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Comparison of VRT Granular Applicators

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Abstract. Granular applicators equipped with variable-rate technology have gained popularity in recent years due to increased interests in variable-rate application. The purpose of this investigation was to characterize distribution patterns at varying rates and quantify rate transitions from various granular applicators. Both uniform- and variable-rate tests were conducted to assess the accuracy of variable-rate application from four granular applicators (2 spinner spreaders and 2 pneumatic applicators). The patterns results indicated a consistent triangular pattern for spinner spreader B and consistent patterns for pneumatic applicators C and D. However, applicator D produced pattern variations at the center and right side. Simulated overlap analysis showed that applicators B and C performed acceptably (CV's < 20%). Applicator A performed well at the two lower rates but not at the highest rate (CV=27.4). The pattern unevenness for applicator D produced undesirable CV's between 25% and 34%. Pattern comparisons showed that pattern shifts occurred for applicator A ($P=0.0092$) but not for applicators B, C, and D. Rate transition tests produced inconsistencies in the delay and transition times for applicators A, B, and D. For these three applicators, their transition times were much longer for the low to high rate change. Applicator C illustrated consistency with delay times around 1.2 to 1.5 seconds and quick transition times (<0.4 sec.). These results demonstrate potential application errors with variable-rate technology which should assist software and equipment manufacturers to develop more accurate products and ultimately the need for a testing standard for this type equipment.

Keywords. Precision agriculture, Site-specific management, Spinner spreader, Pneumatic, variable-rate application, Potash, Distribution patterns.

Introduction

The popularity of variable-rate technology (VRT) is growing since the advent of precision agriculture (PA). One area farmers are tending to focus on is nutrient fertility management. Fertilizer dealers and custom applicators are providing VRT services to farmers, which usually come as an additional cost due to the added equipment and software required to perform variable-rate (VR) application. The notion behind VRT is only applying what is needed based on local soil conditions and crop requirements. This assumes that soil and fertility variability exists and the traditional uniform-rate (UR) application tends to over- and under-apply. Thus, VRT may provide a method to make better use of granular inputs. While VRT seems to be a viable option for managing granular inputs, an understanding of application errors associated with VRT equipment is essential. Quantification of these errors will help establish whether VRT offers an effective way to apply products when contrasted with UR application. There is also the concern as to whether this technology actually pays for itself.

The two main technologies for granular material application are spinner discs spreaders and pneumatic applicators. Spinner spreaders still tend to be the most popular type of granular applicators found in the Midwest due to their lower capital investment. However, air-boom applicators are popular among custom applicators. One concern about granular materials is product variability in terms of material density, particle size, and moisture content. This variability poses a potential problem with regard to the uniformity of application across the width of the machine. Many believe that air-boom technology offers more uniform product distribution across the swath when compared with spinner spreaders. In either case, deposition variability exists due to the nature of granular products, especially with VRT equipment. Producers acknowledge the existence of deposition variability, but they continue to utilize the equipment despite the known variability.

Objectives

The goal of this investigation was to quantify the variability of different VRT applicators in terms of distribution pattern characterization and rate change response. The specific objectives were:

- To characterize the distribution patterns from various granular applicators for varying application rates,
- To evaluate the accuracy of the various applicators under field operation,
- To assess the consistency of the characterized distribution patterns from the various applicators, and
- To quantify the rate change characteristics for various VR control systems.

Background

Precision agriculture (PA) has brought a new technique for managing agricultural land. Many believe that the use of PA practices allows for better nutrient management by applying only what is required for crop growth thereby possibly providing agronomic, economic and environmental advantages over the traditional approach of treating a field as a single unit. While VRT has become a widely accepted method in the agricultural community for varying the application rate of various inputs, potential errors with this technology along with proper calibration and operation is critical to ensure accurate application.

ASAE standard S341.2, Procedure for Measuring Distribution Uniformity and Calibrating Granular Broadcast Spreaders (ASAE S341.2, 2000), provides a uniform procedure for testing, assessing the performance, and reporting the results of broadcast spreaders. The standard outlines a methodology by which to assess the distribution pattern of a broadcast spinner using a 1-D row of trays. While the standard addresses uniform application, it overlooks the testing of broadcast spreaders equipped with VRT. Therefore, Fulton et al. (2001) modified ASAE S341.2 to include a 2-D array of collection pans to assess VR application of granular products. The modified plot layout provided means to characterize distribution patterns while also evaluating distribution patterns and rate response during rate changes. Capturing rate changes within the test matrix also allowed for quantification of system latency for VRT equipment.

The coefficient of variation (CV) provides a means to quantify application variability and accuracy. ASAE S341.2 (2000) requires CV's to be reported when testing applicators while manufacturers and custom applicators have adopted CV calculations when talking about application accuracy. Lower CV's indicate uniform distribution patterns. Spinner spreaders tend to exhibit CV's varying from 5% to 10%; however, terrain irregularities can greatly increase CV's to the upper 20's or lower 30's (Parish, 1991). Sogaard and Kierkegaard (1994) reported that CV's in the range of 15% to 20% are typical of field tests for spinner spreaders.

Fulton et al. (2001) demonstrated distribution variability at different rates from a spinner spreader. They cited that distribution variability could compound application errors when moving to variable-rate application with spinner spreaders. Additionally, pattern shifts during rate changes (Fulton et al., 2001; Olieslagers et al., 1997) plus the existence of system latency (Fulton et al., 2001) causing delayed rate changes creates other sources of application errors for VRT equipment. The problem with pattern shifts is not as easily rectified but needs to be addressed to maintain distribution uniformity at various application rates.

Methodology

Four granular applicators were used for this investigation: 2 spinner spreaders and 2 pneumatic applicators. Table 1 identifies each applicator by its assigned alphanumeric identification along with the type of applicator, nominal test speed, and swath spacing. For each applicator, a total of six tests were conducted: 4 at four different uniform rates and 2 VR transitions (one from low to high and another from high to low) using murate of potash (KCl). The tests were performed by modifying ASAE standard S341.2 (2000), using the same pans, and following the same test protocol outlined by Fulton et al. (2001). The test site was flagged to indicate collection pan positions and applicator paths to cover the test site. Fulton et al. (2001) provides details for testing applicator A. All applicators were calibrated before performing any of the UR and VR tests using murate of potash (KCl).

Table 1. Applicator characteristics.

Applicator	Type	Test Speed (km/hr)	Swath Spacing (m)
A	Spinner	20.4	16.0
B	Spinner	14.5	18.3
C	Pneumatic	9.4	12.2
D	Pneumatic	12.9	21.3

Several application rates were selected for performing the uniform-rate (UR) tests. Applicator A was tested at 56.0 and 168.1 kg/ha (Fulton et al., 2001). The rates selected for Applicator B and C were 56.0, 112.1, 224.2, and 336.2 kg/ha. Applicator C was tested at 112.1, 224.2, 336.2, and 448.3 kg/ha. These application rates are based upon 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). The low application rate of 56 kg/ha was chosen to determine if applicators B and C would perform accurately at a low application rate and to compare against applicator A results. Many spinner spreader manufacturers do not recommend applying fertilizers below 112 kg/ha. However, farmers implementing VRT on these applicators will apply under 112 kg/ha. Applicator D was not tested at the 56.0 kg/ha rate but rather at 448.3 kg/ha as requested by the owners.

Two rate transition tests, representing a VR scenario, were performed for each applicator. Fulton et al. (2001) outlined the rate transition tests and analysis for applicator A. For applicators B, C, and D, these rate transition tests were performed by changing from 112.1 to 336.2 kg/ha and then from 336.2 to 112.1 kg/ha.

The collection pan matrices for applicators B, C and D were developed based on the 2-D pan matrix used by Fulton et al. (2001). Figures 1 presents the pan matrix for applicator D and serves as an example matrix for all applicators. The 0-m transverse distance represents the pans that were straddled by each applicator during a test run. The width of the pan layouts was based upon the effective application and overlap widths for each applicator (Table 1). Therefore, the uniform transverse pan spacing was adjusted to ensure that the total material distribution width was captured. The length of each test matrix was determined by estimating the time for making a rate change. This time was obtained through discussions with experienced VRT equipment operators. The goal was to capture the rate change within the test matrix but keep

the longitudinal pan spacing confined over several rows of pans. The applicators were permitted sufficient area to attain a steady ground speed before entering the test area.

Figure 1. Applicator D collection pan matrix for single-pass UR and VR tests along with the desired rate transition line.

Test pattern data were collected for applicator A using a fixed 13 by 13 matrix (169 total pans; Fulton et al., 2001). As the result of this earlier study, it was decided that more transverse pans were required to better characterize the distribution patterns from the applicators. The number of longitudinal rows was set at 12 to provide 12 replications for characterizing the distribution patterns. The final number of pans for the UR and VR tests was established at 204 for applicators B, C, and D (fig. 1).

The rate transition tests, 112 kg/ha to 336 kg/ha and 336 to 112 kg/ha, were conducted by developing two polygons with the intersection of these polygons representing the desired rate change line (fig. 1). The rate change line was established using an RTK system to mark the outer two pan positions at the desired longitudinal distance (fig. 1). Two prescription maps were developed for each applicator: low to high and high to low. These prescription maps were uploaded into AgView (1999) for applicators B and C. However, similar information was used by the owners of applicator D to generate the two, contoured prescriptions required by this applicator. The contouring process required for applicator D introduces a testing difference from the other applicators.

Upon completion of each test, the murate of potash (KCl) particles in each pan were placed in individual plastic bags, sealed, and labeled according to location. A digital scale was used to measure the mass of each sample under laboratory conditions. The weights were recorded to establish the distribution patterns for the UR tests and rate transition data.

The resulting single-pass distribution patterns were then used to generate the simulated overlap distribution patterns, using the progressive method outlined in ASAE S341.2 (2000) to assess application uniformity. Similarly, the three distribution patterns at 56.0, 112.1, and 168.1 kg/ha for applicator A (Fulton et al., 2003) were used to generate the simulated overlap distribution patterns along with computing the mean application rate and CVs for each applicator. These overlap patterns provide a means to estimate how single-pass distribution pattern variations affect field operation by accounting for overlap of parallel passes. These plots were created

using the manufacturer recommended swath spacing (Table 1). In theory, the overlap data should produce a horizontal line indicating uniform distribution.

The characterized distribution patterns for each applicator were standardized based on the mean application rate calculated for the simulated overlap analysis. Pattern standardization allows for quantifiable comparisons between the characterized patterns for each applicator. An ANOVA was conducted using SAS's (SAS, 2001) GLM procedure, enabling comparisons between rates across all positions (rate), transverse positions across all rates (position), and rates within each position (rate*position). The presence of pattern shifts is indicated by a significant interaction between rate and position.

Surface plots were generated using the software package Surfer (Surfer, 1996) for the VR tests. These plots provide visual depictions of the rate transition dynamics. The rate transition characteristics computed were the "transition time" and the "delay time." The time required for a rate transition represents the time from start to finish of the transition. The delay time characterizes the time difference from when the rate change started to the desired time for when the rate change should have been initiated. These features were calculated for each applicator under each of the two rate transition scenarios.

Results and Discussion

Single-Pass Analysis

Figures 1, 2, and 3 depict the distribution patterns along with the 95% CI's for applicators B, C and D, respectively. A unique feature in these figures is symmetry seems to exist about the center of the patterns for applicators B and C but not for D. Symmetry is a desirable feature in that similar distribution is occurring on both sides for the spinner applicators since they rely on overlap from adjacent passes. For applicator B, there does seem to be a slight shift in the pattern peak for the 112-kg/ha test where the maximum occurred at the -2.3-m position rather than at the center. Applicator Bs peak at the center becomes more prevalent as the application rate increases. The 56 and 112 kg/ha tests for applicator C appears to be rather uniform with more variability occurring at the higher rate tests. But for the most part, the distribution patterns show consistency from side to side for applicators B and C which coincide with the results reported by Fulton et al. (2001) for applicator A.

Figure 2. Characterized distribution patterns for applicator B.

Figure 3. Characterized distribution patterns for applicator C.

Figure 4. Characterized distribution patterns for applicator D.

The mean patterns produced by applicator B could be described as triangular in nature. This shape coupled with the correct swath spacing generates a uniform distribution of material. These results are different than the W- and M- shaped patterns observed for applicator A (Fulton et al., 2001).

Figure 4 demonstrates a definite distribution problem for applicator D at the center and right boom. This problem was consistent from pattern to pattern and increased with application rate. The cause for this problem is unknown. It would appear to be a metering issue because the mean pattern results on either side of the peaks, at the center and 5.33 m positions, are similar to the results for the left boom. If it was a deflector or tube problem, then points on either side the peaks would not be the same. Therefore, more material is being conveyed into the tubes feeding the distributors at these locations.

The 95% confidence intervals reveal that applicator B (fig. 2) and applicator D (fig. 4) are consistent applicators. However, applicator C demonstrated quite a bit of distribution pattern variability about the mean patterns especially at the 224 and 336 kg/ha rates (fig. 3). From these figures, applicator D seems to have the tightest 95% CI indicating that it is the most consistent applicator. Applicator B is a close second with applicator C being a distant third. The smaller CI's for applicators B and D are desirable because this indicates that these applicators produce consistent patterns independent of test rate. However, even though they are consistent, pattern problems from either a metering and/or distribution irregularities can have a profound effect on application accuracy.

Overlap Analysis

Figure 5 presents the overlap results for applicator A. These estimated patterns were similar to those generated from applicator B (fig. 6). Peaks formed in the middle with tails exceeding the desired level on the outside for the two higher rates. These results could indicate trends with spinner spreaders that need to be corrected to provide a more uniform distribution of material. An adjustment needs to be made by moving material from the outside of the pattern towards the center to fill the valleys shown for the higher two application rates for both applicators. The peaks occurring at the center of the pattern do meet or exceed the desired application levels for the higher two rate tests for applicator A unlike what was found with applicator B. The trend appearing for these two applicators is that the patterns deviate more from the desired level with an increase in application rates. The 56-kg/ha test for applicator A and the 56 and 112-kg/ha tests for applicator B produced the most uniform results with small deviations from the desired level and patterns being rather horizontal.

Figure 5. Simulated overlap distribution pattern for applicator A.

Figure 6. Simulated overlap distribution pattern for applicator B.

The results for applicator C show quite a bit of pattern irregularities about the desired level (fig. 7). The overlap pattern at all four rates fluctuates about the desired level except at either end of the pattern. As with the spinner spreader, more variability in the pattern occurred with an increase in application rate. A common feature with all four patterns is the under application at

the tails (± 6.10 m) and over application at the centers (0.0 m). Changes to the hardware of the applicator C to improve distribution could minimize this observed overlap variability.

Figure 7. Simulated overlap distribution pattern for applicator C.

The overlap patterns for applicator D show quite of bit of variability as a result of pattern problems noted previously (fig. 8). The left boom seems to produce uniform distribution of material close to the desired level. The center and the peak occurring at the 5.33 m position generate application errors. Similar to applicator C, the tails on all the patterns under apply suggesting a smaller swath spacing. Correction of these under and over application issues could produce a uniform overlap pattern for applicator D. As with the other applicators, increasing the application rate increases pattern variability for applicator D.

Figure 8. Simulated overlap distribution pattern for applicator D.

The under-application occurring at the overlap pattern tails for applicators C and D could be rectified by reducing the swath spacing thereby increasing overlap and the application rates at the tails. Increasing the swath spacing for applicators A and B would generate the opposite effect at the tails. Future analysis should be performed to establish the optimal swath spacing for each applicator.

Table 2 provides summary statistics for the simulated overlap patterns. The CVs for applicator A were good for the lower two rates but greater than 20% at 168-kg/ha. The 56 kg/ha test produced the best results for all the rates and applicators tested with a CV equal to 5.8%. The main concern for this applicator is improving its performance at the 168.1 kg/ha level. A decrease in the mean application would help slightly but the main cause of error was the resulting W-shaped distribution pattern (fig. 5). The desirable action would be to smooth this pattern out by making some mechanical adjustments. This applicator under applied by 3% at the 56-kg/ha rate and over applied by 4% at the 168-kg/ha rate.

Applicator B performed the best with all CVs below 20%, and three tests producing CVs less than 15%. The 56 and 112 kg/ha tests produced CVs less than 10%. The applicator did tend to under apply for all tests by about 5%. An adjustment of the controller would account for this 5% under application.

Applicator C applied at slightly lower rates than the desired application level with the difference from the desired level increasing with a rate increase. All the computed CVs are within an acceptable range (< 20%) with the higher two rate tests producing CVs below 15%. Again, this applicator tended to under apply by 5% which could be accounted for with an adjustment to the controller.

Conversely, applicator D produced CVs between 25% and 34% which resulted from the identified distribution pattern issue. These CVs are well above the acceptable value of 20%. The applicator did tend to under apply except for the 336-kg/ha test. Rectifying the pattern problem should improve the performance of this applicator and produce CVs below 20%. One note is that the overlap plots (figs. 5, 6, 7, and 8) tended to show more variation than the CVs, meaning that the CVs can be used to quantify distribution variability but overlap plots are needed to draw meaningful conclusions about the spread quality.

Table 2. Simulated multiple pass summary statistics (progressive method).

Desired Rate (kg/ha)	Applicator A			Applicator B		
	Mean (kg/ha)	Diff. (kg/ha)	CV (%)	Mean (kg/ha)	Diff. (kg/ha)	CV (%)
56.0	54.2	-1.8	5.8	54.2	-1.8	9.2
112.1	112.3	0.2	18.6	106.1	-6.0	7.8
168.1	175.2	7.1	27.4	-	-	-
224.2	-	-	-	214.3	-9.9	12.0
336.2	-	-	-	318.6	-17.6	16.1
Desired Rate (kg/ha)	Applicator C			Applicator D		
	Mean (kg/ha)	Diff. (kg/ha)	CV (%)	Mean (kg/ha)	Diff. (kg/ha)	CV (%)
56.0	55.2	-0.8	18.9	-	-	-
112.1	105.4	-6.7	17.9	100.9	-11.2	25.5
224.2	212.5	-11.7	14.0	219.2	-5.0	34.0
336.2	320.6	-15.6	11.6	339.3	3.1	29.3
448.3	-	-	-	445.5	-2.8	31.3

Distribution Pattern Comparison

Figures 9, 10, 11, and 12 show the standardized patterns plotted for applicators A, B, C, and D, respectively. These figures indicate that applicator D patterns were the most consistent, with applicator B and C patterns being fairly consistent, but a noticeable pattern shift for applicator A. Table 3 presents the ANOVA results for the pattern comparisons from each applicator.

Figure 9. Standardized distribution patterns for applicator A.

Figure 10. Standardized distribution patterns for applicator B.

Figure 11. Standardized distribution patterns for applicator C.

Figure 12. Standardized distribution patterns for applicator D.

Table 3. ANOVA results for the various applicators.

Applicator	Source	DF	SS	P-value
A	Rate	1	0.106	0.0092
	Position	12	63.46	<0.0001
	Rate by Position	12	2.08	<0.0001
	Error	312	4.8083	
B	Rate	3	0.006	0.9250
	Position	16	95.245	<0.0001
	Rate by Position	48	1.340	<0.0001
	Error	748	9.0606	
C	Rate	3	0.017	0.9440
	Position	16	120.554	<0.0001
	Rate by Position	48	1.9354	0.6773
	Error	748	33.6453	
D	Rate	3	0.01573	0.8068
	Position	16	163.5132	<0.0001
	Rate by Position	48	0.9404	0.1537
	Error	748	12.0411	

For the application rates tested, there was a significant difference in the standardized amount applied by applicator A as judged by the interaction with rate ($P=0.0092$) and position ($P<0.0001$). The significant differences between the transverse positions are to be expected when evaluating the distribution pattern of a spinner disc spreader, since the pattern decreases with distance from the center. More importantly, however, a significant ($P<0.0001$) pattern shift with rate change was confirmed for applicator A. Pattern shifts are undesirable and indicate that several tests would be required for characterizing distribution patterns. Caution should be taken when calibrating an applicator exhibiting this attribute. Since no technology currently exists to correct pattern shifts simultaneously with rate changes, this spreader should be calibrated at the median rate of the expected application range for which the applicator is predominately operated. Once an acceptable distribution is reached, then distribution tests should be performed at low and high rates within the anticipated operating range.

In contrast, applicator B did not show a significant ($P>0.05$) pattern-rate interaction. However, as with applicator A, applicator B demonstrated a highly significant ($P<0.0001$) pattern-position

interaction. These differences are again attributable to the distribution pattern characteristics from a spinner spreader. There was also a highly significant ($P < 0.0001$) interaction between rate and position, indicating a possible pattern shift for applicator B. Upon observation of the patterns, no discernable trend exists for this interaction in its patterns thereby indicating a single pattern test, within normal operating ranges, would be sufficient to characterize the distribution pattern from this applicator.

Similar to applicator B, pneumatic applicators (C and D) showed no significant ($P > 0.05$) rate effect. The pneumatic applicators also shared the spinner discs spreaders significant ($P < 0.0001$) position effect. In contrast to the spinner discs spreaders, the pneumatic applicators exhibited no significant ($P > 0.05$) interaction between rate and position that would indicate pattern shifts.

The results from the pneumatic applicator tests indicate that application rate as a function of position varied ($P < 0.0001$ for position). While this is to be expected for spinner discs spreaders, such variability across the pattern of pneumatic applicators is not desirable. For both pneumatic applicators, however, the standardized rate applied across all positions was very consistent ($P > 0.05$ for rate). The absence of distribution pattern shifts can be expected within the rate ranges tested for these applicators. Such consistency in the distribution patterns of the pneumatic applicators is a desirable feature, as it implies that a single pattern test can be conducted for distribution pattern characterization.

Rate Change Response

The rate transition surfaces are provided in figures 13, 14, and 15 for applicators B, C, and D, respectively. The black line represents the desired rate transition line where the rate change should start (a delay time equal to zero). In most cases, a high percentage of the rate transition occurred within the test areas. However, two transitions appear to either start or end outside the test area (figs. 13b and 15b). However, a majority of the transition was captured during these tests. These surfaces were generated for easier observation of rate change characteristics.

Figure 13. Rate transition surfaces for applicator B; a) 112 to 336 kg/ha and b) 336 to 112 kg/ha.

Figure 14. Rate transition surface for applicator C; a) 112 to 336 kg/ha and b) 336 to 112 kg/ha.

Figure 15. Rate transition surfaces for applicator D; a) 112 to 336 kg/ha and b) 336 to 112 kg/ha.

The start and end distances for the rate transitions were established by using the same four-parameter, sigmoidal regression function to model the rate change as outlined by Fulton et al. (2001). A sigmoidal fit best described both, the increase and decrease rate transitions for applicators B, C, and D unlike the linear response observed for applicator's A high to low transition (Fulton et al., 2001). Sigma Plot 8.0 (Sigma Plot, 2001) was used to fit the sigmoidal functions to each transverse position of all rate transition tests for these applicators. The two outer two rows of pans for applicators B and D, and the three outer rows of pans for applicator C were omitted from this analysis since little or no material was collected in these pans. The R^2 values resulting from this analysis are not presented but ranged from 0.71 up to 0.97 with a majority of the R^2 values occurring in the 0.87 to 0.94 range indicating a good regression fit.

Figure 16. Example illustration for characterizing rate change dynamics (New Leader 0.0 m transverse position).

Figure 16 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 sigmoidal regression minimum and maximum rates on the asymptotic tails. The “delay distance” can be calculated by subtracting the desired from the start distance. Similarly, the “rate transition distance” equals the end distance minus the start distance. These distances can then be converted into time using the applicator ground speed (Table 1) thereby estimating the “delay” and “rate transition” times. The delay and transition times determined for each transverse position were then averaged to calculate these times for each applicator.

The transition and delay times for applicator’s A 56 to 168-kg/ha test were computed in the same manner since sigmoidal in nature. However, the characterization method was slightly modified for the 168 to 56 kg/ha transition to account for the linear nature of the transition (Fulton et al., 2001). In this case, it is hard to determine from the rate transition surface whether the complete transition was captured. The mean 56 and 168-kg/ha pattern data 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. The outer three rows of pans were omitted from these analyses. The regression analysis resulted in R^2 values ranging from 0.63 up to 0.91 indicating moderate to good fits.

The transition tests for applicator A were performed between 56 and 168 kg/ha (Fulton et al., 2001). The calculated times for applicator A are different for the two tests. The transition time took almost four seconds longer for the 168 to 56-kg/ha test but the transition started 1.7 seconds before the 56 to 168-kg/ha test. These results show inconsistency in rate response for this VR control system.

Table 4. Rate transition characteristics.

Applicator	Test	Transition Time (sec)	Delay Time (sec)
A	56 to 168 kg/ha	6.7	3.3
	168 to 56 kg/ha	10.6	1.36
B	112 to 336 kg/ha	3.6	-0.9
	336 to 112 kg/ha	7.1	-3.5
C	112 to 336 kg/ha	0.4	1.5
	336 to 112 kg/ha	0.3	1.2
D	112 to 336 kg/ha	6.6	0.1
	336 to 112 kg/ha	12.4	-4.3

The rate response characteristics were different for applicator B for increasing versus decreasing rate changes (Table 4). The rate transition time nearly doubled for the 336 to 112-kg/ha transition. The delay time for both tests were negative meaning that the rate change started before zone transition but the delay started 2.6 seconds sooner with decreasing rates.

Applicator C demonstrated the most consistency with nearly the same rate transition and delay times (Table 4). This is a desirable feature for this applicator’s VR system since a single, proper delay time could adjust the rate change to occur at the proper time. The VR control system of

applicator C also produced the quickest rate transition time at less than 0.5 seconds. In general, the VR control systems response for applicators B and C are faster than that of A.

The contouring effect of the prescription maps (applicator D) resulted in longer response times (Table 4). The rate transition time nearly doubled when decreasing the rate. A similar trend observed with applicator B for decreasing rate transition. The delay time for the 112 to 336 kg/ha rate change was close to zero whereas the rate transition started about four seconds ahead of the zone boundary. Due to the magnitude of the rate transition times, it would be desirable to have the rate transition be split between management zones. This could be the reason contouring prescription maps is implemented to help minimize errors at zone boundaries. It was difficult to determine whether the contouring effect or the VR system had a significant impact on the transition times.

One similarity between applicators A, B and D VR systems was that the transition time took longer when decreasing the rate than increasing it. In theory, it would be desirable for the transition times to be similar if not equivalent. In two cases, this time nearly doubled. 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 occurred 4.0 seconds shorter.

The rate response characteristics are important parameters to be considered by VR software developers and users of VRT equipment. While the equipment tested in this investigation varied from applicator to applicator, some important characteristics resulted that could have implications for future system designs and calibration of VRT equipment. These results also emphasize the need for the development of a standard pertaining to VRT systems.

Ideal rate transition times of zero would result in an instantaneous transition or perfect step response. In reality, delay times between 0.0 and 1.0 seconds or even up to 1.5 seconds would be highly desirable for a VR control systems. For applicator D, contouring the prescription map through its software appears to alter the rate transition time for it. The transition times for rate changes dictates management zone resolution especially if they become large. Therefore, the rate transition time can influence the selection of management zone dimensions.

Varying delay times can be accommodated in software using the “look-ahead” feature. The proper delay or “look-ahead” time would ensure rate changes occur at the appropriate time. This assumes that delay times for rate increases and decreases are the same for a VR system. For example, a single rate delay time could be used for applicator C to shift the rate transition to the appropriate point in time. On the other hand, differences in the delay times with the other applicators indicates that two “look-ahead” times made be needed to correctly adjust the rate transition timing. Currently this dual feature is not an option in most VR software packages.

Conclusion

Distribution patterns were characterized from various VR granular applicators to assess application accuracy. Applicator B produced consistent triangular shaped patterns at all test rates unlike the pattern shifts observed the spinner spreader (A) tested by Fulton et al. (2001). Applicator C, a pneumatic applicator, produced a consistent pattern at all test rates but exhibited high variability for each pattern at a particular rate. Applicator D, another pneumatic applicator, produced the most consistent pattern from test to test but exhibited distribution problems at the right and center boom sections.

Simulated multiple-pass overlap distribution patterns were developed to better assess spread quality. Looking only at the computed CVs, applicator B produced desirable results with CVs less than 20% with the three lower rate tests having CVs below 15%. This applicator did under apply by around 5%. Applicator A performed well at the 56 and 112-kg/ha levels but not for the

168-kg/ha test (CV = 27.4). Applicator C performed within acceptable limitations with CVs under 20% for all tests but under applied by about 5% at all rates. The overlap patterns highlighted the distribution pattern problem for applicator D with CVs between 25% and 34%. These CVs are well above the accepted 20% level. However, because of the consistency of this applicator, the CVs would be expected to fall below the acceptable level if the pattern irregularities are resolved. The simulated overlap plots illustrated similar results but indicated more pattern variability for all applicators. These plots also show where pattern correction is needed. Hence, distribution plots should accompany the calculated CVs to assess application quality during calibration and any field tests.

The standardized, single-pass distribution pattern comparisons indicated no difference ($P > 0.05$ for rate and rate*position) existed in the patterns produced by either pneumatic applicator (C and D). The consistency in distribution patterns by each of these applicators means that a single-pass pan test may be sufficient to represent the patterns at all rates. The analysis for applicator B also supported no difference in its four patterns ($P > 0.05$ for rate), but the analysis did show that rates within some transverse positions were significantly different ($P < 0.0001$). However, similar to the pneumatic applicators, one distribution test should suffice to characterize the expected patterns. For applicator A, a significant difference ($P = 0.0092$) was found between patterns verifying a pattern shift. Thus, this result suggests a more intensive testing for an applicator exhibiting patterns shifts.

Rate response tests demonstrated that VR system for applicator C was quick and consistent (rate transition < 0.4 sec.). While the rate transition time was quick, applicator C did have around a 1.2 to 1.5 second delay time. The other applicators were inconsistent in their rate responses producing differing delayed transition times and varying delay times. The rate transitions for applicator D occurred over a longer period of time (> 6.6 sec.) compared to applicators B and C. The transition times for applicator A over both tests were lengthy (> 6.7 sec.). The “look-ahead” feature of most software applications can be utilized to correct for consistent delay times (low to high and high to low). However, differing delay times whether increasing or decreasing, could mean that two “look-ahead” times are required to properly shift rate changes. The results of this investigation can help equipment and software manufacturers develop more accurate products and assist users in properly calibrating VRT equipment. More importantly, this research highlights the need for a standard to test VRT equipment.

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