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Ajay Sharda

Washington State University, shardaj@tigermail.auburn.edu

Joe D. Luck

University of Nebraska-Lincoln, jluck2@unl.edu

John P. Fulton

Auburn University, fultojp@auburn.edu

Timothy P. McDonald

Auburn University, mcdontp@auburn.edu

Scott A. Shearer

Ohio State University, shearer.95@osu.edu

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Field application uniformity and accuracy of two rate control systems with automatic section capabilities on agricultural sprayers

Ajay Sharda,¹ Joe D. Luck,² John P. Fulton,³
Timothy P. McDonald,³ and Scott A. Shearer⁴

1. Center for Precision and Automated Agricultural Systems, Washington State University, Prosser, WA 99350, USA; email shardaj@tigermail.auburn.edu (Corresponding author)
2. Biological Systems Engineering, University of Nebraska Lincoln, Lincoln, NE 68583-0726, USA; email jluck2@unl.edu
3. Biosystems Engineering, Auburn University, 200 Corley Building, Auburn, AL 36849, USA; email fultojp@auburn.edu & mcdontp@auburn.edu
4. Food, Agricultural and Biological Engineering, The Ohio State University, 590 Woody Hayes Drive, Columbus, OH 43210-1057, USA; email shearer.95@osu.edu

Abstract

The adoption of automatic section control (ASC) on agricultural sprayers remains popular since it reduces overlap and application in unwanted areas leading to input savings and improved environmental stewardship. Most spray controllers attempt to maintain the desired target rate during ASC actuation (ON and OFF of control sections which change the width of boom-section actually spraying) but limited knowledge exists regarding controller response and nozzle discharge variation during field operation. Therefore, field experiments were conducted using two common self-propelled sprayers equipped with commercially available control systems with ASC capabilities. Pressure transducers were mounted across the spray booms to record real-time nozzle pressure with data tagged with GPS location and time. Nozzle flow was obtained from nozzle pressure to compute nozzle flow uniformity or coefficient of variations (CVs) across the ON boom, off-rate errors (percent difference between actual and target nozzle flow rate) and settling times. Results indicated that nozzle CVs were >10 % for both auto-boom and auto-nozzle control systems, when each of the auto-boom and auto-nozzle sections were turned back ON for 0.5 and 0.2 s, respectively. Further, nozzle off-rate errors exceeding

± 10 % occurred in both rectangular and irregular shaped fields. These off-rate errors primarily occurred during ASC actuation while at the same time the sprayer was being accelerated or decelerated. The extended nozzle flow settling times of up to 20 s (delayed response) indicated that the rate controller may require intelligent and enhanced control algorithms to minimize nozzle flow stabilization and thereby a reduction in sprayer off-rate errors during field operation.

Keywords: Liquid application, Automatic section control, Distribution, Pressure, As-applied

Introduction

Boom widths for agricultural sprayers continue to increase in the US. It is not uncommon to see widths of 36.6 m being used today along with ground speeds nearing 30 km/h to cover cropland in a timely fashion. This increase in application width coupled with varying field shapes and sizes, commonly found in the southeastern US, demand stable and quick control response to precisely apply products and minimize off-rate errors during field operation. Past surveys on U.S. farms, including those of private herbicide applicators, indicated that more than 50 % of sprayers deviated beyond the accepted 10 % variance from the target application rate largely due to worn nozzle tips, inaccurate calibration, or inability to maintain the required flow rate during field application (Gerling 1985; Grisso et al. 1989; Hofman and Solseng 2004). Spray rate controllers have been implemented over the years on agricultural sprayers to effectively maintain application rates with ground speed changes during field operation (Ayers et al. 1990). Adoption of rate controllers with ability to maintain application provided clear advantages in lowering off-rate errors (Al-Gaadi and Ayers 1994). However, control systems need to have greater control capabilities for precision application of agricultural chemicals within field boundaries to minimize exposure of the environment to pesticides (Matthews, 2008). Today, most if not all spray controllers on large commercial self-propelled sprayers in the U.S. are equipped with rate controllers which manage system flow and not necessarily the overall system pressure. These control systems attempt to maintain the target rate regardless of width (sections or nozzles ON) and/or ground speed changes. However, the accuracy of managing the application rate depends on controller responsiveness along with the resolution of the flow meter to maintain the required flow rate at any point in time. There has been an increase (39 %) in the number of retail dealerships providing GPS-equipped sprayer boom control (CropLife 2011) and also in the number of producers (27 %) currently using section control technology in Alabama (Winstead et al. 2010). Automatic section control (ASC) technology turns individual boom-section valves (auto-boom control) or nozzle solenoids (auto-nozzle control) OFF when traversing a no-spray area or previously sprayed area, and back ON in non-sprayed areas of fields. This technology has demonstrated considerable potential to reduce input application overlap (Batte and Ehsani 2006) resulting in savings on inputs. Luck et al. (2010a) indicated that ASC reduced overlap down to 6.2 % as compared to 12.4 % when compared to manual control by the operator. Additionally, the coverage area for a field can be reduced by between 15.2 and 17.5 % when using ASC in irregular-shaped fields (Luck et al. 2010b). However, an additional concern exists about control systems incorporating ASC technology for large agricultural sprayers with regard to spray application accuracy during field operating conditions.

Rate control systems have inherent time delays when rate adjustments are required during field application. The control system latency in responding to the DGPS receiver while maintaining a horizontal accuracy of 1 m can be up to 2.2 s (Al-Gaadi and Ayers 1999). Apart from the control system and GPS response time delays, Rietz et al. (1997) reported that some flow-based control systems tend to over-apply when only one boom-section was spraying. Grisso et al. (1989) along with Miller and Smith (1992), reported that lateral location of nozzles along the boom can also impact the magnitude and temporal occurrence of application rate errors.

Previous research has stated that precision farming approaches should have control systems with timely response to changing system rate requirements (Rietz et al. 1997). ASC evaluations during static testing indicated that nozzle pressure variation can range from 6.7 to 20.0 %, which equated to an increase of 3.7 to 10.6 % in nozzle flow (Sharda et al. 2010). Additional ASC testing demonstrated nozzle pressure stabilization times approached 25.2 s for auto-boom and 15.6 s for auto-nozzle control when turning sections OFF then back ON. These increased nozzle pressure and delayed pressure stabilization times have indicated that application variability can occur when manually turning sections ON/OFF or implementing ASC during field operation. It has been reported that nozzle flow rate settling time varied from 0.4 to 14.4 s resulting in nozzle off-rate between -36.0 % and +28.7 % during point row operation (Sharda et al. 2011). The disparity in dynamic pressure response and off-rate errors indicated that differences existed between boom-section and nozzle control. The delayed nozzle flow stabilization times during ASC also highlighted inadequate feedback to the control system. Specifically, this occurred when sections turned OFF or ON faster than the designed feedback and response time to accurately manage the desired target application rate. While ASC provides benefits to those adopting the technology, the static tests simulating real field scenarios highlighted that continuous ON/OFF actuation of nozzles can cause pressure variations across the boom (Sharda et al. 2010) leading to over- and under-application. The extent of these errors can escalate when spraying in irregularly-shaped fields and when using larger sprayers.

Though attempts have been made to report flow control hardware time lags, research is needed to understand nozzle flow uniformity and application rate stability when using precision technologies such as ASC. The assessment of nozzle flow uniformity and application accuracy would also ascertain the capability of control algorithms, which is essentially a proprietary item, to manage application rates during field operation. The comparison of static and field test results can aid in predicting field performance of large agricultural sprayers and also in formulating experimental design which can accelerate the process of quantifying nozzle flow uniformity and application rate stability. Therefore, the objectives of this investigation were to: (1) evaluate real-time nozzle uniformity (CV) across the boom for two ASC systems, and (2) quantify and compare nozzle flow settling times (STs) and off-rate errors during static and field testing.

Materials and methods

Static and field experiments were conducted using two common self-propelled sprayers referred to as Sprayer-1 and Sprayer-2. The sprayers were equipped with commercially available rate controllers with ASC capabilities. Sprayer-1 was equipped with auto-boom control (Figure 1a) while Sprayer-2 with auto-nozzle control. Sprayer-1 was a 36.2-m wide, wet-boom sprayer with 95 nozzles spaced at 0.38 m across the boom. Wet boom represents

boom plumbing in which the conduit (e.g. pipe) acts as both the support mechanism for each spray nozzle body along with carrying the spray solution. This sprayer was set up with seven boom sections with the ON/OFF control provided by the seven existing boom section valves. There were 10 nozzles on boom-sections 1 and 7; nine nozzles on boom-sections 2, 4 and 6; and 24 nozzles on boom-sections 3 and 5 (Figure 1a). Sprayer-2 also had a 30.5 m wide wet-boom setup and had 60 nozzles spaced at 51-cm. Auto-nozzle control for Sprayer-2 was obtained using solenoid valves (Capstan Ag Systems, Inc., Topeka, Kansas, USA) mapped within the controller such that the six outer nozzles on each side were controlled individually, the next six inner nozzles on either side coupled, and the remaining controlled in groups of three (Figure 1b). The ASC system comprised of a console (Topcon $\times 20$, Livermore, California, USA) and a 30-channel electronic control unit (Topcon Precision Ag, California, USA) for actuating individual solenoid valves (Capstan Ag Systems, Inc., Topeka, Kansas, USA) mounted on spray nozzle bodies for Sprayer-1. The display (GreenStar-2, Deere & Company, Moline, Illinois, USA) and controller (John Deere SprayStar, Deere & Company, Moline, Illinois, USA) for Sprayer-2 included seven control channels for actuating boom shutoff valves. In order to regulate the target system flow across the spray booms, controllers for both the sprayers utilized feedback from inline flow meters while controlling hydraulic pump speed and thereby the overall system flow rates via hydraulic valves using pulse-width modulation. Both sprayers were also equipped with auto-guidance systems.

Field tests

Field experiments were conducted with the target rate set at 93.5, 112.1 and 140.2 l/ha for Sprayer-1 and at 93.5 and 140.2 l/ha using Sprayer-2. Sprayer-2 was used to collect application data for three irregularly shaped fields (Field 1, 2 and 4) consisting of numerous no-spray areas; mostly grassed waterways (Figure 2). The field experiments using Sprayer-1 were conducted on rectangular and triangular fields. High frequency (≤ 1 ms response time) pressure transducers (Model 1502 B81 EZ 100 PSI G, PCB Piezotronics Inc., Depew, NY, USA) with an accuracy of ≤ 0.25 % full scale were mounted across the

Figure 1. Layout of **a)** Sprayer-1 containing seven individual boom-sections, and **b)** Sprayer-2 which included 30 nozzle sections of either one, two or three nozzles. Sections are numbered from left to right for both booms with the nozzle location along the boom numerically identified.

spray booms to record nozzle pressure. 18 Transducers were used for Sprayer-1 and 15 for Sprayer-2. Transducers were mounted such that at least two were located within each section based on the available boom plumbing (Figure 1). For both sprayers, one pressure transducer was mounted on the main supply line (location for the existing pressure transducer providing feedback to the controller), to measure the overall system pressure. A data acquisition system consisting of National Instruments boards was used to read and record all data at a 5 Hz sampling frequency during field tests and at 50 Hz during static tests. Position and ground speed data were collected simultaneously and provided by a sub-meter GPS receiver (Ag132, Trimble Navigation Ltd., Sunnyvale, CA, USA) for Sprayer-2 and a GNSS RTK receiver (R8 rover and R7 base with the Trimmark 3 radio transmitter; Trimble Navigation Ltd., Sunnyvale, CA, USA) for Sprayer-1. All data were recorded to a text file for analyses.

Nozzle (Teejet AI11003 for Sprayer-1 and Teejet TT11005 for Sprayer-2, Spraying Systems Co., Wheaton, IL, USA) pressures were converted to flow using the manufacture data (Teejet Catalog 50A, Spraying Systems Co., Wheaton, IL, USA). The recommended operating pressure was between 206.8–689.5 and 103.4–620.5 kPa for nozzles on Sprayer-1 and Sprayer-2, respectively and sprayers operated within the recommended pressure ranges. The actual flow rate (l/min) of the boom was calculated by summing and averaging the nozzle flow rate from those sections remaining in the ON-state at each GPS time stamp. The coefficient of variation (CV) was calculated considering only ON sections,

Figure 2. Field boundaries of field 1, field 2 and field 4 for field tests utilizing Sprayer-2.

which represents nozzle flow uniformity across the boom. The target nozzle flow for each GPS time stamp was calculated using the number of ON sections (or nozzles) along with the ground speed and target application rate (set by the operator). The display console on Sprayer-2 also recorded a time stamp along with control channel state (ON = 1 or OFF = 0) for each GPS co-ordinate at a sampling frequency of 5 Hz. The files containing the control channel state and spatial pressure data were synchronized and merged using the GPS time stamps within these files. The control section status was used to calculate spray width at each GPS point. For Sprayer-1, the system pressure and mean nozzle pressure in each section were used to determine the ON/OFF state of a boom valve using MATLAB (version R2008a). The mean nozzle pressure for ON sections was found to be within $\pm 5\%$ of the system pressure. Therefore, for any boom-section in the ON-state, a less than -5% difference between mean nozzle pressure and system pressure would mark that section being OFF at that time stamp. Similarly, if the initial state of the boom-section was OFF, then an average nozzle pressure of >34.5 kPa at any time stamp would result in an ON-state. Finally, the overall nozzle off-rate (rate error) was calculated as a percent difference from the target rate using the following equation:

$$\text{Overall nozzle off-rate (\%)} = \frac{(\text{Actual nozzle flow rate} - \text{target nozzle flow rate}) \times 100}{\text{Target nozzle flow rate}} \quad (1)$$

Nozzle flow rate uniformity (CV) was evaluated by computing the mean and standard deviation of nozzle flow from all the ON nozzles or boom sections. During field and static testing, $\pm 10.0\%$ rate errors were considered acceptable for nozzle off-rate (Rietz et al. 1997). Finally, off-rate and CV maps were generated using ESRI's ArcMap 9.3 to illustrate spatial results across fields and select example scenarios for further investigation.

Static tests

A 93.5 l/ha target rate and simulated ground speeds of 6.4 and 29.0 km/h for evaluating Sprayer-2 were selected based on typical low and high ground speeds observed during field tests. Since Sprayer-1 was unable to simulate different ground speeds, system pressures of 138, 276, 414 and 552 kPa at a constant 19.3 km/h were selected for conducting the static tests. The speed change was accomplished by manually selecting speeds using the self-test feature within the rate controller for Sprayer-1 and because this feature was not available for the controller in Sprayer-2, different target operating pressures were programmed in its rate controller under the setup menu. Experiments were conducted by; (1) turning individual sections ON and OFF (both sprayers); (2) sequentially turning all sections OFF and back ON at 1 and 5 s intervals (both sprayers); and (3) varying machine acceleration from 6.4 to 29.0 km/h and deceleration returning to 6.4 km/h (Sprayer-2 only). During each test, selected sections were turned OFF until nozzle flow stabilized, then the selected sections were turned back ON. The mean nozzle flow using only the ON nozzles was used to calculate off-rate and nozzle flow ST.

Overall nozzle off-rate represented application rate stability during the various static and field tests and therefore provided the extent of over- and under-application. To understand the effect of sprayer acceleration and ASC actuation, specific ASC actuation scenarios (i.e. headland and point-rows operation) were identified and analyzed. The term "re-entry" implied the sprayer was entering into a spray zone while "exiting" refers to the sprayer moving out of a spray zone. In the examples presented in the results section, the seven individual boom-sections for Sprayer-1 were illustrated as gray polygons, the initial

passes around the field boundary as green cross-hatched regions, and areas covered as each section was ON with blue shaded regions. MATLAB was used to compute nozzle flow rate variables including: target rate, final rate, off-rate percentage and ST. ST is defined as the time difference between a $\pm 5\%$ (ST5) or $\pm 10\%$ (ST10) differential from the initial nozzle flow and when the nozzle flow finally reached and stayed within ± 5 or $\pm 10\%$ of the final nozzle flow rate. Both ± 5 and $\pm 10\%$ off-rate was used for determining the ST since static tests were completed with the spray boom stable on level ground. Therefore, under these controlled conditions, nozzle off-rate was evaluated using $\pm 5\%$ threshold while the $\pm 10\%$ was included as the industry-preferred criteria.

Results and discussion

Field experiments using Sprayer-1 (auto-boom) demonstrated that nozzle CVs above 10% and nozzle flow rates beyond $\pm 10\%$ (Figure 3) of the target rate occurred occasionally but were mostly clustered at the field headlands. These errors were attributed to rate controller adjustments to compensate for sprayer acceleration and deceleration. ASC actuation of individual sections was minimal for this field because of its rectangular shape, with nearly all sections turned ON or OFF, simultaneously. The off-rate was well within $\pm 10\%$ of the target rate since operating conditions were stable (e.g. constant ground speed and all sections ON) for the majority of field application. However, this example field highlights undesirable spray nozzle performance resulting from control system lag time associated to ground speed changes. This outcome should be considered by the operator along with the design of the sprayer and control system.

Sprayer-2 results indicated that on average, nozzle CVs were >10.0 for 26% of the time (Figure 4a) and off-rates beyond $\pm 10.0\%$ for 66% of the time (Figure 4b) in the three irregular shaped fields (Figure 5). Nozzle CVs and off-rate results were comparable (Figure 4) for the three fields even though these fields varied in area and shape. Nozzle flow CVs exceeded 10% when exiting and re-entering spray zone and ASC actuation within spray zones. Both situations affect lateral spray distribution resulting in non-uniform application. However, the nozzle CVs were $<10\%$ during stable operating conditions which suggested the nozzle tips were in good condition. Nozzle flow rates were below -10% (under-application) for 49% of the time, typically when re-entering spray zones, and were above $+10\%$ (over-application) for around 17% of the time (Figure 4). These results suggested that under-application occurred more frequently (greater percentage of time) than over-application in these fields. Over-application typically results in unwanted expense, potential damage

Figure 3. Nozzle off-rate map for example field using Sprayer-1 with travel direction indicated by black arrows.

and/or carryover whereas under-application can lead to ineffective pest control. All of these are concerns for operators utilizing precision pesticide application technologies.

Automatic system control actuation occurred for 63.2, 65.5, and 77.9 % of the time in fields 1, 2, and 4, respectively (Figure 6a). Ground speeds for fields 1, 2 and 4 were within 16 to 24 km/h range for 63.1, 51.7, and, 41.7 % of the time, respectively (Figure 6b). The ground speed changed as the operator maneuvered within field boundaries which included grassed waterways and obstructions (electricity poles and sink holes). This led to sprayer acceleration and deceleration beyond $\pm 0.5 \text{ m/s}^2$ for 26.6, 23.8, and 29.6 % of the time in the fields 1, 2, and 4, respectively and off-rate errors beyond $\pm 10 \%$. The ASC actuation (controller turning nozzle control sections ON and OFF and indicated by the number of sections ON) and speed distribution maps (Figure 7) indicated that the system flow rate changed more frequently than expected during field application. Further, a large demand was placed on the rate controller to quickly manage system flow rate changes during ASC actuation and/or ground speed changes. In these cases (Figure 7), it took time for the control system to respond and achieve the required system flow rate. These changes resulted in off-rate errors when operating at angled approaches and departures to no-spray zones (i.e. grassed waterways and other obstacles) within irregular shaped fields. Overall, nozzle off-rate occurred to some extent for both Sprayer-1 and Sprayer-2 with operation outside preferred levels being problematic. These off-rate errors should be corrected to maintain target rates at the nozzles and preserve the desired product efficacy.

Errors from acceleration-field tests

An example re-entry scenario was selected from Field 2 (Location 1, Figure 7) to demonstrate control system response and the potential extent of off-rate application for Sprayer-2. During re-entry at a 30° angle of incidence, system flow increased from 5.6 to 126.3 l/min as the sprayer accelerated from 8.0 to 26.9 km/h with nozzle Sections 4 through 30 turning ON. The results indicated nozzle CVs greater than +10.0 % and the off-rate error was up to -40 % (Figure 5a, Location 1). High CVs across the boom were found to be associated with nozzles or nozzle sections turning back ON and were possibly due to system non-compliance when the plumbing (e.g. hoses and tubing) refilled as sections were turned back ON. Therefore, each time a control section changed from OFF to ON states, the nozzle CVs exceeded +10 % for around 0.2 s. This example demonstrates that Sprayer-2 traveled about 64 m before the controller was able to achieve an appropriate system flow rate as nozzle sections were turned ON and the sprayer was accelerating.

Figure 4. Distribution plots for nozzle CV (a) and off-rate error (b) for three fields using Sprayer-2.

Figure 5. Nozzle off-rate map during application at 93.5 l/ha in irregularly shaped fields 2(a), 1(b) and 4(c) using Sprayer-2. Black arrows represent direction of travel.

A similar scenario was investigated for Sprayer-1 (Figure 8). Here, the sprayer accelerated from 5.7 to 20.7 km/h while boom-sections 1 through 7 were sequentially turned ON as it re-entered the spray zone at 40° angle of incidence. Results indicated that nozzle off-rate error was up to +164.9 % when sections 1 through 3 turned ON and up to -46.5 % when sections 4 through 7 turned ON. Nozzle off-rate errors occurred for almost 60 m before stabilizing within ± 10.0 % of the intended rate. These results for Sprayer-1 were comparable to those found with Sprayer-2 when accelerating and re-entering the spray area.

Errors from deceleration-field tests

The effect of deceleration on nozzle off-rate error was observed in several instances for both sprayers. Location 2 (Figures 5a, 7) depicts nozzle CVs and flow rate response for Sprayer-2 while decelerating accompanied by section turning off. The sprayer decelerated to maneuver around an electricity pole at this location. Here, the required system flow rate decreased from 85.2 to 11.7 l/min as the sprayer slowed from 18.7 to 3.2 km/h (Figure 7b, Location 2). As the sprayer approached the pole at Location 2, almost all nozzle control

Figure 6. Distribution plots for a) the number of nozzles on, and b) ground speed for each of the three fields when using Sprayer-2.

Figure 7. Application maps for Field 2 illustrating: a) number of nozzles on, and b) ground speed along with travel direction (black arrows) for Sprayer-2.

sections were ON until 11 control sections were turned OFF as the sprayer maneuvered around the obstacle. This scenario demonstrated off-rate errors up to +120 % for Sprayer-2.

The scenario in Figure 8 illustrates an example of Sprayer-1 decelerating from 24.3 to 7.4 km/h while exiting a spray zone. The off-rate map (Figure 9) exhibited that deceleration resulted in off-rate errors up to +50 % for Sprayer-1. Sprayer-1 deceleration continuously demanded a new system flow rate during these dynamic conditions and suggests potential feedback and response limitations for the rate controller. However, during these two scenarios, nozzle CVs were within 7.0 % as the sprayers decelerated, indicating uniform deposition across the boom.

Figure 8. Example scenario of Sprayer-1 accelerating and ASC actuation as it re-enters (sections turning on) the spray zone (blue shaded region) when applying at a target rate of 140.2 l/ha. The different horizontal areas represent boom-sections and black arrows indicate direction of travel.

Acceleration and deceleration-static test results

Static tests for Sprayer-2 revealed that acceleration generated deviations between -7.8 and 7.4 % from the target application rate (Table 1). Similar, but larger in magnitude, nozzle off-rate between -7.5 and 37.2 % occurred while decelerating. It is interesting to note, ground speeds <16.1 km/h resulted in positive overall nozzle off-rate while speeds >16.1 km/h resulted in negative values. The overall nozzle flow settling times ST5 during acceleration and deceleration varied from 5.6 to 20.8 s (Table 1). The static tests highlighted that although the final nozzle off-rate was within ± 10 % (except for the 9.7 – 6.4 km/h test), the STs were unexpectedly long. The speed change tests were conducted under controlled operating conditions but the ST5 and ST10 results indicated a delayed response at the nozzle. All ST5 values were above 5.6 s which indicated that frequent acceleration and deceleration can result in off-rate errors at the nozzle. These STs and nozzle off-rate errors were expected based on the maps (Figures 7, 5b) generated for Sprayer-2 during acceleration and deceleration. Nozzle flow STs also decreased during acceleration and increased during deceleration which was expected and observed in the field results.

The steady-state nozzle flow oscillated around the target rate below 16.1 km/h (91.7 l/min). This flow oscillation or instability could be due to fact that the control system attempted to quickly compensate, but was continuously over-shooting the intended set point. This over-compensation contributed to unexpectedly longer STs and off-rate errors which reached $+37.2$ %. Similar off-rate errors were observed during sprayer deceleration at Location-2. It is important to note that acceleration from 6.4 to 9.7 km/h required a 50 % increase in nozzle flow whereas a speed change from 25.7 to 29.0 km/h required only a 12.5 % increase. Hence, the control system response (Table 1) may be impacted by the required magnitude of flow adjustment, control system configuration, and sprayer acceleration or deceleration.

Errors from ASC actuation-field tests

Scenarios for Sprayer-1 (Figure 10) and Sprayer-2 [Location 3, Figure 5(a)] were selected to illustrate the effect of ASC actuation on off-rate error. For these scenarios, the sprayers traversed no-spray zones (grassed waterways) where sections were sequentially turned OFF then ON at a ground speed of 24 km/h. The nozzle off-rate was up to -65 % for Sprayer-1 and -68 % for Sprayer-2 during ASC actuation in these areas. Nozzle CVs were >10 % for a short duration (0.2 – 0.4 s) when re-entering the spray area. In general, the maps depicted that ASC actuation resulted in more negative off-rate or under-application during these scenarios. Under-application can result from feedback or control system

Figure 9. Example of Sprayer-1 decelerating while exiting (sections turned off) a spray zone into a previously applied area (green cross-hatched region) when applying at a target rate of 93.5 l/ha. The different horizontal areas represent boom-sections and black arrows indicate direction of travel.

Table 1. Mean nozzle off-rate and flow settling times (ST) during simulated static acceleration and deceleration tests

Acceleration				Deceleration			
Speed change (km h ⁻¹)	Off-rate error (%)	ST5 (s)	ST10 (s)	Speed change (km h ⁻¹)	Off-rate error (%)	ST5 (s)	ST10 (s)
6.4–9.7	7.4	20.5	12.8	29.0–25.7	–6.4	5.6	a
9.7–12.9	6.5	19	11.7	25.7–22.5	–4.7	7.3	1.6
12.9–16.1	0.9	10.2	2.9	22.5–19.3	–7.5	7.0	1.5
16.1–19.3	–2.0	7.0	0.9	19.3–16.1	–5.1	8.2	2.7
19.3–22.5	–3.5	7.5	1.3	16.1–12.9	4.7	20.8	15.3
22.5–25.7	–5.8	6.2	0.1	12.9–9.7	9.9	20.4	15.1
25.7–29.0	–7.8	6.0	*	9.7–6.4	37.2	20.0	14.8

ST5 = Nozzle flow rate settling time considering final nozzle flow to be within ± 5 % of target rate

ST10 = Nozzle flow rate settling time considering final nozzle flow to be within ± 10 % of target rate

a. The initial nozzle flow within ± 10 % of the final rate

response delays. For instance, the resolution and shorter response time of a flow meter can provide accurate and quick feedback to the controller to implement rate management strategies. Apart from response time of feedback and control components, the strategies and control algorithms used to manage response of control hardware can significantly impact application accuracy. The control system can appropriately look ahead and might include robust algorithms to access the magnitude of rate change required. This assessment can be used to select a dynamic response algorithm to reduce the delay in pressuring the hoses, minimize application rate errors and quickly achieve stable conditions. Finally, flow control point (e.g. boom-valve) can be moved as close to the boom-section as possible to lower transient off-rate errors.

ASC actuation-static test results

During static testing, nozzle off-rate errors during ASC actuation were up to -31.8 % for Sprayer-2 (Figure 11). Nozzle flow analyses for Sprayer-2 showed that the control system responded quickly during required rate changes but the actual nozzle flow was less than the target. Frequently, the control system on Sprayer-2 was unable to achieve the target

Figure 10. Example scenario in which Sprayer-1 was entering and then exiting a no-spray zone (green cross-hatched region) while operating at 24 km/h. A target rate of 140.2 l/ha was set in the controller and the non-existence of off-rate symbols represents all sections in the off-state. The different horizontal areas represent boom-sections and black arrows indicate direction of travel.

Figure 11. Overall mean nozzle flow rate considering only boom-sections which were ON and off-rate error for Sprayer-2 when turning boom-section valves sequentially off and on at 5-s intervals. The sprayer was set to spray at 93.5 l/ha application rate and 16.1 km/h forward speed.

nozzle flow during ASC actuation. Figure 11 illustrates that the Sprayer-2 control system had a slow response when increasing the pump speed to meet the target system flow rate as the control sections were successively turned OFF and then back ON at 5 s intervals. Slow system response was also observed when 2, 3 or 4 boom-sections were simultaneously turned OFF and back ON with overall off-rate error and ST for nozzles remaining ON, up to -23.1% and 54.6 s respectively (Table 2). The nozzle off-rate was only 0.7 % when four boom-sections were turned OFF, but this was achieved after 54.6 s of nozzle flow rate instability. Therefore, under-application would have occurred until all the sections were turned ON and the system stabilized around the target rate which required 0.3–5.1 s. These static results corresponded with the observed response under field conditions at example Locations 1 and 3.

Similar experiments at four target pressures using Sprayer-1 indicated that the control system was able to maintain the nozzle flow rate within $\pm 10.0\%$ of the target when turning all boom sections OFF and ON (Figure 12). The average nozzle off-rate was $+3.8\%$ during this test; however momentary drop occurred when sections were turned ON. These spikes likely resulted from pressure and flow buildup in the system plumbing which was necessary to achieve the target rate and subsided quickly. Similar nozzle flow response

Table 2. Mean nozzle off-rate and settling time (ST) when turning boom-sections OFF and then back ON at 24.1 km h⁻¹ forward speed and 140.2 l/ha application rate for Sprayer-2

Booms OFF	Sections OFF		All sections back ON	
	Off-rate error (%)	ST5 (s)	Off-rate error (%)	ST5 (s)
1 & 2	-11.7	0.6	0.6	0.3
1, 2, & 3	-23.1	17.5	1.2	2.3
1, 2, 3, & 4	0.7	54.6	1.2	5.1

Figure 12. Overall mean nozzle flow considering only boom-sections which were ON and off-rate error for Sprayer-1 when turning boom-sections sequentially off and on at 5-second intervals. For this static test, the target pressure was set at 414 kPa and ground speed at 19.3 km/h equivalent to a 109.2 l/ha target rate or 128.6 l/min system flow.

and off-rate was observed for 138.0, 276.0, and 552.0 kPa. The static ASC actuation tests for Sprayer-1 (auto-boom control) and Sprayer-2 (auto-nozzle control) indicated that there were distinct differences in control system response and nozzle flow rate management between the two sprayers.

Conclusions

Nozzle CVs were greater than 10 % for a short duration when each of the auto-boom (0.5 s) and auto-nozzle (0.2 s) sections were turned ON, while nozzle flow CVs were normally below 10 % during stable operating conditions. The elevated CVs likely resulted from system compliance between the nozzle tip and flow control point, which was greater for the auto-boom system compared to auto-nozzle control. While CVs were calculated using only the ON sections, it was observed that nozzles in Off sections continued to spray for up to 3.5 s for auto-boom and 0.2 s for auto-nozzle control systems.

Off-rate errors during field experiments were attributed to the control system's inability to maintain the target application rate during ASC actuation and ground speed variations. Results indicated that sprayer deceleration coupled with ASC actuation (sections off) contributed to over-application, while ASC actuation (sections on) and sprayer acceleration resulted in under-application. Sprayer-2 static experiments reinforced field test results, which found that under-application may occur more often than over-application from ASC actuation and ground speed changes. Static test results for Sprayer-2 demonstrated that over-application was associated with lower ground speeds (<16.1 km/h) where nozzle flow stabilization required 15.0–20.0 s in some cases. Conversely, under-application was more likely to occur at ground speeds exceeding 16.1 km/h along with ASC actuation for Sprayer-2. These results suggested that a different control strategy may be required

to better maintain the target nozzle flow during ASC actuation and sprayer acceleration and deceleration. The control algorithm may be designed to look ahead at the final target rate and automatically select dynamic control algorithms based on sprayer acceleration, deceleration, ASC actuation and magnitude of required rate change. Static testing for Sprayer-1 indicated that the control system was able to maintain the target rate during ASC actuation. In general, static experiments suggested that control system response was fast and accurate for Sprayer-1. However, overall results suggested that nozzle off-rate errors can occur no matter the type of control technology implemented.

As the number of control sections increase (e.g. auto-nozzle for Sprayer-2), the control resolution (width of control) gets smaller thereby requiring a quicker control system response during ASC actuation and ground speed changes. While increasing the number of control sections can improve application accuracy the demand for improved control system response time is amplified. The inability of the control system to quickly respond during ASC therefore can result in off-rate errors. Sprayer field performance can therefore vary depending upon the feedback response mechanism selected plus algorithms used by rate control systems. The results of this study suggest that a trade-off exists between control resolution and current controller response capabilities. Operators seeking to minimize the impact of nozzle pressure or flow variations should be aware of this tradeoff.

Minimizing system flow adjustments required for ASC actuation or ground speed changes can help address some of the issues reported in this study. Operator skill and behavior contribute to sprayer acceleration, deceleration and ASC actuation required during field operations. Field shape and size may affect how an operator chooses to traverse a field while spraying. Therefore, operators should be educated to understand current sprayer control technology to help enhance system efficiency.

Finally, the similarity between static and field tests suggested that static tests can provide a reasonable understanding of sprayer performance during field operation. While control systems have reduced overall misapplication, caution should be exercised when increasing control system demands. In the end, overall product efficacy must be preserved. Comparative field tests on sprayers with different control systems should be conducted to better understand potential application errors to improve system design and setup.

The following conclusions were drawn from this study:

- Nozzle CVs were >10 % for a short duration likely due to system compliance.
- Nozzle off-rate errors were greater than ± 10 %.
- Nozzle off-rate error was associated with ASC actuation and acceleration/deceleration.
- Static tests highlighted that long settling times (>20 s) can contribute to nozzle off-rate.
- Off-rate errors suggest modification improvement in control algorithms may be improved for enhanced response for control demand during field operations.
- Control algorithms may be modified to enhance response and reduce off-rate errors.

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