EFFECTS OF MULTI−MODE FOUR−WHEEL STEERING ON SPRAYER MACHINE PERFORMANCE

M. A. Miller, B. L. Steward, M. L. Westphalen

ABSTRACT. *A self−propelled agricultural sprayer with four−wheel steering (4WS) was developed. A digital controller was designed and built to control the rear steering angle based on that of the front wheels through electrohydraulic control valves. Three modes of steering were enabled and investigated. Experimental methods were developed to determine what potential 4WS has in improving machine performance. In particular, machine performance of the sprayer was evaluated by measuring turning radius and performance metrics in headland turning and lateral path shift procedures. Coordinated 4WS resulted in smaller turning radii than conventional two−wheel steering (2WS). In the headland turning tests, significant mean increases in aligning distance of 5.58 m and significant mean decreases in rear wheel off−tracking area of 9.3 m^2 were observed in 4WS over 2WS. In lateral path correction tests, crab 4WS substantially decreased the area and magnitude of estimated application errors over conventional 2WS, while coordinated 4WS resulted in increased application errors. These results provide evidence that 4WS could enable improvement in sprayer machine performance.*

Keywords. *Spray boom movement, Sprayer control, Steering control.*

Application of herbicides for weed control is very important to current agricultural practices in the U.S. In 2001, 98% and 96% of corn and soybean acreages, respectively, were treated by herbicides, and over 116 million kg (257 million lb) of herbicides were applied to corn and bean crops alone (USDA, 2002). From 57% to 63% of the herbicide−treated corn acreage and 77% to 83% of the herbicide−treated soybean acreage were treated with post−emergence herbicides (Fernandez−Cornejo and Jans, 1999). Self−propelled boom sprayers are used for much of the application of post−emergence herbicides for these crops. Good machine performance of these vehicles is critical to achieve effective crop protection. While most self−propelled sprayers use two−wheel steering, the use of four−wheel steering (4WS) may add vehicle maneuverability that may directly benefit the machine performance of the vehicle. Self−propelled agricultural sprayers are being designed with boom lengths exceeding 30 m and for field speeds of nearly 32 km/h (20 mph). These two parameters, along with the trend towards automatic guidance of sprayers, make investigations into the effect of 4WS on machine performance of utmost importance.

Agricultural machinery performance is defined in terms of *field capacity*, which is the rate at which the machine can cover field area, and *quality*, which is how well the machine completes its functional task (Hunt, 2001). For an agricultural sprayer, machine capacity is very important and could potentially be increased through the added maneuverability achieved through 4WS. Field efficiency could be improved by the changes in headland turns associated with 4WS. In terms of machinery performance quality, for an agricultural sprayer, chemical application uniformity and minimized crop damage are both important goals.

Multi−mode 4WS has been implemented on agricultural vehicles in the past. J.I. Case Company produced multi−mode 4WS four−wheel drive tractors from 1964 to the early 1990s (Wendel, 1991). The Case tractors used analog solid−state electronic steering controllers interfaced to servo valves to accomplish 4WS in four modes: coordinated 4WS (rear wheels steered in opposite phase from front wheels), conventional 2WS (front wheels steered alone), crab 4WS (all four wheels steered in phase), and independent rear steering (rear wheels steered alone) (Lourigan and Patel, 1979). Cullman (1985) described the design of a multi−mode 4WS system using analog electronics and proportional electrohydraulic valves. 4WS has also been implemented mechanically. Dwyer and Wheeler (1987) described the evaluation of an experimental farm transport vehicle in which 4WS was implemented with a mechanical linkage between articulated front and rear axles. Itoh and Oida (1990) described a 4WS Japanese tractor using a mechanism that enabled a switch from crab steering to coordinated 4WS when the steering wheel was rotated through an angle greater than 200°. The performance of this 4WS system in making steady−state circular turns was evaluated through experiments and simulation (Itoh et al., 1994, 1999). In each case, 4WS clearly added maneuverability to the vehicle. However, the impact of this maneuverability on machine performance was not evaluated.

Article was submitted for review in June 2003; approved for publication by the Power & Machinery Division of ASAE in January 2004.

Journal paper of the Iowa Agriculture and Home Economics Experiment Station, Ames, Iowa, Project No. 3612. Supported by Hatch Act and State of Iowa funds. Additional research support was provided by Deere and Co.

The authors are **Mitchell A. Miller, ASAE Member Engineer,** Maintenance Team Leader, General Mills, Vinita, Oklahoma; and **Brian L. Steward, ASAE Member Engineer,** Assistant Professor, and **Mark L. Westphalen, ASAE Student Engineer,** Graduate Research Assistant, Agricultural and Biosystems Engineering Department, Iowa State University, Ames, Iowa. **Corresponding author:** Brian Steward, Agricultural and Biosystems Engineering Department, Iowa State University, 206 Davidson Hall, Ames, IA 50011; phone: 515−294−1452; fax: 515−294−2255; e−mail: bsteward@iastate.edu.

The application of 4WS to road vehicles has been studied since the mid−1980s as a means to provide better handling and stability (Crolla, 1996). In 1985, Nissan introduced the first practical 4WS system in a passenger car (Irie and Kuroki, 1990). In addition, 4WS has been implemented on automobiles to improve low−speed maneuverability. Delphi's Quadrasteer 4WS, for example, reduces the turning radius of an SUV or pickup truck by 20% (Holt, 2001). Adachi et al. (1991) developed 4WS control strategies to improve low−speed maneuverability with the objective of reducing turning radius and rear end swing out. Driving test results showed that an 18% reduction in turning radius with only a 14% increase in rear end swing out could be achieved with 4WS operating under a front−end path memorizing control method. Watanabe and Katoh's (1990) study of low−speed 4WS maneuverability showed performance advantages in several performance metrics. While off−road vehicles typically have operating conditions and functional objectives that differ from those of automobiles, these results indicate that 4WS has potential to improve low−speed maneuverability in agricultural vehicles. In addition, they provide inspiration for how to experimentally measure performance.

Much work has been done to investigate the effect of sprayer boom movement on spray application. Chaplin and Wu (1989) developed a dynamic model for a trailed−boom sprayer to investigate the effect of vehicle roll on spray distribution. They found that spray distribution was influenced by the amount of water in the sprayer tank and tire pressure. Langenakens et al. (1995) used modal analysis of a spray boom to investigate the effect of vehicle speed and tire pressure on horizontal boom vibrations due to field unevenness, and consequent spray distribution uniformity. Tire pressure was found to have a small effect on boom vibrations, while vehicle speed had a large effect. Through spray pattern simulation, they predicted a minimum underapplication of 20% and a maximum overapplication of 426% at 12 km/h with a 180 kPa tire pressure and an 80° cone nozzle. Clijmans et al. (2000) used a systems identification approach to modeling booms, leading to calculation of longitudinal and vertical boom movement arising from input disturbances. The effect of boom movement on the spray pattern produced by a nozzle at the boom tip was simulated. Research investigating the effect of vehicle steering on spray distribution uniformity has not been found in the literature.

The overall objective of this research was to investigate the effect of multi−mode 4WS on sprayer machine performance metrics in field tests. Three steering modes were investigated: conventional 2WS, crab 4WS, and coordinated 4WS (fig. 1). Specific research objectives were: (1) to measure vehicle turning radii in conventional and coordinated steering modes, (2) to compare vehicle machine performance metrics in headland turning maneuvers across conventional 2WS and coordinated 4WS modes, and (3) to track machine position in lateral shift maneuvers and compare simulated spray distribution uniformity across all three steering modes.

METHODS

4WS CONTROLLER DESIGN

Control Valves and Sensor Hardware

The self−propelled sprayer used for this work was modified from the production unit (model 4710, Deere and Co., Moline, Ill.), which has hydraulic 2WS. The modified sprayer had a rear axle with steerable wheels, hydraulic steering cylinders, and non−contact rotary potentiometer sensors to measure the steering angle at the front and back. The sensors were calibrated to relate sensor voltage output to steering angle. Two electrohydraulic proportional control valves (PVG 32, Sauer Danfoss, Ames, Iowa) were added to the sprayer and were controlled with an analog voltage signal. The valve for the front wheels could be actuated electronically or by hydraulic pilot pressure provided by the steering unit at the steering wheel. For this research, the front wheels were controlled hydraulically by the steering unit, and the rear wheels were controlled electronically. The PVG 32 valves had a linear response with pressure compensation and a narrow deadband region, which eliminated many of the problems with valves used in previous work (Qui et al., 1999).

Controller Hardware and Algorithm

A microprocessor−based, expandable controller (Smart Star 9000, Z−World, Davis, Cal.) was used to control the steering system and provide a user interface. The controller was a modular and expandable control system with a 25.8 MHz CPU card installed on a back plane, which had expansion ports containing digital input/output, analog−to−digital, and digital−to−analog cards. The controller was programmed in C (Dynamic C Premier, Z−World, Davis, Cal.). A rotary switch allowed the user to select the steering mode, and an LED numeric display indicated the steering mode that was currently being used.

For the control algorithm (fig. 2), the driver provided a steering input through the steering wheel. The steering unit then provided a hydraulic pilot signal to the front wheel steering valve, and the front wheels were positioned accordingly. The signal from the front steering angle sensors was used as the setpoint for the proportional controller, which closed the loop around the rear E/H steering valve, hydraulic cylinder, and mechanical linkage. Steering modes were implemented in software by multiplying the front steering angle signal by 1, 0, or −1 to achieve crab, conventional, or coordinated steering respectively.

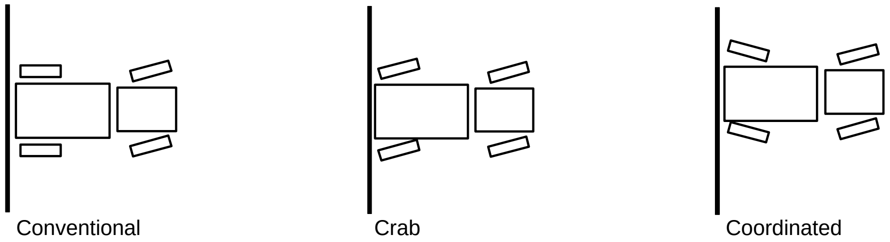


Figure 1. Three modes of steering were investigated: conventional 2WS, crab 4WS, and coordinated 4WS.

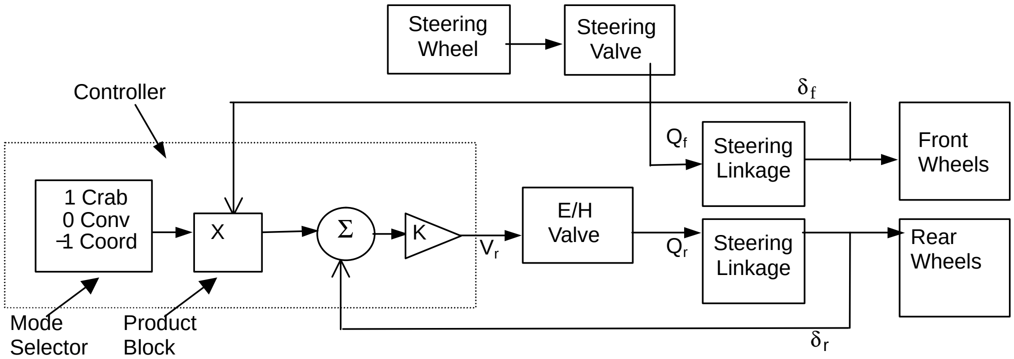


Figure 2. Block diagram of the electrohydraulic 4WS system for sprayer vehicle with steering wheel input. The rear wheels are steered based on mode and front wheel steering angle. V_r is analog voltage input to the E/H valve. Q_f and Q_r are the flow rates to the front and rear steering cylinders, δ_f and δ_r are the steering angles of the front and rear wheels, and K is the proportional gain of the controller.

The controller program sampled the mode setting every 0.1 s. The output of each steering angle sensor was sampled every 0.01 s. Sensor outputs were related to steering angles through calibration curves, and the average steering angle of each set of front or rear wheels was used for steering error calculations. Proportional control was used with deadband compensation through the piecewise continuous function:

$$V_r = \begin{cases} 9; & \Delta\delta_r > 3^\circ \\ 6.6; & 0.1^\circ < \Delta\delta_r \le 0.5^\circ \\ 3.75; & -0.5^\circ < \Delta\delta_r \le -0.1^\circ \\ 3; & \Delta\delta_r \le -3^\circ \\ 6 + K \cdot \Delta\delta_r; & 0.5^\circ < \Delta\delta_r \le 3^\circ; \\ & -0.1^\circ < \Delta\delta_r \le 0.1^\circ; \\ & -3^\circ < \Delta\delta_r \le -0.5^\circ \end{cases} \tag{1}$$

where V_r is the command voltage to the valve, $\Delta\delta_r$ is the steering error signal, and K is the gain, which was set to 1 V/degree. In performance tests of this system, the rear wheels lagged the front wheels by about 2° to 3° when the steering wheel was turned at a fast rate.

Data Acquisition

A 12−bit analog resolution data acquisition system (DaqBook 120, IOTech, Cleveland, Ohio) was used to acquire wheel angle data. This data acquisition system recorded the voltage output of the four steering angle sensors and the input voltage to the valves. Vehicle posture, which is the vehicle position and orientation, was measured at a 5 Hz update rate using two dual−frequency DGPS receivers (StarFire SF2, John Deere, Moline, Ill.) mounted along the centerline of the vehicle 3.8 m (12.5 ft) apart. For time periods of less than 15 min, much of the relative error between the two receivers was due to a slowly changing bias and, therefore, could be removed through calibration. To calibrate the GPS receivers, the sprayer was driven directly north and directly east at the beginning of each experimental replication to determine the bias. In post−processing, the bias was subtracted from the front receiver location data.

A dynamic vehicle model along with dynamic models of the 4WS controller and hardware was developed in order to better understand the vehicle dynamics and to simulate how the vehicle responded to steering inputs. The dynamic vehicle model was developed using the yaw plane and bicycle model (Ellis, 1994; Gillespie, 1992). To validate the model, the vehicle was operated under field conditions, and the experimental results were compared to model simulations. The simulation results matched the experimental results very well and provided support for the experimental method using the DGPS receiver pair to measure vehicle posture. Further details of the vehicle model and simulations can be found in Miller (2001) and Miller and Steward (2002).

TEST PROCEDURES

To justify the additional cost required to implement 4WS, there must be evidence that 4WS can improve machine performance, thereby benefiting the user and crop production system. Vehicle performance was thus evaluated in three ways: (1) by measuring effective turning radii, (2) by measuring maneuverability and tracking metrics in headland turns, and (3) by evaluating the effect of boom movements on spray distribution uniformity in lateral path adjustments. These tests were intended to determine how much added maneuverability from 4WS the driver could use in typical field maneuvers.

Turning Radii

The turning radii of both conventional and coordinated steering modes were measured when the vehicle was moving at about 1.6 km/h (1 mph) with the wheels at the maximum steering angle. The effective turning radius was determined by measuring the distance from the center of the circular path to the center of the rear axle and the front axle on three different surfaces (pavement, tilled soil, and established grass) and while the vehicle was turning in both clockwise and counter−clockwise directions. On pavement, the tires were sprayed with a soap solution to produce visible wheel tracks. On the other surfaces, the wheels left a mark in the soil. The test was replicated four times for each of the 12 experimental conditions (two modes, three surfaces, and two directions). The locations of the front and rear GPS receivers were also logged, and the turning radii were calculated from these measurements. Radii calculated from GPS were equivalent to those calculated manually. The SAS (SAS Institute, Cary, N.C.) General Linear Model procedure (GLM) was used to test for significant differences across steering modes, turning orientation, and soil surface conditions. For factors where significance was detected, Duncan's multiple range test was used to compare means across factor levels.

Headland Turns

Field efficiency is impacted by the time and space required to turn around at the end of a field (Hunt, 2001). Crop damage caused by wheel tracks in the headlands will have an effect on

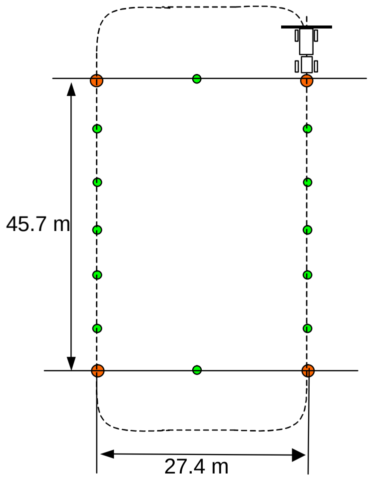


Figure 3. Test path used for the headland turn test. The paths were marked with flags, as indicated by dots.

total field production. If the sprayer is not aligned with crop rows upon re−entry, additional crop damage could occur, or areas at the start of rows could be skipped or undersprayed. The added maneuverability of 4WS could therefore provide benefits in headland turns. Machine performance during headland turns was quantified by using the following metrics: distance required for the vehicle to align with the rows before reentering the crop, headland width required for turning, and off−tracking area of the rear wheels.

Two parallel paths, 45.7 m (150 ft) long and 27.4 m (90 ft) apart, were flagged to simulate field rows for headland turn tests (fig. 3). The first path was followed until the boom reached the end of the path. At this point, the vehicle was turned sharply to establish a vehicle heading perpendicular to the paths. When the vehicle neared the second path, it was turned sharply again to direct it down the second path. This procedure was repeated at both ends of the paths with the entire loop traveled five times for each mode of steering. The test was repeated for two drivers to examine the effect of driver−to−driver differences. This test was performed with the boom extended on both tilled soil and on established grass at speeds between 5.6 and 6.4 km/h (3.5 to 4.0 mph). The locations of the front and rear of the vehicle were logged using DGPS during tests and used to calculate performance metrics.

In actual field operations, when re−entering the crop rows after turning in the headland, an operator first determines the correct set of rows to enter, and then aligns the vehicle to enter those rows. A large aligning distance (i.e., the distance from the start of the crop rows to where the vehicle is aligned with the rows) is desirable so that crop damage is minimized upon re−entry into the rows. A larger aligning distance also helps reduce the area at the beginning of the crop rows that often gets skipped or undersprayed due to vehicle misalignment and provides the operator more time to correctly align the vehicle and to restart chemical application before the boom enters the crop. For these tests, aligning distance was specifically defined as the distance from the start of crop rows to the center of the boom when the centerline of the sprayer was within 5° of being parallel with the rows (fig. 4a).

Minimizing the headland width required to turn around is advantageous as headlands usually are lower yielding and tend to reduce field efficiency. Thus, headland width was used as a machine performance metric and was defined as the distance from the end of the crop rows to the tip of the outside boom during a turn. Specifically, headland width was calculated by first determining the location of the boom through a geometric transformation from each measurement of vehicle posture. Then the difference was found between the mean location of the outside boom tip while operating in the headland area at one end of the test course and that at the other end (fig. 4b). The test course length was then subtracted, and the remaining distance was halved to determine the mean headland width.

Off−tracking area of the rear wheels was defined as the area traveled by the rear tires when they were not in the front wheel track and was a measure of potential crop damage. This metric was calculated by first determining the front and rear wheel tracks through geometric projections from the GPS measurements logged during the tests. The field area covered by the rear wheel track when less than half of the width of the rear wheel covered the front wheel track was then calculated as off−tracking area (fig. 5). These calculations were verified by physically measuring the wheel tracks for a portion of the tests.

Each of the performance metrics was calculated using an Excel spreadsheet. The GLM procedure was used to test for significant differences in each metric across steering modes, drivers, and surface conditions. For factors where significance was detected, Duncan's multiple range test was used to compare means across factor levels.

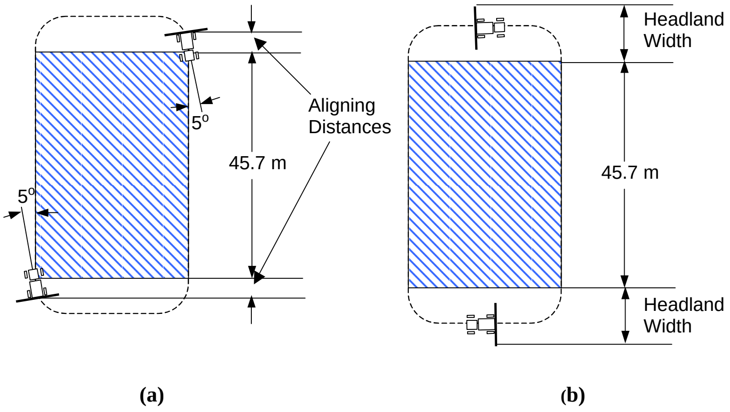


Figure 4. (a) Aligning distance was calculated by determining boom location when the vehicle was aligned with the crop rows to within 5°. (b) Headland width was calculated by determining the location outside boom tip when the vehicle was traveling to within 10° of perpendicular with the crop rows.

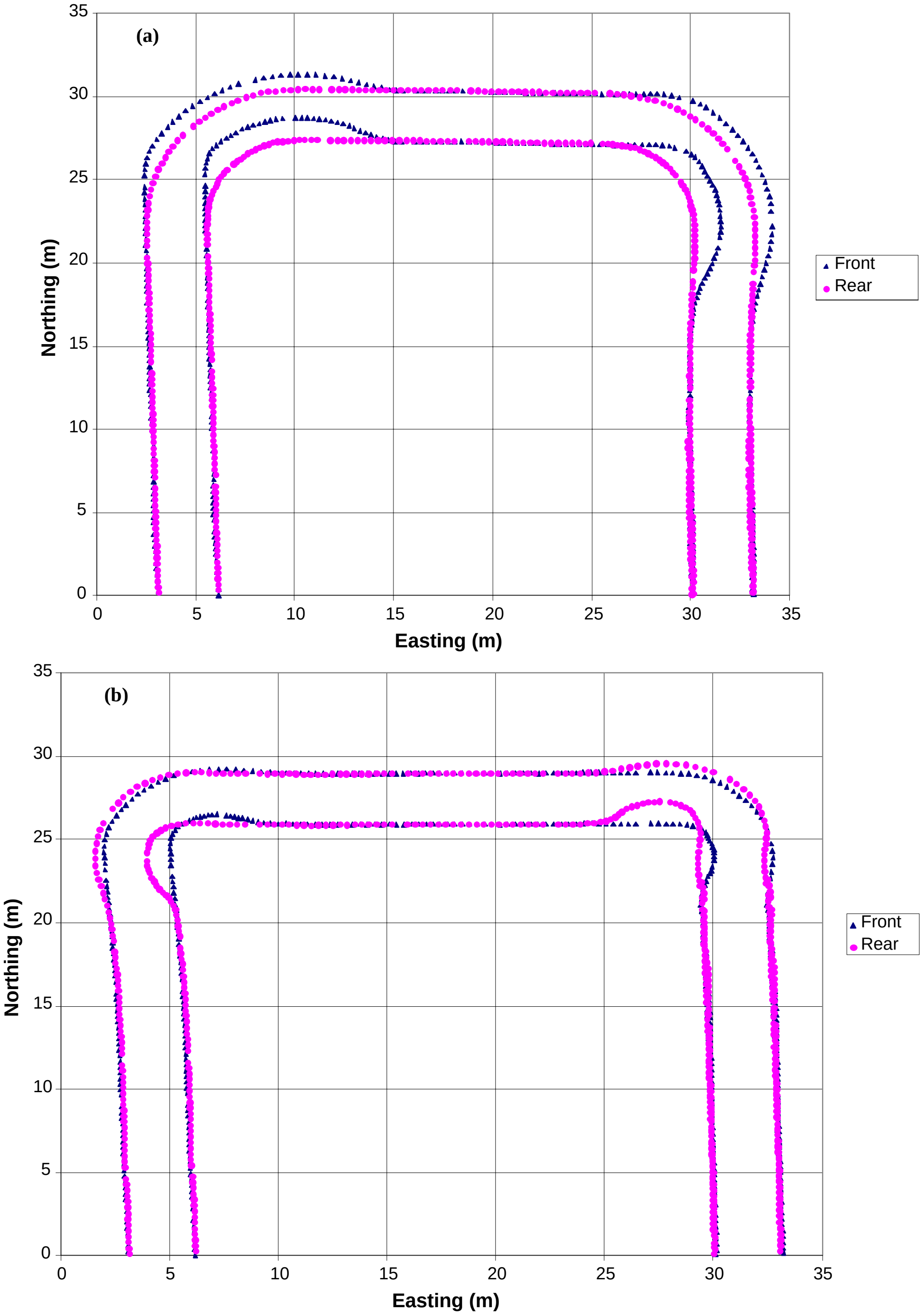


Figure 5. Plots of wheel tracks during the headland turning test in (a) conventional 2WS and (b) coordinated 4WS. Off−tracking area was calculated over the lengths of rear wheels tracks that did not overlap the front wheel tracks by half of their width.

Lateral Path Adjustment

Course corrections will inevitably need to be made during spray applications to avoid field obstacles or to conform to odd−shaped field boundaries. When corrections are made, it is important that the magnitude and areas of over− and under−application are minimized. A test was developed to evaluate the performance of the sprayer vehicle in each of the three steering modes while performing a lateral path adjustment. Two 76 m (250 ft) long paths were set up parallel with each other 3.8 m (12.5 ft) apart. The paths were marked out in the field using marking flags spaced 7.6 m (25 ft) apart. The first path was followed for 15.2 m (50 ft); then the sprayer was guided to the second path and followed the second path until the 45.7 m (150 ft) mark; then the sprayer was returned to the first path for the last 30.5 m (100 ft) of the path (fig. 6). GPS measurements of front and rear sprayer locations were logged during tests. This test was repeated by three different drivers and on two different surfaces: established grass and tilled soil. Each driver repeated the test six times in each mode of steering. All tests were conducted with the boom fully extended, with 570 L (150 gal.) of water in the tank, and a vehicle speed of 9.7 km/h (6 mph).

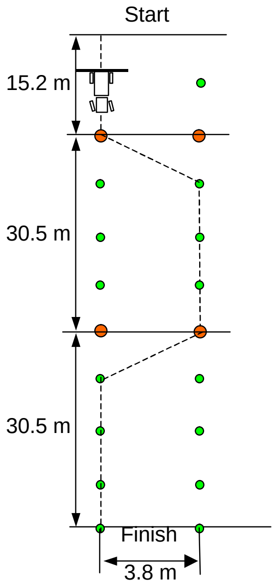


Figure 6. Test path used for lateral path adjustment test. The path was marked with flags, as indicated by dots.

A model of the vehicle, boom suspension, and boom was developed in MatLab script language (The Mathworks, Inc., Natick, Mass.) and was used to estimate the spray distribution during lateral path adjustments. A second−order dynamic model of the boom yaw suspension was developed using an undamped natural frequency of 6.29 rad/sec and a damping ratio of 0.4 based on visual observations of the boom movement. The GPS measurements from each test were used to determine vehicle yaw angles, which drove the dynamic model to find expected boom angles throughout the course. An array of 0.51 × 0.51 m cells covering the area of each test was defined. As the boom passed over the test area, spray volume accumulated in individual cells depending on the time that the nozzles were over each cell. From each resulting spray distribution map, the percentage of cells with greater than 125% overapplied, called POVER, and less than 75% underapplied, called PUNDER, were both calculated as well as the maximum overapplication, called MAX. The root mean squared error (RMSE) of all the cells relative to the target application rate was also calculated. The GLM procedure was used to test for significant differences in application statistics across steering modes, drivers, and surfaces. Duncan's multiple range test was used to compare means across individual factor levels.

RESULTS

TURNING RADII

No evidence of significant differences ($F_{2,36} = 3.1$; $P = 0.057$) in turning radii across different ground surfaces was found, and thus this factor was removed from the model. The turning radii for coordinated steering were significantly smaller than those achieved with conventional steering (fig. 7). When turning counter−clockwise, the mean turning radii were 3.96 m (13.0 ft) for the front and 4.09 m (13.4 ft) for the rear for coordinated steering. For conventional steering in the counter−clockwise direction, the mean turning radii were 7.16 m (23.5 ft) for the front and 5.82 m (19.11 ft) for the rear (table 1). Significant differences in turning radii across turning directions were detected for both axles and both steering modes. The difference between the front and rear turning radii for coordinated steering was about 4%. The tread spacing on the vehicle could have caused this difference. Due to frame constraints on the prototype sprayer vehicle, the rear tread was set about 0.1 m wider than the front tread. Another possible source of this difference was the steering sensor calibration.

The theoretical turning radii for coordinated steering were computed, using a bicycle model, to be 3.9 m (12.8 ft) for both front and rear. For conventional steering, the theoretical turning radii were 7.5 m (24.5 ft) for the front axle and 6.1 m (20.1 ft) for the rear axle. Thus, the experimental results were on average within 3% of the theoretical results, showing that a bicycle model provided a suitable approximation of the vehicle at low speeds. The reduction in turning radius observed with 4WS met expectations but, by itself, does not provide evidence that the added maneuverability of 4WS will provide any advantage in machine performance. The remaining tests were intended to ascertain if advantages in machine performance existed.

HEADLAND TURNS

The performance metrics used to evaluate machine performance during headland turns were the aligning distance achieved when re−entering the crop, the headland width required for turning, and the rear wheel off−tracking area.

Aligning Distance

Significant differences in aligning distances were detected between steering modes ($F_{1,35} = 667$; $P < 0.0001$) as well as between the grass and tilled soil surfaces ($F_{1,35} = 111.2$; $P < 0.0001$). There was no evidence of significant differences between drivers ($F_{1,35} = 2.09$; $P = 0.1574$). There was also evidence ($F_{1,35} = 21.7$; $P < 0.0001$) of interaction between surface conditions and steering mode. Using coordinated steering, a mean increase of 5.58 m (18.3 ft) in aligning distance was observed on grass, and a 3.87 m (12.7 ft) increase on tilled soil, over conventional steering (table 2). These increases would equate to about two to three more seconds for the operator to make adjustments at a vehicle speed of 6.4 km/h (4 mph). The smaller turning radius of coordinated steering allowed the vehicle to be aligned in a shorter distance following a turning maneuver.

Headland Width

Significant differences in headland width were detected across steering modes ($F_{1,35} = 163$; $P < 0.0001$), soil surfaces ($F_{1,35} = 21.4$; $P < 0.0001$), and drivers ($F_{1,35} = 11.5$; $P = 0.0017$). In addition, there was evidence ($F_{1,35} = 19.6$; $P < 0.0001$) of interactions between surface conditions and drivers. The mean headland width associated with coordinated steering was .91 m (3.0 ft) less than that of conventional steering (table 3). The mean difference in headland width between drivers was only 1.1% [0.242 m (0.80 ft)]. There was also a small difference across surface conditions, with the mean width of tilled soil 0.33 m (1.08 ft) more than that of grass field surface.

Rear Wheel Off−Tracking Area

No evidence of differences across surface conditions was found ($F_{1,35} = 0.43$; $P = 0.4281$) in a full model. In a reduced model with surface conditions removed as a factor, significant differences in rear wheel off−tracking area were detected

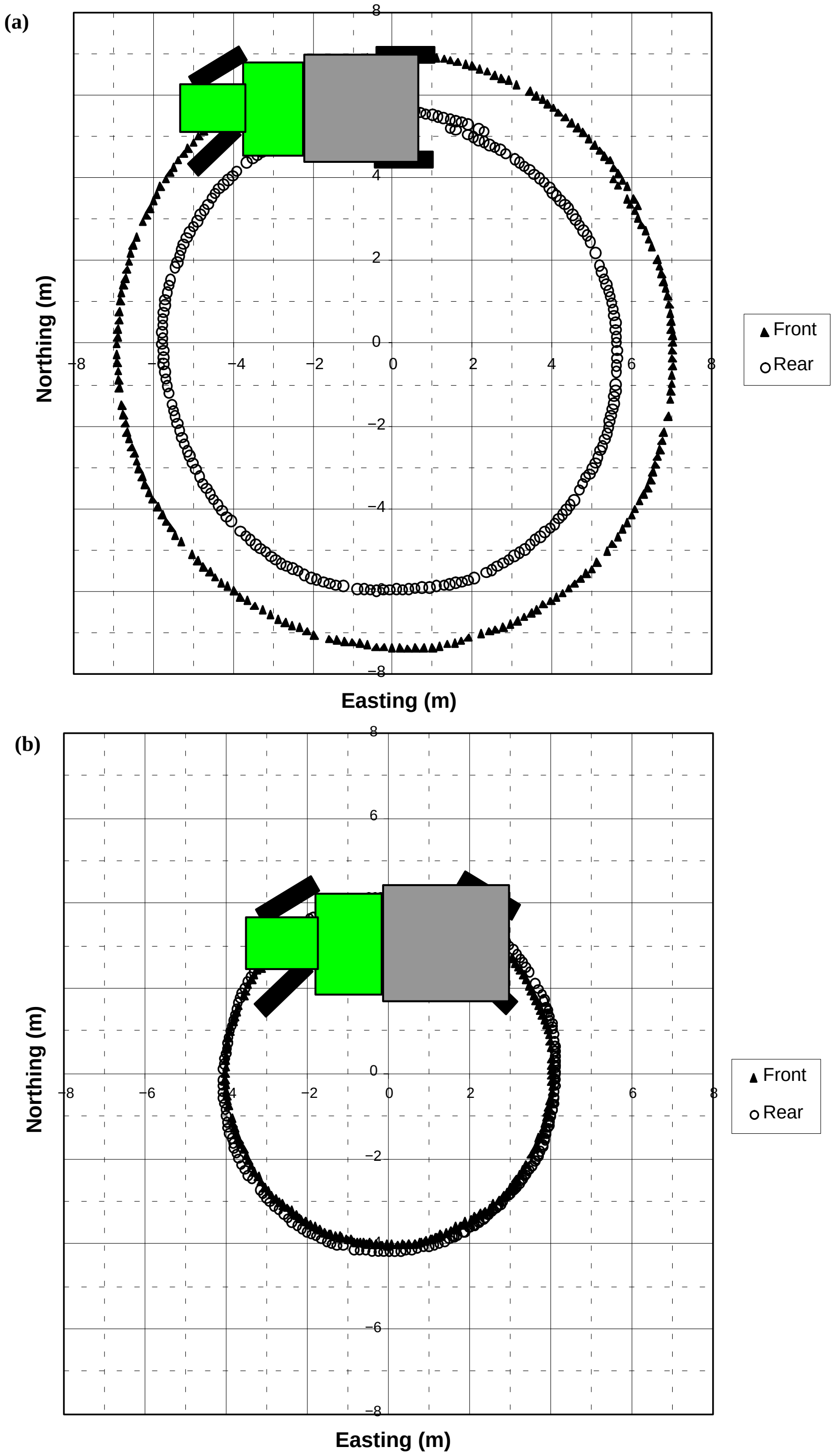


Figure 7. Example paths of front and rear axle centers in turning radii tests for (a) conventional 2WS and (b) coordinated 4WS.

across steering modes ($F_{1,37} = 343$; $P < 0.0001$) and drivers ($F_{1,37} = 4.64$; $P = 0.038$). The mean rear wheel off−tracking area in a headland turn was 38.9 m^2 (419 ft^2) for conventional steering, while coordinated steering had a mean of 27.3 m^2 (294 ft^2) (table 4). One driver had 4% more off−tracking area than the other driver. Of all the metrics, differences in rear wheel off−tracking area across drivers had the largest relative magnitude.

Overall, these results showed that coordinated 4WS has potential to achieve measurable improvements in machine performance in headland turns. The increased aligning distance has potential to aid the operator to better guide the vehicle back into crop rows. The headland width reduction achieved through coordinated steering, though significant, was not substantial when considering that the boom was 27.4 m (90 ft) wide. The reduction in rear off−tracking area has potential to reduce crop damage. However, in the coordinated 4WS mode, rear off−tracking area was not eliminated.

Table 1. Summary of turning radii for conventional and coordinated steering in the clockwise and counter−clockwise directions (mean ±standard deviation of eight replications).

Steering Mode	Direction[a]	Turning Radius (m)[b] Front	Turning Radius (m)[b] Rear
Conventional 2WS	CW	7.26 ±0.15 a	6.04 ±0.13 a
	CCW	7.15 ±0.08 b	5.82 ±0.10 b
Coordinated 4WS	CW	4.08 ±0.13 c	4.25 ±0.06 c
	CCW	3.96 ±0.05 d	4.09 ±0.05 d

[a] CW = clockwise; CCW = counter−clockwise.

[b] Letters indicate Duncan's multiple range test group within a column at the 0.05 significance level.

Table 2. Summary of aligning distances for coordinated and conventional steering on grass and soil surfaces (mean ±standard deviation of ten replications).

Steering Mode	Surface Conditions	Aligning Distance[a] (m)
Coordinated 4WS	Tilled soil	9.43 ±0.50 a
	Established grass	8.35 ±0.63 b
Conventional 2WS	Tilled soil	5.56 ±0.25 c
	Established grass	2.77 ±0.82 d

[a] Letters indicate Duncan's multiple range test group within a column at the 0.05 significance level.

Table 3. Summary of headland width results distances for coordinated and conventional steering on grass and soil surfaces (mean ±standard deviation of ten replications).

Steering Mode	Surface Conditions	Headland Width[a] (m)
Conventional 2WS	Tilled soil	23.4 ±0.41 a
	Established grass	23.0 ±0.27 b
Coordinated 4WS	Tilled soil	22.4 ±0.35 c
	Established grass	22.1 ±0.10 d

[a] Letters indicate Duncan's multiple range test group within a column at the 0.05 significance level.

Table 4. Summary of rear off−tracking area for coordinated and conventional steering on grass and soil surfaces (mean ±standard deviation of ten replications).

Steering Mode	Driver	Rear Off−Tracking Area[a] (m^2)
Conventional 2WS	1	39.1 ±2.2 a
	2	38.7±2.0 a
	All (N = 20)	38.9 ±2.1
Coordinated 4WS	1	28.5 ±1.9 b
	2	26.2 ±1.6 c
	All (N = 20)	27.3 ±2.1

[a] Letters indicate Duncan's multiple range test group within a column at the 0.05 significance level.

LATERAL PATH ADJUSTMENT

Significant differences in spraying error as measured by each of four metrics were detected across all three steering modes. There was no evidence of significant ground surface effects on each metric, so this factor was removed from the model.

RMSE provided an overall measure of the variation in the application rate from the target rate and was significantly different across steering modes ($F_{2,99}$ = 2818; $P < 0.0001$) and across drivers ($F_{2,99}$ = 3.30; $P = 0.0411$). Coordinated steering had the most variation from the target rate on average with an RMSE of 65%, while conventional steering had an RMSE of 52%. Crab steering had the least amount of variability, with a mean RMSE of 9.5%. Significant interaction between the drivers and the steering modes was also detected ($F_{4,99}$ = 2.87; $P < 0.0269$).

POVER was significantly different across steering modes ($F_{2,99}$ = 251; $P < 0.0001$) and drivers ($F_{2,99}$ = 9.89; $P = 0.0001$). The mean percentage of covered area over 125% of the target application rate was 8.2% for coordinated steering, 5.6% for conventional steering, and 2.9% for crab steering. PUNDER was similar, with significant differences across steering modes ($F_{2,99}$ = 2321; $P < 0.0001$) and drivers ($F_{2,99}$ = 5.31; $P = 0.0064$). The average percentage of area underapplied (less than 75% of the target) was 15.9% for coordinated steering, 14.5% for conventional steering, and 0.12% for crab. Crab steering had a larger area overapplied than underapplied because, as the vehicle was steered in this mode, a component of the vehicle velocity vector went into lateral motion. This led to a reduced speed in the component perpendicular to the boom and in areas of overapplication during lateral shifts of the vehicle. Interactions between driver and mode were detected for both POVER and PUNDER.

The maximum application rate found in each trial provided insight into differences in the application rate magnitude across steering modes. While this metric does not include any measure of the extent or area of application error, it does provide estimates of what might be found at points in the coverage error during lateral shifts. Significant differences in the maximum application rate were only detected across steering modes ($F_{2,103}$ = 1042.90; $P < 0.0001$). For coordinated steering, the mean maximum application rate was 1057%, or over ten times the target rate. For conventional steering the mean was 994% and for crab 178%.

The interaction between drivers and steering modes can be explained by the experience level of the drivers. Analysis of the POVER, PUNDER, and RMSE metrics showed that the significant differences between drivers were only consistently detected in the coordinated steering mode. In that mode, the other two drivers had significantly larger metrics than driver 2 (table 5). Driver 2 had the most experience driving the vehicle in coordinated mode, while driver 3 had never driven the vehicle before. Driver 1 had limited experience in driving with coordinated steering. From this limited set of drivers, there is evidence that a driver with more experience with coordinated steering is able to drive the vehicle more effectively. Driving the sprayer vehicle in conventional steering is a skill that comes naturally for drivers who drive a conventionally steered vehicle such as automobiles and trucks on a regular basis. Vehicle handling in the coordinated steering mode, however, is different and requires driver experience to gain skill in using that mode.

Through visual analysis of contour plots of application rate (fig. 8), it can be seen that the magnitude and area of application error can be explained by the turning radius achieved in the different modes. Coordinated steering had the highest error as measured by all of the performance metrics and also had the smallest turning radius of the three modes. In this mode, when a lateral shift is required, the vehicle turns around a point that is approximately one−half the distance of one side of the boom from the vehicle. Beyond this point, the boom passes over the ground surface up to three times. Conventional steering has a larger turning radius. Thus, the point of rotation moves further out toward the end of the boom, which results in a smaller area that has multiple passes of the

Table 5. Summary of application error metrics from simulations with vehicle position measurements during lateral course adjustments. Parallel path results (mean ±standard deviation of 12 replications).[a]

Steering Mode	Driver[b]	POVER[c] (%)	PUNDER[d] (%)	MAX[e] (%)	RMSE[f] (%)
Coordinated 4WS	1	9.4 ±0.7 a	17.0 ±0.9 a	1075 ±90 a	66.3 ±2.8 a
	2	7.2 ±0.7 b	14.8 ±1.1 b	1011 ±133 ab	62.4 ±2.8 b
	3	9.8 ±1.7 a	17.7 ±2.2 a	1010 ±54 ab	66.1 ±3.0 a
	All (N = 36)	8.8 ±1.6	16.5 ±1.9	1032 ±100	64.9 ±3.3
Conventional 2WS	1	5.5 ±0.6 c	14.8 ±1.0 b	981 ±125 bc	54.1 ±2.6 c
	2	5.6 ±0.3 c	14.9 ±1.4 b	932 ±81 c	53.4 ±5.7 cd
	3	5.8 ±0.5 c	14.2 ±1.2 b	1029 ±107 ab	51.0 ±4.8 d
	All (N = 36)	5.6 ±0.5	14.6 ±1.2	980 ±110	52.9 ±4.7
Crab 4WS	1	4.1 ±1.9 d	0.2 ±0.5 c	210 ±45 d	10.7 ±2.2 e
	2	2.9 ±1.0 e	0.1 ±0.1 c	189 ±26 d	9.8 ±0.9 e
	3	2.4 ±1.2 e	0.2 ±0.2 c	187 ±30 d	9.4 ±1.6 e
	All (N = 36)	3.2 ±1.5	0.2 ±0.3	195 ±35	10.0 ±1.7

[a] Letters indicate Duncan's multiple range test group within a column at the 0.05 significance level.

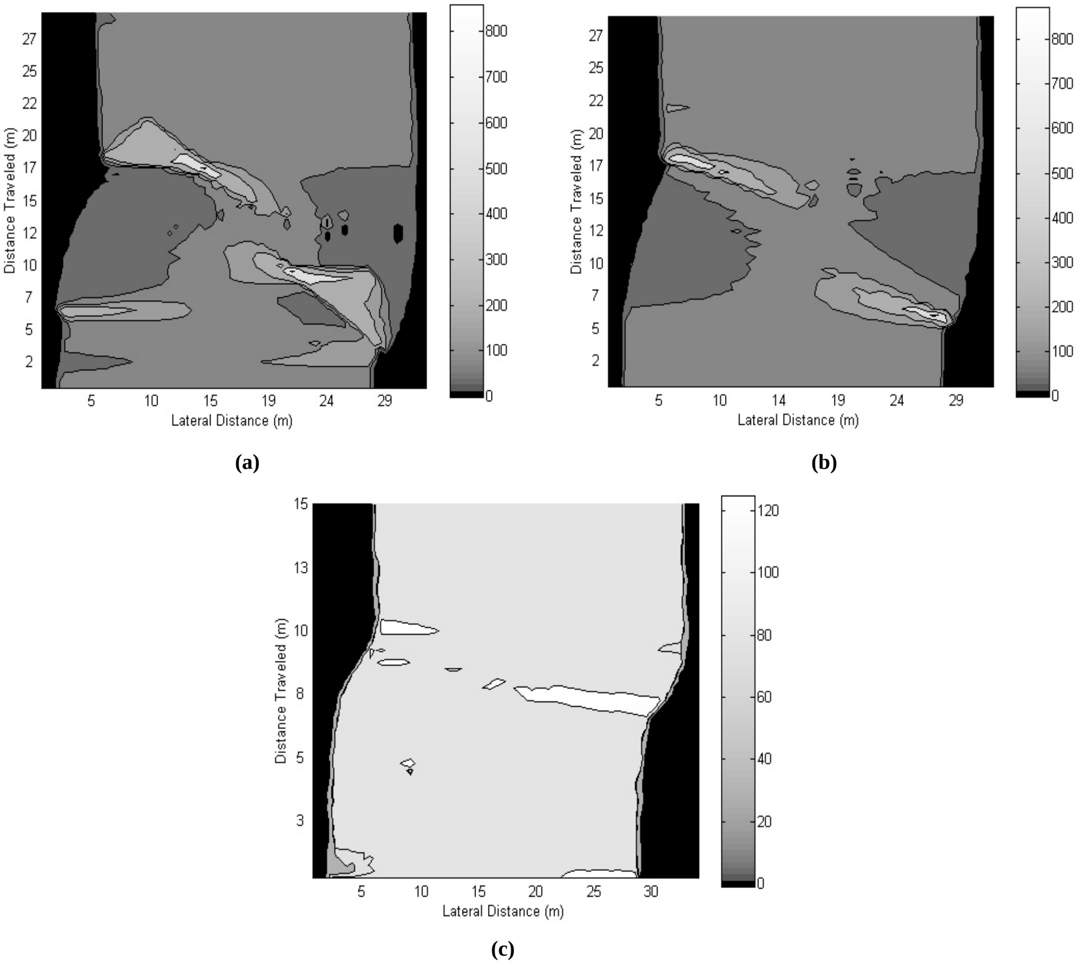
[b] Driver 1 = limited experience; driver 2 = experienced; driver 3 = no experience.

[c] POVER = percentage of the coverage area in test with application rate greater than 125%.

[d] PUNDER = percentage of the coverage area in test with application rate less than 75%.

[e] MAX = largest application rate found in a test as a percentage of the target application rate.

[f] RMSE = standard error across coverage area as a percentage of the target application rate.



(a)

(b)

(c)

Figure 8.Example of application rate plots resulting from lateral shifts under (a) coordinated, (b) conventional, and (c) crab steering modes. Units are in percent of target application rate.

boom over it (fig. 9). Crab steering results in a substantially smaller application error because of a theoretically infinite turning radius. The boom does not yaw, and thus no part of the surface area experiences multiple applications. It is not necessary, however, to use a strictly crab mode to achieve reductions in application error. A system that limits vehicle turning radius so that the point of rotation of the vehicle is beyond the end of the boom should result in a much reduced application error. In addition, the use of a crab mode alone would not have broad applicability under practical operating conditions since it is

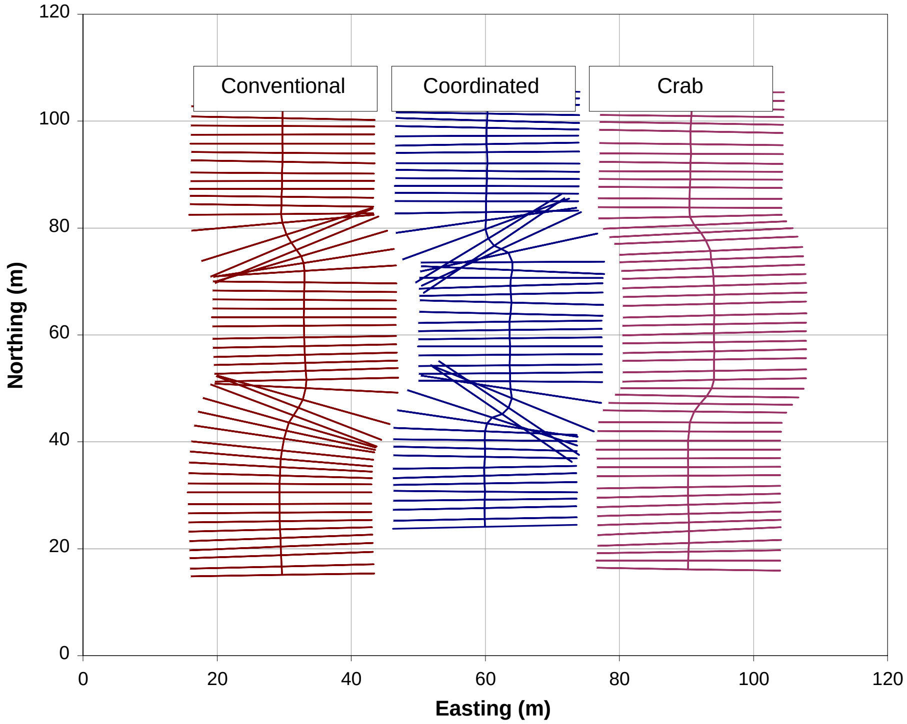


Figure 9. Plot of estimated boom position during the lateral path adjustment test in three different steering modes.

inevitable that steering corrections are needed to change the orientation of the vehicle. Nevertheless, these tests show what is possible with a crab mode and provide motivation to explore more sophisticated 4WS control designs.

CONCLUSION

From this research, we found that the multi−mode 4WS system provided robust, repeatable results. In particular, it can be concluded that:

- In headland turning maneuvers, coordinated 4WS showed performance advantages over conventional 2WS through increased aligning distance, decreased headland width, and reduced rear−wheel tracking area.
- In lateral shifts during chemical application, crab 4WS resulted in substantial reductions of all application error metrics over conventional 2WS. Coordinated 4WS resulted in increased error but revealed an inverse relationship between turning radius and application error.
- Increased vehicle maneuverability was observed with 4WS, as demonstrated by the reduced turning radii. This maneuverability can be used by operators to achieve improved machine performance metrics under controlled test conditions that are related to real−world functional tasks. These results provide evidence that 4WS can lead to improved machine performance in typical field operations.
- A 4WS system with several fixed modes, however, unnecessarily burdens the operator to select a steering mode most appropriate for a particular operation. Being constrained to a fixed number of steering modes will achieve sub−optimal results compared with what may be possible if these constraints were removed.

REFERENCES

Adachi, K., K. Ito, and T. Fujishiro. 1991. Study on a new four−wheel−steering control method at low speeds: Front−end path memorizing method. In *Eighth International Conference on Automotive Electronics*, 214−218. IEEE Conference Publication 346. Piscataway, N.J.: IEEE.

Chaplin, J., and C. Wu. 1989. Dynamic modeling of field sprayers. *Trans. ASAE* 32(6): 1857−1863.

Clijmans, L., H. Ramon, P. Sas, and J. Swevers. 2000. Sprayer boom motion: Part II. Validation of the model and effect of boom vibration on spray liquid deposition. *J. Agric. Eng. Research* 76(2): 121−128.

Crolla, D. A. 1996. Vehicle dynamics: Theory into practice. *Proc. Institution of Mechanical Engineers, Part D: J. Automobile Eng.* 210(2): 83−94.

Cullman, J. 1985. Multi−mode electrohydraulic steering system for off−road vehicles. SAE Paper No. 85−1491. Warrendale, Pa.: SAE.

Dwyer, M. J., and J. A. Wheeler. 1987. Preliminary results from the on−farm evaluation of an experimental farm transport vehicle. *J. Agric. Eng. Research* 38(1): 15−26.

Ellis, J. R. 1994. *Vehicle Handling Dynamics.* London, U.K.: Mechanical Engineering Publications.

Fernandez−Cornejo, J., and S. Jans. 1999. *Pest Management in U.S. Agriculture.* Agricultural Handbook No. 717. Washington, D.C.: USDA Economic Research Service.

Gillespie, T. 1992. *Fundamentals of Vehicle Dynamics*. Warrendale, Pa.: SAE.

Holt, D. 2001. Four wheel steering. *Service Tech Magazine* (Sept): 17−18.

Hunt, D. 2001. *Farm Power and Machinery Management.*10th ed. Ames, Iowa: Iowa State University Press.

Irie, N., and J. Kuroki. 1990. 4WS technology and the prospects for improvement of vehicle dynamics. In *Vehicle Electronics in the 90's: Proc. International Congress on Transportation Electronics*, 429−437. Piscataway, N.J.: IEEE.

Itoh, H., and A. Oida. 1990. Dynamic analysis of turning performance of 4WD−4WS tractor on paved road. *J Terramechanics*27(2): 125−143.

Itoh, H., A. Oida, and M. Yamazaki. 1994. Measurement of forces acting on 4WD−4WS tractor tires during steady−state circular turning on a paved road. *J Terramechanics* 31(5): 285−312.

Itoh, H., A. Oida, and M. Yamazaki. 1999. Numerical simulation of a 4WD−4WS tractor turning in a rice field. *J Terramechanics* 36(5): 91−115.

Langenakens, J. J., H. Ramons, and J. De Baerdemaeker. 1995. A model for measuring the effect of tire pressure and driving speed on horizontal sprayer boom movements and spray pattern. *Trans. ASAE* 38(1): 65−72.

Lourigan, P., and Patel, K. 1979. Agricultural tractor electro−hydraulics. SAE Paper No. 79−0848. Warrendale, Pa.: SAE.

Miller, M. A. 2001. Development and evaluation of multi−mode four−wheel electrohydraulic steering system on a sprayer vehicle. MS thesis. Ames, Iowa: Iowa State University.

Miller, M. A., and B. L. Steward. 2002. Control and evaluation methods for multi−mode steering. In *Proc. Automation Technology for Off−Road Equipment Conference*, 357−366. Q. Zhang., ed. St. Joseph, Mich.: ASAE.

Qui, H., Q. Zhang, J. F. Reid, and D. Wu. 1999. Modeling and simulation of an electrohydraulic steering system. ASAE Paper No. 993076. St. Joseph, Mich.: ASAE.

USDA. 2002. Agricultural chemical usage: 2001 field crops summary. Washington, D.C.: USDA National Agricultural Statistics Service.

Watanabe, Y., and H. Katoh. 1990. An investigation into the turning behavior of an experimental four−wheel steering medium−duty truck. In *Proc. 18th FISITA Congress: The Promise of New Technology in the Automotive Industry*, 423−428. Warrendale, Pa.: SAE.

Wendel, C. H. 1991. *150 Years of J.I. Case*. Sarasota, Fla.: Crestline Publishing.