Response time of a direct injection type-variable-rate sprayer

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Abstract: An approach to developing variable-rate sprayer technologies is to install electronic control systems on conventional sprayers. This study introduces a direct injection type electronic solution concentration control system. This control system was installed on a field sprayer, and then a map-based variable-rate sprayer was developed. The control system consisted of a chemical tank, a chemical metering pump, the metering pump’s driver, the metering pump’s speed sensor, the implement’s travelling speed sensor, an Electronic Control Unit (ECU), a GPS receiver and a mixing unit. The metering pump discharge was measured at different carrier liquid (water) working pressures (3, 4 and 5 bar) and different chemical metering pump shaft speed (100, 200, 300 and 400 r/min, i.e. pump’s working range). Data analysis showed that the effect of metering pump speed, sprayer working pressure and their interaction was significant (P<0.001) on the metering pump’s discharge. Metering pump’s discharge function and the independent variables of pump speed and working pressure were calculated. In order to determine the system response time, an electromotor replaced on the right hand front wheel of the tractor (the implement’s traveling speed sensor location), thus simulating the implement’s movement. An Electrical Conductivity (EC) sensor was mounted on rightmost nozzle of the boom. The chemical tank was filled with thick brine. The system response time was measured at different working pressures (3, 4 and 5 bar), travelling speeds (3, 6 and 9 km h^{-1}) and spraying concentration change rates (2, 3 and 4 L ha^{-1}). The working pressure was the only variable with a significant effect on the response time at the 1% level. The mean of response times were 25.8, 22.8 and 17.9 s at 3, 4 and 5 bar working pressures, respectively. The look-ahead firmware of the system was designed using the determined response time.

Keywords: direct -injection system; variable-rate sprayer; system response time

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1 Introduction

The past decades experienced a significant rise in using agrichemicals for producing agricultural products. Annually, more than 2.2 billion kg of pesticides are used in the world (Kiely et al., 2004). Although this amount is translated into more protection for products and higher yields, their uniform-rate application gives rise to soil and water contamination. A key approach to reduce environmental pollution is to use variable-rate technologies (Morgan and Ess, 2003). The Variable Rate Technology (VRT) appears to provide a method for improving input use efficiency by applying near-optimum rates based on local soil conditions and crop requirements (Forouzanmehr and Loghavi, 2012). In this approach, chemicals are applied according to local requirements on the field. The development of computer, sensor and actuator technologies has paved the way for achieving higher accuracies and efficiencies in field sprayers when using chemicals (Al-Gaadi, 1992). The conventional implements can be turned into variable-rate ones using control systems (Jafari et al., 2010). An advantage of injection type Variable Rate Application (VRA) over pressure-based VRA is the ability to perform instantaneous changes in herbicide type (or any other

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chemical) and also in its concentration (Stone et al., 1999). One of the most important injection-type systems is the Direct Injection (DI), in which ingredients are pumped into a carrier fluid carrying them to the boom. The system's advantage is in mixing the required amount of chemicals with water, saving the excess amount for later use (Landers, 1999). A key indicator of determining a DI sprayer's precision is the control system response time. The shorter its response time, the higher its field precision. In DI sprayers applying chemicals, there is always an error in these systems since the response times of all nozzles in one boom are not similar (Rockwell and Ayers, 1996). The response time in DI sprayers depends on the injection point to nozzle head distance, solution transfer tube diameter, solution discharge, and the number of injectors (Frost, 1990).

Numerous studies have been performed on the hydraulic performance DI sprayers and reducing their response time,reporting response times ranging from 4 to 55 seconds (Budwig et al., 1988; Tompkins et al., 1990; Sudduth et al., 1995; Koo and Summer, 1998; Angluned and Ayers, 2003; Zhu et al., 1998; Hloben, 2007; El Aissaoui, 2007;Hassen et al., 2014).

Knowing the response time of variable-rate map-based sprayers allows using the looking-ahead approach. Therefore, a control system was developed for a variable-rate sprayer which was installed on a tractor-mounted boom sprayer to measure the sprayer's performance characteristics and response time, in a workshop.

2 Materials and methods

2.1 Research objectives

First, the electronic controller of solution concentration was prepared. The controller system was then mounted on a 400 L tractor-mounted field sprayer. This sprayer had an 8 m boom with a three-cylinder diaphragm type pump (Bertolini, Italy) made by Zarghami Co. Steel tee-jet 11004 nozzles were also employedFinally, the system response time was measured in the Agricultural Machinery Workshop of Imam Khomeini Higher Education Center.

2.2 System components

Solution concentration controller consisted of a chemical tank, a metering pump, an actuator (electromotor), a pump rotational speed sensor, an electronic control unit, a GPS receiver, a tractor travelling speed sensor anda water-solution mixing unit (Figure 1). The following is a description of the system components.

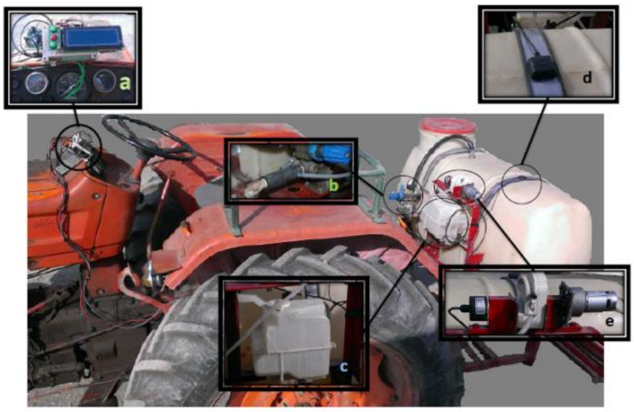

Figure 1 The controller system components

a) electronic control unit and GPSreceiver module, b)mixing unit, c) chemical tank, d) GPS antenna, e) metering pump, rotational speed sensor and actuator

2.2.1 GPS receiver

To determine the geographical position (geographical coordinates) of the implement in a field, a GPS receiver (NEO-5Q, made by U-blox AG, Switzerland) with a 2.5 m Circular Error Probable (CEP) was used. This receiver consisted of a module and a magnetic antenna (Figure 2). The Antenna was installed at the middle of the sprayer's working width. The receiver worked based on the NIMEA protocol.

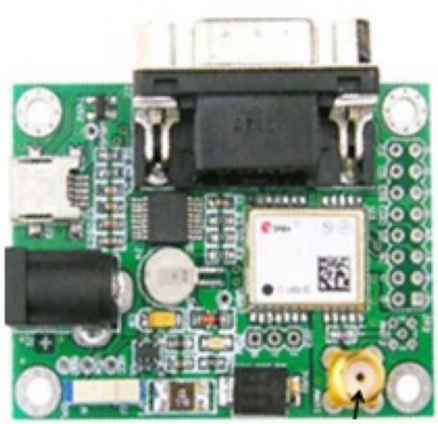

Figure 2 GPS receiver module

2.2.2 Tractor travel speed sensor

A 12-24V DC shaft encoder (Model E50S8-100-3-T-24, made by Autonics, Korea) measured the travel speed of the implement. This sensor was coupled to the tractor front axis via a gear (Figure 3).

Figure 3 Tractor travel speed sensor location

The sensor was calibrated by passing a 20 m marked distance on a field at three travel speeds (3, 6 and 9 km h^{-1}) with three replications. Pulses from the encoder were measured at each run. The 2,000 cm distance was divided by the mean pulse number, showing that the encoder generated a pulse per 0.56 cm of travelled distance.

2.2.3 Metering pump rotational speed sensor

Variation in the metering pump's rotational speed, as a determinant of solution flow rate, was measured by a rotational speed sensor. A shaft encoder (similar to the travel speed sensor) was used as a rotational speed sensor (Figure 4).

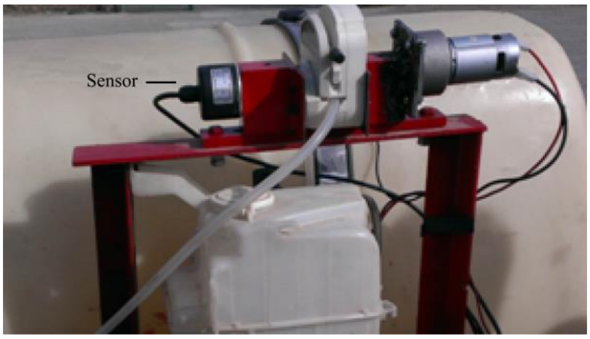

Figure 4 Location of metering pump rotational speed sensor

2.2.4 Metering pump actuator

An electromotor (37GB-3540-12V-560RPM, made by LANDA) was used as metering pump's axis actuator (Figure 4). The mentioned electromotor speed was regulated using Pulse Width Modulation by an Electronic Control Unit (ECU). The operating speed was continuously sent by the rotational speed sensor to the ECU. The ECU, in turn, modulated the pulse width so that the feedback from metering pump's rotational speed control would display the target speed (Figure 5).

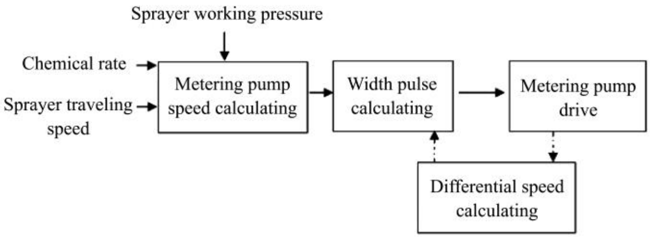

Figure 5 Electromotor speed control procedure schematic

2.2.5 Chemical metering pump

In order to regulate the chemical rate, a peristaltic pump (model YZ2515X, Longer Pump Co., China) with a roller design was used (Figure 4). The pump consisted of three rollers coupled to its shaft (Figure 6). A silicone tube was fixed to a point on the circular movement perimeter of rollers. As the rollers pass, the liquid inside the tube moves from the inlet to the outlet. The amount of liquid pumped by these pumps depends on its type, liquid's viscosity, number of rollers, tube diameter, outlet ambient pressure and rotational speed of pump shaft.

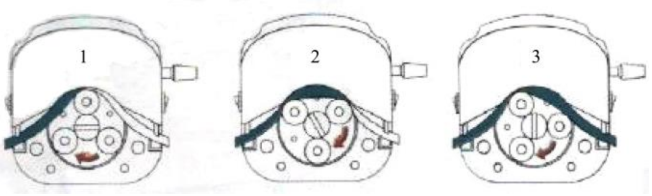

Figure 6 Peristaltic pump workflow

Since the outgoing liquid from the metering pump is injected to the carrier liquid (water) pumped by the sprayer main pump, the working pressure of sprayer affects the flow rate of the metering pump. The metering pump was calibrated within the working pressure range of the sprayer (3-5 bar).

2.2.6 ECU

This component contained an electronic board with an AVR microcontroller (ATmega32). It was installed at the front of the tractor cabin, providing the operator with information on travel speed, solution concentration and metering pump's actuator speed on its LCD display (Figure 7).

The data gathered by sensors was sent to the ECU, and analyzing the data, the AVR took the proper decision according to the algorithm and working conditions. That is, the ECU computed the target speed of actuator shaft consistent with the implement's location on the field (target chemical rate), the travel speed of the tractor, and the working pressure of the sprayer, drawing its speed to the target speed.

Figure 7 Electronic Control Unit (ECU)

2.2.7 Chemical tank and agitator

This system consisted of a 4 L container for holding chemicals with a small electro-pump (12 V) at the bottom as its hydraulic agitator (Figure 8). This agitator can be activated to prevent deposition while using powder chemical solutions.

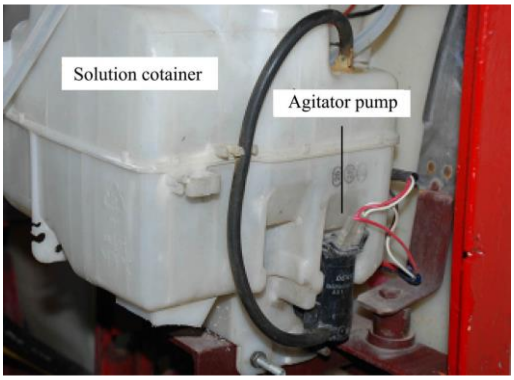

Figure 8 Chemical container (tank) and agitator pump

2.2.8 Water-solution mixing unit

The pump's outlet was connected to a set of an injection nozzle and a Venturi tube. The Venturi tube was connected to flow control valves of the boom in the water transfer path from sprayer pump and the regulator (Figure 9).

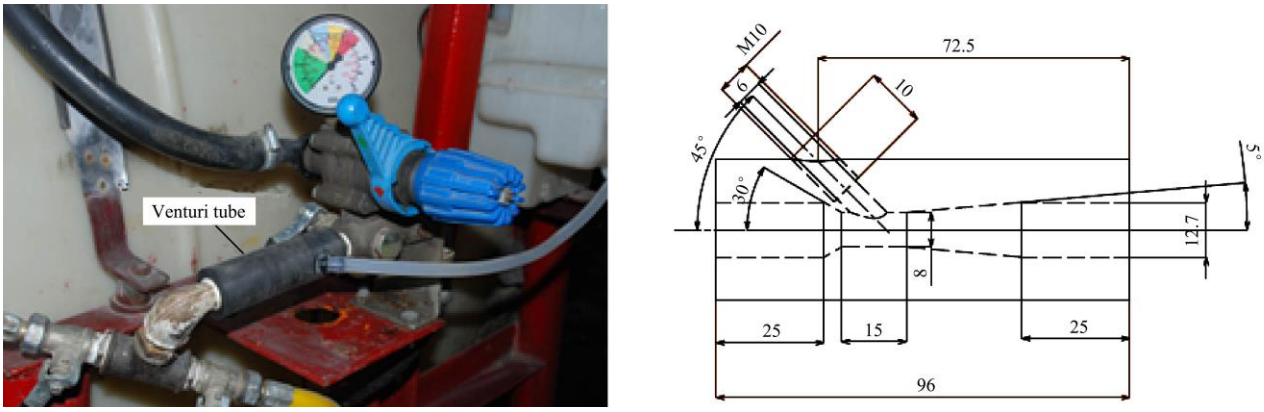

Figure 9 The Venturi tube and actual chemical injection nozzle (left) and their dimensions (right)

2.3 System procedure

The main sprayer container is filled with water (400 L), and the main pump pumps only water (carrier liquid) to the boom and nozzles. The chemical metering pump sends the required amount of chemical to the mixing unit (Venturi tube), where it is mixed with the passing water. The final chemical solution rate is controlled by adjusting the amount of injected chemical. The ECU uses Equation (1) and the travel speed reported by its sensor to calculate the needed metering pump flow rate to achieve targetchemical solution rate.

$$D = V \times W \times C \times 6 \tag{1}$$

where, D = metering pump discharge, mL/min; V = implement's travel speed, m/s; C = required chemical solution rate, L/ha.

The implement's location on the field is determined by the GPS receiver. Information from system sensors is sent to the ECU which, in turn, determines the instantaneous chemical rate demand (L/ha) based on implement location on the field and the GIS map of chemical rate demand on its memory (Figure 10).

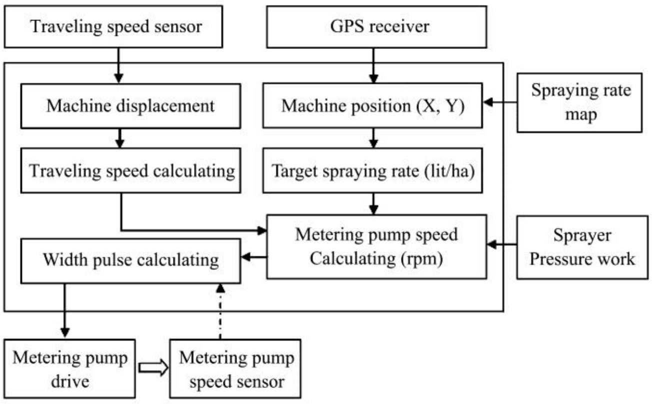

Figure 10 System procedure

2.4 Workshop tests

2.4.1 Determining metering pump's flow rate function

In doing so, the chemical tank was replaced with a 1,000 mL graduated cylinder (Figure 11). The passing water pressure was adjusted at three different levels (3, 4 and 5 bar) using the regulator. The tractor was started, and the PTO shaft was fixed at 540 RPM while in the idle mode. The rotation speed of the chemical metering pump was also adjusted at four different levels (100, 200, 300 and 400 r/min) by the ECU. The amount of liquid (water) leaving the graduated cylinder per minute was measured at three carrier liquid pressures (3, 4 and 5 bar) and four rotational speeds (100, 200, 300 and 400 r/min). The tests were carried out in three replications. Data was analyzed as a factorial test with a completely randomized design. The Duncan test was then performed to describe the data and determine a regression function between the metering pump's output (mL/min) (dependent variable) and independent variables.

Figure 11 The location of the graduated cylinder

2.5 System response time

When entering another management zone and changing the target spraying rate, the ECU performs the necessary calculations and sends a proper message to the actuator. The time interval between changing the target chemical rate and actually making the desired changes at the last nozzle on the boom is called the system response time. The shorter the response time, the faster the implement can change the chemical rate. In fact, for more accurate spraying, the system triggers these changes before actually reaching the target change point, thus achieving the target rate at the right time. This advance change is proportionate to the travel speed and response time.

In workshop tests, in order to simulate the tractor movement, an electromotor replaced the tractor's right front wheel where travel speed sensor was located. The electromotor allowed changing the travel speed. Its speed range was enough to simulate the proper working speed of a sprayer (3 to 9 km h^{-1}).

An electrical conductivity (EC) sensor was mounted on nozzle tubes and before the rightmost nozzle on the boom. The chemical tank was filled with thick brine. The tractor was started, while in the idle mode, the PTO shaft speed was fixed at 540 r/min (equal to the rated speed of tractor engine). The carrier liquid pressure (water) was adjusted within the operational range (3, 4 and 5 bar) by the regulator. The ECU was set to reach zero L/ha of chemical rate while in the normal mode. By pressing the button on the ECU, the chemical spraying rate was switched between 2, 3 and 4 L/ha. Experiments were carried out in three replications. The EC sensor output was connected to a data logger. Using these data, the EC diagram for the brine solution leaving the last nozzle was drawn against time. The time interval between sending the rate change message and changing the EC at the last nozzle was used as the system response time. Effects of independent variables – namely the carrier liquid working pressure (3, 4 and 5 bar), implement travel speed (3, 6 and 9 km/h) and chemical rate (2, 3 and 4 L/ha) – on the system response time (s) was evaluated through a factorial design.

3 Results and discussions

ANOVA results showed that the effect of pressure, rotational speed of the chemical metering pump and their interaction on metering pump discharge was significant (Table 1).

Table 1 ANOVA results of pressure and pump speed on metering pump discharge (mL/min)

Factor	Degree of Freedom (DoF)	Sum of squares	Mean squares
Treatment	11	2705000	245911.84**
Pressure	2	82333.72	41166.86**
Speed	3	2619879.19	873293.06**
Speed*Pressure	6	2817.39	469.56**
Error	24	197.33	

Note: ** Significant at level of 1%.

Duncan’s test results indicated that discharge outputs from all pressure levels and pump speed levels were significantly different (Figures 12 & 13). Metering pump discharge had significant differences at the three levels of carrier liquid pressure. Increasing the carrier liquid (water) pressure decreased the discharge of metering pump. Moreover, metering pump discharges from its four rotational speed levels had significant differences. Increasing the metering pump speed increased the injected solution discharge into the fluid stream.

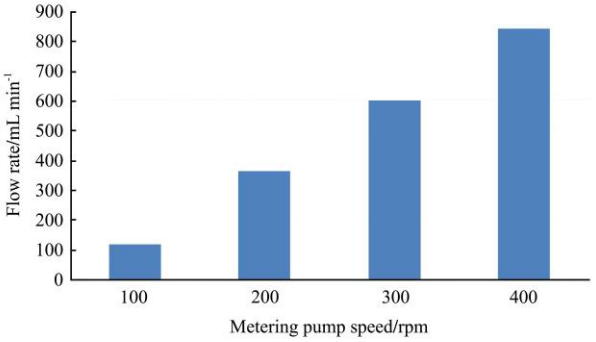

Figure 12 Average of output flow rates of metering pump at different metering pump speed

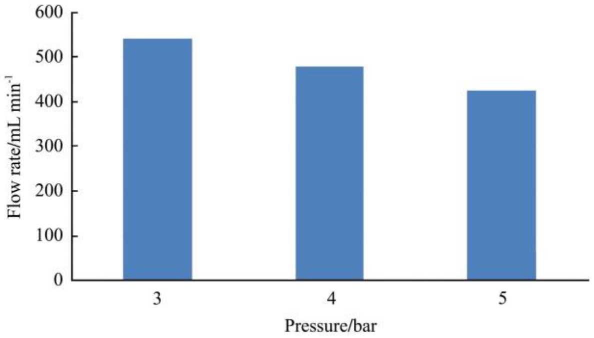

Figure 13 Average of output flow rates of metering pump at different carrier pressure

According to ANOVA results, the regression relation between effective factors (i.e. pump rotation speed, carrier liquid pressure and their interactions) in the output discharge of the metering pump was developed. The results are presented in Equation (2).

$$q=2.497*n-(53.167*P)-(0.021*P*n)+93.667 \quad (2)$$

where, q = chemical metering pump discharge, mL/min; P = carrier liquid pressure, bar; n = metering pump’s rotational speed, r/min.

As is shown in Equation (2), increasing the carrier liquid pressure reduced the injected chemical rate, and increasing the pump rotational speed also increased this rate. These variations are presented in Figure 14.

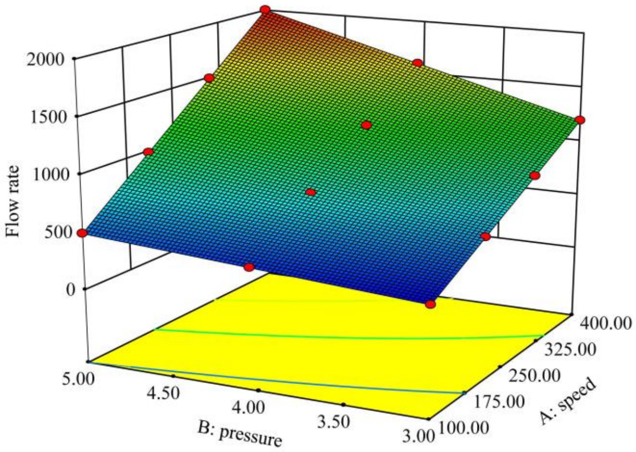

Figure 14 Metering pump discharge variations with changes in pump speed and liquid carrier pressure

3.1 System response time

Sprayer working pressure was the only parameter with a significant effect on system response time at the level of 1% (Table 2).

Table 2 ANOVA results for working pressure, travel speed and spraying rate on system response time (s)

Factors	DoF	Sum of squares	Mean squares
Working pressure	2	859.5	429.7**
Traveling speed	2	0.00024	0.00012
Rate	2	0032	0.0016
Error	54	58.9	1.09

Note: ** Significant difference at the level of 1%.

Increasing the carrier liquid pressure also increased its flow rate and speed, thus it travelled the distance between the mixing unit and the last nozzle (the EC sensor location) in a shorter time period. Therefore, higher working pressure decreases the response time (Figure 15). The mean system response time at 3, 4 and 5 bar pressures was 25.8, 22.8 and 17.9 s, respectively.

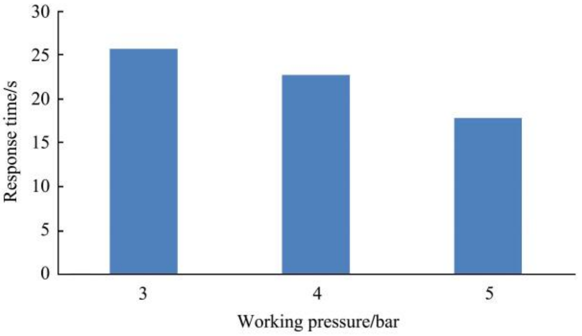

Figure 15 System response time variations at different sprayer working pressures

The above-mentioned response times were used in the

ECU firmware. The product of implement traveling speed and system response time was the required distance for triggering changes to the spraying rate before reaching the target point. The ECU controls the operation with a looking ahead approach using these calculations.

4 Conclusions

The following results were concluded from this study

a) Changes in sprayer working pressure lead to changes in the metering pump output. In order to spread the right amount of chemical per hectare, it is necessary to adjust the carrier liquid pressure manually (before the spraying operation) or should be sent to the ECU by the sensor on-the-go.

b) Changing the sprayer working pressure changes the flow rate and speed of the carrier liquid. Therefore, the working pressure has a significant effect on system response time.

c) The system determines the response time and required distance for completing the change in the chemical spraying rate. The system begins to change of spraying rate when the implement distance to new management zone is equal to the response time. Therefore, the sprayer output would be equal to the target spraying rate when reaching the point on the field.

d) It is recommended to reduce the distance between the mixing unit and spraying boom to achieve shorter response times and higher accuracy.

e) It is recommended to determine the sprayer's accuracy by a field test.

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