THEORETICAL JUSTIFICATION OF THE TURN OF A WIDE SPAN TRACTOR (VEHICLE) FOR CONTROLLED TRAFFIC FARMING
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ТЕОРЕТИЧНЕ ОБҐРУНТУВАННЯ ПОВОРОТУ ШИРОКОКОЛІЙНИХ ТРАКТОРІВ (ТРАНСПОРТНИХ ЗАСОБІВ) ДЛЯ КОЛІЙНОЇ СИСТЕМИ ЗЕМЛЕРОБСТВА

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ABSTRACT
A new scheme of the turn of a wide span tractor (vehicle) is presented for controlled traffic farming on the turning strip. The turn of the tractor, according to the presented scheme, allows moving the tractor to the next working position with better kinematic parameters. In addition to it, the improvement of the turnability characteristics is achieved at such a design embodiment of a wide span tractor when the ratio of its wheelbase to the width of the wheel track is as small as possible. The obtained equations about the movement of the wide span tractor for the offered new scheme of the turn allow estimating the impact of its design, performance, kinematic and power parameters upon the criteria of static and dynamic turnability.

РЕЗЮМЕ
Запропонована нова схема розвороту ширококолійного трактора для колійної системи землеробства на поворотній смузі, за якою переміщення трактора на наступну робочу позицію здійснюється з кращими кінематичними параметрами. При цьому покращення характеристик повороткості досягається при такому конструктивному виконанні ширококолійного трактора, коли відношення його колісної бази до ширини колії є якомога меншим. Отримані рівняння руху для запропонованої нової схеми повороту дозволяють оцінити вплив його конструктивних, експлуатаційних, кінематичних і силових параметрів на критерії статичної та динамічної повороткості.

INTRODUCTION
A peculiarity of using a wide span tractor (vehicle) for controlled traffic farming is the division of the field into the agrotechnical and the engineering area *(Antille et. al., 2015; Chamen, 2015; Chen et. al., 2010; Gasso et. al., 2013; Gasso et. al., 2014; Kingwell et. al., 2011).* Turning of the wide span tractor (vehicle) on the turning strip may be accomplished in different ways. Each way of turning has impact on the kinematics of its *curvilinear movement. Besides, it is desirable that the unproductive losses of energy on the turn and the engineering area should be as low as possible. From the minimization standpoint of unproductive losses, the fields under the engineering area must have a possibility to perform a turn of the* wide span tractor in such a way that the actuators of one of its sides remained within the same transport and technological track on which they were positioned but the actuators of the other side transferred their undercarriage to the next operating position *(Kuvachov, 2016).*

Turnability (a property of the tractor to perform turns with a pre-set curvature of the path) is characterised by kinematic and power parameters. Therefore, correct choice of the latter parameters from a position of the required turnability ensures the movement of the wide span tractor under optimal conditions and minimises the unproductive losses of energy and areas of the field during the turn. For this reason, the scientific investigations aimed at in the study of wide span tractor (vehicle) static and dynamic turnability are highly topical. The turning control of contemporary wide span tractors (*Chamen, 1992; Chamen et al., 1994; Chamen, 2000; Chamen, 2015; Onal I., 2012; Pedersen, 2011; Pedersen et. al., 2013; Kuvachov, 2015),* equipped with wheeled actuators, is adapted for a manual or an automatic mode *(Jasiński et al., 2016),* and they are based on a kinematic or a power principle of performing this turn. In kinematic turning there are used schemes for turning steered wheels (front, rear or both simultaneously) in relation to the frame of the machine. There is also known a power (board) method of changing the direction of the movement by turning the machine in a suspended condition *(Uleksin, 2011).*

In the opinion of the author of the scientific publication, the use of the latter method of turning is efficient under the conditions of limited space on the turning strip, and it allows turning of a machine in the automatic mode without causing damage to the plants in the crossing areas of the traffic track. The theory of the static and the dynamic turnability of a wheeled vehicle has been studied in sufficient detail *(Popp, 2010; Rajamani, 2006; Tullberg, 2000; Wong, 2001).*

There is a great number of scientific investigations devoted to the turnability issue of agricultural machine and tractor aggregates *(Gorin, 2012; Nadykto et. al., 2005; Nadykto et. al., 2012).* However, the obtained analytical dependencies cannot practically be applied to the turnability analysis of wide span tractors (vehicles). The reason is the main difference in the design and kinematic scheme of its turn in the coordinate transport system of movement. Still less suitable for further analysis are the results obtained by scientists investigating the turning dynamics of the conventional machine and tractor aggregates.

The aim of the work was theoretical research and justification of the static and dynamic turnability of wide span tractors (vehicles) for controlled traffic farming in order to improve the kinematic and power parameters of the movement.

MATERIALS AND METHODS

We consider in an analytical way two schemes of the turn of a wide span tractor (vehicle) (Fig.1) the kinematic parameters of which – the turning radius, wheels movement angular and linear velocities, the movement path, etc. depend on the design and operating factors (the wheelbase, track width (wheel spacing), maximal turning angles of the steerable wheels, their turning speed, the movement speed, tyre characteristics and so on.

According to the first scheme, which is most widespread among the contemporary brands of wide span tractors (vehicles), the turn is executed by the movement of all the steerable wheels of the tractor around the turning centre positioned in the symmetry centre of its undercarriage (Fig.1*a*). According to the second scheme, proposed by us, the turn of the tractor is carried out by turning the undercarriage platform, using the steerable wheels from its one board, around the turning centre positioned in the centre of the space between the wheels from the other board (there the wheels may remain during the turn within the limits of their transport technological track (Fig.1*b*).

There are at least two ways how to embody our proposed scheme of the turn of a wide span tractor (vehicle) (Fig.1*b*):

1) by kinematic turning of the platform, using the steerable wheels from one board by means of an articulated turning mechanism positioned in the centre of the space between the wheels from the other side;

2) by kinematic power turning of the wide span tractor by suspending one of its boards, using lifting mechanisms.

Let us analyse the influence of the basic design parameters of a wide span tractor on the turning kinematic characteristics of the two considered schemes (Fig. 1): the turning radius and the turning angle of the steerable wheels which determine the width of the turning strip. It is clear that the value of the desired width of the turning strip E should be as small as possible but sufficient for the wide span tractor to pass. Depending on the parameters of their undercarriage the optimal width of the turning strip has to be equal to:

$$E = K + b_p, \tag{1}$$

where

K – the wheel track (wheel spacing) width of the wide span tractor;

b_p – the width of the transport technological track.

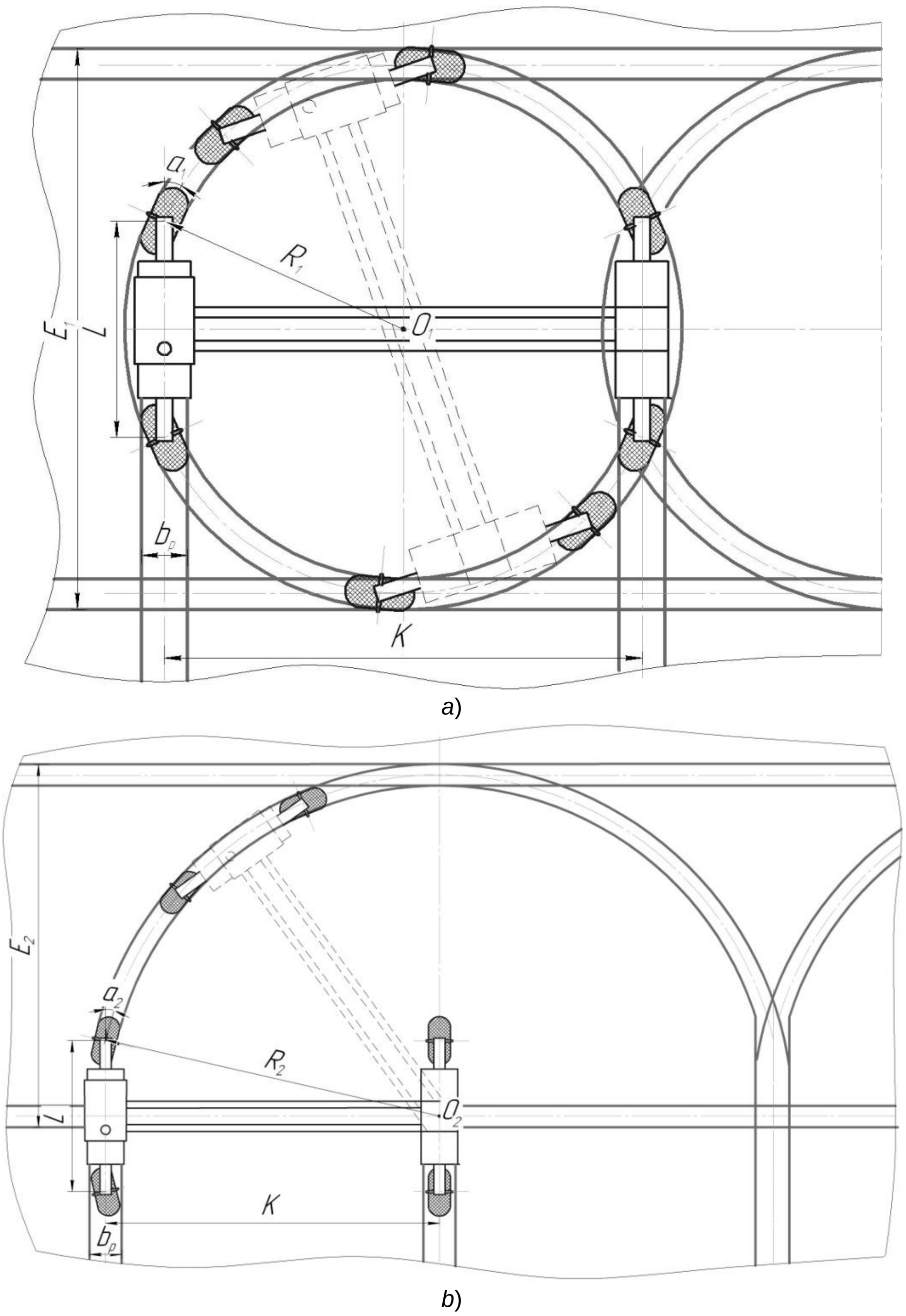

Fig. 1 –Schemes of a wide span tractor (vehicle) turn around the turning centre positioned in its undercarriage symmetry centre (*a*) and in the centre of the space between one of the boards' wheels (*b*)

Let us present the basic design parameters of a wide span tractor as a generalised characteristic parameter μ, numerically equal to the relation of its wheelbase *L* with the width of the wheel track *K*, which, as a rule, does not exceed 1, that is:

$$\mu = \frac{L}{K} \leq 1 \qquad (2)$$

The methods used in the research methodology are: the methods of theoretical mechanics, the tractor theory and operation of agricultural aggregates, using the Mathcad packet. The theoretical investigations, synthesis of wide span tractor (vehicle) design maps and parameters were conducted by simulating the conditions of their performance on the PC.

RESULTS

According to the conventional turn scheme of a wide span tractor (Fig.1*a*), the relationship between the kinematic indicators of the turn (the turning angle of the wheels α_1, the turning radius R_1 and the actual width of the turning strip E_1) and the design parameters, presented as μ, can be expressed by the following dependencies:

$$R_1 = \frac{1}{2}\sqrt{K^2+L^2} = \frac{1}{2}K\sqrt{1+\mu^2},$$
$$E_1 = 2R_1 + b_p = \sqrt{K^2+L^2} + b_p = K\sqrt{1+\mu^2} + b_p \quad (3)$$
$$\alpha_1 = arctg\left(\frac{L}{K}\right) = arctg(\mu)$$

According to second turn scheme, offered by us, (Fig. 1 *b*) we find in a similar way that:

$$R_2 = \frac{1}{2}\sqrt{4K^2+L^2} = \frac{1}{2}K\sqrt{4+\mu^2},$$
$$E_2 = R_2 + b_p = \frac{1}{2}\sqrt{4K^2+L^2} + b_p = \frac{1}{2}K\sqrt{4+\mu^2} + b_p, \quad (4)$$
$$\alpha_2 = arctg\left(\frac{L}{2K}\right) = arctg\left(\frac{\mu}{2}\right).$$

By means of the Mathcad packet we estimate the influence of the wide span tractor characteristic parameter μ on the variability degree of the turning strip actual width in relation to the desired one (Fig.2) and the value of the steerable wheels' turning angle (Fig.3) for the two discussed schemes of the turn.

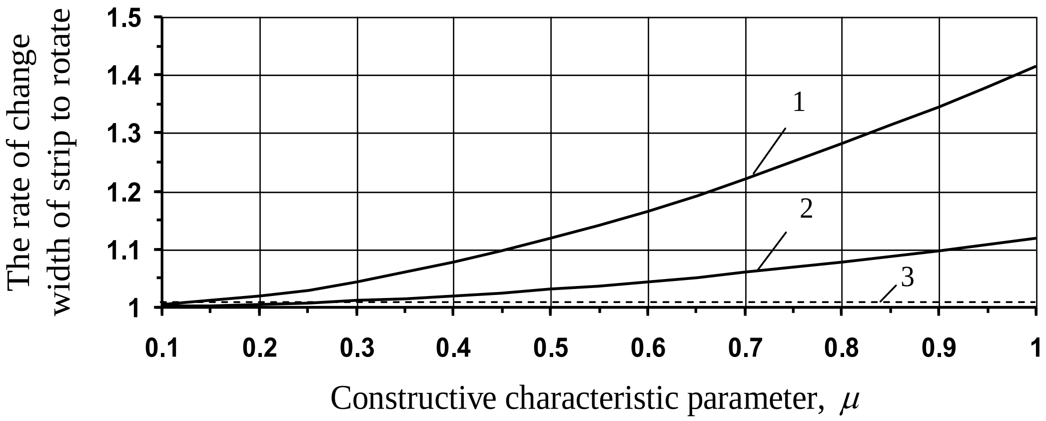

Fig. 2 – Dependence of the variability degree of the turning strip actual width on the constructive characteristic parameter μ for different turn schemes for wide span tractors (vehicles):

1 –scheme in Fig. 1 a; 2 –scheme in Fig. 1 b; 3 – the preferred characteristic

From the analysis of Fig. 2 it results that it is not desirable to increase wide span tractors (vehicles) characteristic parameter μ because it increases the turning strip width. Yet the degree and intensity of such an increase for the discussed turn schemes are different. Thus, increasing μ to 1, the turning strip width for the most widespread first turn scheme (Fig. 1 *a*) is by 30% bigger than for the other scheme, proposed by us (Fig. 1 *b*). And, if value μ for the contemporary brands of wide span tractors (vehicles) does not exceed μ < 0.5, then increase in the width of the turning strip according to scheme in Fig.1 *b* does not exceed 3% of the desired value.

Such a result is on the allowed deviation level from the rectilinear movement of the wide span tractors (vehicles). However, in this case, the organisation of the turn according to the scheme in Fig. 1 *a* requires an increase in the turning strip to 12%, which is highly undesirable in terms of optimal land use. Therefore, from this position, the organisation of a wide span tractor (vehicle) turn according to the scheme offered by us Fig. 1 *b* is more appropriate.

Of similar character is the dependence of the steerable wheels turning angle α of the wide span tractor (vehicle) on *μ* (Fig. 3).

When the turn is executed according to the scheme in Fig. 1 *a*, angle α is twice as great as in the scheme of Fig. 1 *b*. It is not desired to increase the steerable wheels turning angle α, since it requires corresponding complication of the tractor wheels turning mechanism design and higher energy consumption for this process.

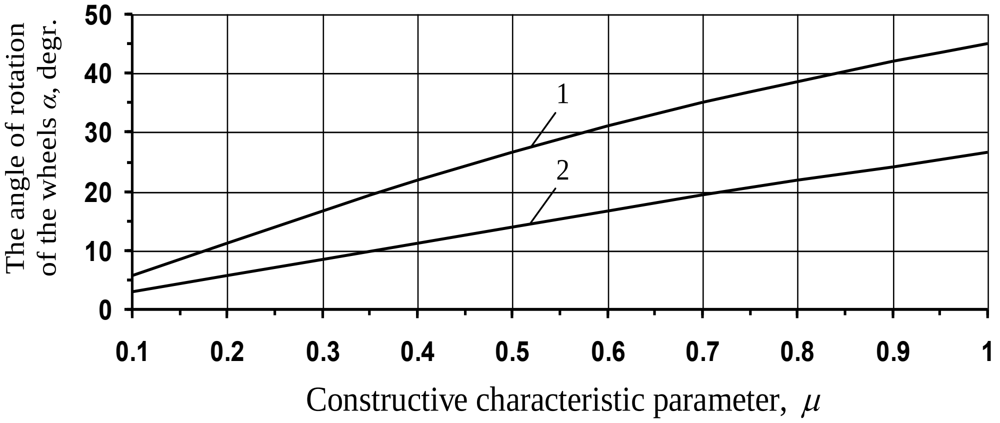

Fig. 3 – Dependence of the steerable wheels turning angle of wide span tractors (vehicles) on the constructive characteristic parameter μ for different turn schemes:

1) – a scheme in Fig. 1 a; 2) – a scheme in Fig. 1 b

The kinematic parameters discussed by us provide wider but not full information about the *curvilinear movement of the* wide span tractors. Full information about the possibility of a movement with preset kinematic parameters can be obtained by determining the power parameters (the tangential traction forces on the driving wheels, the losses of energy consumed by the tractor to overcome the resistance of the total angular momentum of rotation, etc.) that characterise the static and the dynamic turnability of the wide span tractor.

In order to obtain characteristics of the static turnability, let us consider circular movement of a wide span tractor flat model around the turning centre (point *O*) (Fig. 4) with a constant angular velocity $\omega = \text{const}$, $\dot{\omega} = 0$. The steerable wheels of one board (in the given case – the left one) are turned by angles α_1 and α_2.

In constructing equations of the movement, we start from the generally accepted concept about a correct turn in accordance with which all the driving wheels of the tractor (in Fig. 4 – the two left-side wheels) are moving without lateral slipping, but crossing of their axes takes place at a point which is the curvature centre of the path travelled. We do not take into account the lateral skid of the wheels since the tractor performs circular movement around its fixed axis, and there is no movement in a perpendicular direction. We consider only those elements of the wide span tractor which execute plane-parallel movements.

Due to the low absolute value, the tangential inertia forces and the inertial moments of resistance to the turn of the wide span tractor and its technological part are ignored. We strictly connect the wide span tractor with the mobile Cartesian coordinate system xSy, the origin of which we place at the centre of its left board masses (point S). We draw axis x in parallel to the longitudinal axis of the tractor but its positive direction – in the direction of the movement. In the turning mode, a series of corresponding forces act upon the wide span tractor (vehicle).

First of all, these are the driving forces of the front and rear steerable wheels (in our case – the left ones) F_{k1} and F_{k2}, and the resistance forces to the movement F_{f1} and F_{f2}, applied at their centres (points P_1 and P_2), and the inertia force. In order to perform further actions exactly at these points, it is appropriate to divide mass m_b to be applied to its left board into two parts (m_1 and m_2).

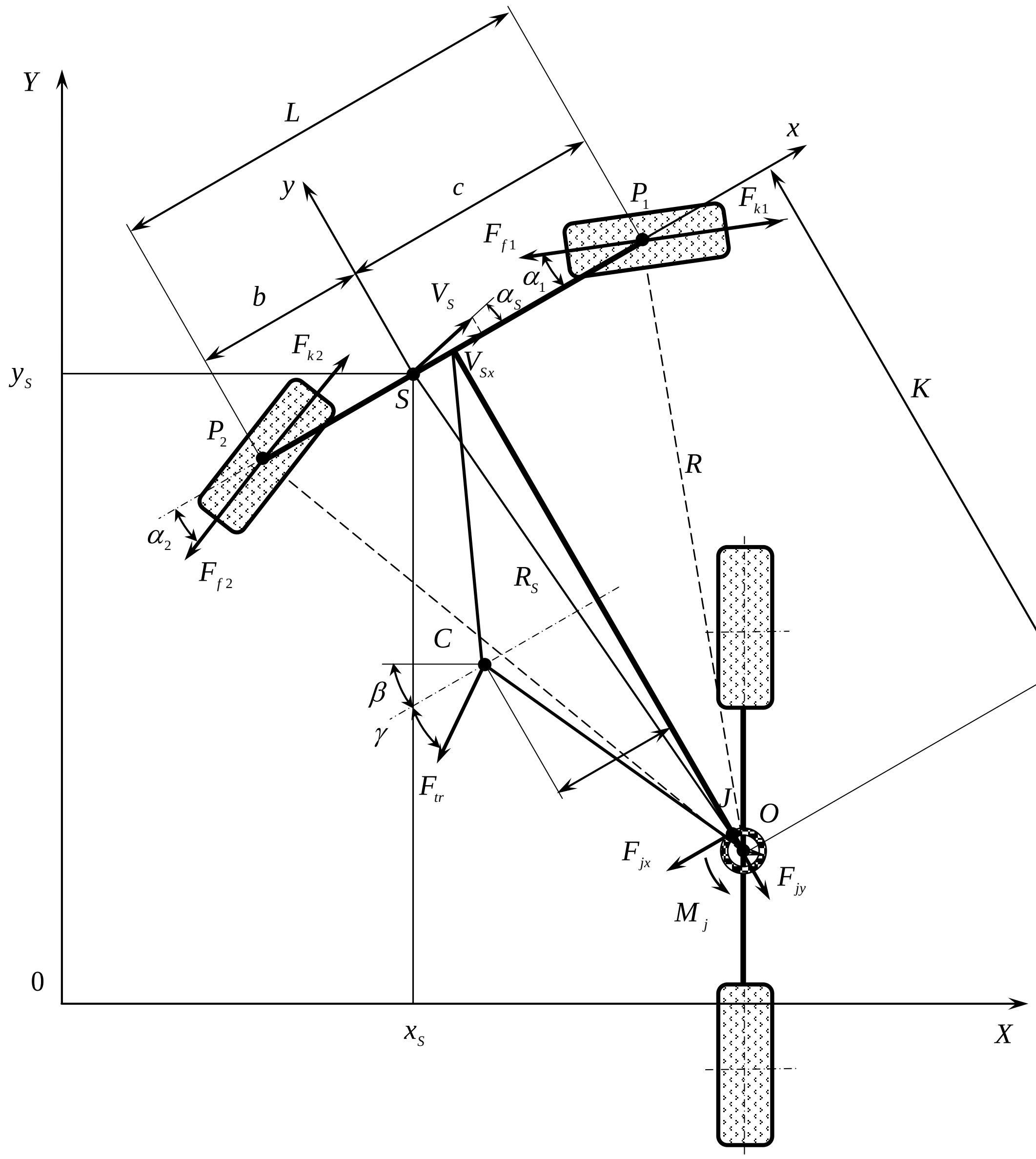

Fig. 4 – An equivalent turn scheme of a wide span tractor (vehicle) with left board steerable wheels

We'll present the impact of the resistance of the tractor technological part operating tools by the main vector F_{tr}, applied at the centre of resistance (point C), the action direction of which on the turn makes angle γ with the tractor longitudinal axis. We present the reactions arising in the articulated turning mechanism of the wide span tractor (vehicle) by forces F_{jx} and F_{jy}, applied at point J, as well as by the resistance moment M_j.The equation of the wide span tractor (vehicle) movement describing the static turnability in relation to the mobile coordinate system xSy is illustrated by the following system of familiar dependencies:

$$\left.\begin{aligned} m_b a_{Sx} &= \sum_{j=1}^{n} F_{xj}, \\ m_b a_{Sy} &= \sum_{j=1}^{n} F_{yj}, \\ M_R &= \sum_{i=1}^{n} M_{Si}, \end{aligned}\right\} \tag{5}$$

where