ACTA UNIVERSITATIS AGRICULTURAE ET SILVICULTURAE MENDELIANAE BRUNENSIS

Volume 71 20 Number 5, 2023

EFFECTIVENESS OF THE USE OF AUTOMATIC DRIVING SYSTEMS IN TECHNOLOGICAL PROCESSES OF CROP CULTIVATION IN THE NORTHERN REGION OF KAZAKHSTAN

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Link to this article: https://doi.org/10.11118/actaun.2023.020
Received: 19. 4. 2023, Accepted: 2. 10. 2023

Abstract

This study aims to identify the influencing factors and assess the efficiency of implementing automatic driving systems in the key processes of cultivating agricultural crops in the zonal conditions of the region. The research methods included field testing of machine-tractor units equipped with automatic driving systems during the main technological processes of crop cultivation, considering factors such as the specified precision of the automatic driving system, the constructive working width of the machine, the speed of the unit, the operator's qualification, and the soil conditions.

It was found that the use of automatic driving systems leads to a reduction in overlap values between adjacent passes of the unit by 3 to 20 times compared to driving without the systems. Moreover, technological and technical indicators showed enhancements ranging from 2.0% to 3.8% during sowing, 4.7% to 6.1% during main tillage, 4.6% to 22.1% during chemical treatment of crops, and 3.4% to 9.9% during crop harvesting. Additionally, it was observed that driving accuracy decreases with increasing speed and low qualification of the operator. The influence of the constructive working width requires further investigation. The impact of soil and climatic conditions on the effectiveness of using automatic driving systems was not established in our current research.

Keywords: precision agriculture, comparative tests, automatic driving system, technological processes, sowing, chemical weeding, grain harvesting, deep soil tillage

INTRODUCTION

Over the past 20 years, a new direction in agricultural production, known as precision agriculture, has been effectively developing through the use of the global positioning system GPS (GOST R 56084-2014 – Navigational and dataware system of coordinate agriculture. Terms and definitions, 2014).

The use of precision agriculture systems leads to increased efficiency of agriculture, particularly in terms of profitability, productivity, amount of yield, and environmental protection (Keskin *et al.*, 1999; Yakushev *et al.*, 2007; Yakushev, 2016). The costs of fertilizers, seeds, plant protection products, and fuel are reduced by an average of 20% (From precision farming to smart farms, 2019). Precision agriculture helps to balance the physical and agrochemical properties of the soil in cultivated fields (Garcia *et al.*, 2016; Kelc *et al.*, 2019).

Precision agriculture systems are successfully applied in the USA, Canada, Australia, Brazil, and European countries (Barocco, 2017; Fulton *et al.*, 2010; Tsirulev *et al.*, 2008). All elements of the precision agriculture system are used in agricultural production in Kazakhstan. However, parallel and automatic driving systems are more prevalent on farms. The experience of using these systems in other regions shows a positive effect on productivity, fuel consumption, and financial costs. Thus, when using parallel driving in the conditions of Krasnodar Krai in Russia for spreading of mineral fertilizers, the working width of the Bogballe M2 – base spreader increased from 19.5 m to 20.4 m (by 4.6%), the shift productivity increased by 6.1%, specific fuel consumption decreased by 10.0%, the actual fertilizer consumption decreased by 1.3% (Fedorenko and Voronkov, 2015). According to Martin Mees and Jonas Hedtrich (2019), the use of parallel driving in the conditions of Germany resulted in resource savings of 3% for seeds, 3% for plant protection products, 3% for fertilizers, and 5% for operating costs. When using parallel driving for sowing in the Tyumen region in Russia, the area of reseeding decreased by 4.2%, the overuse of seeds and fertilizers decreased by 4%, excessive fuel consumption decreased by 4% (Semizorov, 2015). In the conditions of Germany, when using parallel driving with a cultivator with a constructive working width of 5 m, the overlap area was reduced from 8.0% to 4.4%. When using parallel driving with a sprayer with a working width of 24 m the overlap area was reduced from 4.2% to 0.92%. Under the same conditions, when using automatic driving, the overlap area was reduced to 0.96% and 0.20%, respectively (Shpaar *et al.*, 2009).

In the conditions of Kazakhstan, there are much fewer results of research on parallel and automatic driving systems. Often, in the arid conditions of the regions of Kazakhstan, the effect of using parallel and automatic driving systems is reduced due to insufficient consideration of all organizational and production and natural-climatic factors. Thus, the conducted comparative tests of automatic driving systems in the zone of ordinary chernozems of the northern region of Kazakhstan showed the effectiveness of modern navigation systems on technological processes of sowing and chemical treatment (Polishchuk *et al.*, 2021). Under the same conditions, when testing parallel driving systems on grain harvesting the effect was obtained at the level of an experimental error (1–2%), while for deep tillage, the negative result was obtained. It should be noted that these studies (Polishchuk *et al.*, 2021) were conducted on fertile soils of the northern region of Kazakhstan, on ordinary chernozems. On the southern chernozems, which significantly differ in soil conditions from the ordinary chernozems, such studies have not been conducted. In the north, in the zone of ordinary chernozems, the amount of precipitation that falls during the summer period is 200–280 mm, while in the zone of southern chernozems – 80–120 mm. Ordinary chernozems of Northern Kazakhstan contain up to 6% of organic matter in the arable horizon, while southern chernozems – no more than 4%. By mechanical composition, the most common among the southern chernozems are heavy loam (50.7%) and medium-loam (21.2%) soils. These soil types contain from 45 to 80% of physical clay in their composition and tend to self-compact when there is a lack of moisture. The plain relief of the area and the large number (more than 70%) of windy days per year with a wind speed exceeding 5 m/s cause the possibility of wind erosion of the soil. Southern chernozem soils occupy up to 60% of the areas of cultivation of the main grain crop, which is spring wheat.

Given the above, it can be stated that the evaluation of the efficiency of parallel and automatic driving systems in the technological processes of cultivating and harvesting crops as part of various agricultural units under the soil and climatic conditions of the regions of Kazakhstan is of scientific interest and is in demand by the industry. Conducting tests of such systems in the arid conditions of the southern chernozems of Northern Kazakhstan expands the database for an objective assessment of the effectiveness of the precision agriculture system elements in various soil and climatic conditions.

The aim of this work is to identify influencing factors and determine the effectiveness of using automatic driving systems in key processes of cultivating agricultural crops in the zonal conditions of the region. To achieve this goal, the study addressed the following research objectives:

- identify technological and techno-economic indicators of units when using automatic driving systems during sowing, chemical weeding, harvesting, and deep soil tillage;
- investigate the impact of the operator's qualification on the technological and techno-economic indicators associated with using driving systems;
- establish technological and techno-economic indicators at various levels of precision in the configuration of driving systems;
- identify the main factors influencing the effectiveness of using automatic driving systems in the conditions of the region.

MATERIALS AND METHODS

The objects of the research are the processes of operating agricultural machinery using automatic driving systems. The composition and parameters of agricultural units and the driving systems under study are presented in Tab. I.

In all cases, the automatic driving systems were serviced using a free satellite signal.

The research methods consisted of field tests of machine-tractor units on the specified technological processes listed in Tab. I. These tests involved determining the technological and techno-economic

I: *Composition and parameters of agricultural units and automatic driving systems under study*

Type and scope of work, soil type	Composition of agricultural units	Constructive working width, m	Driving systems	Specified straightness parameters, cm
Sowing, 367 ha, southern chernozem	AXION 950 tractor + Kuzbass PK-12.2 sowing complex	12.2	Claas GPS PILOT automatic parallel driving system	± 15–30
Sowing, 397 ha, ordinary chernozem	John Deere 9410 tractor + John Deere 1890 sowing complex	12.9	GreenStar-3 navigation system + AutoTrac automatic steering system	± 23
Main tillage, 177 ha, southern chernozem	AXION 950 tractor + John Deere 2720 disc ripper	5.3	Claas GPS PILOT automatic parallel driving system	± 15–30
Chemical treatment, 2155 ha, southern chernozem	John Deere 4730 self-propelled sprayer	30.5	GreenStar-3 navigation system + AutoTrac automatic steering system	± 15
Chemical treatment, 2170 ha, ordinary chernozem	John Deere 4730 self-propelled sprayer	30.5	GreenStar-2 navigation system + AutoTrac automatic steering system	± 23
Chemical treatment, 1130 ha, southern chernozem	MTZ-82 tractor + OP-30 Don Mar trailed sprayer	30	Teejet Matrix Pro 570 GS navigation system + automatic steering system “Teejet Unipilot”	± 15
Chemical treatment, 520 ha, southern chernozem	MTZ-82 tractor + OP-30 Don Mar trailed sprayer	30	Teejet Matrix Pro 570 GS navigation system	± 30
Grain crops harvesting, 403 ha, southern chernozem	John Deere W540i combine harvester with a John Deere 930D header	9.15	GreenStar-3 navigation system + AutoTrac automatic steering system	± 15
Grain crops harvesting, 427 ha, southern chernozem	John Deere W540i combine harvester with a John Deere 930D header	9.15	GreenStar-3 navigation system + AutoTrac automatic steering system	± 23

efficiency of the automatic driving systems installed in the tractors.

The research methodology included determining the technological and techno-economic indicators of the units when changing the following factors:

- specified precision of the automatic driving system;
- constructive working width of the machine;
- the machine's speed;
- operator's qualification;
- soil conditions.

The evaluation criteria of the automatic driving systems included the agrotechnical, operational-technological, and economic performance indicators of the units. Comparative test conditions were determined in accordance with the requirements of GOST 20915 – Testing of agricultural tractors and machines. Procedure for determination of test conditions (2013).

The working width of the machine was determined by measuring the width of the processed area over 20 working passes using the formula (GOST 31345-2017 – Seeders tractor. Test methods, 2018; GOST R 53053-2008 – Machinery for crop protection. Spraying equipment. Test methods, 2009; GOST 28301-2015 - Grain harvesters. Test methods, 2016; GOST 33736-2016 – Agricultural machinery. Machines for deep tillage. Test methods, 2017):

$$B_w = \frac{L_y}{20}, \quad (1)$$

where

L_y.... total working width for 20 working passes of the machine, m;

20... amount of working passes.

The overlap width B_o was determined by measuring the width of the processed area over 20 working passes using the formula (GOST 31345-2017 – Seeders tractor. Test methods, 2018; GOST R 53053-2008 – Machinery for crop protection. Spraying equipment. Test methods, 2009; GOST 28301-2015 – Grain harvesters. Test methods, 2016; GOST 33736-2016 – Agricultural machinery. Machines for deep tillage. Test methods, 2017):

$$B_o = B_c - \frac{L_y}{20}, \quad (2)$$

where

B_c.... constructive working width of the sowing unit, m.

To determine the actual seeding rate of the calibrated and seed-filled sowing unit, containers were attached beneath the seed tubes of the coulters. The machine operated over a 50 m long section in operating mode, with five repetitions conducted (GOST 31345-2017 – Seeders tractor. Test methods, 2018). The weight of the seeds sown by all devices was measured with an error of no more than ± 1 g, and the obtained data were recorded in the record sheet.

The actual seeding rate was determined using the following expression:

$$Q = \frac{\sum_{i=1}^{n_n} q_i}{B \times l} \times 10^4, \quad (3)$$

where

q_i..... mass of seeds sown by all devices on the measured area in the i-th repetition, kg;

B..... working width of the sowing machine, m;

l...... length of the sown area, m.

The actual consumption of working fluid during chemical weeding was determined by emptying the entire tank of the sprayer. The actual consumption per hectare was determined by measuring the volume of fluid poured out and the area treated, following the guidelines of GOST R 53053-2008 – Machinery for crop protection. Spraying equipment. Test methods (2009).

To determine the operational and technological indicators, time-motion studies were conducted. These studies were performed for each agricultural unit during three standard shifts, each lasting seven hours. During the observations, the following information was recorded (GOST 24055-2016 – Agricultural machinery. Methods of operational-technological evaluation, 2017):

- details regarding the organization of tests (date and location of tests, type of work, and composition of the unit);
- test conditions (characteristics of the test area);
- operational parameters (speed, working width);
- the amount of work completed in hectares;
- duration of time elements during the shift;
- fuel consumption.

Productivity per 1 hour of main time was calculated according to the formula:

$$W_m = \frac{F}{T_m}, \quad (4)$$

where

F..... the amount of work completed during the observation period, ha;

T_m... the total main time during the observation period, h.

Productivity per 1 hour of shift time is calculated according to the expression:

$$W_{sh} = W_m \times K_{sh}, \quad (5)$$

where

K_{sh}..... the coefficient of utilization of shift time.

The coefficient of utilization of shift time (K_{sh}) was calculated based on the duration of elements of the working time observed during time-motion studies, including the working stroke, turnings, seed loading, and others.

Specific fuel consumption was determined by dividing the amount of fuel consumed during the time and motion studies by the amount of work performed.

II: *Devices used*

Measured parameter	Measuring instrument	Measurement errors
Linear dimensions	Metal ruler	± 1 mm
	Tape measure RZ-20	± 1 mm
Distance	Tape measure RZ-20	± 1 mm
	Laser tape measure Disto D210	± 0,5 mm
Time	Stopwatch	± 1 s
Weight	Laboratory scale CAS MWP-300 N	± 1 mg
	Scale RN-3Ts13U	± 5 g
Soil, plant, seed moisture	Weighing bottles	-
	Drying Cabinet SNOL 58/350	-
	Laboratory scale CAS MWP-300 N	± 1 mg
Soil hardness	Revyakin's penetrometer	± 5%
Bulk density of the soil	Drying Cabinet SNOL 58/350	-
	Weighing bottle	-
	Laboratory scale CAS MWP-300 N	± 1 mg
Fuel consumption	Fuel meter PPO-25-1.6SU-0.2	± 0,5%

The amount of fuel consumed during the time-motion studies was determined during daily refueling of the agricultural units using a fuel-servicing truck's fuel meter with an error of ± 0.5%. The area (productivity of the unit) covered during the shift was determined using GPS satellite navigation, with a measurement accuracy within ± 0.5%.

The average relative error in the agrotechnical assessment did not exceed 2.0%, and in the operational-technological assessment, it was no more than 3.0%.

The processing of the obtained data was carried out using the mathematical statistics method (Dospehov, 1985).

The calculations involved determining the mean value, standard deviation, and coefficient of variation.

The reliability of the obtained results was assessed by comparing the index of indicator variation and the relative error of the measurements performed.

Information on the devices used in the tests is presented in Tab. II.

During the economic assessment, the total cash costs for carrying out technological processes were determined according to ST RK GOST R 53056-2010 - Agricultural machinery. Economic appraisal method (2010):

$$C_t = C + C_{ql} + C_{wc} + C_e, \quad (6)$$

where

C_t.......total costs, tenge/ha;

C........direct operational costs, tenge/ha;

C_{ql}......costs accounting for changes in the quantity and quality of production (losses), tenge/ha;

C_{wc}.....costs accounting for the level of working conditions of the maintenance personnel, tenge/ha;

C_e.......costs accounting for the negative impact on the environment, tenge/ha.

Operational costs include:

- labor costs for maintenance personnel, tenge/ha;
- cost of fuel and lubricants, tenge/ha;
- costs of technical maintenance, current maintenance, and major overhauls of - machinery, tenge/ha;
- costs for machinery depreciation, tenge/ha.

The tests were carried out by a team of scientists from the Kostanay branch of the "Scientific and Production Center of Agroengineering".

The test locations were:

- southern chernozem soils, agricultural experimental station "Zarechnoye", Kostanay region.
- ordinary chernozem soils, "Toysay" LLC, Kostanay Region.

RESULTS AND DISCUSSION

Comparative tests of the Claas GPS PILOT automatic driving system installed on the AXION 950 tractor in combination with the Kuzbass PK-12.2 sowing complex were conducted from 20 May to 26 May 2019 on southern chernozems.

The Kuzbass PK-12.2 sowing complex in combination with the Claas AXION 950 tractor is shown in Fig. 1.

1: *Kuzbass PK-12.2 sowing complex in combination with the Claas AXION 950 tractor in operation*

Comparative test conditions for spring wheat sowing were typical for the zone: soil moisture – 16.6%; soil bulk density – 1.4 g/cm^3; soil hardness – 2.3 MPa. The values of the indicators were determined at a soil depth of 15 cm. Soil type – southern chernozem, soil texture – heavy loam. The preceding soil treatment was early spring harrowing.

The results of comparative tests of the Claas GPS PILOT automatic driving system, installed on the AXION 950 tractor, coupled with the Kuzbass PK-12.2 sowing complex during spring wheat sowing are presented in Tab. III.

When using the automatic driving system, the constructive working width of the sowing unit is utilized more efficiently. This is achieved by reducing the overlap area between adjacent passes, resulting in an increased working width. As a result, productivity increases, and the technical, technological, and economic performance of the unit improves.

Below are the test results of the AutoTrac automatic driving system during sowing, conducted in the area of ordinary chernozems. The tests of the GreenStar-3 navigation system with the AutoTrac automatic driving system, installed on the John Deere 9410R tractor coupled with the John Deere 1890 sowing complex, were carried out from May 16 to May 22, 2019.

The test conditions for spring wheat sowing were typical for the zone, but somewhat milder than on the southern chernozems: soil moisture – 20.6%; bulk density – 1.2 g/cm^3; soil hardness – 1.3 MPa. The values of the indicators were determined at a soil depth of 15 cm. The soil type is ordinary chernozem, soil texture – heavy loam. The preceding soil treatment was early spring harrowing.

The test results of the AutoTrac automatic driving system during spring wheat sowing in conjunction with the John Deere 9410R tractor and the John Deere 1890 sowing complex are presented in Tab. IV.

The analysis of the obtained test results of the Claas GPS PILOT and AutoTrac automatic driving systems during the sowing of grain crops leads to the following conclusions:

- both systems provide approximately the same technical and technological effect of application, ranging from 2.0% to 3.8%;
- the difference between the options “with auto-driving system” and “without auto-driving system” is close to the experimental error, which prevents us from stating a significant difference between them;
- it is not possible to conclusively determine the significant impact of different soil conditions - southern and ordinary chernozems - on the test results.

Testing of the Claas GPS PILOT automatic driving system installed on the Claas AXION 950 tractor coupled with a John Deere 2720 disc ripper was carried out during stubble field cultivation in the zone of southern chernozems from September 20 to September 26, 2019.

III: *Results of comparative tests of the Claas GPS PILOT automatic driving system on spring wheat sowing*

Indicator	Indicator value		Indicator index when using the system, %
	Without auto-driving system	With auto-driving system	
Average speed, km/h	8.5		
Working width, m	11.9	12.3	+ 3.3
Productivity per 1 hour of shift time, ha	6.9	7.1	+ 2.9
Specific fuel consumption, kg/ha	8.5	8.2	- 3.5
Actual seed consumption, kg/ha	147.5	144.0	- 2.4
Overlap size, m	0.30	- 0.10	- 133.3
Total cash costs, tenge/ha	25,364	24,556	- 3.2

IV: *Results of tests of the AutoTrac automatic driving system during spring wheat sowing*

Indicator	Indicator value		Indicator index when using the system, %
	Without auto-driving system	With auto-driving system	
Average speed, km/h	11.3		
Working width, m	12.5	12.8	+ 2.4
Productivity per 1 hour of shift time, ha	10.5	10.8	+ 2.9
Specific fuel consumption, kg/ha	5.3	5.1	- 3.8
Actual seed consumption, kg/ha	71.4	70.0	- 2.0
Overlap size, m	0.40	0.10	- 75.0
Total cash costs, tenge/ha	10, 870	10, 038	- 7.7

2: *The 2720 disk ripper coupled with AXION 950 tractor in operation*

The 2720 disc ripper coupled with the AXION 950 tractor is shown in Fig. 2.

The test conditions for deep soil tillage were typical for the zone: soil moisture – 16.2%, soil bulk density – 1.4 g/cm^3, soil hardness – 2.9 MPa. The values of indicators were determined at a depth of 30 cm. Soil type – southern chernozem, soil texture – heavy loam.

Humidity – 22%, air temperature – 20.0 °C, wind speed – 3.5 m/s.

The test results of the Claas GPS PILOT automatic driving system during main tillage of a stubble field using the 2720 disc ripper coupled with the AXION 950 tractor are presented in Tab. V.

It should be noted that the same operator managed the unit with the AXION 950 tractor during both main tillage (Tab. V) and sowing (Tab. III). Comparing the obtained results from operating the units during main tillage and sowing leads to the following conclusions:

- Claas GPS PILOT automatic driving system ensures an increase in technical and technological performance during main tillage at a level of 4.2% to 6.1%;
- this allows us to confidently affirm the significance of the differences between the options “with auto-driving system” and “without auto-driving system”;
- during the main tillage, the constructive working width of the unit is only 5.3 m due to the high energy intensity of the process. During operation, the machine is subject to significant destabilizing and deflecting forces caused by differences in soil hardness. For this reason, in the scenario without the auto-driving system, the operator allows significant overlaps of 0.40 m, which is about 8% of the constructive working width. By using the auto-driving system, overlaps are reduced by 4 times;

V: *Results of tests of the Claas GPS PILOT automatic driving system during main tillage of a stubble field*

Indicator	Indicator value		Indicator index when using the system, %
	Without auto-driving system	With auto-driving system	
Average speed, km/h	9.0		
Working width, m	4.9	5.2	+ 6.1
Productivity per 1 hour of shift time, ha	3.5	3.7	+ 5.7
Specific fuel consumption, kg/ha	14.9	14.2	- 4.7
Overlap size, m	0.40	0.10	- 75.0
Total cash costs, tenge/ha	15,520	14,999	- 3.3

- when keeping the tractor, operator, and precision of the automatic driving system configuration constant, the variation in the index of technological process indicator values “when using the system” depends on the working width of the machine being used. As the working width increases from 5.2 m (Tab. V) to 12.3 m (Tab. III), indices of technical and technological indicators, when using the system decrease. However, this issue requires further study.

When testing the automatic driving systems during chemical treatment of crops, more significant changes in technological and techno-economic indicators of the units were observed.

The testing of the AutoTrac automatic driving system installed on a John Deere 4730 self-propelled sprayer was conducted between June 22 to June 28, 2019, in the zone of southern chernozems during chemical weeding of spring wheat. The work was carried out at night, as there was a strong wind and high temperatures during the day. Test conditions for chemical weeding of spring wheat were typical for the zone: soil moisture was 6.0%, soil bulk density was 1.4 g/cm^3, and soil hardness was 1.9 MPa. The values of the indicators were determined at a depth of 10 cm. Air humidity was 38.1%, air temperature was 20.0 °C, wind speed was 1.7 m/s, atmospheric pressure was 99.0 kPa, working fluid temperature was 17 °C, plant height was 13.5 cm, number of weeds was 124 pcs/m^2.

The John Deere 4730 sprayer in operation is shown in Fig. 3.

3: *John Deere 4730 sprayer in operation*

VI: *Results of tests of AutoTrac automatic driving system during chemical weeding in the zone of southern chernozems*

Indicator	Indicator value		Indicator index when using the system, %
	Without auto-driving system	With auto-driving system	
Average speed, km/h	27.0		
Working width, m	25.1	30.2	+ 20.3
Productivity per 1 hour of shift time, ha	42.0	51.3	+ 22.1
Specific fuel consumption, kg/ha	0.98	0.80	- 18.4
Actual consumption of working fluid, l/ha	59.8	49.6	- 17.0
Overlap size, m	5.40	0.30	- 94.4
Total cash costs, tenge/ha	2, 296	1, 957	- 14.8

VII: *Results of tests of the AutoTrac automatic driving system during chemical weeding of flax in the zone of ordinary chernozems*

Indicator	Indicator value		Indicator index when using the system, %
	Without auto-driving system	With auto-driving system	
Average speed, km/h	26.2		
Working width, m	27.8	30.2	+ 8.6
Productivity per 1 hour of shift time, ha	41.5	44.9	+ 8.2
Specific fuel consumption, kg/ha	0.88	0.80	- 9.1
Actual consumption of working fluid, l/ha	54.2	48.8	- 9.0
Overlap size, m	2.70	0.30	- 88.9
Total cash costs, tenge/ha	9, 795	9, 170	- 6.4

The test results of the AutoTrac automatic driving system during chemical weeding of spring wheat in the zone of southern chernozems are presented in Tab. VI.

The peculiarity of the conducted tests was that the wide-coverage self-propelled sprayer was operated by a low-qualified operator (with no prior experience in driving wide-coverage sprayers). When the automatic driving system was disabled, the overlaps between adjacent passes of the unit reached 5.4 m, while the constructive working width of the sprayer was 30.5 m. This significantly affected the reduction in productivity.

When using the automatic driving system, the overlap between adjacent passes of the machine was only 0.3 m. Using AutoTrac automatic driving system for chemical weeding of spring wheat when operated by a low-qualified operator in the conditions of southern chernozems resulted in a significant increase in technical and technological indicators during chemical weeding by 17–22%.

In the area of ordinary chernozems, the testing of the AutoTrac automatic driving system, installed on the John Deere 4730 self-propelled sprayer, was conducted from June 20 to June 27, 2019, during the chemical treatment of flax. The unit was operated by a highly qualified operator.

The work was carried out at night. Test conditions for chemical weeding of flax were typical for the zone: soil moisture – 20.1%, soil bulk density – 1.3 g/cm^3, soil hardness – 1.6 MPa. The value of indicators was determined at a depth of 10 cm. Air humidity was

4: *The John Deere W540i combine harvester with the 930D header in operation*

VIII: *Test results of the AutoTrac automatic driving system during grain harvesting operated by a low-qualified operator*

Indicator	Indicator value		Indicator index when using the system, %
	Without auto-driving system	With auto-driving system	
Average speed, km/h	8.9	8.9	0
Working width, m	8.6	9.0	+ 4.7
Productivity per 1 hour of shift time, ha	5.81	6.09	+ 4.8
Specific fuel consumption, kg/ha	4.0	3.8	- 5.0
Overlap size, m	0.55	0.15	72.7
Total cash costs, tenge/ha	23, 144	23, 083	- 0.3

36.0%, air temperature – 15.6 °C, wind speed – 1.8 m/s, atmospheric pressure – 99.2 kPa, working fluid temperature – 15 °C, plant height – 13.8 cm, number of weeds – 186 pcs/m^3.

The test results of the AutoTrac automatic driving system during chemical weeding of flax in the zone of ordinary chernozems are presented in Tab. VII.

Analysis of the test results of the AutoTrac automatic driving systems during the chemical treatment of crops leads to the following conclusions:

- when operating wide-coverage units with the automatic driving system disabled, the overlap between adjacent passes of the unit ranged from 2.7 to 5.4 m, while the constructive working width was 30.5 m. This led to a significant reduction in the working width, productivity, and other technical and technological indicators of the units;
- when using automatic driving systems, the overlap between adjacent passes was 0.3 m. This resulted in an increase in shift productivity by 8.2% to 22.1%, compared to the option “without an auto-driving system”;
- as the working width of the units increased to 30 m and the travel speed reached 26.2 to 27.0 km/h, the indices of technical and technological indicators “when using the system” significantly increased in absolute value;
- an analysis of Tabs. III–VII suggests a preliminary conclusion that the decrease in the accuracy of automatic driving is influenced by an increase in travel speed and an increase in the constructive working width;
- the difference in test results in the conditions of southern and ordinary chernozems is explained by the qualification of an operator. The use of the automatic driving system had a greater impact on improving the performance of a low-qualified operator.

Below are the results that also demonstrate the impact of the operator's qualification level on the technological and techno-economic indicators of operating a combine harvester during grain harvesting in the zone of southern chernozems. These tests were conducted from August 23 to August 30, 2019. The AutoTrac automatic driving system was installed on the John Deere W540i combine harvester with a 930D header. The combine harvester was operated by a low-qualified operator (in their first year of operating a combine harvester). The John Deere W540i combine harvester with the 930D header is shown in Fig. 4.

Test conditions during spring wheat harvesting were typical for the zone: soil moisture – 3.6%, soil hardness – 1.5 MPa. The values of the indicators were determined at a depth of up to 10 cm.

Grain yield of spring wheat was 9.5 c/ha, weight of 1000 grains – 33 g, grain moisture – 9.5%, straw moisture – 8.1%, plant height – 0.4 m, plant density – 176 pcs/m^2, weed infestation – 4.2%.

The test results of the AutoTrac automatic driving system on a W540i combine harvester during grain harvesting operated by a low-qualified operator are presented in Tab. VIII.

With the automatic driving system accurately configured within ± 15 cm, a low-qualified operator hesitated to increase the driving speed during automatic driving. This led to a decrease in productivity and other techno-economic performance indicators of the harvesting machine.

When a more experienced operator with over 10 years of experience operated the machine in similar zonal conditions, but with a less accurate configuration of the automatic driving system (± 23 cm), the technological and techno-economic performance indicators of the harvesting unit were higher compared to those achieved with a precision of ± 15 cm (Tab. IX).

Analysis of the test results of the AutoTrac automatic driving systems during the grain crops harvesting leads to the following conclusions:

- the system provides an increase in shift productivity by up to 9.9% and other technological and technical indicators by 3.4 to 5.7%;
- this allows us to affirm the significance of the differences between the options “with the auto-driving system” and “without the auto-driving system”;
- the technological and technical effectiveness of using the automatic driving system was significantly influenced by the qualification of

IX: *Results of comparative tests of the AutoTrac automatic driving system during grain harvesting by a highly qualified operator*

Indicator	Indicator value		Indicator index when using the system, %
	Without auto-driving system	With auto-driving system	
Average speed, km/h	8.7	9.0	+ 3.4
Working width, m	8.7	9.0	+ 3.4
Productivity per 1 hour of shift time, ha	5.75	6.32	+ 9.9
Specific fuel consumption, kg/ha	3.5	3.3	- 5.7
Overlap size, m	0.45	0.15	66.7
Total cash costs, tenge/ha	40, 099	37, 551	- 6.3

X: *Comparison of driving systems with different levels of precision during chemical weeding of grain crops by the OP-30 sprayer coupled with the MTZ-82 tractor*

Variable indicator when using the system	Without system (control)	Parallel driving system Teejet Matrix Pro 570 GS	Parallel driving system Teejet Matrix Pro 570 GS with automatic steering system Teejet Unipilot
Average speed, km/h	11.60	11.60	11.7
Working width, m/index of change, %	28.0	29.8/+ 6.4	30.1/+ 7.5
Productivity per 1 hour of shift time, ha/index of change, %	26.1	27.7/+ 5.7	28.2/+ 8.0
Specific fuel consumption, kg/ha/index of change, %	0.44	0.42/- 4.6	0.42/- 4.6
Actual consumption of working fluid, l/ha/index of change, %	85.3	80.4/- 5.8	79.7/- 6.6
Overlap size, m/index of change, %	2.0	0.20/90.0	- 0.10/105.0
Total cash costs, tenge/ha/index of change, %	6, 976	6, 809/- 2.4	6, 510/- 6.7

the operator. The inexperience of an operator halves the productivity growth when using the automatic driving system. A qualified operator ensures achieving higher technological and techno-economic indicators of the harvesting unit, even with less accurate system configuration.

Tab. X shows the comparison of indicators during chemical weeding of grain crops using the OP-30 Don Mar sprayer coupled with the MTZ-82 tractor equipped with driving systems with different levels of precision in the conditions of southern chernozems.

Analysis of the test results of driving systems with different levels of precision during chemical weeding of grain crops allows us to make the following conclusions:

- the use of the parallel driving system reduced the size of overlaps between adjacent passes of the unit by 0.2 m, compared to the control, resulting in a 5.7% increase in productivity;
- the use of the parallel driving system resulted in significant operator fatigue by the end of the working shift;
- the use of the automatic steering system reduced the overlap between adjacent passes of the unit in comparison with the compared variants by 2.1 m and 0.3 m, respectively;
- analysis of Tabs. III–VII and Tab. X clarifies that the decrease in the accuracy of automatic driving is influenced by an increase in travel speed. The conclusion regarding the influence of the constructive working width is not confirmed by the results of Tab. X;
- the use of the automatic steering system resulted in a 6.7% reduction in specific total costs compared to the control and a 4.4% reduction compared to the parallel driving option.

Summary and analysis of the test results of automatic driving systems lead to the following conclusions:

1. When using automatic driving systems, the actual overlap value ranges from 10 to 30 cm, depending on the specified driving precision, varying from ± 15 to ± 15–30.
2. The use of automatic driving systems reduces overlaps between adjacent passes of the unit by 3 to 20 times compared to driving without the systems.
3. When using the systems, factors that reduce the accuracy of automatic driving include increased

travel speed and the operator's low qualification. The impact of the constructive working width requires further investigation. The influence of soil and climatic conditions on the effectiveness of using automatic driving systems was not established in our current research.

4. When the system is not used, the driving accuracy is reduced due to the following factors: an increase in the constructive working width, an increase in the travel speed, and the operator's low qualification.
5. Increasing the travel speed by three times leads to a corresponding reduction in driving accuracy by three times.
6. During main tillage, the constructive working width of the unit is only 5.3 m due to the high energy intensity of the process. During operation, the unit is subject to significant destabilizing and deflecting forces caused by differences in soil hardness. Without using the auto-driving system, the operator allows significant overlaps of 0.40 m, which accounts for about 8.0% of the constructive working width. When using the auto-driving system, overlaps are reduced by four times.

It is known that driving by an experienced operator using GPS navigation provides an accuracy of up to 1.5% (Lichman, 2011). In our conducted research, in most experiments, driving accuracy was obtained at the level of 1.0%. Currently, with the use of automatic driving systems, it is possible to achieve accuracy levels below 1.0% (Antamonova, 2017).

The obtained results are in good agreement with the research results of Martin Mees and Jonas Hedtrich (2019), as well as Shpaar (2009), obtained in conditions of Germany. They also align well with the research results of Semizorov (2015) obtained in the conditions of the Tyumen region in Russia.

The obtained results significantly supplement our previous studies conducted on ordinary chernozems of the northern region of Kazakhstan under more favorable soil conditions (Polishchuk *et al*., 2021). In our opinion, the difference in soil and climatic conditions has a less significant impact. When assessing the effectiveness of a driving system under given conditions, the operation of agricultural machinery with and without the driving system is compared under comparable conditions. At the same time, the influence of soil and climatic conditions is neutralized.

A significant difference between this work and the works (Mees and Hedtrich, 2019; Semizorov, 2015; Shpaar *et al*., 2009; Polishchuk *et al*., 2021; Solovyev *et al*., 2016) is the investigation of various factors influencing the accuracy of automatic driving of agricultural units. The obtained results and analysis presented in this paper on the influence of factors such as operator qualification, travel speed, working width, and soil conditions on the effectiveness of driving systems are new. They significantly supplement and develop previously conducted studies in this direction.

It should be stated that testing various driving systems on different technological processes, with different combinations of machine-tractor units expands the database for an objective assessment of the effectiveness of the precision agriculture system elements in different soil and climatic conditions of the regions.

CONCLUSION

The summary of the results obtained in the conditions of southern and ordinary chernozem soils of the northern region of Kazakhstan leads to the following conclusions:

1. When using automatic driving systems, the actual overlap value ranges from 10 to 30 cm, with the specified driving precision varying from ± 15 to ± 15–30.
2. The use of automatic driving systems allows for a reduction in overlap values between adjacent passes of the unit by 3 to 20 times compared to driving without systems.
3. The use of automatic driving systems leads to improved technological and technical performance during different agricultural operations:
   - during sowing by 2.0–3.8%;
   - during main tillage by 4.7–6.1%;
   - during chemical treatment of crops by 4.6–22.1%;
   - during harvesting of agricultural crops by 3.4–9.9%.
4. When driving without the system, the following factors lead to a reduction in driving accuracy: an increase in constructive working width, increased speed, and low qualification of the operator.
5. When using automatic driving systems, driving accuracy is reduced by the following factors: increased speed and low qualification of the operator. The impact of the constructive working width requires further investigation. The influence of soil and climatic conditions on the effectiveness of using automatic driving systems was not established in our current research.
6. Low qualification of the operator reduces the productivity growth by half when using the automatic driving system. A skilled operator achieves a higher technological and techno-economic performance of the harvesting unit, even with a less precise configuration of the driving system.

Acknowledgements

The results of the research were obtained as part of the implementation of applied scientific research in the field of the agro-industrial complex of the Republic of Kazakhstan for 2018–2020 under budget program 267 "Increasing the Availability of Knowledge and Scientific Research". The authors express their gratitude to the Ministry of Agriculture of the Republic of Kazakhstan for funding the scientific research.

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