LABORATORY EVALUATION OF A TURN COMPENSATION CONTROL SYSTEM FOR A GROUND SPRAYER

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LABORATORY EVALUATION OF A TURN COMPENSATION CONTROL SYSTEM FOR A GROUND SPRAYER


ABSTRACT. The ability to compensate sprayer nozzle flow across a horizontal boom has the potential to mitigate the problem of inaccurate chemical application rate due to lateral speed differences when sprayers are turning. A laboratory testing platform and procedure were developed and tested with a commercial turn compensation control system for a ground sprayer. Virtual paths consisting of simulated GPS signals representing right and left turns separated by straight segments were simulated with four turning radii (75%, 125%, 250%, and 500%) based on boom width. Actual application rates from 11 nozzles spread across the boom were measured using load cells in real time and were compared with desired application rate. Mean flow rate and coefficient of variation by nozzle position for each segment of the test paths showed a general consistency between the expected application rate and actual application rate for most nozzles at most cases with a small discrepancy for a few nozzles. Application errors were within the accepted ±10% range specified by ASABE. This study contributes to the formation of a test standard for turn compensation control systems calibration in the future.

Keywords. Pulse-width modulation, Spray misapplication, Contour spraying, GPS, Rate control.

Chemical application is a crucial part of modern agricultural production. In addition, conservation tillage practices have increased the use of herbicides in place of mechanical tillage. Chemical applications typically occur multiple times throughout a production season and are usually applied with a ground-based sprayer. Most ground-based sprayers have wide booms which make irregular shaped or smaller fields a challenge when it comes to double application or multiple turns. As precision agriculture progresses, more attention by researchers and farmers has been given to site-specific chemical application. Application rate errors can be found in many forms such as skipped-application, multiple-application, over and under application, or unintentional-application on environmentally sensitive areas (Luck et al., 2010). Field surveys conducted in Nebraska and Iowa revealed that only 25% to 30% of treated area received pesticide application rates within 5% of the targeted rate (Rider and Dickey, 1982; Grisso et al., 1988, 1989).

Chemical application errors may cause not only yield loss but also rising production costs and environmental contamination. Under-application of fertilizers or pesticides is known to cause yield loss while over-application inhibits crop growth. Data collected from a four-year soybean production study showed that the cost of fertilizers and pesticides accounted for about 24% of the total non-land cost (Gibson, 2004). In terms of environmental stewardship, over-applied chemicals can accumulate in soils and runoff can contaminate surface and underground water supplies. The chemical application error is magnified in no-till farming due to the lack of mechanical disturbance and increased residue which requires more pesticide application than traditional farming (Luck et al., 2010c).

Application rate errors caused by several factors could be characterized as static and dynamic errors. Static errors can result from chemical mixing, pressure or ground speed readings, sprayer and nozzle calibration. Dynamic error factors include sprayer path overlap, velocity difference across the boom, pressure change across the boom during section actuation and boom height change from undulating terrain (Salyani and Serdynski, 1993; Luck et al., 2010c). Chemical mixing error and sprayer calibration error can be minimized by training and maintenance. Devices and techniques have been developed to assist with sprayer calibration (Salyani and Serdynski, 1993). Thus once the calibration and static errors are corrected the focus should be on the next problem, in this case dynamic error factors. Dynamic factors causing application rate errors have recently received attention. A study has shown that application rate error resulting from multiple-application in irregular-shaped fields could cause an additional application equivalent to 15% to 17% of the field area (Luck et al. 2010a). Grisso et al. (2002; 2004) reported that both planting and harvesting efficiencies are consistently lower in fields with contours versus those with straight rows. The lower efficiencies can be directly attributed to the higher number of turns associated with...
contours. The increase in turns will also increase the opportunity for overlap and off rate applications due both to field patterns within the turns and dynamic reactions of the header, toolbar, or boom of the equipment during turns whether that is a planter, harvester, or a sprayer. Steering angle greatly increased in the Grisso et al. (2004) study from more than 80% of the straight field having a steering angle ranging from 0-5° and the contour field only having 50% to 60% of the field within the 0-5° range. To obtain 80% of the field area in the contour fields the steering angle had to be increased to the 0 to 20° range. These ranges are for planting, the harvesting steering was slightly lower due to the use of a 12-row planter and a six-row corn head and eight-row platform head on the combine. Thus, the relationship of increasing steering angle with increasing equipment can be observed. If these numbers are extrapolated for a much wider boom on a sprayer the steering angle will drastically increase. Thus, the potential for application errors is greater with wider equipment specifically sprayers in this case.

Variable rate and section control technology has been developed to aid in the solution of this problem. Rockwell and Ayers (1996) developed a sprayer with variable rate and direct nozzle injection. The sprayer consistently achieved an average flow rate response time of 2.5 s. A fast response time is a necessity at faster travel speeds during spray application to minimize application errors. The low response time is relevant in this study because without the controller and direct injection capabilities transport lag was observed to range from 48 to 240 s (Rockwell and Ayers, 1996). Boom section control is a recently developed technology to aid in mitigating off-rate application problems by controlling boom sections individually to avoid multiple-application or undesired application. This technology improves application accuracy, reducing the amount of chemical used and increases environmental stewardship (Sharda et al., 2008). Multiple studies have been performed (Luck et al. 2010a, 2010b, 2011; Sharda et al., 2008, 2010) to evaluate dynamic boom response during field operations such as turning and section control responses. Luck et al. (2011) studied the effects of controller response and turning movements on application rate uniformity. The Luck et al. (2011) study divided the nozzle flow rates calculated from the recorded nozzle pressure data by the estimated control section coverage areas calculated from the recorded GPS coordinates. This data was used to estimate actual application rates. They found that only 25% to 36% of the area in the field tested received application rates within ±10% of the target rate. They also found in another study that, as the change in heading increased, application error also increased (Luck et al., 2011). Greater than vehicle velocities are observed at the outside tip and lower than vehicle velocities are observed at the inside tip of application equipment during turns. These velocities are magnified as the radius of the turn’s decreases. Thus verifying turns have a large impact on application errors along the boom of application equipment. Most of these studies mainly focused on discovering sprayer dynamic properties, determining sources of the application error, and quantifying them under field conditions. There have been very few studies found concentrating on the evaluation of boom section control systems. To evaluate a boom section control system such as the ones in the Luck et al. studies, field tests would induce interferences from uneven terrain, sprayer acceleration, deceleration, and noise in GPS data. A lab evaluation standard procedure of boom section control system independent of those factors is needed to fairly evaluate the control system performance.

Equipment has been developed by industry for both individual nozzle control and individual nozzle flow rate compensation for turns. This equipment has the capabilities for each individual nozzle to act as an independent boom section. This ability also allows each individual nozzle based on programmed boom location to adjust its flow rate as the sprayer performs turns. The flow rate at outside nozzles can be increased and the flow rate at inside nozzles can be decreased proportional to the radius and magnitude of the turn determined from sprayer heading.

The main objective of this study was to systematically evaluate a commercial turn compensation system, specifically the Capstan PinPoint® Controller (PinPoint®, Capstan Ag Systems, Inc. Topeka, Kan.). The specific objectives were to determine the performance of a turn compensation system at properly controlling flow rates during predetermined turns, and to use flow data from the system, to determine the actual versus the theoretical application rate and associated errors.

**METHODS**

A commercial turn compensation control system was evaluated in a lab setting. The PinPoint® is a spray controller that has many features including individual nozzle control, turn compensation, nozzle-valve diagnostics, and an in-cab operator interface. The PinPoint® system uses boom geometry, nozzle location, and GPS data such as position, speed, and heading to adjust individual nozzle flow based on the local speed of the nozzle when the sprayer is turning. The system controls nozzle flow using pulse-width modulation (PWM), signals, and solenoid valves (Giles and Comino, 1990; Giles et. al., 2002.). The Pinpoint® was set to synchro-operation mode, with inline valve servo types and the pulse frequency was set to 10 Hz. The pulse width is modulated independently at each nozzle by the task controller. The nozzles were selected for a nominal 50% duty cycle of the PWM system allowing for a greater range of rate changes. The geometry and response of large booms during turns causes the inside of the boom to move at a slower speed or in some cases in reverse while the outside boom during the same turn will move forward at a faster speed than the vehicle is moving. Section control has the ability to shut the inside boom off if it moves in reverse, but cannot compensate for the increasing velocity seen by the outside boom to the end of the boom. The PinPoint® system is programmed to account for all of these instances using GPS location, boom geometry, and nozzle location.
The PinPoint® system was set up for a 36.6 m boom, however only eleven out of 72 total nozzles spaced at 0.36 meters were used. The use of fewer nozzles made the test setup manageable from a data acquisition standpoint while insuring that greater variation between nozzle travel speeds during turns was created. It was assumed that if nozzles sampled at even intervals along the boom were reacting and controlling the flow rate correctly then all of the nozzles located between these would also apply the correct rate based on their boom location. The 11 nozzles, one in the center and five on each side, were programmed into the PinPoint® for 3.6 m spacing (fig. 1). Though nozzles were theoretically spaced 3.6 m apart, each nozzle had an application width of 0.36 m. The system requirements allowed the use of an appropriately sized fixed orifice nozzle with the PWM system.

For all tests an application rate of 112.3 L ha⁻¹ and pressure of 275.8 kPa was kept constant. Combo-jet MR110-10 (Wilger Lexington, Tenn.) nozzles were used on each solenoid. A Raven SCS 440 spray control system (Raven Industries, Sioux Falls, S.D.) was used for control of the flow rate and had the following settings: two booms programmed with lengths 3.05 and 2.54 m for left and right booms, respectively, a flow meter calibration number of 700, and a valve calibration number of 233.

A laboratory test stand (fig. 2) simulating a sprayer boom with a turn compensation system was constructed for laboratory tests. A test “boom” (fig. 3) was constructed using PVC pipe. A 1.5 kW centrifugal pump was attached to a 380 L tank and was used to supply water to the system. The test boom was built in a U-shape with a main line feeding both booms to keep it compact and uniform (Sharda et al., 2010). The nozzles were evenly spaced 46 cm apart six on the left and five on the right to ensure there was enough room for flow collection using 18.9 L buckets.

The main pressure line to the booms included a pressure relief valve so that the system pressure can be controlled and kept constant (at 275.8 kPa), a Raven 60P flow meter (Raven Industries, Sioux Falls, S.D.), and a pressure transducer that is standard with the PinPoint®. At the end of each boom a dial pressure gage and pressure transducer was installed to monitor individual boom pressure. A frame was constructed from rectangular metal tubing to support the boom and attach it to a test stand.

A Raven 440SCS controller was used in conjunction with the PinPoint® as a rate controller. The PinPoint® has a splitter for the flow meter so that both the Raven and the PinPoint® are able to monitor the application rate of the system. The Raven has the ability to adjust application rate to a user-defined value in a typical system, but the PinPoint® controls the flow rate of this system using PWM for the individual nozzles. To reduce vibration noise in the data acquisition system, a separate frame was built to attach the load cells. Eleven load cells corresponding to each of the 11 nozzles were used to measure the flow. An 18.9 L bucket (fig. 4) was suspended from each load cell to dynamically catch nozzle discharge. Tubing was attached to each nozzle to reduce the width of the flat fan spray and ensure all of the fluid applied flowed into the buckets.

The load cells were rated for 22.7 kg and had a rated output of 3 millivolt per volt (mV V⁻¹). The load cells were powered with a 10 V excitation voltage. Therefore the operating range of the load cells was 0 to 30 mV. Each of the load cells were connected to an AD524 instrumentation amplifier (Analog Devices Norwood, Mass.) with a gain of 100 to amplify the output signal to a maximum of 3 V. A National Instruments USB-6218 Data Acquisition System (DAQ) (National Instruments Corporation, Austin, Tex.) and a LabVIEW (National Instruments Corp., Austin, Tex.) program were used to interface load cells and pressure transducers and acquire their signals into a PC at 1000 Hz frequency. The first rising edge of GPS serial signal was used as a starting trigger for data recording of all channels in the LabVIEW program.
Software was written to simulate GPS paths for the “virtual sprayer” to follow. The use of simulated paths allowed testing of the turn control system without actually driving a sprayer in the field. The simulated paths also allowed the user to generate turns of various radii and speed if desired. Though varying simulated speed was possible, for simplicity these tests were conducted only at 19.3 km h⁻¹. An S-shaped pattern was used as a path to ensure the system operated in a straight line as well as turns in both directions. Both turns in the simulated path were of equal radii and the straightaway lengths were equivalent to three times the turn radius to allow the system enough time to stabilize before a turn. The turn radii chosen for this study were directly related to the simulated boom width. The radii tested were equivalent to 75%, 125%, 250%, and 500% of the boom width. For example, a sprayer with a 36.6 m boom with a 75% radius will have to make a turn of 27.5 m radius (or 54.9 m diameter). The turn radii and straightaway lengths being directly proportional to the implement width produced a standardized width-turn radii relationship across all testing parameters. The simulated path used in this study was oriented North/South and was divided into five segments for data processing. There are three straight sections (S1, S2, and S3), a right turn (RT) and a left turn (LT) (fig. 5).

A MATLAB (MathWorks, Natick, Mass.) program was developed to generate the National Marine Electronics Association (NMEA) GPS sentences for the simulated paths. The PinPoint® required three types of GPS sentences: longitude and latitude information in GPGGA sentence, the speed information in GPVTG sentence, and time stamps in the GPZDA sentence. The text file with these sentences...
was sent from a computer through the serial port to the PinPoint® system. All of the GPS sentences were necessary for the system to accurately calculate application rate for each nozzle. The MATLAB program required a starting location, straight segment length, turn radius, speed of the sprayer and the sampling rate of the GPS signal in order to calculate the NMEA GPS sentences. The PinPoint® system requires an update rate of 10 Hz for GPGGA sentences. The MATLAB program calculated each type of NMEA sentences using 10 Hz sampling rate and grouped three types of them together based on the time stamp. The MATLAB program then output the sentences one group at a time to PinPoint® system through the serial port at 10 Hz. A text file containing all generated GPS sentences was exported after each trial and used as reference for later processing of the application rate data.

The simulated paths for each turn radius were repeated for five data collections. The data files were processed using MathCad (PTC Needham, Mass.) to determine the steady state flow rates for each segment of the test path. Errors were calculated based on the expected flow rate for each nozzle based on its location on the boom and speed.

RESULTS AND DISCUSSION
Since flow rate was measured directly, the results are presented as flow rates. The application rate should be uniform; however, the flow rate should change to account for changes in boom speed at different locations during turns. The system was checked to ensure proper calibration both during straights and turns at all nozzles using a timed calibration system and found to be properly calibrated and operating correctly. The measured and target nozzle flows are shown in figure 6 for the three straight segments during the 75% turn radius tests. Some deviation from the target rate is evident and appears to be somewhat consistent. The nozzle located at -11.0 m consistently had a greater flow rate than the target rate (table 1). Furthermore, the nozzle at 11.0 m was consistently below the target flow rate.
from the target nozzle flow ranged from -8.3% to 7.2% for the three straight segments (table 1). These two error extremes occurred during the first straight segment (S1). Though there was some error in the applied rates and it appeared to be consistent. The flow rate coefficients of variation (CV) across the boom calculated for each straight segment and repetition ranged from 1.5% to 5.7%. Out of 15 straight segment repetitions, only one observation (one nozzle for one run) fell outside the ±10% flow range specified by ASABE Standard S592 (ASABE Standards, 2011).

Measured and target flow rates for the left (LT) and right (RT) hand turns are shown in figure 7. The measured nozzle flow is close to the target flow for all nozzle locations. It is important to note that a 5:1 nozzle flow range was necessary in order to maintain the desired application rate in this turn. Error from the target nozzle flow ranged from -4.5% to 6.6% for the two turning segments (table 1). The measured data for the turns show a similar trend as the straight data with respect to nozzle location. It is worth noting that error based on the mean flow from the five repetitions for the nozzle located on the boom centerline ranged from -2.0% to 0.9% for the five segments. It is also worth noting that CV for nozzle flow by location and segment ranged from 0.3% to 3.8%. These CVs were calculated from the flow values in each test path segment for the five repetitions, thus there is a CV for each nozzle location on the boom within each test path segment. The low CVs and consistency of the centerline nozzle indicate that the results are repeatable.

The nozzle at -11.0 m was consistently above the target flow rate in all segments of the test path. The general trend for this data set was lower flow rates on the right side of the boom, specifically nozzles located at 7.3, 11.0, and 18.3 m. However, the errors were within an acceptable range as evidenced by the lateral CVs previously mentioned.

The measured and target nozzle flows are shown in table 2 for the five segments during the 125% turn radius tests. The data are not shown graphically because it was very similar in appearance to the data for the 75% turn radius tests. Nozzles located at -18.3, -11.0, and 0.0 m consistently had greater flow rates than the target and the nozzles at 7.3, 11.0, 14.6, and 18.3 m were below the target flow rate for all five segments (table 2).

Error from the target nozzle flow ranged from -3.6% to 4.8% for the three straight segments and -3.8% to 3.8% for the two turning segments (table 2). As with the previously described data for the 75% turn radii test, there was less error during the turning segments than the straight segments. The CVs across the boom calculated for each straight segment and repetition ranged from 2.1% to 2.8%. The nozzle flow for the 15 straight segment repetitions for the 125% tests ranged from -4.2% to 6.5% of the mean nozzle flow. Though variation exists, it was acceptable for this application (ASABE Standards, 2011).

Error based on the mean flow from the five repetitions for the nozzle located on the boom centerline ranged from 0.0% to 2.1% for the five segments (table 2). The CV for nozzle flow by location and segment ranged from 0.1% to 1.1%.

The measured and target nozzle flows are shown in figure 9 for the three straight segments during the 250% turn radius tests. Some deviation from the target rate is evident and appears to be somewhat consistent. The nozzles located at -11.0 and 3.7 m consistently had greater flow rates than the target (table 3). The nozzles at 7.2, 11.0,

<table>
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<th>Nozzle Position (m)</th>
<th>Segment</th>
<th>-18.3</th>
<th>-14.6</th>
<th>-11.0</th>
<th>-7.3</th>
<th>-3.7</th>
<th>0.0</th>
<th>3.7</th>
<th>7.3</th>
<th>11.0</th>
<th>14.6</th>
<th>18.3</th>
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<tbody>
<tr>
<td>S1</td>
<td>1.8</td>
<td>0.7</td>
<td>3.3</td>
<td>0.0</td>
<td>-0.4</td>
<td>0.0</td>
<td>-0.5</td>
<td>-1.7</td>
<td>-3.6</td>
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<td>RT</td>
<td>1.0</td>
<td>-0.4</td>
<td>2.4</td>
<td>-0.5</td>
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<td>0.7</td>
<td>0.2</td>
<td>-1.7</td>
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<td>-1.8</td>
<td>-3.2</td>
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<tr>
<td>S2</td>
<td>3.0</td>
<td>2.0</td>
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<td>0.7</td>
<td>1.7</td>
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<td>-3.3</td>
<td>-3.0</td>
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<tr>
<td>LT</td>
<td>1.3</td>
<td>-0.4</td>
<td>3.8</td>
<td>0.6</td>
<td>0.0</td>
<td>1.7</td>
<td>0.4</td>
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<tr>
<td>S3</td>
<td>3.7</td>
<td>2.7</td>
<td>4.8</td>
<td>2.0</td>
<td>1.5</td>
<td>2.1</td>
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<td>-0.9</td>
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and 18.3 m were below the target flow rate. Error from the target nozzle flow ranged from -4.4% to 4.5% for the three straight segments (table 3). These two error extremes occurred during the final straight segment (S3). Though there was some error and it appeared to be consistent, the CVs across the boom calculated for each segment and repetition ranged from 1.9% to 2.9%. These low CVs are indicative of consistent performance. The nozzle flow for the 15 straight segment repetitions for the 250% turn tests were within ±6.0% of the mean nozzle flow. Though variation exists, it was deemed acceptable for this application (ASABE Standards, 2011).

Measured and target flow rate data for the two turning segments during the 250% turn are shown in figure 9. The data show the same trend as the straight segments with nozzles located at -11.0 and 3.7 m having flow rates greater than the target and nozzles located at 7.2, 11.0, and 18.3 m having flow rates less than the target. Error from the target nozzle flow ranged from -3.0% to 3.8% for the two turning segments (table 3).

The measured and target nozzle flows are shown in table 4 for the five segments during the 500% turn radius tests. The data are not shown graphically because it was very similar in appearance to the previously graphed data for the 250% turn radius tests. Nozzles located at -14.6, -11.0 and 3.7 m consistently had greater flow rates than the target and the nozzles at -3.7, 7.2, 11.0, and 18.3 m were below the target flow rate for all five segments. With the greater turn radius, there was only a 0.03 L min⁻¹ difference between target flow rates of adjacent nozzles.

Error from the target nozzle flow ranged from -3.6% to 4.5% for the three straight segments and -2.9% to 3.8% for the two turning segments (table 4). As with the previously described data for the other three turn radii tests, there was less error during the turning segments than the straight segments. The system has a dead band programed into its GPS heading calculations. The dead band in the system helps it to account for poor GPS signal quality. Thus after returning to a fabricated straightaway the system does not return fully to “straight.” The nozzles then appear to still be in a very slight turn and their errors are exaggerated. The CVs across the boom calculated for each straight segment and repetition ranged from 1.9% to 2.7%. The nozzle flow for the 15 straight segment repetitions for the 500% tests ranged from -4.5% to 5.1% of the mean nozzle flow. Though variation exists, it was acceptable for this application (ASABE Standards, 2011).

![Figure 8. Target and measured nozzle flow as a function of nozzle position on the boom for three straight segments for the 250% turn radius tests.](image1)

![Figure 9. Target and measured nozzle flow as a function of nozzle position on the boom for left and right turns with a 250% turn radius.](image2)

<table>
<thead>
<tr>
<th>Table 3. Percent error between target and measured nozzle flow (averaged over five repetitions) for each nozzle location on the boom and segment of the test path for the 250% turn radius tests.</th>
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<td>Nozzle Position (m)</td>
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<th>Table 4. Percent error between target and measured nozzle flow (averaged over five repetitions) for each nozzle location on the boom and segment of the test path for the 500% turn radius tests.</th>
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<td>Nozzle Position (m)</td>
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Error based on the mean flow from the five repetitions for the nozzle located on the boom centerline ranged from 0.3% to 1.1% for the five segments (table 4). The CV for nozzle flow by location and segment ranged from 0.2% to 1.1%.

While the errors measured in this study were within the acceptable range specified by ASABE (ASABE Standards, 2011), there were trends across the different turn radii tests for errors at specific boom locations. The error trends indicated a potential problem within the application system. The error source was either the nozzle, solenoid valve, or the program within the controller. An effort was made to isolate the error source through additional testing. All 11 nozzles were numbered based on boom position from left to right. Nozzle flow was measured on a spray table with an operating pressure of 275.8 kPa. Flow was measured for each nozzle in six replications of a randomized test sequence. Nozzle flow error ranged from -1.0% to 1.5%. Difference in nozzle flow was deemed to not be the source of errors in the data. The solenoid valves were also numbered based on boom position from left to right. Nozzle and solenoid pairs were randomly relocated on the boom and the 125% radius tests were repeated. Results from these tests did not follow the previous trends based on boom location, thus eliminating programming as the error source. However, there was consistency among the nozzle/solenoid sets. When a solenoid nozzle pair was placed at a different boom location, it performed similar to its initial location. Since the nozzles were not deemed to be the source of the errors and the trends based on location along the boom were not consistent, the trends demonstrated in the errors were attributed to minor differences in solenoid valves.

CONCLUSION

A commercial turn compensation system was systematically evaluated and the following conclusions drawn:

- Nozzle flow rates during turns were consistently within the accepted standard of ±10% allowable error as set by ASABE.
- 125% and greater turns had consistent errors. The errors were slightly higher for 75% turns. In general the errors were greater in straight segments than in turns.
- Error trends were consistent at some nozzle locations during turns and straight segments of the test. These errors were attributed to minor differences in solenoids.

The evaluated system performed as expected and had errors well within an acceptable range, meaning it is a reliable and accurate product for producers to aid in reducing application errors during turns. However, tighter turns did result in higher errors. The system tended to have higher errors during straight segments, but this was only due to a dead-band incorporated into the programming to account for lower accuracy GPS signals. The consistent error trends that were discovered aided in determining that the control system as a whole was not responsible for the recurring trends, but were attributed to minor solenoid differences.

ACKNOWLEDGEMENTS

The authors would like to thank Capstan Ag Systems for donating the turn compensation system for these tests and providing monetary support. Troy Kolb, Jeff Grimm, and Gordon Hooper of Capstan Ag Systems and Marvin Stone, retired Oklahoma State University faculty provided technical advice that helped make this project successful.

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