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AUTOMATION IN COMBINE HARVESTING - A FIELD PERFORMANCE STUDY

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Abstract: This study presents the results of four comparative field tests evaluating the performance of combine harvester operation under manual and automatic control modes. The tests -planed and performed in real harvesting conditions during the 2024 season- assessed key performance parameters such as throughput, field capacity, travel speed, and fuel consumption across multiple test configurations and crop types. The automatic control system consistently outperformed manual operation, with improvements ranging from 5% to 18% in core efficiency indicators. While total fuel consumption was slightly higher under automation, specific fuel efficiency (litres per ton of grain harvested) showed parity or improvement. The findings confirm the operational and energetic benefits of automated optimization in modern harvesting and highlight its potential to mitigate operator variability, improve productivity, and support sustainable large-scale agricultural practices.

Keywords: combine harvester automation; precision agriculture; adaptive control; telematics; field performance evaluation

1. Introduction

The global agricultural sector is undergoing a profound transformation driven by the increasing integration of automation, data analytics, and intelligent control systems. Among these technological developments, precision agriculture stands out as a paradigm shift, enabling real-time optimization of farming operations to enhance productivity, sustainability, and profitability. In this context, combine harvester automation has emerged as a critical area of innovation, offering tangible improvements in the main technical parameters like harvesting efficiency, fuel consumption, crop throughput. Szabó et al. [1] worked out a metohodology for measuring the operator's behaviour inside off-road vehicle cabin. They found the operator's workload also plays an important role in the machine process efficiency. Intensive development is evident not only in the area of automated (self) driving, but also in the field of cabin ergonomics. On the base of agricultural field tests, they their results highlighted that better understanding of the operator's gaze in addition to the change according to the mental and physical workloads inside the tractor cabin will lead to optimal designs for higher productivity operation. [2, 3]

Modern combine harvesters are no longer passive mechanical devices but dynamic, sensor-integrated platforms capable of continuous self-adjustment. One of the most advanced examples of this evolution is the CLAAS CEMOS AUTOMATIC system, which applies real-time sensor feedback to optimize key harvesting parameters such as threshing intensity, separation efficiency, grain cleaning, and engine load. This closed-loop automation allows the machine to adapt instantly to varying field conditions, thereby reducing dependency on operator experience and mitigating the risk of human error.

Although numerous studies have explored the potential benefits of precision agriculture technologies, a need remains for comparative, field-based evaluations that directly quantify the performance advantages of automated systems over traditional manual control. This study aims to fill that gap by presenting a comparative performance analysis of CEMOS AUTOMATIC versus manual control during real harvesting conditions. Using a consistent experimental design across crop types and environmental conditions, the study investigates multiple performance parameters -including throughput capacity, travel speed, field capacity, fuel consumption, and engine load -collected through the CLAAS TELEMATICS platform.

The findings contribute to the growing body of evidence supporting smart mechanization in agriculture and provide practical insights into the operational and economic implications of integrating automation into combine harvesting workflows.

2. Technological trends and field applications in combine harvester automation

Over the past two decades, precision agriculture has evolved into an integrated system of digital technologies, data analytics, and machine automation. A key innovation in this domain is the combine harvester automation, where adaptive control systems and sensor integration aim to improve operational efficiency and reduce operator dependency.

Modern combine automation platforms rely on multi-sensor fusion and AI-assisted control logic to continuously regulate travel speed, threshing intensity, fan and sieve settings, and engine load. Wang et al. [4] simulated and validated an autonomous driving system for unmanned harvesters based on integrated sensor inputs. Liu et al. [5] demonstrated that intelligent sensor fusion enables fine-grained optimization of yield monitoring, while Yin et al. [6] validated the use of edge computing and IoT for real-time data processing and control in subsoiling systems, offering a transferable approach for combine harvester automation.

Field-based validation is essential to confirm the impact of these systems on performance. Qian and Quan [7] developed a cooperative control model for distributed electric-drive combine harvesters. Their findings showed that coordinated regulation of threshing, separation, and cleaning units significantly improved throughput and grain quality under variable field loads. Zhang et al. [8] proposed a large-scale agricultural decision support system integrating environmental sensing and AI-based automation level regulation, which they tested on unmanned combine harvesters in cereal production.

Operator-induced performance variability is a recurring theme in combine harvester studies. Jotautienė and Juostas [9] compared manual and auto-steering modes, revealing significant differences in field efficiency. Juostas and Jotautienė [10] extended this work by analysing telemetry data to identify operator-based performance fluctuations. Fuentes-Peñailillo et al. [11] applied artificial intelligence methods to analyse telematics and sensor data in real-time crop management, illustrating how predictive adjustments of harvesting parameters can enhance overall operational efficiency. Savickas et al. [12] evaluated environmental performance metrics of automated combines, emphasizing the benefits in sustainability.

Telematics platforms also serve benchmarking purposes. Wang et al. [13] employed GNSS and telemetry data to analyse spatial differences in combine performance across field zones, demonstrating how automation reduces variability and supports consistent output. Fan et al. [14] developed a concave clearance control system responsive to feed rate, which reduced grain damage and improved energy use.

Human factors such as fatigue and decision-making delays further amplify the variability in manual harvesting. Zhu et al. [15] evaluated operator fatigue using heart rate variability metrics and confirmed that prolonged exposure to vibration and workload contributes significantly to performance decline. Similarly, Grisso et al. [16] demonstrated that driver behaviour has a measurable effect on fuel efficiency, reinforcing the role of automation in reducing human-induced variability.

The energetic impact of automation is mixed. Baillie et al. [17] argued that while fuel consumption may increase slightly, specific fuel use per ton of output improves. Chaplygin and Starostin [18] demonstrated that hybrid-electric combine harvesters with automated control systems reduce energy losses by ensuring balanced power distribution. Complementing this, Pustovaya et al. [19] showed that real-time adjustment of cleaning systems enhances efficiency and lowers unnecessary energy use, confirming that automation contributes to both productivity and reduced emissions.

Navigation systems also play a key role. Wang et al. [13] introduced a GNSS-based framework for analysing combine path efficiency. Udompant et al. [20] confirmed that RTK-GNSS navigation enhances control on sloped fields where manual driving is less efficient. Chen et al. [21] further developed a feed rate

monitoring system for combine harvesters using GNSS and force-based sensing, demonstrating its potential to optimize harvesting performance through real-time telemetry.

New sensing technologies also support automation at the header level. Haydar et al. [22] utilized UAV-based plant height maps to dynamically adjust the header position, thereby reducing grain loss and enabling more uniform crop intake. These findings align with Thomasson et al.'s [23] earlier work, emphasizing that yield mapping and real-time sensor input are critical to automation in variable field conditions.

On the base of a research resalts performed on real farming conditions, Bártfai et al. [24] established that with the aim of modernization, in order to work more efficiently and economically, it is desirable to automate agricultural machinery with lower technical levels as far as possible, with the aim of integrating it into precision technologies, which represents an investment that will pay for itself in the short term.

Together, these studies provide strong evidence that automation enhances productivity, consistency, and sustainability in combine harvesting, while reducing the influence of operator variability and supporting data-driven optimization in precision agriculture.

3. Materials and Methods

3.1. Experimental setup

The field tests were performed during the 2024 summer harvest season at the fields of a large-scale Hungarian agricultural enterprise. The experiments aimed to assess the operational performance of the CLAAS LEXION combine harvester equipped with the CEMOS AUTOMATIC system under real conditions and to compare it with traditional manual operation. The study design enabled both within-machine and between-machine comparisons, ensuring a priority assessment of system performance.

Two different experimental approaches were applied:

1. Single-machine dual-mode testing: The same combine harvester was operated sequentially in both modes – manual control and CEMOS AUTOMATIC – on identical field sections during barley and wheat harvest. This ensured that all external factors, such as crop density, slope, and moisture, were kept constant.
2. Parallel-machine testing: In wheat harvesting, two CLAAS LEXION combines were used simultaneously, one in manual control and the other with the automation system activated. Both machines operated under identical crop and field conditions, allowing for a direct comparison of performance indicators.

The harvested crops included barley (harvest date: 15 June) and wheat (harvest dates: 25, 26, and 28 June).

3.2. Data acquisition

Operational data were collected using the CLAAS TELEMATICS system, which automatically recorded and transmitted real-time performance parameters. For each harvesting run, the following variables were monitored:

- Throughput (t/h): tons of grain processed per hour
- Field capacity (ha/h): harvested area per unit time
- Travel speed (km/h): average forward speed
- Fuel consumption (l/h and l/t): both absolute hourly and specific per ton of harvested grain
- Engine load (%): average utilization of engine power

The TELEMATICS database provided synchronized, minute-level resolution data for both machines, which were then aggregated into hourly and daily averages for evaluation.

3.3. Experimental procedure

In the barley tests, the same machine was first operated in manual mode and then in automatic mode on adjacent field sections of similar conditions. In this setup, operator skill and crop variability did not influence the comparison, as only the control mode differed.

In the wheat tests, the two combine harvesters worked simultaneously in the same field. One was operated conventionally, while the second used CEMOS AUTOMATIC throughout. Operators remained with their

assigned machines, and no swapping occurred during the tests, ensuring a consistent operational style within each treatment.

The experiments were conducted under stable weather conditions, with crop maturity and moisture levels suitable for harvesting. Fuel tanks were filled to equal levels, and both machines started harvesting at the same time each day.

3.4. Data analysis

Data were exported from the TELEMATICS platform for post-harvest evaluation. Comparative performance was assessed through descriptive statistics (mean values, percentage differences) for each harvesting session. The results are presented separately for barley and wheat, reflecting both machine-level and system-level performance indicators.

4. Results

The field tests were performed to evaluate the performance of CLAAS CEMOS AUTOMATIC in comparison with conventional manual control under real harvesting conditions. The analysis is based on data from four separate field tests in two crop types – barley and wheat – using within-machine (same machine operated in both modes) and parallel-machine (two machines operated concurrently) testing frameworks. Operating features were monitored by the CLAAS TELEMATICS platform and included throughput (t/h), field capacity, travel speed (km/h), engine load (%), and fuel consumption (l/h).

4.1. Barley harvest – 15 June 2024 (Within-machine controlled test)

The first experiment was performed on 15 June 2024 during a winter barley harvest, under stable meteorological and field conditions in the early afternoon (12:45–15:15). During this test a within-machine methodology was applied, meaning that the same combine harvester – a CLAAS LEXION 7600 TT equipped with a CLAAS VARIO 930 header – was operated in two sequential modes (automated and manual) by the same experienced operator on the same field section. This configuration eliminated inter-operator variability and ensured that all external conditions – crop maturity, soil composition, slope, and moisture – remained consistent.

The combine operated with full telemetry, and all operational data were recorded using the CLAAS TELEMATICS system with a 15-second resolution. The first phase (12:45–14:00) was carried out in automated mode using CEMOS AUTOMATIC combined with CRUISE PILOT active speed control. In the second phase (14:00–15:15), the operator manually controlled all harvesting parameters, with CRUISE PILOT disabled.

4.1.1. Throughput

Throughput (measured in tons per hour) represents the machine's capacity to process grain over time and is directly influenced by both travel speed and material intake efficiency. The CEMOS-controlled interval began with some initial oscillations typical of warm-up or transition zones but stabilized quickly. By 12:50, throughput values consistently exceeded 22.6 t/h, showing a steady upward trend. The system reached a peak of 28.7 t/h at 13:31, which was sustained for approximately 12 minutes. The mean throughput during the CEMOS interval was 25.54 t/h.

In contrast, the manual control interval began with a throughput of 22.77 t/h, which progressively declined. A local minimum of 18.28 t/h was recorded at 14:48, followed by a partial recovery toward 24.8 t/h at the end of the session. The mean throughput during this interval was 21.61 t/h—18.19% lower than that achieved using CEMOS AUTOMATIC.

4.1.2.Field capacity

Field capacity, measured in hectares per hour, follows a similar trend to throughput but is also affected by turning time, machine path efficiency, and travel speed. In the automated interval, values ranged from 4.47

ha/h to 5.86 ha/h, with a mean of 5.28 ha/h. The manual interval showed a lower and more fluctuating range (4.59–5.44 ha/h), with a mean of 4.91 ha/h, resulting in a 7.53% increase in favour of CEMOS.

4.1.3. Travel speed

Travel speed showed clear systematic differences between the two modes. The average travel speed under CEMOS AUTOMATIC was 6.75 km/h, peaking at 7.19 km/h, while the manual operation achieved an average of 6.29 km/h, with a maximum of 7.16 km/h. Although the peak values are close, CEMOS provided more stable and sustained acceleration, evidenced by narrower fluctuation bands and longer periods near peak speed. The 7.31% increase in average speed contributed directly to both higher throughput and field capacity.

4.1.4. Engine load and fuel consumption

Engine load, which reflects the relative utilization of engine capacity, increased from 41.32% in manual mode to 49.37% in automated mode – a relative rise of +8.05%. While higher engine loads may initially appear disadvantageous, in this context, the increase signals better utilization of engine power closer to its optimal torque-efficiency curve. This is further supported by the smoothness of the engine load curve under automation, indicating fewer abrupt shifts and lower risk of under- or overloading.

The average fuel consumption under automated control was 50.81 l/h, compared to 47.88 l/h during manual operation, indicating a 6.12% increase. However, when normalized against output (e.g., fuel per ton of grain), this increase is neutralized by the higher throughput. Thus, specific fuel efficiency (l/t) remained approximately constant between the two modes, while time efficiency improved significantly in favour of automation.

Mean values of throughput, field capacity, and travel speed under manual vs. CEMOS AUTOMATIC control can be seen in Figure 1.

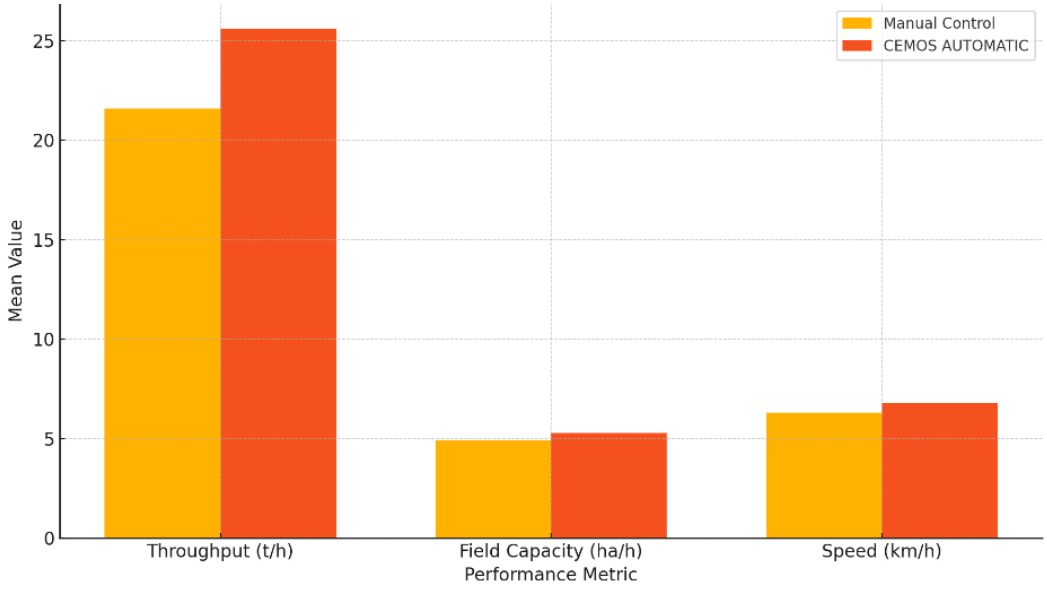

Figure 1. Average values for throughput, field capacity, and travel speed with manual and CEMOS AUTOMATIC control on June 15 Barley Test.

Mean values for key indicators under manual and CEMOS AUTOMATIC control, along with relative improvement percentages, are presented in Table 1.

This experiment offers a controlled and detailed demonstration of the automation system's operational benefits. It shows that even under ideal conditions and with skilled manual operators, the CEMOS AUTOMATIC system outperforms manual operation across all key performance indicators. Moreover, it does so with greater consistency, a faster response to changing field conditions, and a lower cognitive burden

on the operator. These findings form a robust baseline for evaluating CEMOS in more complex harvesting scenarios.

Table 1. Summary of performance parameters for the June 15 barley test (within-machine test)

Parameter	Manual control	CEMOS AUTOMATIC	Change
Throughput (t/h)	21.61	25.54	**+18.19%**
Field capacity	4.91	5.28	**+7.53%**
Travel speed (km/h)	6.29	6.75	**+7.31%**
Engine load (%)	41.32	49.37	**+8.05%**
Fuel consumption (l/h)	47.88	50.81	**+6.12%**

4.2 Wheat harvest – 25 June 2024 (Extended within-machine test)

The second experimental session was performed on 25 June 2024, focusing again on winter wheat. Unlike the previous test, this session extended over a full harvesting day from 10:00 to 18:00, allowing for the evaluation of performance over prolonged operating periods. The combine harvester – a CLAAS LEXION 7600 TT with a CLAAS VARIO 930 header – was operated for 4 hours under manual control and subsequently for 4 hours using CEMOS AUTOMATIC. The same experienced operator was involved in both phases, and the machine was recalibrated prior to switching modes to ensure identical starting conditions.

Environmental factors such as temperature, crop moisture, and field consistency remained favourable and stable throughout the day. The extended duration of this test allowed for a robust observation of dynamic performance under both operating modes, including the impact of operator fatigue and time-dependent variations in machine behaviour.

4.2.1. Throughput

The average throughput under manual control was 31.90 t/h, while during CEMOS-controlled operation, this rose to 36.53 t/h, marking a substantial +14.51% increase. The automated system not only achieved higher peak values (up to 40.95 t/h at 16:25), but also demonstrated more consistent performance, especially between 14:00 and 16:30, when throughput remained steadily above 35 t/h. The manual section showed more pronounced fluctuations, with a peak of 36.03 t/h early in the session and a gradual decline approaching 25.39 t/h near the end of the manual interval – likely attributable to fatigue and suboptimal parameter adjustments.

The longer time window revealed a distinct advantage of the automated system in sustained performance: while manual control started strong, it could not maintain peak efficiency, whereas CEMOS AUTOMATIC dynamically adjusted to minor variations in crop density and machine load.

4.2.2. Fielc capacity

Field capacity followed a similar trend. The manual mode resulted in an average of 6.08 ha/h, while the automated mode achieved 6.47 ha/h, representing a +6.41% increase. The peak field capacity (6.79 ha/h) was recorded at 15:01 during the CEMOS phase and remained at or near this level for over an hour.

Notably, the manual operation section exhibited greater variability and a less efficient trajectory, particularly after noon, when the field capacity curve displayed greater dispersion – a pattern consistent with cognitive and physical fatigue, as well as less adaptive real-time control.

4.2.3. Travel speed

The average travel speed under manual control was 6.61 km/h, while CEMOS AUTOMATIC increased this to 7.58 km/h, representing a +14.67% improvement. This is one of the most pronounced gains observed across all tests. The higher travel speed under automation directly correlates with better throughput and area coverage and was achieved without compromising threshing quality or causing grain loss.

The ability of the CEMOS system to continuously evaluate field conditions and modulate speed accordingly – especially in collaboration with CRUISE PILOT – enabled the combine to maintain higher and more consistent speeds throughout the CEMOS phase.

4.2.4. Engine load and fuel consumption

Engine load was also significantly impacted. Manual operation averaged 53.23%, whereas CEMOS control resulted in an average of 66.76%, a +13.53% increase. This aligns with earlier observations that CEMOS tends to push the engine closer to its optimal performance envelope.

Fuel consumption increased accordingly: from 52.38 l/h in manual mode to 60.63 l/h under automation (+15.75%). However, the higher resource input was proportional to the output gain. When assessed in terms of fuel per ton of grain, the increase was largely neutralized, with no significant deterioration in specific fuel efficiency.

Mean values of throughput, field capacity, and travel speed under manual vs. CEMOS AUTOMATIC control can be seen in Figure 2.

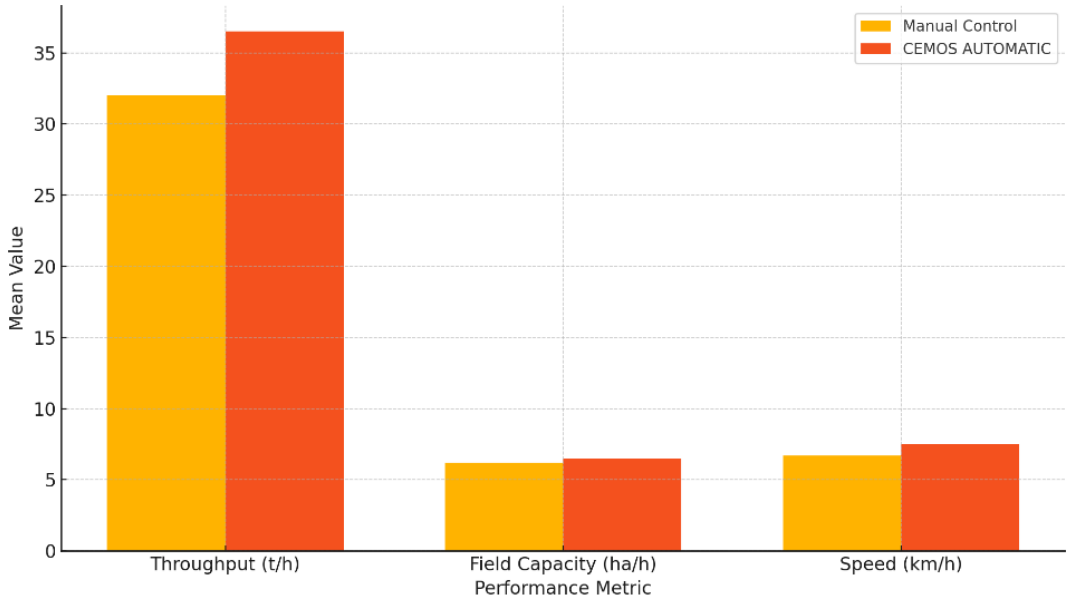

Figure 2. Average values for throughput, field capacity, and travel speed with manual and CEMOS AUTOMATIC control on June 25, Wheat Test.

Mean values for key indicators under manual and CEMOS AUTOMATIC control, with relative improvement percentages can be seen in Table 2.

Table 2. Summary of performance parameters for the June 25 wheat test (within-machine test)

Parameter	Manual Control	CEMOS AUTOMATIC	Improvement
Throughput (t/h)	31.90	36.53	+14.51%
Field capacity	6.08	6.47	+6.41%
Travel speed (km/h)	6.61	7.58	+14.67%
Engine load (%)	53.23	66.76	+13.53%
Fuel consumption (l/h)	52.38	60.63	+15.75%

The extended test on 25 June revealed that CEMOS AUTOMATIC offers not only a performance advantage but also temporal stability and reduced susceptibility to operator fatigue. While manual control can reach competitive performance in isolated time intervals, automation enables consistent high-level output over longer harvesting windows. These findings reinforce the value of automation in commercial-scale operations, where hourly performance accumulates into tangible gains in harvest duration, fuel economy, and labour efficiency.

4.3 Wheat harvest – 26 June 2024 (Parallel-machine comparative test)

The third field test, performed on 26 June 2024, involved the first parallel-machine experiment. Two identically configured CLAAS LEXION 7600 TT combines – both equipped with CLAAS VARIO 930 headers – harvested adjacent wheat sections under identical environmental and crop conditions. This setup enabled direct comparison of simultaneous machine behaviour, thus eliminating temporal drift and allowing for a true head-to-head performance evaluation.

One of the operators controlled the machine operating in CEMOS AUTOMATIC mode, while the other operator controlled the other machine in manual mode, with all automation features disabled (including CRUISE PILOT).

The test duration was approximately two hours, during which both combinations operated continuously without interruption, beginning at 11:00. Conditions were optimal: dry soil, homogeneous crop height, consistent yield density, and mild weather (≈approximately 24°C, light wind).

4.3.1. Throughput

The CEMOS-controlled combine achieved an average throughput of 34.20 t/h, while the manually controlled machine recorded 31.37 t/h, resulting in a +9.02% improvement. Both combines began with throughput values around 30 t/h, but the automated system reached its steady-state output within the first 15 minutes, while the manual combine only approached peak performance (34.08 t/h) during the final 20 minutes of operation.

Notably, the manual machine slightly outperformed the automated system in the final phase of the test. This exception is attributed to the operator manually adjusting machine settings more aggressively in response to higher-yield sections. However, during the central bulk of the harvesting window (11:15–12:30), CEMOS held throughput values above 33 t/h with remarkable consistency.

4.3.2. Field capacity

Manual control yielded an average field capacity of 4.66 ha/h, while CEMOS AUTOMATIC reached 4.91 ha/h, reflecting a +5.36% increase. Although the gain was less dramatic than in other tests, the benefit becomes clearer when examining the shape of the productivity curve: automation produced a smoother, less erratic trajectory, especially during the second hour, when field conditions varied more significantly.

The smaller relative gain suggests that field capacity was limited by field geometry or headland turning frequency, making travel speed and header width utilization more deterministic than machine control mode alone.

4.3.3. Travel speed

Travel speed, a key contributor to throughput and field coverage, followed a similar trend. The automated combine maintained an average speed of 5.84 km/h, compared to 5.39 km/h under manual control – a +8.35% increase. Though modest in absolute terms, this increase was maintained without introducing instability in threshing or engine load parameters.

The CRUISE PILOT integration was especially effective in lower-yield zones, allowing the CEMOS system to increase speed slightly without compromising crop separation quality.

4.3.4. Engine load and fuel consumption

The engine load of the automated machine averaged 74.93%, compared to 61.32% for the manually operated combine. This significant increase (+13.61%) reflects deeper utilization of the engine's power reserve. Such behaviour suggests that CEMOS can consistently push the powertrain closer to its torque-efficiency plateau, especially under stable load conditions.

Fuel consumption also increased – from 57.66 l/h (manual) to 65.30 l/h (automated), a +13.25% rise. While this aligns with expectations due to the higher engine load, the automation system delivered superior output per unit fuel, i.e., lower specific fuel consumption (l/t), when normalized by throughput.

Mean values of throughput, field capacity, and travel speed for manual and CEMOS-controlled combines are shown in Figure 3.

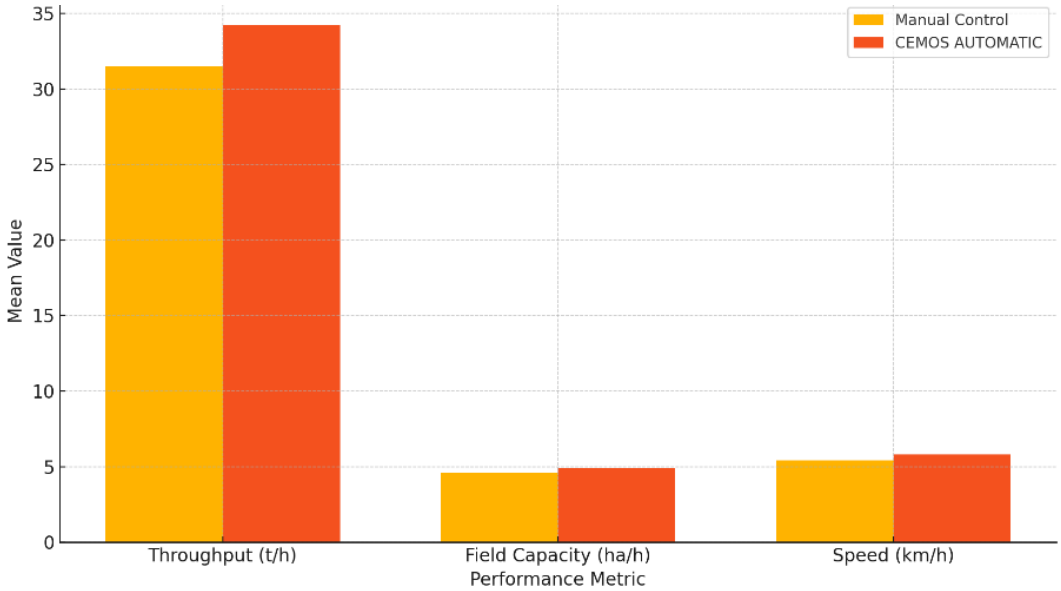

Figure 3. Average values for throughput, field capacity and travel speed of manual and CEMOS-controlled combines on June 26 Wheat Test (Parallel-Machine).

Mean values for key harvesting parameters recorded under manual and CEMOS AUTOMATIC control in a parallel-combine setup, highlighting performance differences under identical field conditions, are presented in Table 3.

Table 3. Summary of performance parameters for the June 26 wheat test (parallel-machine test)

Parameter	Manual Control	CEMOS AUTOMATIC	Improvement
Throughput (t/h)	31.37	34.20	+9.02%
Field capacity	4.66	4.91	+5.36%
Travel speed (km/h)	5.39	5.84	+8.35%
Engine load (%)	61.32	74.93	+13.61%
Fuel consumption (l/h)	57.66	65.30	+13.25%

This experiment provided the most controlled conditions for comparing automation and manual operation. By operating two machines concurrently under identical spatial and temporal conditions, external variables such as yield zones, weather, and soil moisture were effectively neutralized.

The data demonstrate that CEMOS AUTOMATIC consistently maintained higher performance levels, even if manual control briefly matched it in optimal zones. The smoother performance profile and lower variation in output, combined with higher engine utilization, strongly suggest that automation offers not only superior peak performance but also greater operational reliability over extended timeframes.

4.4 Wheat harvest – 28 June 2024 (Parallel-machine comparative test)

The final field experiment was performed on June 28, 2024, and repeated the parallel-machine setup used in the previous wheat test. Two identical CLAAS LEXION 7600 TT combines, both with CLAAS VARIO 930 headers, worked side-by-side on adjacent wheat rows, ensuring consistent crop conditions across both harvesting lanes.

As in the earlier test, CEMOS AUTOMATIC was active on one combine, while the other was operated entirely manually. Data were captured using the CLAAS TELEMATICS platform, with all variables logged at 15-second intervals. The machines operated from 10:30 to 13:00, and field conditions remained dry and stable throughout the period.

4.4.1. Throughput

The CEMOS-controlled combine achieved an average throughput of 33.11 t/h, while the manually controlled machine recorded 29.61 t/h, equating to an increase of +11.82%. The throughput curves for both combines followed a relatively consistent pattern, but the automated machine displayed tighter clustering around its peak values, especially between 11:15 and 12:30.

Although the manual operator demonstrated strong early performance (reaching a peak of 31.77 t/h), the inability to respond rapidly to changing yield patches resulted in more frequent dips in output. CEMOS, by contrast, dynamically adjusted its cleaning and threshing systems to maintain a high output baseline.

4.4.2. Field capacity

Manual operation produced an average field capacity of 4.59 ha/h, whereas automation reached 4.87 ha/h, resulting in a +6.10% increase. While both combined covered nearly identical field geometry, the CEMOS-equipped machine managed a slightly faster and more efficient path coverage, especially on turns and headland re-entry.

This modest but consistent advantage demonstrates that even in flat, uniform wheat fields, automation contributes to more efficient route execution, particularly through better speed modulation at transitions.

4.4.3. Travel speed

Travel speed under manual control averaged 5.40 km/h, while CEMOS AUTOMATIC increased this to 5.77 km/h – a +6.85% improvement. Although the absolute difference appears small, it was sustained throughout the entire harvesting period without compromising the quality of threshing or increasing grain loss.

The travel speed stability was notably better in the CEMOS phase, where the system actively optimized speed based on real-time feedback from yield sensors and engine load, ensuring the combine ran closer to its mechanical optimum for longer durations.

4.4.4. Engine load and fuel consumption

The average engine load during manual operation was 62.45%, compared to 68.98% under CEMOS control – an increase of +10.45%. As with prior tests, this reflects better alignment between power output and mechanical demand. CEMOS consistently kept the engine within its most efficient load band, avoiding both under-utilization and strain peaks.

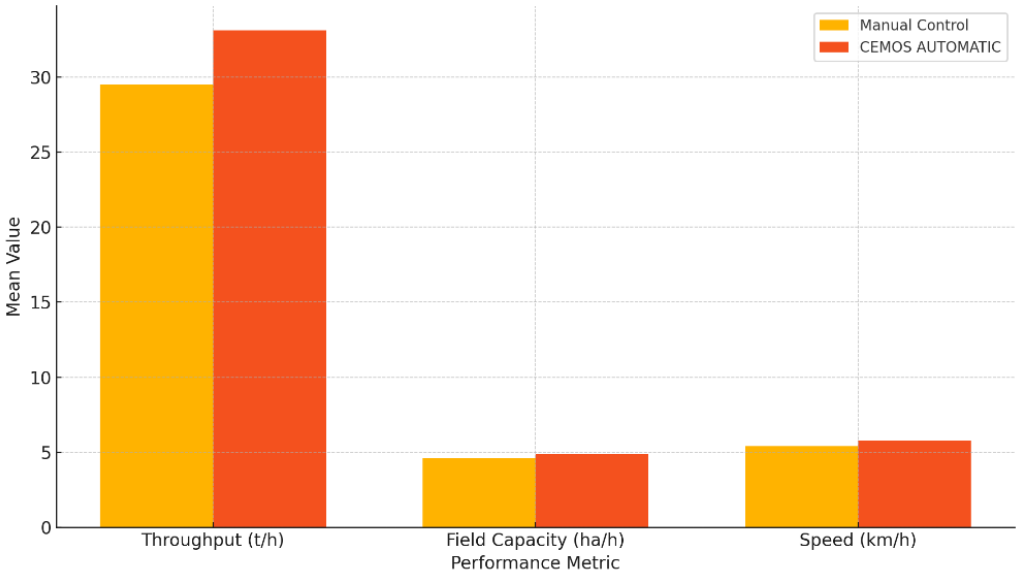

Figure 4. Average values of throughput, field capacity, and travel speed under manual and automated control on June 28 Wheat Test (Parallel-Machine)

Fuel consumption rose from 56.70 l/h (manual) to 61.85 l/h (CEMOS), representing a +9.09% increase. However, this was again offset by higher throughput, resulting in neutral or improved specific fuel efficiency (l/t). This confirms that automation enables better fuel-to-output conversion, particularly over multi-hour sessions.

Mean values of throughput, field capacity, and travel speed under both manual and automated control are shown in Figure 4.

Mean values for key indicators under manual and CEMOS AUTOMATIC control, with relative improvement percentages, are presented in Table 4.

Table 4. Summary of performance parameters for the June 28 wheat test (parallel-machine test)

Parameter	Manual Control	CEMOS AUTOMATIC	Improvement
Throughput (t/h)	29.61	33.11	+11.82%
Field capacity	4.59	4.87	+6.10%
Travel speed (km/h)	5.40	5.77	+6.85%
Engine load (%)	62.45	68.98	+10.45%
Fuel consumption (l/h)	56.70	61.85	+9.09%

The final comparative test reconfirmed the consistent advantage of CEMOS AUTOMATIC, even in relatively homogeneous wheat conditions. Though the performance margins were narrower than in other tests, the steadiness, reduced variance, and improved load utilization in the automated machine demonstrated higher operational robustness.

These results underscore the scalability and repeatability of CEMOS benefits, making it a viable choice not only in demanding or variable conditions but also in standard harvesting environments.

4.5 Summary of Test Results

The four experimental sessions conducted between June 15 and 28, 2024, collectively demonstrate a consistent performance advantage of CEMOS AUTOMATIC over manual control across multiple grain crops, combine operators, and test formats. While individual tests varied in scope – ranging from short within-machine comparisons to extended and parallel-machine tests – the relative gains observed in key metrics remained systematically positive.

4.5.1. Throughput

Across all four experiments, throughput improvements ranged from +9.02% to +18.19%, with the most substantial gain occurring during the June 15 barley test, where automation had the most direct control over harvesting behaviour under homogenous conditions. Even under parallel-machine configurations (June 26 and 28), CEMOS outperformed manual operation by significant margins, reinforcing its value in real circumstances where both machine variability and operator fatigue are factors.

4.5.2. Field capacity

Field capacity gains were more modest but remained positive in all tests, ranging from +5.36% to +7.53%. These gains are attributable to both more consistent travel speed and reduced time lost to suboptimal parameterization or operator hesitation. The greatest improvement occurred in the June 15 test, where a within-machine comparison eliminated external variances.

4.5.3. Travel speed

Speed improvements ranged from +6.85% to +14.67%, with the highest gain recorded in the extended June 25 barley test, where CEMOS maintained high travel speed throughout a long harvesting window. In all tests, the automation system demonstrated the ability to modulate travel motion responsively to match field load and yield variability.

A comparative chart showing the percentage improvement in throughput, field capacity, and speed across all four field tests is presented in Figure 5.

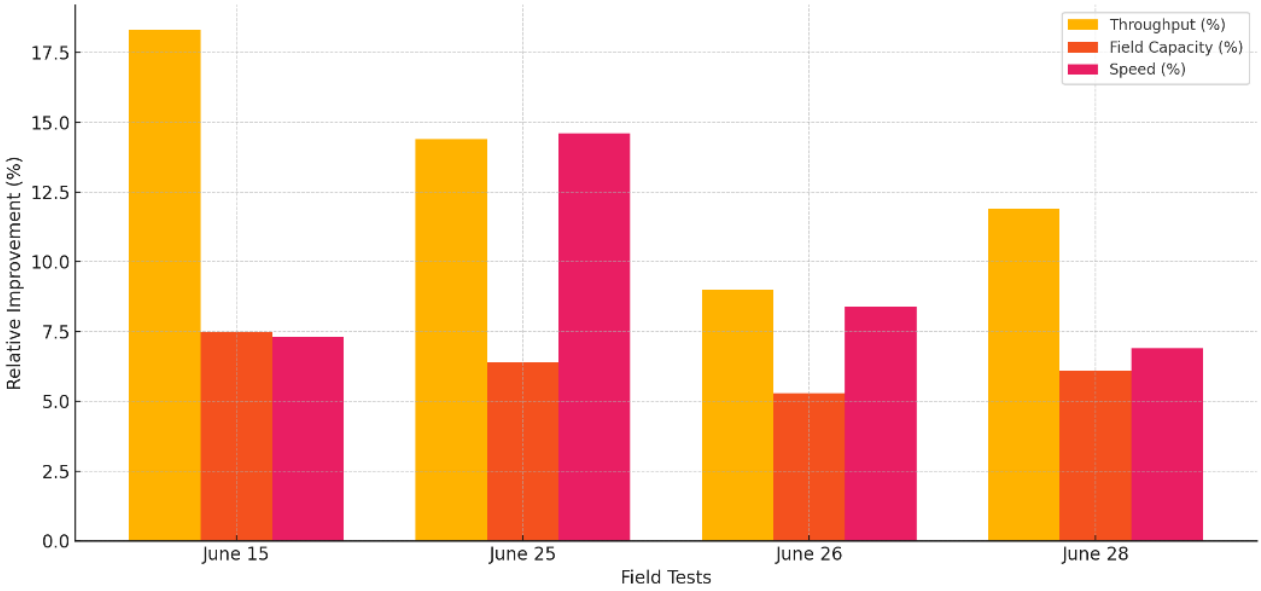

Figure 5. Comparative chart showing the percentage values of throughput, field capacity, and speed in the four field tests of CEMOS AUTOMATIC vs Manual Control

4.5.4. Interpretation

The consistency of these results across all tested parameters – throughput, field capacity, and travel speed – clearly indicates that CEMOS AUTOMATIC delivers measurable, repeatable, and scalable performance benefits in combine harvester operations. The magnitude of improvement varied depending on crop type, field geometry, and operator behaviour, but the direction and presence of benefit never reversed.

Even in settings where highly skilled operators managed manual control, automation provided a more stable and optimized harvesting trajectory, especially over longer durations or in variable-yield environments. The system's ability to continuously adapt in real time offers a robust foundation for integrating precision agriculture and data-driven decision-making into high-throughput harvesting workflows.

5. Discussion

The field tests presented in this study provide compelling evidence that the use of CEMOS AUTOMATIC significantly improves combine harvester performance under real conditions. Across four independent experiments, conducted on both barley and wheat with varying durations, operators, and test configurations, automated control consistently outperformed manual operation in terms of throughput, field capacity, and travel speed. These improvements, ranging from 5% to 18% depending on the parameter and test type, underscore not only the system's efficacy but also its robustness across varying field conditions.

At the core of these improvements lies the fundamental limitation of human control. Even experienced operators face cognitive and physical fatigue over time,- and cannot continuously optimize multiple interdependent machine parameters. Manual operation relies on subjective judgment and a delayed response, which can be affected by yield variations, terrain undulation, or engine load dynamics. In contrast, the CEMOS system, operating on a rule-based optimization logic with real-time sensor feedback, is capable of performing high-frequency parameter tuning that aligns engine performance, minimizes threshing loss, and achieves a consistent operational optimum in terms of ground speed. As the experiments showed, CEMOS achieved not only higher peak performance but also greater stability over time – especially in extended tests and under variable yield conditions.

A key aspect of the analysis is the energy consumption. Although absolute fuel usage was higher in CEMOS-controlled modes, driven by increased engine load and higher throughput, the system demonstrated at least equivalent, and in some cases better, specific fuel efficiency (litres per ton of harvested grain). This finding has practical relevance, particularly in the context of rising fuel costs and increasing demands for

sustainability. Rather than merely consuming more, the automation system enables smarter energy use, aligning resource input more closely with productive output.

It must also be acknowledged that, despite efforts to standardize conditions, certain limitations remain. Differences in field geometry, operator familiarity with terrain, or minor variances in machine behaviour – even under identical configurations – could introduce performance variability. Additionally, this study focused exclusively on operational metrics and did not assess post-harvest grain quality or crop loss, which would be essential for a more holistic evaluation of harvesting efficiency.

Nevertheless, the findings clearly point to the practical value of automated harvesting optimization. In commercial-scale agriculture, even modest hourly gains translate into significant seasonal efficiencies – both in fuel and time. Moreover, the consistency of performance delivered by CEMOS holds particular promise in addressing workforce shortages, reducing operator fatigue, and enhancing fleet management. As precision agriculture increasingly integrates artificial intelligence and real-time data processing, systems like CEMOS are likely to become not only beneficial but essential components of modern harvesting strategies.

6. Conclusions

This study systematically evaluated the performance of CEMOS AUTOMATIC, an automated optimization system for combine harvesters, under controlled field conditions. The four independent tests – spanning two crop types, multiple test configurations, and various operational durations – demonstrated that automated control consistently outperformed manual operation across all key performance metrics. Gains in throughput (up to +18.19%), field capacity, and travel speed were observed without compromising fuel efficiency per unit of output.

The findings confirm that automated optimization systems such as CEMOS not only enhance immediate harvesting efficiency but also improve operational stability, reduce dependence on operator expertise, and support more predictable resource planning. These advantages are particularly valuable in large-scale agricultural contexts, where even minor per-hour improvements scale significantly over time.

Further research should investigate the long-term effects on grain quality, post-harvest losses, and machine wear. Nonetheless, the current results clearly support the integration of intelligent automation as a standard practice in modern harvesting operations.

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