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Rate Response Assessment from Various Granular VRT Applicators

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RATE RESPONSE ASSESSMENT FROM VARIOUS GRANULAR VRT APPLICATORS

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ABSTRACT. *Variable-rate technology (VRT) adds complexity to application equipment, thereby confounding the assessment of applicator performance. The intent of this investigation was to assess the rate response of various VRT granular applicators: two spinner spreaders (A and B), and two pneumatic applicators (C and D). Variable-rate (VR) tests were conducted to quantify the rate response characteristics (delay and transition times) for the applicators. A sigmoidal function was used to model the rate response for five of the six tests. Applicator A exhibited a linear response during decreasing rate changes. Results indicated that only applicator B demonstrated consistent delay and transition times, enabling the use of a single "look-ahead" time for rate response time correction. Contouring of prescription maps increased the transition times for applicator D by enlarging the adjustment area between management zones. Rate changes were quicker for the two newer VR control systems, signifying advancement in hydraulic control valve technology. This research illustrates the need for standard testing protocols for VRT systems to help guide VRT software developers, equipment manufacturers, and end users.*

Keywords. *Fertilizer distributors, Pneumatic, Potassium, Precision agriculture, Site-specific management, Spinner spreaders, Variable-rate application and technology.*

While variable-rate technology (VRT) has become an accepted method for spatially varying inputs within production agriculture, elimination of application errors through proper calibration and operation is critical to ensure accurate performance. VRT equipment increases the complexity of material application and thus requires a new level of knowledge and skill to utilize this technology effectively. Those individuals and companies implementing precision agriculture (PA) technologies often lack technical information and training programs to properly assemble and utilize PA systems (Leer, 2003). Prior research and current understanding regarding correct implementation of VRT is limited.

ASAE standard S341.2, Procedure for Measuring Distribution Uniformity and Calibrating Granular Broadcast Spreaders (*ASAE Standards*, 2000), provides a uniform method for assessing and reporting the performance of broadcast granular spreaders. The standard focuses on uniform-rate (UR) application but does not contain considerations for testing VRT equipment. Modifications to ASAE S341.2 were discussed by Fulton et al. (2001) to assess rate change response for granular applicators. To date, no standard or defined test protocol has been published to evaluate VRT. One concern is identifying what should be tested to quantify application accuracy of VRT: the VR system as a whole or its individual components. More importantly, few VRT equipment manufacturers provide accurate application rate control for VR fertilization (Cointault et al., 2003), and future research is required to understand the effects of various sources of VRT errors (Schueller and Wang, 1994). Thus, standard test and reporting procedures are needed to assess VRT equipment since traditional UR application errors might not be indicative of VRT application inaccuracies.

VRT adds another dimension to granular fertilizer application. Instead of the applicator rate remaining at a fixed value during field operation, it changes dynamically based on spatial location. Applicator dynamics affect VRT applicator performance (Schueller and Wang, 1994). A typical VR applicator system integrates components such as a global positioning system (GPS) receiver, software, and rate controller. Each component produces some level of error, which in turn contributes to an overall VRT system error. The overall error is a summation of individual component errors, understanding that interactions also exist. The addition of VRT components may require unique calibration procedures and operation of equipment to minimize application errors when contrasted with traditional practices. Most research into VRT has been directed towards hardware and software development, and the implementation of these VR systems. Work on application accuracy and the identification of error sources has lagged. Concerns over VR accuracy and

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map-based pesticides and fertilizer were articulated by Goense (1997).

Research has suggested that adjusting ground speed (not the mass flow) is perhaps the best approach to regulate the prescribed application rate, because the rotational constant speed of the spinner disc is independent of ground speed (Hofstee, 1995). Most, if not all, VRT systems adjust the mass flow of material rather than varying ground speed. However, if satisfactory pattern uniformity cannot be maintained during mass flow adjustments with a VRT system, then speed adjustments or a combination of speed and mass flow may be an option for achieving acceptable material distribution.

The "look-ahead" feature provided in most software packages may reduce application errors, providing that VRT system latency or delay time can be quantified and there is a similar system response for increasing and decreasing rate changes. Schueller (1989) described liquid fertilizer mixing and flow control to minimize material transport lag times. He concluded that rate and mixture variations are improved by: (1) controlling flow to each system component, (2) decreasing the response times of the pumps and valves involved, (3) minimizing the volume of connecting hoses, (4) adequate mixing, and (5) mixing as close as possible to the nozzles. It was also found that varying pump speed or recirculation flows were viable options for flow control. The key feature noted was lag or delay time of the entire system. For liquid application, transport lag of a VRT injector ranged from 15 to 55 s, indicating that the lag time varies across the boom for each nozzle (Anglund and Ayers, 2003). These delay times produce application errors by having the rate transition occur after or before the desired time. Considerable improvement in VRT performance was achieved through feed-forward control (Schueller and Wang, 1994). However, distribution pattern errors were introduced with the existence of substantial lag times at different nozzles or application points across the spread width.

Cointault et al. (2003) noted that an accurate spatial fertilizer application requires instantaneous fertilizer flow and distribution controls. Currently, no commercially available spreaders possess both features. Molin et al. (2002) reported that the response time for a particular VR fertilizer spinner spreader was 3.1 s for an increasing step rate change and 5.6 s for the decreasing step change. These results were based on urea application with only two rows of longitudinal pans placed symmetrically at 6 m on either side from the centerline of the spreader. The VR spreader applied up to −27% less than the desired rate during these tests. These results indicate that different "look-ahead" times are required to adjust rate changes to the desired location in time. Currently available software, designed for VR control, only permits one "look-ahead" time to be set. Although Molin et al. (2002) did not provide a detailed calibration description, under-application of material during the VR tests indicated that different calibration procedures are needed for VRT applicators to maintain desired application rates.

The goal of this investigation was to evaluate VRT application accuracy in support of VR systems refinements. The specific objectives were to: (1) develop a procedure by which rate transitions can be characterized for granular VRT applicators, and (2) quantify the delay and transitions times for spinner disc and pneumatic VRT applicators under increasing and decreasing rate transitions.

MATERIALS AND METHODS

APPLICATOR OVERVIEW

Four granular applicators equipped with VRT were used for this investigation: two spinner disc spreaders (A and B), and two pneumatic applicators (C and D). Variable-rate (VR) pan tests for applicators A, B, and C were performed at the University of Kentucky's Animal Research Center (ARC) in Woodford County, Kentucky. Applicator D testing was conducted in Christian County, Kentucky. For each applicator, two VR transition tests were conducted using murate of potash (KCl): one test from low to high, and another test from high to low. Table 1 identifies each applicator by its assigned alphanumeric identification along with the type of applicator, nominal test speed, swath spacing, and type of control valve.

Data from Fulton et al. (2001) were used to assess the performance of applicator A. Performance data for the remaining three applicators were collected during the summer of 2003. Fulton et al. (2001) provides a full description of applicator A and its VRT control system. Applicator A was upgraded with the addition of AgView software by GIS Solutions (AgView, 1999) and Trimble's Ag132 DGPS receiver with Coast Guard radiobeacon correction.

The VRT control system for applicator B included a Rawson hydraulic drive manufactured for this model spreader. AgView software (AgView, 1999) and a Trimble Ag132 DGPS receiver (Coast Guard radiobeacon correction) were used to implement VR on this spreader. The truck was operated in first gear at 2300 rpm, generating a nominal ground speed of 14.5 km/h for all tests. Spreader bed settings included: spinner hydraulic control valve positioned at 6.25 generating a nominal spinner speed of 800 rpm, a gate height of 3.8 cm, and the spinner discs positioned at 3.25.

Applicator C was a pull-type applicator using a single, hydraulically driven centrifugal blower to produce airflow in each air tube for conveying material from the centrally located storage hopper to all deflector plates mounted along the boom. A Rawson hydraulic drive was used to drive the fluted metering rollers. A John Deere 6220 was used to pull the applicator and provide hydraulic power. A computer with AgView software (AgView, 1999), a Rawson controller, and a Trimble Ag132 DGPS receiver (Coast Guard radiobeacon correction) were mounted on the tractor to provide VR capabilities.

The VR control system for applicator D was one developed by the applicator manufacturer utilizing a proprietary Controller Area Network (CAN) echelon for communications. It contains a PC-based computer mounted in the truck cab running the company's mapping software package. DGPS was provided by a Trimble Ag132 receiver using Coast Guard radiobeacon correction. Applicator hardware and software settings were in accordance with manufacturer

Table 1. The different applicator nomenclature and testing characteristics.

Applicator	Type	Test Speed (km/h)	Swath Spacing (m)	Control Valve
A	Spinner	20.4	16.0	Source fluid power
B	Spinner	14.5	18.3	Rawson
C	Pneumatic	9.5	12.2	Rawson
D	Pneumatic	12.9	21.3	Proprietary

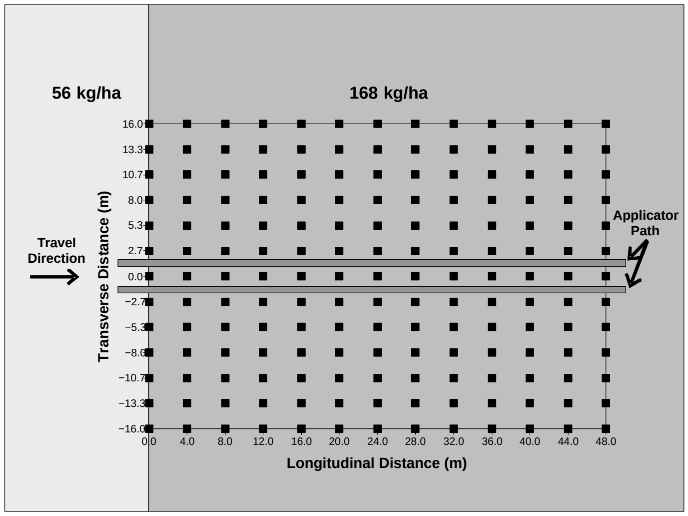


Figure 1. Applicator A collection pan matrix for single-pass, rate transition tests (low-to-high test illustrated; Fulton et al., 2001).

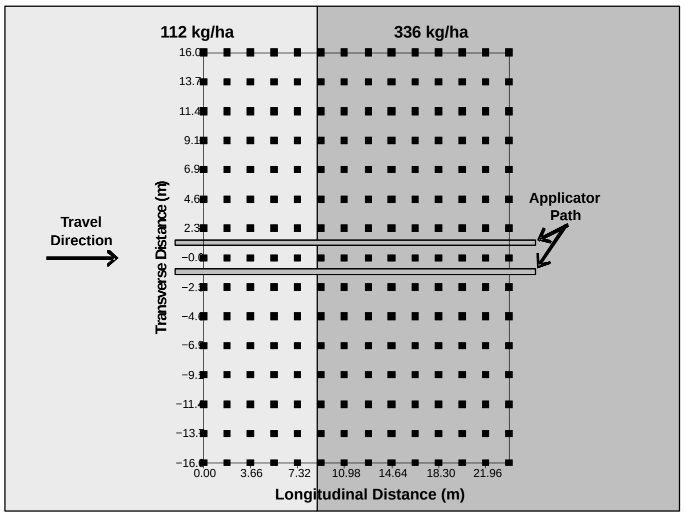


Figure 2. Applicator B collection pan matrix for single-pass, rate transition tests (low-to-high test illustrated).

literature. All adjustments were made by the equipment owners/operators.

Experimental Layout

Deposition tests were performed by modifying ASAE standard S341.2 (*ASAE Standards*, 2000), using the same pans and following the same test protocol outlined by Fulton et al. (2001). Collection pan dimensions were 40.6 cm wide × 50.8 cm long × 10.2 cm in height, with an aluminum divider with a 10.2 × 10.2 cm (5.1 cm height) grid placed inside each pan. Figures 1, 2, 3, and 4 present the pan matrices for applicators A, B, C, and D, respectively. Sufficient space was provided for application equipment to navigate the test pan matrix by straddling the center row (0 m transverse distance) of pans. The test site was flagged to indicate collection pan positions and application equipment paths. The applicators were permitted sufficient area to attain the desired ground speed (table 1) before entering the test area. Upon completion of each test, the KCl particles collected in each pan were placed in individual plastic bags, sealed, and labeled according to location. A digital scale was used to measure and record the mass of each sample under laboratory conditions for computing the application rate.

Calibration procedures were previously documented for applicator A (Fulton et al., 2001), while applicators B, C, and D were calibrated using murate of potash (KCl) following the manufacturers' recommendations provided within the operator manuals. Rate transition data were collected for applicator A using a fixed 13 × 13 collection matrix (Fulton et al., 2001; fig. 1 and table 2). Results of this earlier investigation indicated the need for an expanded collection matrix to capture complete rate transitions.

The width of the pan layouts was based on the effective application width for each applicator (table 1). Therefore, the uniform transverse pan spacing was adjusted to ensure that the total material distribution width was captured. The number of transverse pans for each row was set at 15 for applicators B and C but at 17 for applicator D (table 2). The length of each test matrix was determined by estimating the time for making a rate change and the typical ground speed of each applicator. The time to make a rate change was obtained through discussions with experienced VRT equipment operators and by conducting preliminary tests with each applicator. The goal was to capture a full rate change within the test matrix while minimizing the longitudinal pan spacing. For rate changes that occur quickly, the start and end

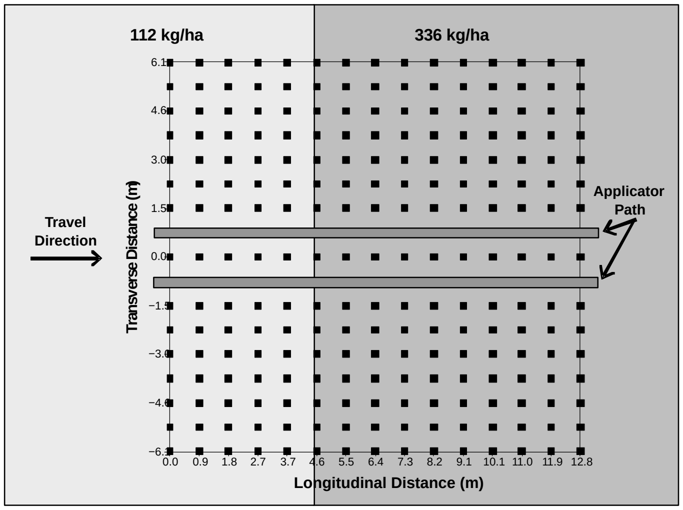


Figure 3. Applicator C collection pan matrix for single-pass, rate transition tests (low-to-high test illustrated).

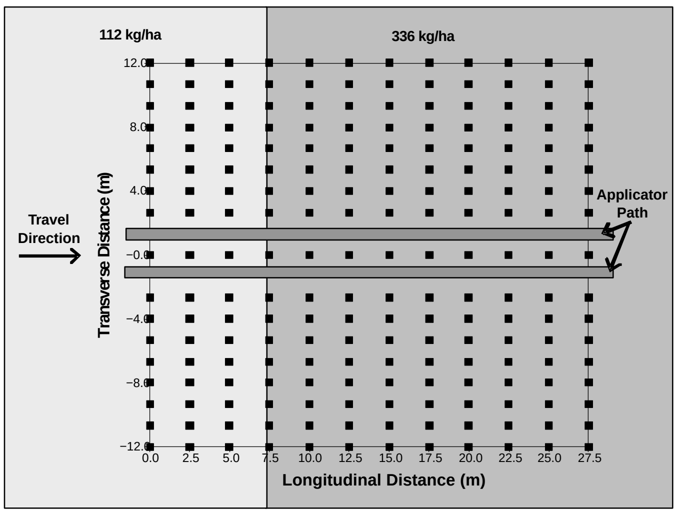


Figure 4. Applicator D collection pan matrix for single-pass, rate transition tests (low-to-high test illustrated).

Table 2. Collection pan matrix spacing and number of pans for each applicator.

Applicator	Transverse Spacing (m)	Longitudinal Spacing (m)	No. of Transverse Pans	No. of Longitudinal Pans	Total No. of Pans
A	2.67	4.00	13	13	169
B	2.29	1.83	15	14	210
C	0.76	0.91	15	15	225
D	1.33	2.50	17	12	204

of the rate transition period is difficult to establish at increased longitudinal pan spacing. Experience with prior tests suggests a maximum of 225 pans is a practical limit for an individual test. Pan spacings are presented in table 2 and vary in accordance with the machine being tested.

The range of rate change for applicators B, C, and D was established by using the maximum application rates for potassium from the University of Kentucky's Lime and Fertilizer Recommendations (AGR-1, 2002) along with the Tri-State Fertilizer Recommendations for Corn, Soybeans, Wheat, and Alfalfa (Tri-State, 2000). Based on these recommendations, 112 kg/ha was used for the low rate and 336 kg/ha was used for the high rate. Rate transition tests for applicators B, C, and D were conducted by developing two polygons, with the intersection of these polygons representing the desired rate change position. This polygon dissection simulates the boundary of two management zones, supplying a means for characterizing rate transitions when moving between management zones. The rate change location for applicators B and C was determined using a Trimble RTK GPS survey grade system to lay out the transition line (figs. 2 and 3, respectively). A Trimble Ag132 DGPS receiver was used to locate the rate change line for applicators A and D. Two prescription maps were developed for each applicator: low to high, and high to low. These prescription maps were uploaded into AgView for applicators B and C. However, this information was imported into a software package to generate the two prescriptions for applicator D. The inclusion of this additional step was required to create prescription files that could be uploaded into the control software for applicator D. The software generated a contoured prescription map that differed from those used for applicators A, B, and C (fig. 5). This prescription map generation influenced the rate response for applicator D, as the contouring routine smoothed the transition at management zone boundaries.

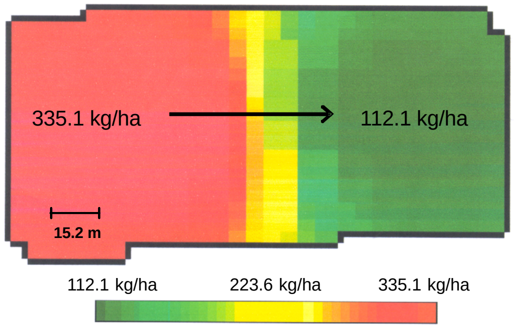


Figure 5. Applicator D prescription map required for the 336.2 to 112.1 kg/ha rate transition test.

Rate Response Analysis

Surface plots were generated using the software package Surfer (Surfer, 2003) for each set of pan test data. These plots provide a visual rendering of application variability and rate transition dynamics, since a 2-D collection pan matrix was used. Arrows were included to indicate applicator direction of travel. Rate transition parameters (*transition time* and *delay time*) were computed for each data set. Transition time is defined as the elapsed time from the actual start to finish of the rate change. The delay time characterizes the time difference from when the rate change actually commenced to the desired start time.

The start and end distances for the rate transitions were established by using a four-parameter, sigmoidal regression function to model rate changes, as outlined by Fulton et al. (2001). A sigmoidal fit best described both the increasing and decreasing rate transitions for applicators B, C, and D, unlike the linear response observed for the increasing transition for applicator A (Fulton et al., 2001). Several different regression functions were used to model the step rate change in application rate, but a first-order sigmoidal model continually produced the best overall results. Sigma Plot 8.0 (Sigma Plot, 2001) was used to fit the sigmoidal functions to each transverse position of all rate transition tests for applicators B, C, and D.

Figure 6 illustrates the procedure for defining the start and end distance for the rate transitions. The start and end points were defined by using a 5% settling time. This corresponds to a 5% and 95% change in the overall rate transition, defined by the resulting sigmoidal regression minimum and maximum rates on the asymptotic tails. A 5% settling time was selected because of the small-scale variability (noise) in the observed data. Therefore, the selection of this time would indicate that a rate transition had been initiated or completed, better representing the actual start and end of a transition. The *delay distance* can then be calculated by subtracting the desired change distance from the start distance. Similarly, the *rate transition distance* is the difference between the start and end distances. These distances were then converted to elapsed time values by assuming a constant ground speed (table 1), thereby estimating the delay and transition times. The field application file (FAF) or as-applied file generated by the VR control software for applicators B, C, and D served to double-check the test speed. Ground speed is logged within the FAF using the GPS. In one case, the high-to-low transition for applicator B, the average ground speed was 15.0 km/h rather than the established 14.5 km/h test speed. These values were averaged for all transverse positions to establish the overall delay and transition times for each applicator under either rate change scenario.

The transition and delay times for applicator A's low-to-high rate change were obtained using the sigmoidal curve fitting approach (Fulton et al., 2001). This approach was not used for the high-to-low rate change with applicator A, as the rate change was nearly linear (Fulton et al., 2001). For this case, difficulty existed in determining from the surface plot whether the complete transition was captured within the pan matrix. Therefore, the mean 56 and 168 kg/ha pattern data from the prior study were used to define the upper and lower limits of the transition. A 5% settling time was again utilized to define the start and end positions for comparable analyses.

It should be noted that little or no material was collected in the outer rows of pans for all applicators. These transverse rows were omitted from analysis for a particular test since they did not reflect the actual rate transitions.

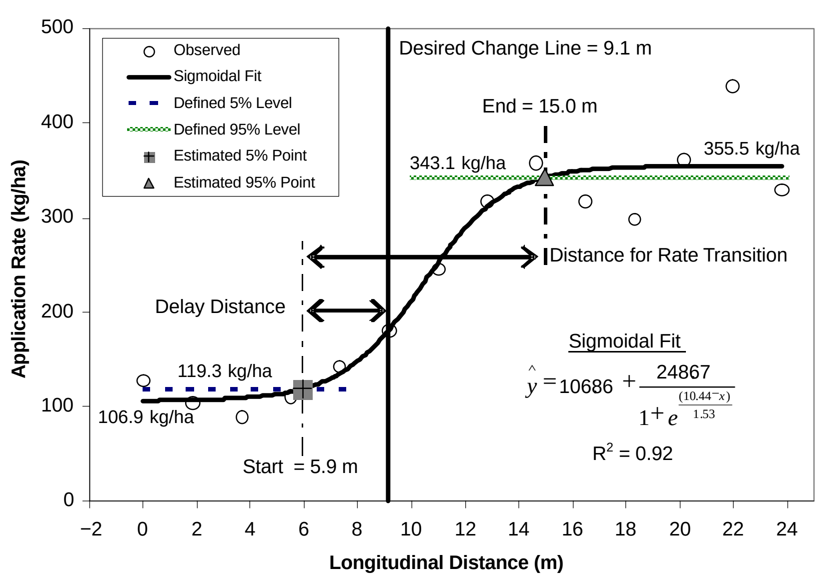


Figure 6. Example illustration for characterizing rate change dynamics (applicator B; 0.0 m transverse position).

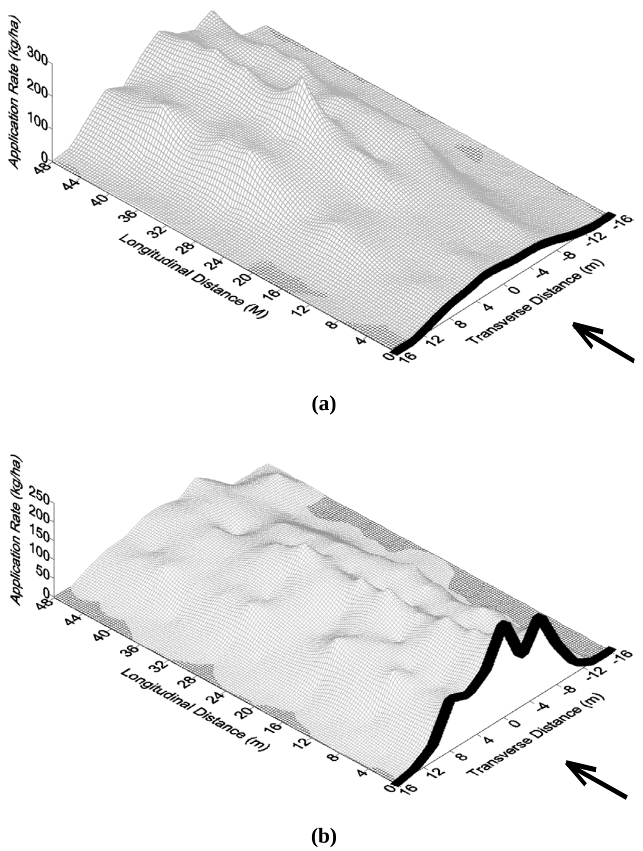


Figure 7. Rate transition surfaces for applicator A: (a) 56 to 168 kg/ha, and (b) 168 to 56 kg/ha (Fulton et al., 2001).

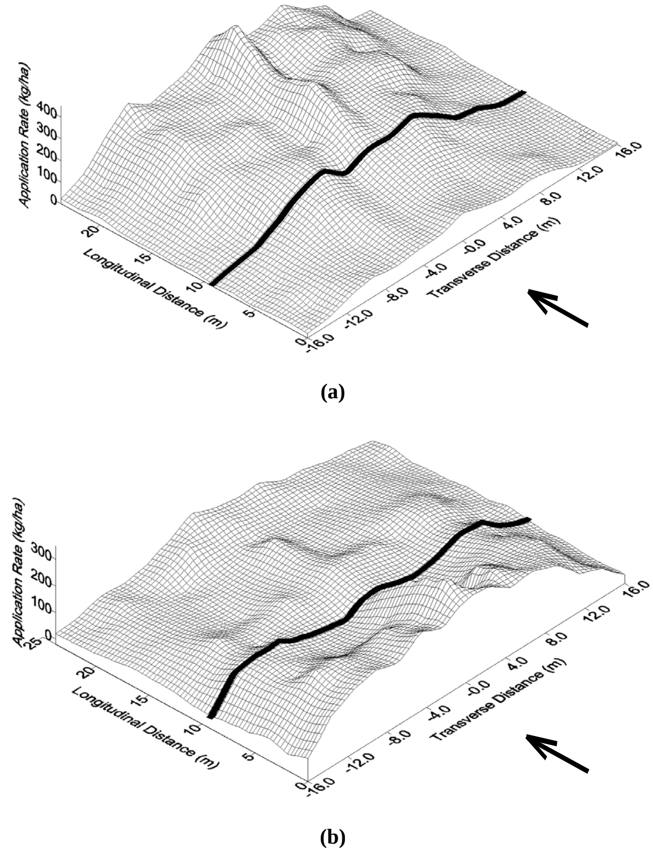


Figure 8. Rate transition surfaces for applicator B: (a) 112 to 336 kg/ha, and (b) 336 to 112 kg/ha.

RESULTS AND DISCUSSION

SURFACE ANALYSIS

The rate transition surfaces plots for applicators A, B, C, and D are provided in figures 7, 8, 9, and 10, respectively. The black line represents the desired rate transition line where the rate change should start (delay time equal to zero). In most cases, a high percentage of the rate transition occurred within the collection pan matrices. However, several of the transitions appear to either start or end outside the collection matrix (figs. 8b and 10b). In most cases, a majority of the rate transition was captured, providing sufficient data to compute the delay and transition times for each applicator.

The generated surfaces for applicator A demonstrate varying performance by its VR control system (fig. 7). The rate transition appears to initiate after the desired line for both tests. The 56 to 168 kg/ha transition took less time to occur compared to the 168 to 56 kg/ha transition. For the 168 to 56 kg/ha transition, the rate transition occurred over the entire test area, whereas the 56 to 168 kg/ha transition occurred well within the test matrix. An interesting feature in each transition is the existence of a W-shaped pattern

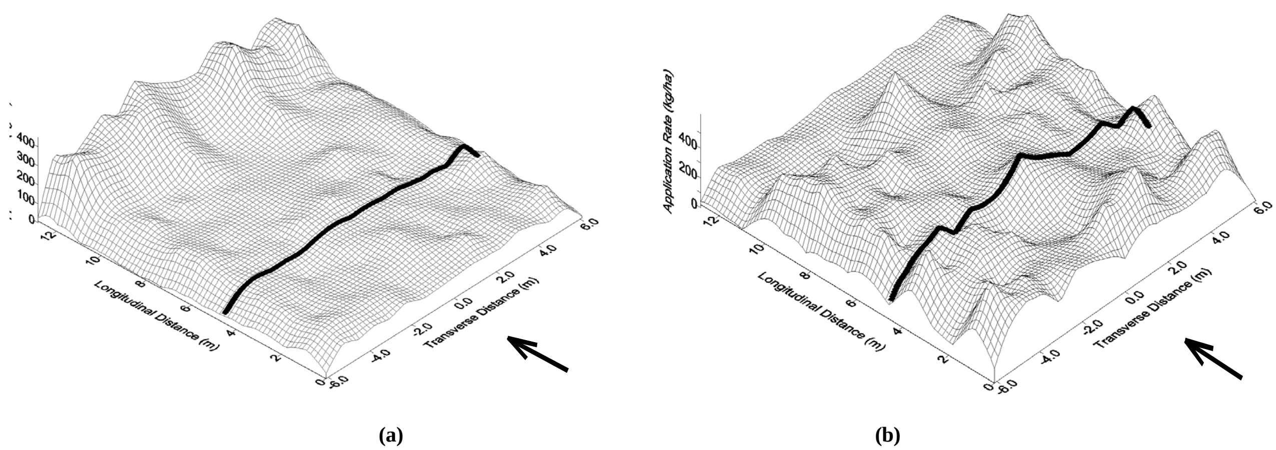
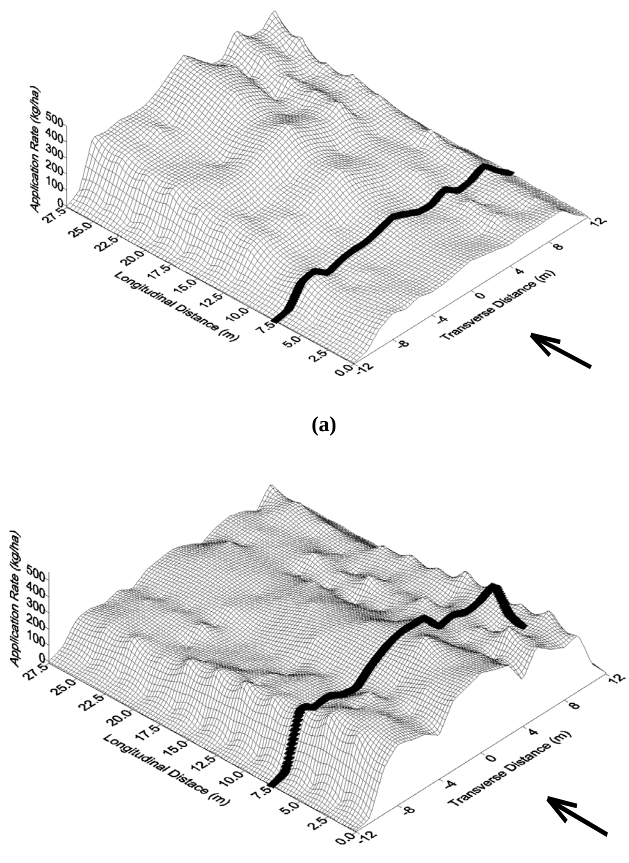


Figure 9. Rate transition surface for applicator C: (a) 112 to 336 kg/ha, and (b) 336 to 112 kg/ha.



(a)

(b)

Figure 10. Rate transition surfaces for applicator D: (a) 112 to 336 kg/ha, and (b) 336 to 112 kg/ha.

occurring at the high application rate, which converts to a more Gaussian pattern when transitioning to the lower rate. This variation in the distribution pattern was reported previously by Fulton et al. (2001) for this applicator.

Surfaces created for applicator B indicate that the rate change started slightly before the desired rate transition line and occurred fairly quickly. By adjusting the initiation time, rate transitions should occur at management zone boundaries, thereby minimizing deviations from the desired rate. A majority of the 112 to 336 kg/ha transition for applicator B appears to take place in the next zone (fig. 8a). Conversely, a high percentage of the 336 to 112 kg/ha transition occurs in the first zone. Equivalent transition times for increasing or decreasing rate changes are highly desirable from a systems integration perspective. All of the surfaces for applicator B show slightly higher deposition at the center of the spread pattern, causing a distinct peak in the patterns at the higher rates for both tests (fig. 8).

The rate response for applicator C occurred after crossing into the second zone (fig. 9). However, the rate transitions occurred abruptly in both tests. Applicator C exhibited a more rapid rate transition than the other applicators (discussed in more detail later). From observations, the rate transition times were the same for both tests and with initiation occurring at nearly the same location. The delay in the rate response is handled in most VRT software packages through the specification of a "look-ahead" factor, which shifts the rate change in time to coincide with zone boundaries.

The rate transitions for applicator D (fig. 10) were of longer duration than those for applicators B and C. Contouring of prescription maps for applicator D was in part responsible for this delay. The rate transition started at different locations for each test. The 112 to 336 kg/ha rate transition started around the zone boundary, whereas the 336 to 112 kg/ha transition started before the spreader boom crossed the boundary (fig. 10a). The high-to-low transition took longer than the low-to-high transition.

Quantification of Rate Transition

Table 3 provides the R^2 values for all the sigmoidal fits for applicators B, C, and D. A majority of the R^2 values were in the 0.87 to 0.94 range, indicating an acceptable regression fit. The 336 to 112 kg/ha transition for applicator C produced the worst fits, with several R^2 values of less than 0.87, which is to be expected when considering the observed application variability during this test (fig. 9b). The R^2 values from the regression analysis for applicator A are presented in table 4.

The rate response characteristics for applicator B were different for increasing versus decreasing rate changes (table 5). The rate transition time nearly doubled (6.8 s) for

Table 3. Sigmoidal regression results for applicators B, C, and D rate transitions based on transverse positions.

Applicator B			Applicator C			Applicator D		
Position (m)	Test 1[a] R^2	Test 2[b] R^2	Position (m)	Test 1 R^2	Test 2 R^2	Position (m)	Test 1 R^2	Test 2 R^2
−13.7	0.81	0.95	−5.33	0.91	0.74			
−11.4	0.92	0.92	−4.57	0.93	0.72	−9.3	0.93	0.81
−9.1	0.93	0.97	−3.81	0.93	0.84	−8.0	0.94	0.93
−6.9	0.94	0.92	−3.05	0.93	0.79	−6.7	0.90	0.92
−4.6	0.95	0.90	−2.29	0.95	0.88	−5.3	0.87	0.78
−2.3	0.94	0.86	−1.52	0.96	0.82	−2.7	0.93	0.92
0.0	0.92	0.95	0.00	0.73	0.44	0.0	0.94	0.90
2.3	0.90	0.92	1.52	0.83	0.95	2.7	0.89	0.93
4.6	0.95	0.93	2.29	0.91	0.85	5.3	0.92	0.92
6.9	0.92	0.95	3.05	0.91	0.87	6.7	0.94	0.89
9.1	0.84	0.97	3.81	0.97	0.74	8.0	0.91	0.87
11.4	0.93	0.85	4.57	0.82	0.63	9.3	0.97	0.89
13.7	0.71	0.87	5.33	0.84	0.56			

[a] 112 to 336 kg/ha rate transition.
[b] 336 to 112 kg/ha rate transition.

Table 4. Regression results for applicator A rate transitions.

Transverse Position (m)	Sigmoidal 56 to 168 kg/ha Transition, R^2	Linear 168 to 56 kg/ha Transition, R^2
−8	0.95	0.82
−5.3	0.83	0.76
−2.7	0.94	0.63
0	0.88	0.91
2.7	0.97	0.79
5.3	0.83	0.82
8	0.71	0.76

the 336 to 112 kg/ha transition. The delay times for both tests were negative, meaning that the rate change started before zone transition, but the delay started 2.5 s sooner with decreasing rates. Ideally, the specification of two "look-ahead" times will be required to correct for this anomaly.

Applicator C demonstrated consistency, with nearly the same rate transition times (table 5). The delay times for applicator C differed only slightly (0.5 s difference). The difference between the delay times would be considered negligible at the test speed of 9.5 km/h, which equates to about 1.3 m. Therefore, this consistency is a desirable feature of this VR system, since a single "look-ahead" time could be used to adjust the rate change timing to coincide with crossing management zone boundaries. For the given ground speed, a "look-ahead" time of around 2.0 s could be used for this applicator. The VR control system for this applicator also produced the quickest rate transitions (less than 0.5 s). These quick transition times might be attributed to the difference in the material metering and delivery systems between boom and spinner disc applicators. Both applicators (B and C) utilized the same VR control system.

Applicator D exhibited longer response times compared to the other applicators (table 5). The rate transition time nearly doubled for rate decreases, similar to the trend observed with applicator B. The delay time for the 112 to 336 kg/ha rate change was close to zero, whereas the rate transition started about 5.0 s ahead of the zone boundary. Ideally, it is desirable to have the rate transition be split between either management zone rather than initiating the change at a zone boundary. Contouring may help minimize application errors at zone boundaries, but it appears to increase the transition time for rate changes. The contribution of prescription map contouring and VR control system response could not be separated.

The transition tests for applicator A were performed between 56 and 168 kg/ha (Fulton et al., 2001). Similar to applicators B and D, the calculated times for applicator A are different between the two tests (table 5). The transition time

Table 5. The rate transition characteristics for the different applicators.

Applicator	Test (kg/ha)	Transition Time, s (95% CI)		Delay Time, s (95% CI)	
A	56 to 168	4.8	(3.7)	2.3	(1.6)
	168 to 56	7.5	(1.1)	1.2	(0.8)
B	112 to 336	3.6	(2.1)	−0.9	(0.7)
	336 to 112	6.8	(3.7)	−3.4	(0.9)
C	112 to 336	0.4	(0.3)	2.3	(0.2)
	336 to 112	0.3	(0.2)	1.8	(0.2)
D	112 to 336	6.6	(2.4)	0.1	(1.0)
	336 to 112	12.4	(3.8)	−4.9	(2.5)

for the 168 to 56 kg/ha test was 2.7 s longer, while initiation of the transition started 1.1 s before that of the 56 to 168 kg/ha test. In general, the VR control system's responses for applicators B and C were faster than that for applicator A. This could be attributed to the style of the control valve that controls the hydraulic motors used for applicators B and C, suggesting that valve technology is in part responsible for a portion of the VR application error.

One similarity between the VR control systems of applicators A, B, and D was that the transition time took longer when decreasing the rate than when increasing it. In two cases, this time nearly doubled. Applicator C was the only one that exhibited similar transitions times. The delay time also occurred earlier for the decreasing rate changes in contrast to the increasing rate changes. For applicators B and D, this delay was 2.5 s and 5.0 s earlier, respectively.

Ideal rate transition times of zero would result in an instantaneous transition, or a perfect step response. In reality, delay times of up to 1.5 s would be acceptable for VR control systems. In some cases where the rate transition time is greater, there may be a need to limit ground speed to reduce application errors. For applicator D, the software contours the prescription map, which inherently alters the rate transition time for this equipment. The transition times for rate changes may dictate management zone resolution, which is an issue largely not addressed within precision agriculture research. For example, the 7.5 s transition time for applicator A when decreasing the application rate calculates into 42.5 m when driving at the test speed of 20.4 km/h (table 1). A 0.40 ha management zone results in a 63.4 m grid, resulting in the changing application rate occurring across a majority of the zone length.

Specification of the proper delay or "look-ahead" time ensures that rate changes occur at the appropriate location. This assumes that delay times for rate increases and decreases are the same. For example, a single rate delay time could be used for applicator C to shift the rate transition to the appropriate point in time. Differences in the delay times with the other applicators suggest that two "look-ahead" times may be necessary to correctly adjust rate transition timing. It is important to note the magnitude of the rate transition may also affect selection of the proper delay time, thereby adding more complexity to the selection of the proper "look-ahead" process.

VR system response times are important parameters to be considered by software developers and users of VRT equipment. Immediately, quantification of these times may permit post-processing correction of "as-applied" maps (Fulton et al., 2003). Further, this work highlights the need for manufacturer reporting of transition and delay times to support end users of this equipment. The times reported in this investigation varied from applicator to applicator, suggesting the need to develop a standardized approach for determining and reporting these values.

Conclusion

A methodology was developed to determine rate change characteristics from granular applicators to quantify VR system response. Current practices require a 2-D collection pan matrix with a rate change line (representing management zone intersection) established approximately 25% to 33% of the length of the matrix (in the direction of travel) from the applicator entry point. Pan matrices, for each applicator, were established based on applicator spread width and estimated rate change time. Prescription maps were then generated and uploaded into the VR control systems of each applicator. The applicators then traversed the pan matrix. Material deposited in each pan was collected and weighed to determine application rate. All rate changes, whether increasing or decreasing, were sigmoidal in nature, except the decreasing rate change for applicator A, which was linear. Each rate transition was fit with the appropriate model using regression. A 5% settling time or change in the maximum (95%) and minimum (5%) rates was used to establish the start and end of a rate change. The start and end locations were then utilized to compute the delay and transition times for each applicator.

Rate response tests demonstrated that only one of the VR systems produced consistent delay and transition times, while the other three exhibited varying delay and transition times. The transition time for applicator C was quick and consistent for both the increasing and decreasing rate transitions. While the rate transition occurred quickly, applicator C did have around a 1.8 to 2.3 s delay time prior to initiation of the rate change. The other applicators (A, B, and D) were inconsistent in their rate responses, producing differing delay and transition times when comparing low-to-high rate changes with high-to-low rate changes. For applicators B and D, the transition time approximately doubled for the high-to-low change when compared to the low-to-high change. The rate transition for applicator D occurred over a longer period of time compared to applicators B and C, which may have resulted from contouring of management zone boundaries during creation of the prescription maps. Applicator A transition times for both tests were considerable slower when considering a net rate change of 112 kg/ha when compared with a 224 kg/ha change for the other applicators. One possible reason for the delayed response could be the control valve styles used on applicators A in comparison to B and C. In conclusion, if application equipment owners expect accurate VRT systems, then manufacturers, system integrators, and software developer must have access to VR controller performance data that include rate transition and delay times.

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