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Field Sprayer with Application Rate Control Using Fast Response Proportional Valves under Variable Speed Conditions

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Abstract: In modern agriculture, which is characterised by dynamic field environments, challenges are faced in maintaining consistent application rates due to varying tractor speeds, field conditions, and certain calibration errors. Conventional control systems, which rely on slower valves, have difficulty adapting to these dynamic field conditions. By contrast, the integration of fast-acting proportional valves improves the precision and flexibility of flow rate adjustment during spraying applications. This research focused on evaluating the accuracy of spraying applications under different tractor speed conditions through field experiments and data analysis. This study involves a field sprayer with boom wings divided into right and left sections, where the flow rate of the liquid to each section is controlled by proportional valves with a 3 s full opening and closing time, dependent on speed information. Using a closed-loop control system consisting of a flow meter, proportional valve, and PLC, the valves are controlled by the PLC's internal PID blocks. Observations reveal that as the tractor speed increases to a certain level, the system effectively adjusts the application rate close to the target value and maintains control against the changing ground speed during all field tests. The study included five different application tests, with target application rates of 100, 150, 200, 250, and 300 L ha^{-1}, with each repeated three times, resulting in a total of 15 field tests at different ground speeds. During these tests, the data were meticulously recorded every second, covering the tractor speed, flow rate, and pressure values for both right and left boom sections, along with regulator pressure, proportional valve opening rates, and application rates. The durations for each application rate were documented alongside instances within specified periods where error boundaries of ±10% were exceeded. During the total test duration of 9734 s, the actual application rate value exceeded error boundaries during only 209 s. Within the application durations, the speed variation intervals ranged from 5.10 to 10.23 km h^{-1}, 4.64 to 9.91 km h^{-1}, 3.68 to 7.89 km h^{-1}, 4.80 to 8.21 km h^{-1}, and from 4.90 to 8.69 km h^{-1}. The absolute percentage mean application errors were recorded as 2.81%, 2.68%, 2.28%, 2.14%, and 2.51% for respective application rates. Furthermore, statistically significant correlations ($p < 0.01$) were identified among the variables (speed, valve opening rate, flow rate, pressure) in both the right and left boom sections across all application rates.

Keywords: field sprayer; flow rate control; PID; pesticide

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1. Introduction

The continuous advancement of pesticide application technologies has yielded a diverse range of pesticides that are crucial to meeting today's consumer demands and ensuring ample food supplies. However, these pesticides, while instrumental in crop protection and growth, pose certain environmental and health risks to living organisms, including the human population [1–3]. Maintaining a uniform application rate per unit area is critical to the efficient use of pesticides with field sprayers, as their uneven distribution compromises treatment efficacy and contributes to residues of non-target pesticides [4]. Application errors can result in pesticide residues found in everyday consumer products, such as cooked meals, water, wine, fruit juices, and animal feeds [5]. Several factors related to equipment and application methods can affect the coverage and effectiveness of pesticide application. In particular, parameters such as ground speed and the type of nozzle/droplet size are crucial in influencing spray coverage, quality, efficacy, and potential droplet drift. Higher ground speeds have been shown to lead to a heightened generation of smaller droplets, consequently raising the risk of spray drift. Several studies have documented greater pesticide drift and reduced coverage associated with increases in the travel speed of the tractor [6–10]. In addition, resistance to pests can develop over time, which impairs the effectiveness of pest control. Successful pesticide application hinges on the utilisation of calibrated sprayers operated by trained individuals [11]. However, the inadequacies resulting from improperly calibrated equipment result in the waste of thousands of gallons of pesticides and billions of dollars. [12–14]. A study conducted in North Dakota in the United States revealed significant variations in pesticide application rates, with 60% of applicators delivering over or under their intended rate by more than 10% and with several instances exceeding 30% [15]. The study primarily attributed these issues to factors such as worn nozzle tips, imprecisely calibrated equipment, or the inability to sustain necessary flow rates during field application [16,17].

Efficient sprayer rate control is deemed essential for the accurate application of pesticides. Traditional pressure-based field sprayers that lack control systems require operators to continually manage both tractor speed and system pressure in order to maintain a consistent application rate. Inherent variations in the forward speed of tractors during application, coupled with operational errors, make maintaining a target rate significantly challenging. However, achieving the desired target application rate is crucial for optimal pesticide coverage and efficacy [18], as well as economic viability.

The application rate (L ha^{-1}) is determined by the flow rate (L min^{-1}) and the tractor speed (km h^{-1}). Therefore, the precision of the feedback signals from flow rate and speed sensors and the accuracy of the valves that control the flow are critical to minimising application errors. To measure the flow rate in the pressure line of a sprayer system, there are several types of liquid flowmeters, such as turbine, vortex, electromagnetic, and ultrasonic flowmeters. When different flow measurement systems are examined, ultrasonic flowmeters are widely used due to their high sensitivity [19–21].

Over time, spray rate controllers have been integrated into agricultural sprayers in order to effectively manage application rates in cases where the ground speed changes during field operations [22–24]. Some such control methods are now widely available for use in agricultural spraying control systems and related fields as follows: PID (Proportional Integral Derivative) control [25,26], fuzzy control [27–29], neural network control [30], and intelligent control systems [31,32].

These systems primarily employ proportional valves to control liquid flow in the pressure line. However, the slow opening and closing times of these valves, extending up to 15 s, indicate unacceptable motion dynamics [33]. As the sprayer equipment accelerates or decelerates, the limitations of the rate controller and system become more apparent, potentially leading to under or over-application [34]. The current study aims to effectively control the application rate in field sprayers through the utilisation of fast-response proportional valves in order to reduce errors due to speed changes.

2. Materials and Methods

The field tests were conducted on a flat area of 1.5 hectares on the campus of Kahramanmaras Sutcu Imam University, Turkey (37′35″18° N–36′48″47° E). The sprayer system used in this study consisted of a piston-diaphragm pump (71 L min^{-1}, max 50 bar), a 400 L tank capacity, and a 10 m boom width. The boom is divided into two sections (right and left), with each section controlled independently. A total of 20 flat-fan spray nozzles

(Agroer Co. Ltd., Istanbul, Turkey) were mounted on the boom at spacing intervals of 0.5 m. The colour codes and flow rates of the nozzles were as follows: yellow 0.65–1.03 L min^{-1}, blue 0.97–1.53 L min^{-1}, and red 1.29–2.09 L min^{-1} (see Figure 1a). An appropriate nozzle type was selected for each different application test based on the information specified in the product catalogue. The hardware of the flow rate control system consisted of a PLC (Programmable Logic Controller) (S7 1200, 6ES7214-1AG40-0XB0, 14 digital inputs, 10 digital outputs, and 2 analogue input) with an analogue module (SM 1234, 4 analogue inputs, 2 analogue outputs), flow meters (Christian Bürkert GmbH & Co. KG., Karlsruhe, Germany, 8081, 0.5–50 L min^{-1}), proportional valves (Christian Bürkert GmbH & Co. KG., Karlsruhe, Germany 3280, with a fully opening time of 3 s and a 4–20 mA input signal), and pressure sensors (Dwyer Instruments, LLC., USA, Wyoming, a 0–10 bar for right and left boom sections, and 0–100 bar for regulator output). Proportional valves and flow meters were mounted between the regulator output point and both boom sections (see Figure 1b). Power for the PLC, sensors, modem, and valves was supplied from the tractor's battery. Due to the different input voltage levels of the equipment used, a 12–220 V inverter device and a 220–24 V converter device were used.

(**a**) (**b**)

Figure 1. Sprayer system with application rate controller. (**a**) Boom sections and pressure sensors; (**b**) proportional valve and flow meter connection.

The speed of the tractor was measured using a proximity sensor attached to the front wheel (see Figure 2). To record the speed, 32 pieces of metal were attached evenly to the wheel at regular intervals. To acquire speed information, the pulse values detected by the proximity sensor, determined according to the distance covered by the wheel in one revolution, were fed into the PLC High-Speed Counter (HSC) input. As a result of this operation, speed in kilometres per hour was obtained by utilising mathematical functions within the PLC program.

Figure 2. Tractor speed measurement.

The output signals of the flow meter (4–20 mA), the output signals of the pressure sensor of the boom section (4–20 mA), and the output signals of the pressure sensor of the regulator (0–10 V) were successively applied to the analogue input terminals of the PLC module (AI0, AI1, AI2, AI3, and AI4). PID (Proportional Integral Derivative) controller blocks, which are commonly used in PLC programming, were used to control the proportional valves.

The target application rate was calculated depending on the tractor's speed, the flow rate, and the boom width for each boom section, and the target application rate was then applied to the PID input terminals. The control signal (4–20 mA) generated by the PID controller using these parameters was then applied to the proportional valves through the analogue output terminals (AQ0 and AQ1). The overall structure of the system used is illustrated as shown in Figure 3.

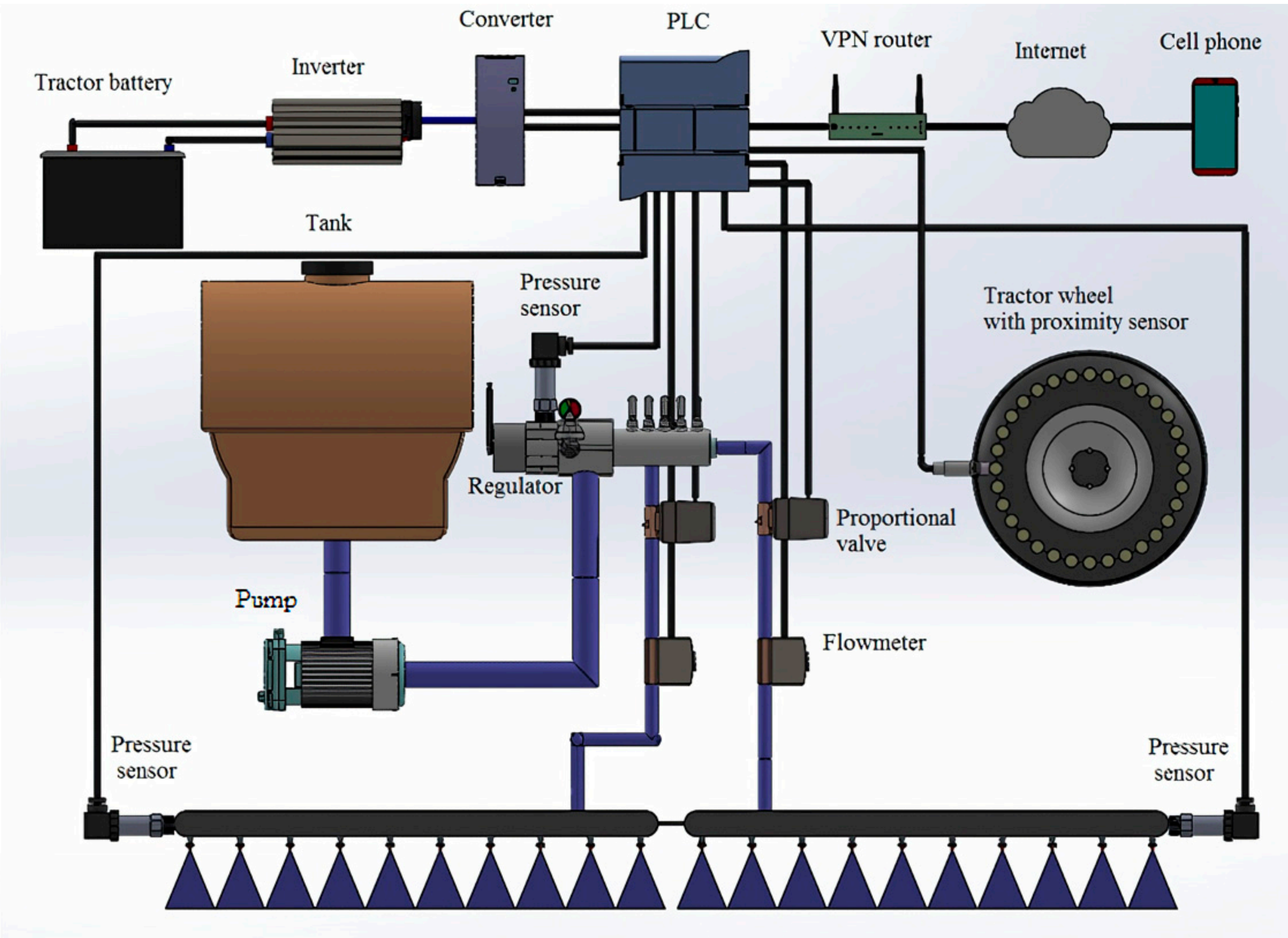

Figure 3. General structure of the system.

Five different target application rate tests (100, 150, 200, 250, and 300 L ha^{-1}) were conducted, each with three repetitions, resulting in a total of 15 different field tests conducted at varying tractor speeds of between 5 and 10 km h^{-1}. The sequential process followed for each test was as follows: (1) sprayer tank filled with water, (2) target application rate determined, (3) sending the pulse signal to the corresponding input of the controller for data recording, (4) starting the PTO (power take-off), (5) performing the application in the field at different ground speeds for about 10 min, and (6) transferring the data from the PLC memory to the computer in a 'csv' file format. When calculating the application error, the deviation between the actual application rate and the target application rate was evaluated, as shown in Equation (1) for the absolute application rate error as a percentage.

$$\text{Absolute Application Rate Error } (\%) = \frac{(|\text{Actual Application Rate } - \text{ Target Application Rate}|)}{\text{Target Application Rate}} \times 100 \quad (1)$$

The recorded data encompassed tractor speed, the flow rate of the right boom section (FRoRS), the flow rate of the left boom section (FRoLS), the valve opening rate of the right boom section (VORoRS), valve opening rate of the left boom section (VORoLS), the application rate of the right boom section (ARoRS), the application rate of the left boom section (ARoLS), regulator pressure (RP), right boom section pressure (RSP), and left boom section pressure (LSP). Data logging occurred every second through the data logger block within the PLC program, which comprised the following five instructions: (1) 'DataLogCreate' to generate a data log file, (2) 'DataLogOpen' to access an existing data log file, (3) 'DataLogWrite' to record a data record, (4) 'DataLogClose' to conclude an open data log, and (5) 'DataLogNewFile' to create a new data log with similar properties as an existing file but with a new name [35].

The data analysis revealed that sudden changes in real-time sensor data have a disruptive impact on the output values of the PID blocks responsible for regulating the proportional valve opening rate. To mitigate this, the data obtained from the sensors in real-time were smoothed using the "Moving Average" block. This block calculated the (Moving) Average based on the set window width, where the window width indicates the maximum number of values last read (set to 100). As soon as the maximum number of values was reached, "WindowSizeReached" was set, and each newly read value replaced the oldest value (FIFO principle; First Input First Output) [36].

Web server software (TIA Portal V.15) was developed to monitor real-time data over the internet, which is transmitted via a mobile 4G VPN router (Robustel Co. Ltd., Guangzhou, China). An index.htm file was created to display the sensor data directly via the PLC web server (PWS). This file displayed the outputs of the sensor data assigned to the variables in real-time via the server interface.

Prior to undertaking the tests, a fine-tuning test was conducted by setting the target application rate to 100 L ha^{-1} in order to determine the PID controller coefficients based on flow rate variations at different ground speeds (5–10 km h^{-1}). PID fine-tuning was employed so as to achieve the desired system response, to minimise errors, and also to improve stability within the control system. The P component responds to the current error, which is the difference between the desired setpoint and the actual process variable, and the I component considers the cumulative sum of past errors over time, which helps eliminate any steady-state error and brings the system to the desired setpoint. The D component predicts the future trend of the error based on its current rate of change, helping to dampen oscillations and prevent overshooting. This test involved continuously varying the tractor's speed within certain limits. After approximately 20 min of fine-tuning, the obtained PID coefficients presented in Table 1 were achieved.

Table 1. Determined PID coefficients during fine-tuning process.

Coefficient	Right Section	Left Section
Proportional gain	10.20958	17.89999
Integral action time (s)	1.967492	2.348299
Derivative action time (s)	0.528921	0.590065

3. Results

Figure 4 depicts the application rate of the right boom section (ARoRS), the application rate of the left boom section (ARoLS), the target application rate (TAR), and the error boundary (EB) value for 100 L ha^{-1} target application rate tests. In this test period, the interval speed variations ranged from 5.10 to 10.23 km h^{-1}. Of the 1726 s duration of this test period, the actual application rate exceeded the error boundaries for 49 s, representing an absolute mean application error value of 2.81%. Notably, the initial speed change, which was greater than subsequent changes in travel speed during the application, delayed the controller in approaching the set point for the target application rate. The proportional valve's complete closure during the initial movement resulted in no liquid passing through the flow meter, even when the tractor was in motion. In order to address this, an alert signal was sent to the flow meter output for a 3 s duration when the travel speed reached 1 km h^{-1}. In this scenario, the valve opened slightly, allowing liquid to enter the flow meter.

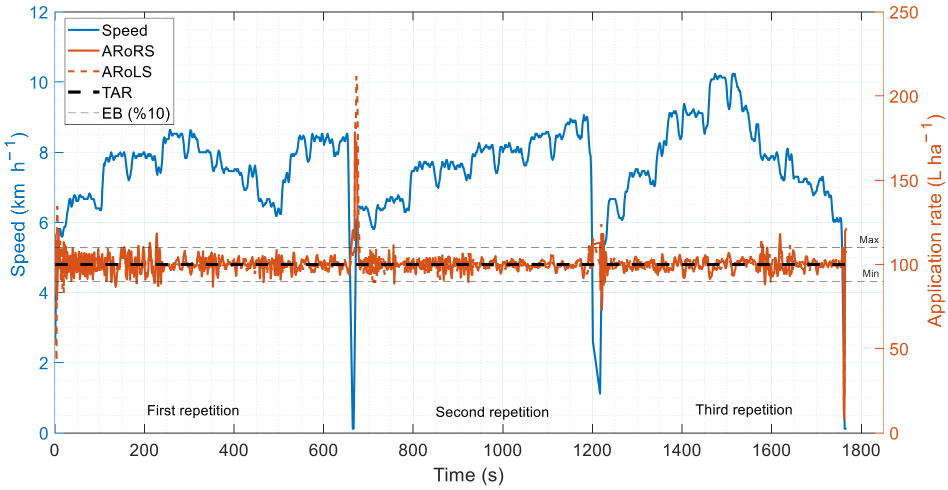

Figure 4. Speed vs. actual application rate (100 L ha^{-1}).

Figure 5 shows the graph of the actual application rate corresponding to the different ground speed values for the target application rate of 150 L ha^{-1}. In this test period, the interval speed variations ranged from 4.64 to 9.91 km h^{-1}. Of the 1810 s duration of this test period, the actual application rate exceeded the error boundaries for 46 s, representing an absolute mean application error value of 2.68%.

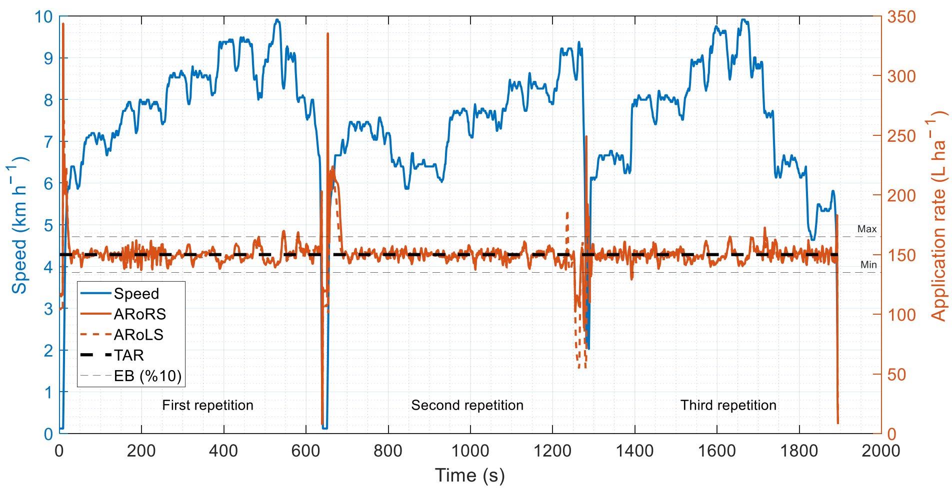

Figure 5. Speed vs. actual application rate (150 L ha^{-1}).

Figure 6 shows the graph of the actual application rate corresponding to the varying speed values for the target application rate of 200 L ha^{-1}. In this test period, the interval speed variations ranged from 3.68 to 7.89 km h^{-1}. Of the 1973 s duration of this test period, the actual application rate exceeded the error boundaries for 21 s, representing how the absolute mean application error value was found to be 2.28%. During this test period, the actual application rate consistently remained within acceptable levels due to smoother speed changes.

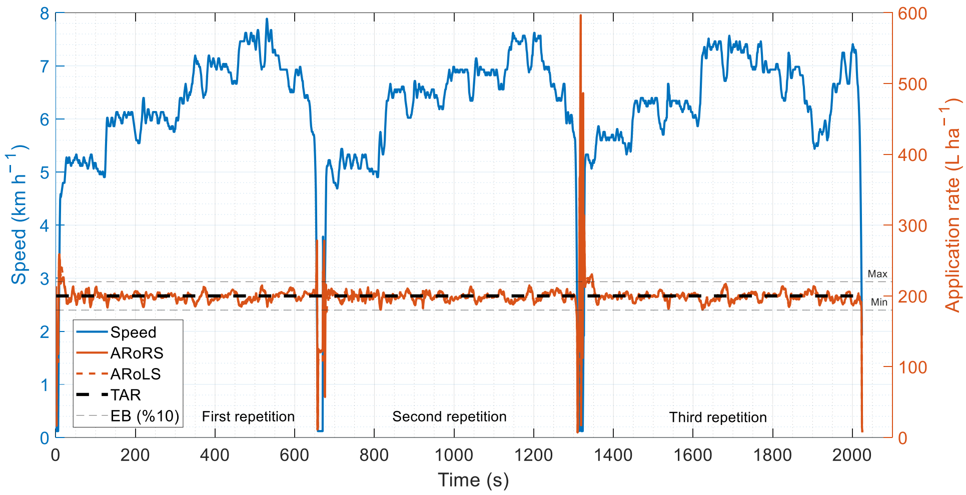

Figure 6. Speed vs. actual application rate (200 L ha^{-1}).

Figure 7 shows the graph of the actual application rate corresponding to the varying speed values for the target application rate of 250 L h^{-1}. In this test period, the interval speed variations ranged from 4.80 to 8.21 km h^{-1}. Of the 1848 s duration of this test period, the actual application rate exceeded the error boundaries for 40 s, representing how the absolute mean application error value was found to be 2.14%. During the second and third repetitions of this test period, it was observed that where there was a sudden change in speed (approx. 1 km h^{-1}), the application rate value exceeded the error limits for a few seconds.

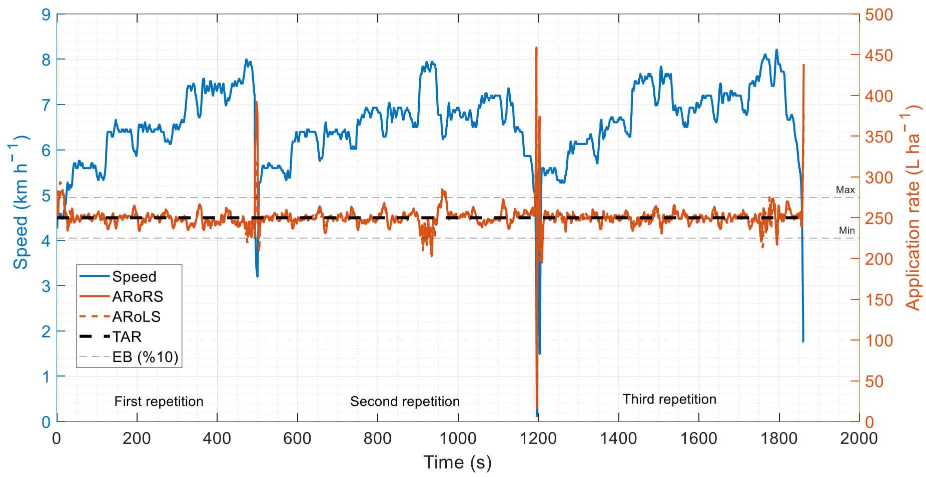

Figure 7. Speed vs. actual application rate (250 L ha^{-1}).

Figure 8 shows the graph of the actual application rate corresponding to the varying speed values for the target application rate of 300 L h^{-1}. In this test period, the interval speed variations ranged from 4.90 to 8.69 km h^{-1}. Of the 2168 s duration of this test period, the actual application rate exceeded the error boundaries for 53 s, representing how the absolute mean application error value was found to be 2.51%.

Figure 9 presents the regulator pressure, right boom section pressure (RSP), and left boom section pressure (LSP) for the 200 L ha^{-1} target application rate. Throughout the application, the regulator pressure (RP) maintained a steady level of approximately 6–7 bars, while the pressures associated with the boom sections varied in the range of 1.5–3.5 bars, contingent on speed changes and, consequently, flow rate. Notably, the precise regulation of the liquid pressurised by the pump prior to its application to the proportional valves significantly contributed to enhancing the stability of the system.

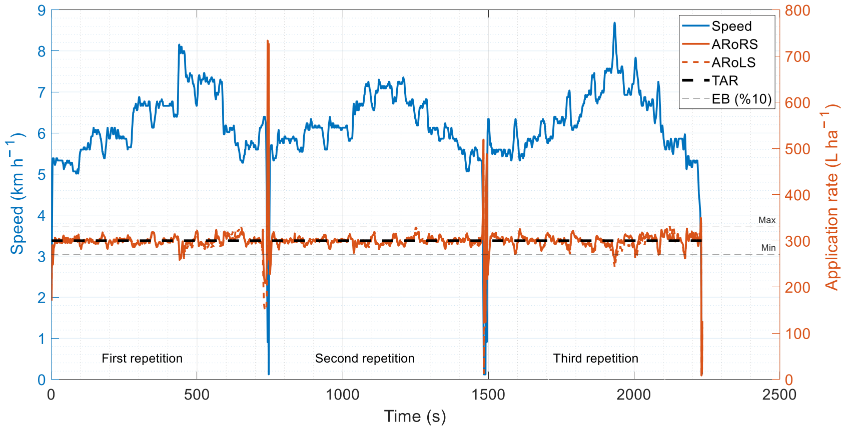

Figure 8. Speed vs. actual application rate (300 L ha^{-1}).

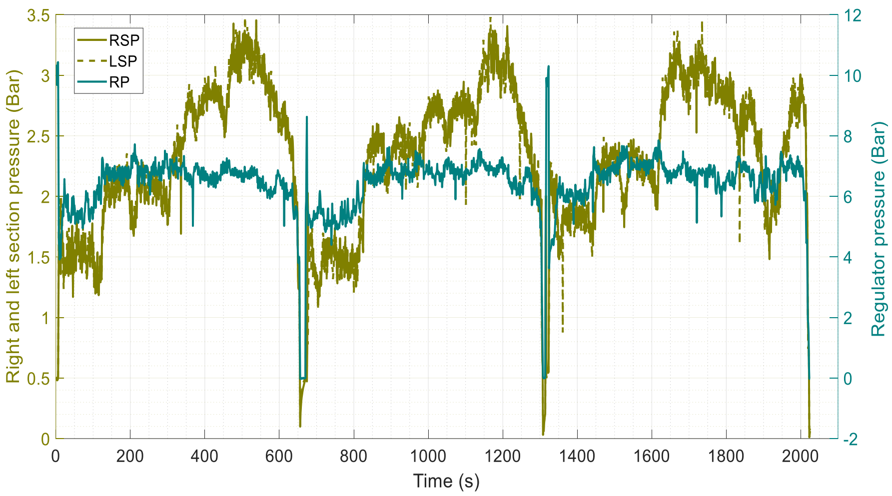

Figure 9. Boom sections and regulator pressure (200 L ha^{-1}).

Figure 10 shows the relationship between the opening rate of the proportional valves (VORoRS and VORoLS) and the speed and flow rates in the right and left boom sections (FRoRS and FRoLS). The left *y*-axis represents the travel speed of the tractor and the flow rate of the boom sections, while the right *y*-axis depicts the valve opening rate of the boom sections. The results indicate that the proportional valves adeptly regulated the flow rate, responding effectively to changes in speed.

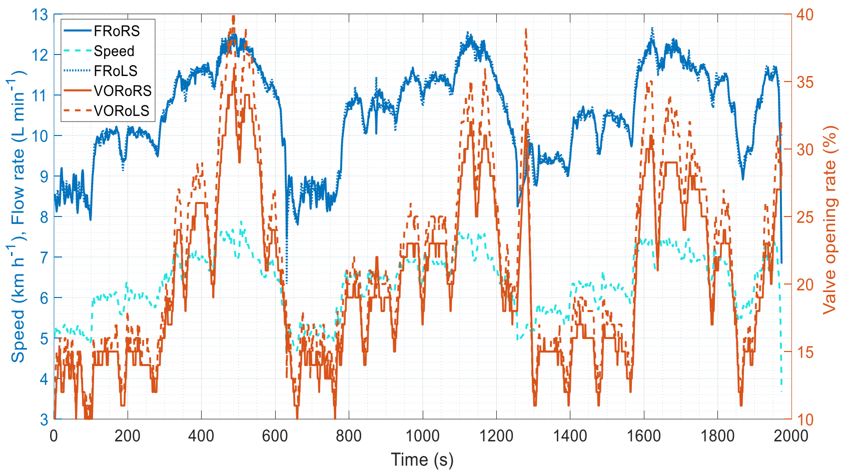

Figure 10. Speed and flow rate vs. proportional valve opening rate (200 L ha^{-1}).

The correlation analysis performed for different target application rates (100, 150, 200, 250, and 300 L ha^{-1}) provides valuable insights into the relationships between the variables in both the right and left boom sections. Speed exhibits robust positive correlations, VOR, flow rate, and pressure, indicating a simultaneous increase in these parameters as the application rate increase. This correlation is particularly pronounced at higher application rates. The positive correlations between speed, and flow rate emphasise the interdependence between these two factors. This relationship indicates that the actual application value is maintained over the entire test period. VOR shows positive correlations with flow rate and pressure, and the correlation becomes more stable at higher application rates. The correlation between speed and VOR, as well as the correlation between speed and flow rate, indicate a strong interaction of factors in the system. The system regulates the liquid delivered to the nozzles to ensure uniform application, potentially smoothing out fluctuations caused by changes in speed and reflectance. Similarly, pressure shows positive correlations with speed, VOR and flow rate with these correlations as the application rates increase. These results indicate the synchronised behaviour of the variables, especially in scenarios with an increased application rate (see Tables 2–6).

According to the analysis of variance performed on the basis of the randomised complete block design, the analysis of variance performed for the factor boom sections and application rate indicates a significant effect on the speed variable. This means that changes in the application rate have a significant influence on the speed variable. As far as the VOR variable is concerned, the analysis of variance, which examines the interaction of the factor boom sections and application rate with VOR, shows a significant change in the VOR variable. This indicates that VOR can vary considerably in both the boom sections and the application rates. For the variable flow rate, the analysis of variance carried out of the factor boom sections and application rate shows a significant effect on the variable flow rate. This means that changes in the application rate have a noticeable impact on the flow rate. As with the pressure variable, the variance analysis carried out with the boom sections, and the factors for the application rate show a significant change in the pressure variable. This emphasises the significant impact that changes in application rate have on pressure (see Table 7).

The results revealed from the variance analysis offer a more detailed explanation of the relationships identified in the correlation analysis. For instance, when examining the interaction of speed with actual application rate and boom section factors, it was observed that these factors have a significant impact on speed. Similarly, the effects of VOR, flow rate, and pressure are associated with both the boom section factors and the actual application rate. The lack of significance for the boom sections and the significant influence of application rate (F-statistic: 2224.353, *p*-value: 0.000) indicate that changes in the actual application rate have a pronounced effect on VOR, while boom sections are not shown to significantly impact this relationship. The variance analysis indicates that the actual application rate significantly affects the flow rate (F-statistic: 16,613.497, *p*-value: 0.000), which emphasises the impact of changes in the actual application rate on the variability of the flow rate. The boom sections, however, were not found to have any significant influence on this relationship.

Table 2. Correlation analysis of values of variables for the target application rate (100 L ha^{-1}).

Variables	Right Boom Section					Left Boom Section				
	Speed	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**	**Speed**	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**
Speed (km h^{-1})	1	0.696 **	0.959 **	0.787 **	7.55 ± 0.03	1	0.348 **	0.946 **	0.670 **	7.55 ± 0.03
VOR (%)		1	0.658 **	0.819 **	5.75 ± 0.05		1	0.356 **	0.638 **	6.56 ± 0.07
Flow rate (L min^{-1})			1	0.770 **	6.29 ± 0.03			1	0.677 **	6.31 ± 0.03
Pressure (Bar)				1	1.49 ± 0.01				1	1.36 ± 0.01

** $p < 0.01$.

Table 3. Correlation analysis of values of variables for target application rate (150 L ha^{-1}).

Variables	Right Boom Section					Left Boom Section				
	Speed	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**	**Speed**	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**
Speed (km h^{-1})	1	0.471 **	0.951 **	0.859 **	7.55 ± 0.03	1	0.472 **	0.962 **	0.867 **	7.55 ± 0.03
VOR (%)		1	0.578 **	0.720 **	12.59 ± 0.16		1	0.544 **	0.703 **	13.94 ± 0.17
Flow rate (L min^{-1})			1	0.898 **	9.47 ± 0.04			1	0.882 **	9.47 ± 0.04
Pressure (Bar)				1	1.94 ± 0.01				1	1.93 ± 0.01

** $p < 0.01$.

Table 4. Correlation analysis of values of variables for target application rate (200 L ha^{-1}).

Variables	Right Boom Section					Left Boom Section				
	Speed	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**	**Speed**	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**
Speed (km h^{-1})	1	0.765 **	0.972 **	0.894 **	6.25 ± 0.02	1	0.768 **	0.977 **	0.897 **	6.25 ± 0.02
VOR (%)		1	0.762 **	0.853 **	19.47 ± 0.15		1	0.777 **	0.852 **	20.51 ± 0.16
Flow rate (L min^{-1})			1	0.883 **	10.37 ± 0.04			1	0.890 **	10.37 ± 0.04
Pressure (Bar)				1	2.32 ± 0.01				1	2.32 ± 0.01

** $p < 0.01$.

Table 5. Correlation analysis of values of variables for target application rate (250 L ha^{-1}).

Variables	Right Boom Section					Left Boom Section				
	Speed	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**	**Speed**	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**
Speed (km h^{-1})	1	0.677 **	0.696 **	0.658 **	6.33 ± 0.02	1	0.504 **	0.738 **	0.663 **	6.33 ± 0.02
VOR (%)		1	0.629 **	0.641 **	24.16 ± 0.24		1	0.569 **	0.642 **	30.96 ± 0.47
Flow rate (L min^{-1})			1	0.923 **	14.17 ± 0.04			1	0.929 **	14.11 ± 0.05
Pressure (Bar)				1	1.84 ± 0.01				1	1.82 ± 0.01

** $p < 0.01$.

Table 6. Correlation analysis of values of variables for target application rate (300 L ha^{-1}).

Variables	Right Boom Section					Left Boom Section				
	Speed	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**	**Speed**	**VOR**	**Flow Rate**	**Pressure**	**Mean ± SE**
Speed (km h^{-1})	1	0.677 **	0.916 **	0.898 **	6.20 ± 0.02	1	0.592 **	0.891 **	0.888 **	6.20 ± 0.02
VOR (%)		1	0.688 **	0.721 **	25.58 ± 0.28		1	0.524 **	0.588 **	37.22 ± 0.57
Flow rate (L min^{-1})			1	0.918 **	15.47 ± 0.04			1	0.905 **	15.39 ± 0.04
Pressure (Bar)				1	2.19 ± 0.01				1	2.16 ± 0.01

** $p < 0.01$.

Table 7. Analysis of variance for the variables.

Variations	VK	SD	KO	F	p
Speed	Boom sections	1	0.000	0.000	1.000
	Actual application rate	4	1849.475	1466.551	0.000 **
	Actual application rate × Boom sections	4	0.000	0.000	1.000
	Error	19,288	1.261		
VOR	Boom sections	1	89,485.513	501.684	0.000 **
	Actual application rate	4	396,758.542	2224.353	0.000 **
	Actual application rate × Boom sections	4	23,481.152	131.643	0.000 **
	Error	19,288	178.370		
Flow rate	Boom sections	1	3.112	1.013	0.314
	Actual application rate	4	51,068.190	16,613.497	0.000 **
	Actual application rate × Boom sections	4	1.630	0.530	0.713
	Error	19,288	3.074		
Pressure	Boom sections	1	7.771	28.302	0.000 **
	Actual application rate	4	433.479	1578.791	0.000 **
	Actual application rate × Boom sections	4	2.434	8.866	0.000 **
	Error	19,288	0.275		

** $p < 0.01$.

4. Discussion

When applying pesticides under field conditions, the error rate (the deviation between the actual application rate and the target application rate) should not exceed 10% [37,38]. In modern application rate control systems used for commercial purposes, it has been observed that the proportional valve, which is responsible for regulating the flow rate, has a limited ability to respond to control signals. In this study, if errors in the system approaching the set point at the beginning of each test are not considered (from the moment the error value is less than 10 percent), the application times for all tests and the duration of exceeding the error limit (±10%) within these application times are shown as follows: 1726 × 49, 1810 × 46, 1973 × 21, 1848 × 40, and 2168 × 53 s, respectively. The range of speed changes within these application times was 5.10–10.23, 4.64–9.91, 3.68–7.89, 4.80–8.21, and 4.90–8.69 km h^{-1}, respectively. Despite the approximately 2-fold change in speed in all tests, the absolute mean percentage application errors were 2.81, 2.68, 2.28, 2.14, and 2.51, respectively. In another study conducted by Atcıoglu [39] using a commercially available application rate control system, the percentage rate of change in application rates compared to the percentage rate changes for the same actual application rate values were as follows: 17–24.5, 4.9–13.9, 9.2–13.9, 3.5–6.6, and 5.8–7.9. It can be said that the proportional valves, which are responsible for flow control and respond effectively to the control signal, maintain the actual application rate around the set point as the rate changes.

5. Conclusions

Pesticide application errors can be exacerbated when proportional valves, responsible for flow control in sprayer systems, fail to respond rapidly to control signals. In the current study, a closed-loop control system consisting of flow meters and proportional valves was implemented in order to mitigate such errors in pesticide applications using field sprayers. The boom was subdivided into independent right and left sections, with each being autonomously controlled. It was observed that application discrepancies between these two sections were statistically insignificant, which was expected. These findings highlight the potential of fast-response proportional valves to enhance the performance and adaptability of agricultural sprayer systems. Consequently, as the tractor speed increases, the valve opening rate rises, converging the application rate toward the set point. Once the travel speed of the tractor reaches a certain level, the system effectively controls the actual application rate. Instances of a sudden increase or decrease in the tractor's speed temporarily push the actual application rate value beyond its acceptable limits; however, it has also been shown to swiftly return within its acceptable boundaries. Despite the intentional changes to travel speed applied in all tests conducted in the current study, considering that speed variations during pesticide applications are typically smoother, this system was shown to adeptly maintain application errors within acceptable limits.

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