallest compared to the other turns.

РЕЗЮМЕ
Производителността на машинно-тракторните агрегати зависи от дължината на неработния ход извършван в ивицата за завиване. В статията са посочени аналитични зависимости за определяне на дължината на неработния ход 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 дължината на неработния ход за конкретен машинно-тракторен агрегат съставен от трактор и навесна редова сеялка. Установено е, че неработният ход на машинно-тракторния агрегат е с най-малка дължина когато посоката на извършване на завоя е отдясно наляво. За три от изследваните завои дължината на неработния ход при отворени и затворени завои е еднаква при движение отдясно наляво. Доказано е, че отворените и затворените гъбовидни завои извършвани отдясно наляво осигуряват еднаква дължина на неработния ход на агрегата в ивицата за завиване, която е най-малка в сравнение с останалите завои.

INTRODUCTION
The idle move length performed by a machine-tractor unit in the field had an effect on its productivity. In most mechanized operations turns in the headland had the greatest share among idle moves *(Sabelhaus et al., 2013*). It has been found in a study by Bochtis and Sorensen (2009) that turns comprised 5.27 % and 6.48 % of the total distance travelled the machine-tractor unit (*Bochtis et al., 2009*). When the machine needs to be stocked on the field, for example with liquid fertilizer, the distance travelled by the unit for making turns is the second longest idle distance after the distance travelled to the loading station. It is 14 – 42 % of the idle moves or an average of 29 % (*Jensen et al., 2015*).

Therefore, minimizing the length of moves and the time for making them will have a positive effect on the productivity of machine-tractor units. This can be done by an appropriate choice of turns in the headland and a method of making the working moves. In order to minimize the time for making turns and servicing the machine on the field (loading and unloading of materials and crop), the orientation (angle) of moves, the order of making moves and the types of turns among them are to be optimized. The angle between the direction of the working moves and the field border has an effect on 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*).

To optimize the trajectory of machine-tractor units on the field, graphical and functional methods are used. The graphical method makes use of simple forms such as circles, arcs and lines to present the trajectory of motion. In the methods based on functions, the trajectory of motion is presented as equations of spirals, clothoids, etc. (*Khan et al., 2018*).

Determining the length of turns composed of straight lines and arcs of permanent radius only is not precise, since the deflection of the tractor control wheels for reaching the necessary radius of a turn does not happen immediately (*Trendafilov, 2022*). Due to that reason, some researchers use clothoids connecting straight-line areas with curved-line areas of a turn with permanent curve radius, comprising an arc of a circle (*Sabelhaus et al., 2013*). The length of the turn and the width of the headland when using clothoids depend on the forward speed of the machine-tractor unit and the angular speed with which the deflection of its control wheels is carried out. As the speed of the turn increases, its length increases (*Vezirov et al., 2011*).

The actual length of turns cannot be determined analytically, as it is also influenced by factors such as driver skill, soil conditions, interaction between the tractor wheels and the soil, etc. These factors result in extending turns relative to their theoretical length. This additional path travelled by the aggregate cannot be determined analytically and is a stochastic quantity (*Bochtis and Vougioukas, 2008*). Due to the driver's inability to make a perfectly shaped turn and the interaction between soil and machine-tractor unit, there is a difference between the theoretical and the actual length of turns. In some studies, it is 3.6 – 12 % (*Bochtis and Vougioukas, 2008*).

Very often, a geometric model is used to determine the length of turns. The length of a turn is a function of the operating width, the minimum radius of a turn, the angle between the direction of travel and the headland, the number of missed moves when making the turn *(Bochtis et al., 2010; Bochtis and Sorensen, 2009; Spekken et al., 2015*). It is calculated analytically as the sum total of the lengths of straight and curved sections. The shape and length of turns in the headland changes depending on the angle between the direction of motion of the machine-tractor unit when making the operating move and the field border (*Trendafilov, 2021*). With a different value of this angle, turns have different length and require different width of the headland (Trendafilov K., 2020; Trendafilov K. 2021 a, b; Trendafilov K. 2022 a, b).

The type of turn can be automatically selected and its parameters can be determined according to the information about the headland obtained from the navigation system and the type of unit (*Freyberger and Jahns, 2000*). Such a system of motion in the headland can be successfully connected to a device making repeated actions on the machine-tractor unit (for example, control of the tower, the power take-off shaft, hydraulic valves), which allows fully automated turning by the units (*Cariou et al, 2010 a,b*). Automatic turning will allow the operator to focus more on performing the relevant operation (*Freyberger and Jahns, 2000).* During turning at the edge of the field, wheel slip takes place, which impairs the ability to follow a predetermined trajectory. Incorporating a slip estimation mechanism leads to an increase in the operating accuracy of the control system (*Bayar et al., 2016*).

In order to find a fully automated solution and reduce the workload of workers, even to create unmanned machine-tractor units, the motion of the units in the headlands has to be studied with the greatest accuracy (*Cariou et al., 2010*).

The objective of this article is to make a comparative analysis of the length of the idle stroke when making different T-turns in the headland of an irregularly shaped field and to justify the choice of a type of turn and direction of its execution in the field in order to ensure minimum length of the idle moves of the unit.

MATERIALS AND METHODS

Five types of T-turns performed by a machine-tractor unit have been discussed:

- T-turns with straight-line backward move parallel to the field border;
- T-turns with straight-line backward move not parallel to the field border;

- T-turns with arc-shaped backward move;
- T-turns with straight-line move upon entering the headland;
- T-turns with straight-line move upon exiting the headland.

Each of the turns is in two variants - open and closed and is performed in two directions - from left to right and from right to left. A geometric method was used for designing the turns in which turns are represented by lines and arcs of circles with the same radius. Fig. 1 shows the diagrams of some of the turns. The length of the turn is the distance travelled by the unit from point *A* (bringing the machine-tractor unit into transport position at the beginning of the turn) to point *B* (bringing the machine-tractor unit into working position at the end of the turn). Points *A* and *B* are in the centre of the unit, i.e. in the middle of the rear axle of the tractor. The idle run length in the headland includes the length of the turn and the length of straight runs before and after it has been made within the headland.

The headland is determined in two ways depending on the type of unit, the operation performed and the direction of making the turn. When the unit does not need to enter the field when making a turn in order not to damage the plants, for example, when working with perennial plantations and field crops the headland has greater width *E'*. If there are no such restrictions, the headland had smaller width *E*. A stripe with width *E'* is available only in some turns. According to some authors, the headland strip is not necessary when the angle between the direction of motion of the unit and the field border is less than 15° (*Oksanen, 2007*). Others accept that the field has a headland when the angle between the direction of motion and the field border is greater than 10° (*Aurbacher and Dabbert, 2009*).

To compare the length of the idle move in the different turns, calculations have been made about a specific machine-tractor unit composed of tractor Lamborghini Sprint 674-75 and seeder Gaspardo M300 (Fig. 2). The analytical relations given in Table 1 have been used (*Trendafilov, 2020; Trendafilov 2021 a, b; Trendafilov, 2022 a, b*). The designations used on Fig. 1 and in the formulas have the following meanings:

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

point *A* – beginning of the turn;

point *B* – end of the turn;

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

β – central angle of the respective curvilinear motion;

R – radius of the unit turn;

H – longitudinal base of the tractor;

l_a – kinematic length of the unit;

M – tractor track;

B – operating width of the unit;

E – minimum headland width;

E' – headland width limited by the tractor wheels;

l_g – length of the straight idle move in the headland. When the straight line before and after the turn is of different length, it is denoted respectively:

l_{g1} – length of the straight idle move before the beginning of the turn;

l_{g2} – length of the straight idle move after the end of the turn.

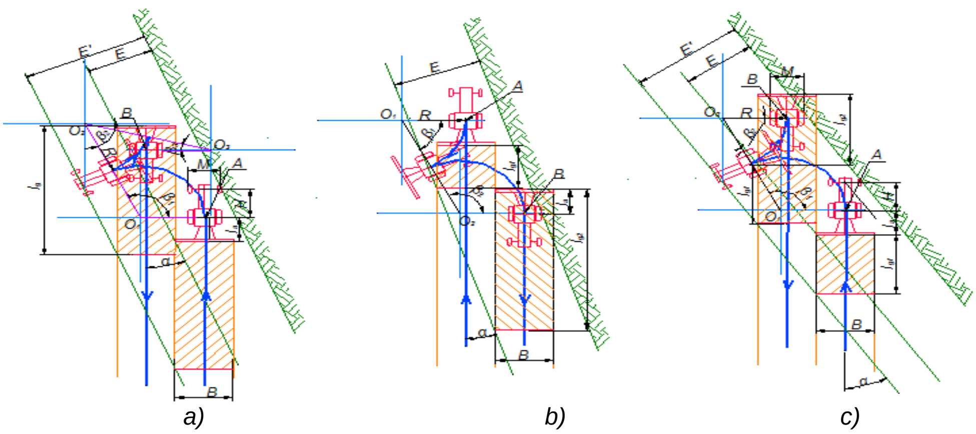


Fig. 1 – Diagrams of closed T-turns

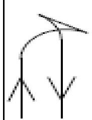
a – with arc-shaped backward move and motion from right to left; b – with straight move upon entering the headland and motion form left to right; c – with straight move upon entering the headland and motion from right to left

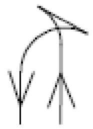
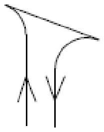
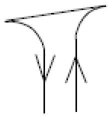
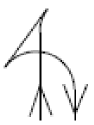
The machine-tractor unit has the following parameters: Operating width B = 3 m; kinematic length l_a = 3.1 m; radius of turn R = 2 m; longitudinal tractor base H = 2.25 m and tractor track M = 1.34 m. A range of variation of angle α from 10° to 90° has been adopted. Since there are no restrictions for entering the field for the particular unit, the calculations have been made for a headland of width E. The obtained results about the length of the idle move are presented graphically.

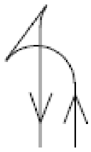
Fig. 2 – Machine-tractor unit

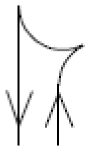
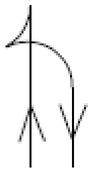
Table 1

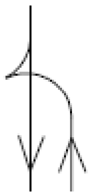
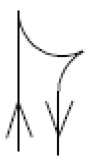
Analytical relations for determining the length of the idle move when making turns by a machine-tractor unit on a field of an irregular shape *(Trendafilov K., 2020; Trendafilov K. 2021 a, b; Trendafilov K. 2022 a, b)*

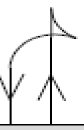
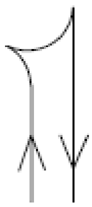
Name of the turn	Direction of execution	The idle move length when making T-turns
1	2	3
T-turn with straight-line backward move parallel to the field border		
open turns	left to right 	$l_n = l_T + l_g$ (1) where $l_T = \pi \cdot R + \dfrac{2R+B}{\sin\alpha}$ (2) $l_g = \dfrac{2R}{\tan\alpha} - 2l_a$ (3) when $\alpha > \tan^{-1}\left(\dfrac{R}{l_a}\right)$ (4) $l_g = -\left(\dfrac{2R}{\tan\alpha} - 2l_a\right)$ (5)
	right to left 	$l_n = l_T + l_g$ (1) where l_T is determined by dependence (2) $l_g = \dfrac{2R}{\tan\alpha} + 2l_a$ (6)
closed turns	left to right 	$l_n = l_T + l_g$ (1) where $l_T = \pi \cdot R + \dfrac{2R-B}{\sin\alpha}$ (7) l_g is determined by dependence (6)

	right to left 	$l_n = l_T + l_g$ where l_T is determined by dependence (7) l_g is determined by dependence (3), (4) и (5)	(1)
T-turn with straight-line backward move not parallel to the field border			
open turns	left to right 	For a headland of width *E* $l_n = l_T$ where $l_T = \pi \cdot R + \sqrt{(2R+B)^2 + \left(\frac{B}{\tan\alpha} + 2l_a\right)^2}$	(8) (9)
	right to left 	For a headland of width *E* $l_n = l_T$ where $l_T = \pi \cdot R + \frac{2R+B}{\sin\beta_2}$ The central angle *β₂* is determined by the dependence: $\beta_2 = \tan^{-1}\left(\frac{2R+B}{\frac{B}{\tan\alpha} - 2l_a}\right)$ After substituting dependence (11) into (10) for the length of the turn is obtained: $l_T = \pi \cdot R + \sqrt{(2R+B)^2 + \left(\frac{B}{\tan\alpha} - 2l_a\right)^2}$ when $\alpha > \tan^{-1}\left(\frac{B}{2l_a}\right)$ the central angle β_2 is determined by the dependence: $\beta_2 = 180 + \tan^{-1}\left(\frac{2R+B}{\frac{B}{\tan\alpha} - 2l_a}\right)$	(8) (10) (11) (12) (13)
		For a headland of width *E`* $l_n = l_T + 2l_g$ where l_T is determined by dependence (10) $l_g = \frac{(0.5M - R)\cos\beta_2 + R + 0.5B}{\tan\alpha} + (0.5M - R)\sin\beta_2 + l_a$ $l_g = 0$ when $\alpha = \tan^{-1}\left(\frac{(0.5M - R)\cos\beta_2 + R - 0.5B}{(R - 0.5M)\sin\beta_2 - l_a}\right)$	(14) (15) (16)
closed turns	left to right 	For a headland of width *E* $l_n = l_T$ where $l_T = \pi \cdot R + \frac{2R-B}{\sin\beta_1}$ The central angle β_1 is determined by the dependence: $\beta_1 = \tan^{-1}\left(\frac{2R-B}{\frac{B}{\tan\alpha} + 2l_a}\right)$	(8) (17)

		After substitution in dependence (17) is obtained: $l_T = \pi \cdot R + \sqrt{(2R-B)^2 + \left(\frac{B}{\tan\alpha} + 2l_a\right)^2}$ (18) (19)
		For a headland of width *E*\` $l_n = l_T + 2l_g$ (14) where l_T is determined by dependence (17) $l_g = \frac{(2R-B)\cdot\sin(\alpha+\beta_1)}{\sin\alpha\cdot\sin\beta_1} + \frac{(0.5M+R)\cdot\cos(\alpha+\beta_1)}{\sin\alpha} - l_a - (0.5B+R)\cdot\cot\alpha$ (20) when $\alpha > \tan^{-1}\left(\frac{l_a + \sqrt{l_a^2 + (2R-B)B}}{2R-B}\right)$ (21) $l_g = \frac{(2R-B)}{\tan\alpha} + \frac{(R-0.5M)\cos\beta_1}{\tan\alpha} - (R-0.5B)\sin\beta_1 + l_a$ (22) where $\sin\beta_1 = \frac{2R-B}{\sqrt{\left(\frac{B}{\tan\alpha}+2l_a\right)^2 + (2R-B)^2}}$ (23) where $\cos\beta_1 = \frac{\frac{B}{\tan\alpha}+2la}{\sqrt{\left(\frac{B}{\tan\alpha}+2l_a\right)^2 + (2R-B)^2}}$ (24)
	right to left 	For a headland of width *E* $l_n = l_T$ (8) where $l_T = \pi \cdot R + \sqrt{(2R-B)^2 + \left(\frac{B}{\tan\alpha} - 2l_a\right)^2}$ (25) The central angle β_2 is determined by the dependence: $\beta_2 = \tan^{-1}\left(\frac{2R-B}{\frac{B}{\tan\alpha} - 2l_a}\right)$ (26) when $\alpha > \tan^{-1}\left(\frac{B}{2l_a}\right)$ the central angle β_2 is determined by the dependence: $\beta_2 = 180 + \tan^{-1}\left(\frac{2R-B}{\frac{B}{\tan\alpha} - 2l_a}\right)$ (27)
		For a headland of width *E*\` $l_n = l_T + 2l_g$ (14) where $l_g = \frac{(R+0.5)\cdot\cos(\alpha+\beta_2) + H\cdot\sin(\alpha+\beta_2)}{\sin\alpha} + (R-0.5B)\cdot\cot\alpha - l_a$ (28) $l_g = 0$ with $\alpha = \tan^{-1}\left(\frac{(R-0.5M)\cos\beta_2 + H\cdot\sin\beta_2 - R - 0.5B}{(R-0.5M)\sin\beta_2 + 2l_a - H\cdot\cos\beta_2}\right)$ (29)

T-turn with arc-shaped backward move		
open turns	left to right 	$l_n = l_T + l_g$ (1) where $l_T = \pi R$ (30) $l_g = \frac{B}{\tan\alpha} + 2l_a - \sqrt{4R^2 - B^2}$ (31) $l_g = 0$ when $\alpha = \tan^{-1}\left(\frac{B}{\sqrt{4R^2 - B^2} - 2l_a}\right)$ (32)
	right to left 	$l_n = l_T + l_g$ (1) where l_T is determined by dependence (30) $l_g = \frac{B}{\tan\alpha} - 2l_a - \sqrt{4R^2 - B^2}$ (33) $l_g = 0$ when $\alpha = \tan^{-1}\left(\frac{B}{\sqrt{4R^2 - B^2} + 2l_a}\right)$ (34)
closed turns	left to right 	$l_n = l_T + l_{g_1} + l_{g_2}$ (35) where l_T is determined by dependence (30) where $l_{g_1} = (R - 0.5M)\frac{\sqrt{4R^2 - B^2}}{2R} - l_a + \frac{R - B + \frac{M \cdot B}{4R}}{\tan\alpha}$ (36) where $l_{g_2} = l_a - (R + 0.5M)\frac{\sqrt{4R^2 - B^2}}{2R} + \frac{R + \frac{M \cdot B}{4R}}{\tan\alpha}$ (37) when $\alpha > 90^\circ - \cos^{-1}\left(\frac{B}{2R}\right)$ (38) $l_{g_1} = (R + 0.5M)\frac{\sqrt{4R^2 - B^2}}{2R} - l_a + \frac{R - B - \frac{M \cdot B}{4R}}{\tan\alpha}$ (39) $l_{g_2} = (0.5M - R)\frac{\sqrt{4R^2 - B^2}}{2R} + l_a + \frac{R - \frac{M \cdot B}{4R}}{\tan\alpha}$ (40) when the angle α is greater than that determined by dependence (32) l_T is determined by dependence (30) $l_{g1} = l_{g2} = (R + 0.5M)\sin\beta_3 - 2R \cdot \sin\beta_1 - l_a + \frac{(R + 0.5M)\cos\beta_3 + 2R \cdot \cos\beta_1 - R - 0.5B}{\tan\alpha}$ (41) where $\beta_1 = \cos^{-1}\left(\frac{2R - B}{4R \cdot \cos\left(\tan^{-1}\left(\frac{\frac{B}{\tan\alpha} + 2l_a}{2R - B}\right)\right)}\right) - \tan^{-1}\left(\frac{\frac{B}{\tan\alpha} + 2l_a}{2R - B}\right)$ (42)

		$\beta_3=\cos^{-1}\left(\dfrac{2R-B}{4R\cdot\cos\left(\tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}+2l_a}{2R-B}\right)\right)}\right)+\tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}+2l_a}{2R-B}\right)$ (43)
	right to left 	For a headland of width *E* $l_n=l_T$ (8) where $l_T=\pi R+\dfrac{B}{\tan\alpha}-2l_a-\sqrt{4R^2-B^2}$ (44) l_T decreases to $l_T=\pi R$ at α determined by dependence (34)
		For a headland of width *E*\` $l_n=l_T+2l_g$ (14) where l_T is determined by dependence (44) $l_g=\dfrac{H\cdot B}{2R}-\left(0.5+\dfrac{M}{4R}\right)\sqrt{4R^2-B^2}-l_a+\dfrac{R+\frac{M\cdot B}{4R}+\frac{H\sqrt{4R^2-B^2}}{2R}}{\tan\alpha}$ (45) When the angle α is greater than defined by dependence (32) l_T is determined by dependence (30) $l_g=\dfrac{R-0.5B}{\tan\alpha}+\dfrac{H\cdot\sin(\beta_1-\alpha)-(R+0.5M)\cos(\beta_1-a)}{\sin\alpha}-l_a$ (46) $l_g=0$ when $\alpha=\tan^{-1}\left(\dfrac{R-0.5B-(R+0.5M)\cos\beta_1+H\cdot\sin\beta_1}{l_a+(R+0.5M)\sin\beta_1+H\cdot\cos\beta_1}\right)$ (47) where $\beta_1=\cos^{-1}\left(\dfrac{2R-B}{4R\cdot\cos\left(\tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}-2l_a}{2R-B}\right)\right)}\right)+\tan^{-1}\left(\dfrac{\frac{B}{\tan\alpha}-2l_a}{2R-B}\right)$ (48)
T-turn with straight-line move upon entering the headland		
open turns	left to right 	$l_n=l_T+l_g$ (1) where l_T is determined by dependence (30) where l_g is determined by dependence (31) $l_g=0$ with α is determined by dependence (32) When the angle α is greater than defined by dependence (32) the straight-line move l_g is when the unit enters the headland and its length is determined by the dependence: $l_g=\sqrt{4R^2-B^2}-\dfrac{B}{\tan\alpha}-2l_a$ (49)

	right to left 	For a headland of width *E* $l_n = l_T + l_{g_1}$ (50) where l_T is determined by dependence (30) $l_{g1} = \sqrt{4R^2 - B^2} + \frac{B}{\tan\alpha} - 2l_a$ (51) The straight-line move decreases to $l_{g1} = 0$ at $\alpha = \tan^{-1}\left(\frac{-B}{\sqrt{4R^2 - B^2} - 2l_a}\right)$ (52)
		For a headland of width *E*\` $l_n = l_T + l_{g_1} + 2l_{g_2}$ (53) where l_{g1} is determined by dependence (51) $l_{g2} = \frac{R + \frac{M \cdot B}{4R} - B}{\tan\alpha} - \sqrt{4R^2 - B^2}\left(0.5 - \frac{M}{4R}\right) + l_a$ (54)
closed turns	left to right 	$l_n = l_T + l_{g_1} + l_{g_2}$ (35) where l_T is determined by dependence (30) l_{g_1} is determined by dependence (36) $l_{g_2} = l_a - (R + 0.5M)\frac{\sqrt{4R^2 - B^2}}{2R} + \frac{R - B + \frac{M \cdot B}{4R}}{\tan\alpha}$ (55) when condition (38) is fulfilled for angle l_{g1} is determined by dependence (39) l_{g2} is determined by dependence (40) $l_{g2} = 0$ when $\alpha = \tan^{-1}\left(\frac{R - \frac{M \cdot B}{4R}}{\left(0.5 - \frac{M}{4R}\right)\sqrt{4R^2 - B^2} - l_a}\right)$ (56) When the angle a is greater than defined by dependence (56) $l_{g2} = \sqrt{4R^2 - B^2} - 2l_a - \frac{B}{\tan\alpha}$ (57)
	right to left 	$l_n = l_T + l_g$ (1) where l_T is determined by dependence (30) $l_g = \sqrt{4R^2 - B^2} - 2l_a + \frac{B}{\tan\alpha}$ (58)
T-turn with straight-line move upon exiting the headland		
open turns	left to right 	$l_n = l_T + l_{g_1} + l_{g_2}$ (35) where l_T is determined by dependence (30) $l_{g_1} = \frac{R - B + \frac{M \cdot B}{4R} + \frac{H\sqrt{4R^2 - B^2}}{2R}}{\tan\alpha} + \left(\frac{M}{4R} - 0.5\right)\sqrt{4R^2 - B^2} - \frac{H \cdot B}{2R} - l_a$ (59)

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$l_{g_2} = \dfrac{R + \dfrac{M \cdot B}{4R} + \dfrac{H\sqrt{4R^2 - B^2}}{2R}}{\tan\alpha} + \left(\dfrac{M}{4R} + 0.5\right)\sqrt{4R^2 - B^2} - \dfrac{H \cdot B}{2R} + l_a$ (60)
$l_{g1} = 0$ when $\alpha = \tan^{-1}\left(\dfrac{R - B + \dfrac{M \cdot B}{4R} + \dfrac{H\sqrt{4R^2 - B^2}}{2R}}{\dfrac{H \cdot B}{2R} + l_a - \left(\dfrac{M}{4R} - 0.5\right)\sqrt{4R^2 - B^2}}\right)$ (61)
When the angle a is greater than defined by dependence (61)
$l_{g2} = \sqrt{4R^2 - B^2} + 2l_a + \dfrac{B}{\tan\alpha}$ (62)
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$l_n = l_T + l_g$ (1)
where $l_T = \pi R + \dfrac{B}{\tan\alpha} - 2l_a - \sqrt{4R^2 - B^2}$ (63)
l_T decreases to $l_T = \pi R$ at α determined by dependence (34)
At a larger angle, the unit performs a straight move before exiting the headland with length
$l_g = \sqrt{4R^2 - B^2} + 2l_a - \dfrac{B}{\tan\alpha}$ (64)
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<td>closed turns</td>
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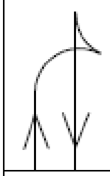</td>
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$l_n = l_T + l_g$ (1)
where l_T is determined by dependence (30)
$l_g = \sqrt{4R^2 - B^2} + 2l_a + \dfrac{B}{\tan\alpha}$ (65)
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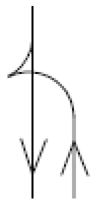</td>
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For a headland of width *E*
$l_n = l_T + l_{g_2}$ (66)
where l_T is determined by dependence (63)
When the angle α increases, the length of the straight-line back move decreases and reaches $l_b = 0$ when α is determined by dependence (34)
At a larger angle α the unit performs a straight line move before exiting the headland with length
$l_{g2} = \sqrt{4R^2 - B^2} + 2l_a - \dfrac{B}{\tan\alpha}$ (67)
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For a headland of width *E`*
$l_n = l_T + l_{g2} + 2l_{g1}$ (68)
where $l_{g1} = \dfrac{H \cdot B}{2R} - \left(0.5 + \dfrac{M}{4R}\right)\sqrt{4R^2 - B^2} - l_a + \dfrac{R + \dfrac{M \cdot B}{4R} + \dfrac{H\sqrt{4R^2 - B^2}}{2R}}{\tan\alpha}$ (69)
where α is determined by dependence (38)
$l_{g1} = \dfrac{H \cdot B}{2R} - \left(0.5 - \dfrac{M}{4R}\right)\sqrt{4R^2 - B^2} - l_a + \dfrac{R - \dfrac{M \cdot B}{4R} + \dfrac{H\sqrt{4R^2 - B^2}}{2R}}{\tan\alpha}$ (70)
where $\alpha > \tan^{-1}\left(\dfrac{B}{\sqrt{4R^2 - B^2} - H}\right)$ (71)
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		l_{g1} is determined by dependence (67) l_{g2} is determined by dependence (64) $l_{g1}=0$ when $\alpha=\tan^{-1}\left(\dfrac{R-\dfrac{M\cdot B}{4R}+\dfrac{H\sqrt{4R^2-B^2}}{2R}}{l_a+\left(0.5-\dfrac{M}{4R}\right)\sqrt{4R^2-B^2}-\dfrac{H\cdot B}{2R}}\right)$ (72)

RESULTS

Since the discussed machine-tractor unit has different parameters from the one for which the relations given in Table 1 have been made, mainly due to its greater kinematic length l_a, for some of the turns the following additions have to be made.

- *For a closed T-turn with arc-shaped backward move when moving from left to right*.

Upon entering the headland, the unit does not make an arc-shaped move to the left, only a straight one. The length of the straight move upon entering the headland is $l_{g1}=0$. However, the length of l_{g2} increases with the value of l_{g1} determined by the formulas, but with the opposite sign. It is recorded as follows:

$$l'_{g2}=\frac{B}{\tan\alpha}+2l_a-\sqrt{4R^2-B^2} \tag{73}$$

The same result is obtained when the values obtained from formulas (37) and (36), as well as from formulas (40) and (39) are deducted, regardless of the fact that l_{g1} is obtained with a negative sign. Therefore, for the length of the straight move upon exiting the headland the following can be denoted:

$$l'_{g2}=l_{g2}-l_{g1} \tag{74}$$

The length of the idle move is determined by the relation:

$$l_n=l_T+l'_{g2}=l_T+l_{g2}-l_{g1} \tag{75}$$

- *For an open T-turn with straight move upon entering the headland and motion from right to left*

At angle α greater than the one determined by relation (52), the straight move l_{g1} is when the unit exits the headland and its length is determined by the relation:

$$l_{g1}=2l_a-\sqrt{4R^2-B^2}-\frac{B}{\tan\alpha} \tag{76}$$

- *For a closed T-turn with straight move upon entering the headland and motion from left to right*

Since the machine-tractor unit had great length l_a, the headland is limited towards the field on the right side of the machine and not by the tractor wheels when making the turn with backward motion. For this reason, there is no straight move l_{g1} upon entering the headland, and the straight move upon exiting the headland has length determined by relation (70).

- *For a closed T-turn with straight move upon entering the headland and motion from right to left.*

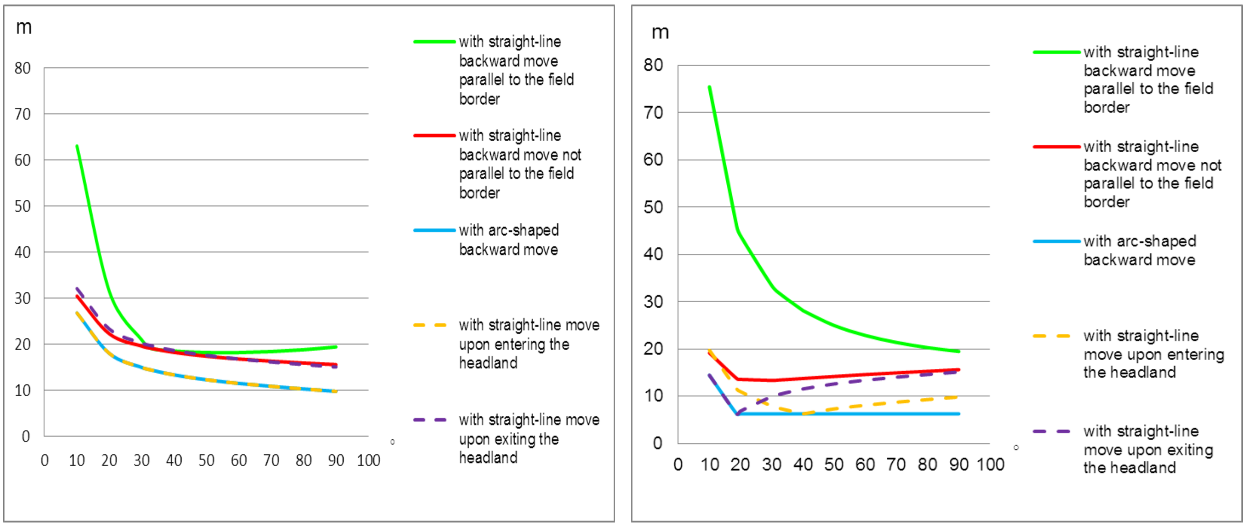
The straight move upon entering the headland decreases and becomes $l_g=0$ at:

$$\alpha=\tan^{-1}\left(\frac{B}{2l_a-\sqrt{4R^2-B^2}}\right) \tag{77}$$

At greater angle the straight move is already when the unit exits the headland and is determined by the relation:

$$l_g = 2l_a - \sqrt{4R^2 - B^2} - \frac{B}{\tan\alpha} \tag{78}$$

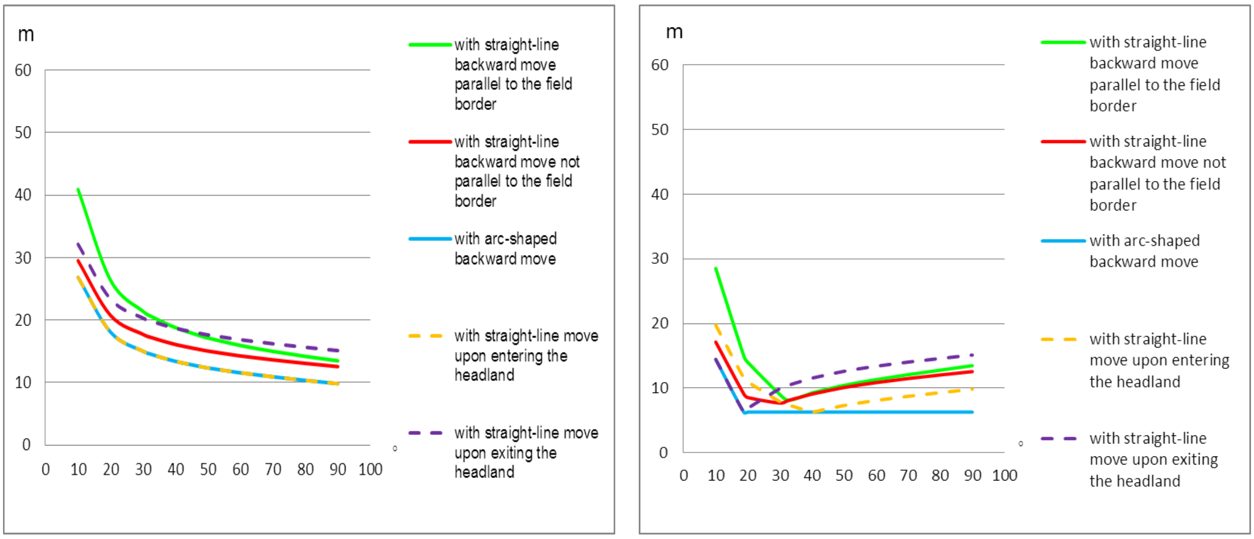
Fig. 3 and Fig. 4 show the results from the calculations for the different types of turns. It is also seen that the open turns are shorter in length when made from right to left except for the straight backward move turn. The shortest idle move is when making a turn with an arc-shaped backward move and a turn with a straight move upon entering the headland.



a) *b)*

Fig. 3 – Length of the idle move depending on the angle between the direction of motion of the machine-tractor unit and the field border when making open T-turns and motion in the field:

a) from left to right; b) from right to left



a) *b)*

Fig. 4 – Length of the idle move depending on the angle between the direction of motion of the machine-tractor unit and the field border when making closed T-turns and motion in the field:

a) from left to right; b) from right to left

When making closed turns, the idle move is also shorter in direction from right to left. The difference between the two directions in making the turn is greater at a small angle between the direction of motion and the field border. At a large angle, the difference in the length of the idle move in different directions of the turn decreases and in some turns it is equal at an angle of 90°. Here, as in the case of open turns, the idle move is the shortest when making a turn with an arc-shaped backward move and a turn with a straight move upon entering the headland.

It can also be seen from the figures that in three of the turns, the length of the idle move in open and closed turns is the same in motion from right to left - a turn with an arc-shaped backward move, a turn with a straight move upon entering the headland and a turn with straight move upon exiting the headland.

CONCLUSIONS

The theory for determining the length of the idle move when making various types of open and closed T-turns in the headland of a field with an irregular shape has been supplemented.

It has been established that the idle move of the machine-tractor unit has the smallest length when the direction of making the turn is from right to left.

It has been established that for three of the studied turns, the length of the idle move in open and closed turns was the same when moving from right to left.

Right-to-left open and closed T-turns have been shown to provide the same length of the idle move of the unit in the headland, which is the smallest compared to other turns.

For the practice, it can be recommended to use an open and closed turn with an arc-shaped backward move and a turn with a straight move upon entering the headland, the direction of making the turn should be from right to left. At a small angle between the direction of motion and the field border, a turn with a straight move upon exiting the headland may be used.

The development of the theory for determining the length of the idle move and the width of the headland in a field with an irregular shape can be used to develop an algorithm for automatic selection of a turn and direction of making it depending on the parameters of the unit and the angle between the direction of motion and field border. This will exclude the subjective decision of the operator when choosing motion in the headland, which will result in an increase in the efficiency of agricultural operations performed.

ACKNOWLEDGEMENT

This work was supported by the Bulgarian Ministry of Education and Science under the National Research Programme „Smart crop production" approved by Decision of the Ministry Council № 866 / 26 November 2020.

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