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EVALUATING A MOBILE CONTINUOUS-WEIGHING FLOW RATE MEASUREMENT SYSTEM

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Abstract

In 1996, cotton yield monitors were not commercially-available. To facilitate in-field yield variability research, a weighing basket was installed in a Case IH 2155 cotton picker. Data gathered with the weighing basket allowed generation of cotton yield maps containing one data point per second of machine operation. Following basket installation, a set of tests was planned to evaluate measurement system performance. Tests were designed to allow evaluation of the uncertainty expected in each individual yield measurement. System dynamic response was also evaluated. One important objective was to generate data representative of typical operating conditions, thus tests were conducted while the harvester traveled along the edge of a cotton field. Known flow rates were provided by pumping water into the weighing basket, and a turbine flow meter was used as a comparative reference. Step loads were applied to allow investigation of system response time requirements. Result reporting techniques were derived from the American National Standard for test uncertainty and common system analysis texts. According to test results, the uncertainty associated with any individual steady-state flow rate measurement could be expected to fall in the range of ± 0.4 lb/s (95% confidence). This corresponded with ± 480 lb seed cotton per acre (95% confidence) assuming a four-row picker configured for 40-in. rows traveling at 2 mph. Random uncertainty was dominant (±0.4 lb/s, max) when compared with systematic uncertainty (±0.04 lb/s, max), thus spatial averaging has potential to reduce uncertainty in yield measurements. Dynamic responsiveness was limited by filtering techniques used to reduce the effect of transients in basket weight versus time data. Rise time was used as the measure of dynamic responsiveness, and had a maximum value of 11 seconds when responding to a step load. The assumed 4-row harvester covers 0.01 acres in 11 seconds. Testing and result reporting methods used in this study can be modified for future use in performance testing of mobile, continuous-weighing flow rate measurement systems.

Introduction

In 1996, cotton yield monitors were not commercially-available. To facilitate yield variability research, a weighing basket was installed in a Case IH 2155 cotton picker. After installation, a set of tests was planned to evaluate system performance. Test objectives included estimation of the uncertainty expected in steady-state cotton flow rate measurements and quantification of measurement system dynamic response. In contrast to tests that depended on integration of uncertainty over one or more basket loads, these tests were intended to produce uncertainty estimates for individual flow rate measurements. Testing the system under typical field conditions was considered important. Although the literature contained many examples of performance testing for similar devices, no single report provided methods that completely fulfilled these objectives. Elements from several different testing regimens were combined into a suitable method. The American National Standard for test uncertainty and common system analysis texts were used to guide result reporting. The techniques described herein can be modified for future use in performance testing of mobile, continuous-weighing flow rate measurement systems.

Weighing Basket Description

The cotton weighing basket was functionally similar to that described by Fernandez (1999). Basket dimensions were 9 ft x 10 ft x 5.5 ft to yield a floor area of 90 ft^2 and volume of 495 ft^3. Because of uneven filling, only 85% of the volume was usable, thus the volumetric capacity of the device was 420 ft^3. Although ASAE standards suggest that bulk density of unpacked seed cotton blown into a harvester basket is 5 lb/ft^3 (ASAE, 2001), experience with the weighing basket suggested a much lower density, and 1000 lb was considered the maximum load. Basket structure was provided by a steel frame, and walls were covered with 3/4-in. flattened expanded metal. Twin-wall polycarbonate sheet 5/16 in. thick was used for the floor. Approximate empty weight was 700 lb. Four 1000-lb load cells suspended the basket inside the picker. Two four-bar linkages, one attached to the rear and one attached to the right side, connected the weighing basket to the cotton picker frame and minimized lateral motion. Links were jointed with spherical bearings which allowed enough free-play to accommodate load cell elongation. The left side of the basket included a large door to allow manual unloading. Figure 1 depicts the left side of the weighing basket as installed in the harvester.

In order to minimize the effect of off-highway vehicle dynamics, harvester travel speed was maintained at a constant 2 mph while the weighing basket was in use. During operation, force measurements from the load cells were acquired at a rate of 10 Hz. Once every second, the ten previous measurements were averaged, and individual cell results were summed to obtain a basket weight measurement which was recorded. This sampling technique generated a data set containing one basket weight measurement per second of operation. Data were post-processed and combined with position information to produce site-specific cotton yield estimates.

Post-processing involved application of a running average to reduce the magnitudes of transients, and a running regression to estimate the slope of the weight versus time function. A common window-width was used for both the average and regression operations. As shown in figure 2, increasing the window-width reduced the uncertainty in steady-state flow rate measurements, but increased the time required to respond to a step load. After reviewing an initial data set, a nine-second window-width was selected.

The moving average minimized effects of transients in basket weight measurement caused by off-highway vehicle dynamics. Figure 3(a) is a typical graph of basket weight as a function of time. In figure 3(b) results of the nine-second running average are shown. After averaging, basket weight was converted to flow rate through application of a running regression. This included a least-squares linear regression performed on basket weight values from the nine-second moving window, similar to that described by Thomas et al. (1999). The result was a data set containing an individual cotton flow rate measurement per second of system operation. Ground speed was derived from position information provided by a Global Positioning System receiver and was combined with machine width to produce harvest rate. Harvest rate and flow rate were combined to obtain seed cotton yield, shown graphically in figure 3(c).

Measurement system performance evaluation required investigation of two properties. Estimation of uncertainties associated with individual cotton yield measurements was needed. In addition, a measure of dynamic responsiveness was required. Evaluating dynamic response was especially important since the running average and running regression techniques used in data processing increased response time. A literature review was conducted to explore testing and result reporting methods previously applied in similar work.

Literature Review

Crop Yield Quantification Tests

Crop yield quantification tests allow comparisons between site-specific yield measurements generated by the system of interest and measurements based on samples harvested by other means. Godwin et al. (1999) evaluated the performance of an instrumented trailer that served a sugar beet harvester. The researchers compared yield data generated by the trailer with yield estimates generated by batch weighing sets of machine-lifted sugar beets from nearby field locations. Results were reported in terms of differences between wagon-generated and sample-based yield measurements. Searcy (1998) used seed cotton yield estimates based on hand-harvested samples as references while evaluating a weight-based cotton yield measurement system. Sample areas were defined by visually assessing a cotton field and selecting areas with different yield levels. Two samples were hand-harvested from each area, and the resulting reference yield values were compared with system-generated yield measurements. Results were reported as a 95% yield prediction confidence interval developed using least-squares linear regression.

Crop yield quantification tests have a distinct advantage over other methods in that they allow direct evaluation of uncertainties in yield measurements. However, two disadvantages associated with this type of tests discouraged application. Crop yield quantification tests rely on the assumption that spatial yield differences between sampling locations and system measurement locations are negligible. Searcy's work illustrated problems with that assumption. Although cotton yield within each sample area in the study appeared to be uniform, considerable differences between pairs of hand-harvested samples from common sample areas were discovered (Searcy, 1998). Another negative feature associated with crop yield quantification tests is the assumption that harvest efficiency of the yield measurement device will be equal to that of the method used to harvest the reference samples. Verification of this assumption is often difficult.

Weighing System Tests

Most of the system tests reported in the literature involved separating the weighing device from other system components, and evaluating it alone. This approach is adequate, provided it is understood that site-specific yield measurement errors arise from all system components, not just the weighing device. Both mobile and stationary weighing system tests have been performed. Mobile tests are generally more difficult to conduct than stationary tests, but provide information about system performance under normal operating conditions. Within the stationary and mobile groupings, several test procedures have been used.

Stationary Tests. Stationary, incremental weight addition tests consist of adding known increments of weight to a stationary system. Tests of this type were reported by Wild and Auernhammer (1999), who added weights to a large round-baler equipped with weighing instrumentation. Results of these replicated tests were reported in terms of mean differences between measured and known weight values. A 95% weight prediction confidence interval was also reported. While this type of test is well suited for evaluating stationary scales, it is of limited value for evaluating weight-based flow rate measurement systems since it provides no opportunity to directly assess flow rate measurement uncertainty.

Stationary, known flow rate tests consist of adding material to a stationary system at known constant flow rates. One such test was reported by Thomas et al. (1999). Water was pumped into a combine-mounted peanut weighing basket at several constant flow rates. Multiple measurements were recorded at each rate, and results were reported in terms of standard deviation. This type of test produces valuable information describing system response to known flow rates. However, it may tend to produce results that are overly optimistic since effects of vehicle dynamics are not included.

Mobile Tests. Mobile, zero-flow tests consist of collecting flow rate data under typical operating conditions while the actual inflow rate is zero. Tests of this type were reported by Godwin et al. (1999). A trailer instrumented for continuous weighing was operated under typical field conditions with no crop inflow. Flow rate measurements that deviated from zero were recorded and presented as results of the study. This type of test gives results that describe the random uncertainty associated with off-highway vehicle dynamics, however the correct method for applying the results to situations in which the flow rate is greater than zero is unclear.

Mobile, load weight prediction tests consist of operating the system under typical field conditions and integrating flow rate measurements over time to calculate predicted load weights. These predicted load weights are compared with weight measurements made with scales. Tests of this type were reported by Wild and Auernhammer (1999). A large round-baler equipped with weighing instrumentation was used to bale hay. Flow rate measurements were integrated over time to predict the weight of each bale. After each bale was deposited, it was weighed using scales. Results were reported in terms of deviations between system-predicted and scale-measured load weights. In a similar study, the same authors reported harvesting pre-weighed samples of forage from partial swaths. The partial swaths were arranged with clean gaps in between, and the machine was operated to achieve a pattern of forage intake, no forage intake, forage intake, etc. System-generated estimates of the weight accumulated during each period of forage intake were recorded and compared to reference measurements. Again, deviations between the system-generated weight estimates and scale-measured weights for each partial swath were reported. A negative feature of load weight prediction tests is that integration over the time required to accumulate a load reduces random uncertainty. This produces results that may underestimate the uncertainty of individual flow rate measurements.

Tests for Evaluating Dynamic Responsiveness

Many mobile, continuous-weighing flow rate measurement systems described in the literature use averaging or filtering techniques to reduce errors introduced to weight versus time data by off-highway vehicle dynamics. These processing techniques increase system response time. While extremely important to the overall performance of a flow measurement system designed to gather site-specific crop yield data, dynamic responsiveness testing is not widely reported in the literature. In one reported test, Godwin et al. (1999) measured the dynamic responsiveness of an instrumented trailer by subjecting the system to a step load of known flow rate and measuring response time. Results were reported in terms of the time required for flow rate measurement system output to reach 100% of the step load.

Reporting Techniques

As evident in the above descriptions, test results have been reported in many forms. Ideally, results should give an estimate of the uncertainty expected in future measurements, and of the confidence to place in that estimate. The regression-based confidence intervals reported by Searcy (1998) address this need. Test results that allow decomposition of uncertainty estimates into random and systematic components are also desirable since different methods are available for reducing magnitudes of these components. Regression-based analysis does not readily provide separate estimates. The American Society of Mechanical Engineers (ASME) has published a guide for formulating and reporting estimates of measurement uncertainty (ASME, 1998). This document is in harmony with international standards (ISO, 1995) and has been approved as an American National Standard. When applied to weighing system test data, the ASME method provides uncertainty estimates with associated confidence levels. Unlike regression-based techniques, the calculation procedure suggested by ASME generates separate estimates of uncertainties due to random and systematic components. Random and systematic uncertainty components are combined using the root-sum-square technique to produce an overall uncertainty estimate. This method for formulating and reporting test results was selected.

Expressing information about dynamic responsiveness is not covered in the ASME document. Results reported by Godwin et al. (1999) that included response time after application of a step load were reasonable. Rise time is a standard measure of response to a step load, and is defined in many texts as the time required for a step response to go from 10% to 90% of its final value (Jones and Hale, 1982; Shahian and Hassul, 1993). Rise time has the most utility when magnitude of the step load is carefully chosen such that it corresponds with expected operating conditions.

Test Methods

Overview

A test procedure for evaluating weighing basket performance was developed to fulfill the overall goals of estimating uncertainty present in individual flow rate measurements and quantifying system response time. Specific objectives were formulated to provide data required for application of the ASME test uncertainty calculation procedure and for rise time determination. The ASME procedure depends on estimates of both systematic and random uncertainty. Systematic uncertainty can be estimated through comparison with an alternate measurement technique, thus reference flow rate measurements were required. Random uncertainty estimates can be derived from a measure of scatter present in repeated measurements of a constant measurand. Generating these data required the ability to hold flow rate constant while making repeated measurements. Rise time determination required application of step input functions of reasonable magnitudes. Objectives also included test execution under typical field conditions, and application of flow rates over the complete expected range.

The work of others was considered, and techniques were adapted from that work. To allow direct comparison of known and system-generated flow rate measurements, a procedure similar to the one reported by Thomas et al. (1999) was chosen. Water was pumped into the weighing basket at a constant flow rate while multiple measurements were acquired. A turbine flow meter provided reference flow rate measurements. Water flow was diverted to the weighing basket during each test to approximate a step input function, and the steady flow portion of the test continued long enough to allow collection of more than 40 measurement observations. Tests were performed while the host machine traveled across typical field terrain in a manner similar to that of Godwin et al. (1999). Water flow rates were selected to approximate the entire range of expected cotton flow rates. Five target flow rates of 0.7, 2.0, 3.4, 4.7, and 6.1 lb/s were used, and two tests were performed at each flow rate. One test began with an empty basket, and the other included an initial 500-lb load.

Equipment

Test equipment included a water reservoir, pumping and distribution system, catch vessel, and reference flow meter. A schematic of the test equipment layout is given in figure 4. The cotton picker had a 365-gallon tank as part of the spindle moistening system, and that tank was used as the reservoir. A Honda WP30X water pump unit equipped with a 5.5-hp engine and 264-gpm centrifugal pump was used to transfer water from the reservoir to the catch vessel. The pump unit was also used to empty the catch vessel as necessary. One three-way valve was used to establish the proper flow rate for a test by diverting a portion of the flow back to the reservoir. A second three-way valve was provided to allow switching flow from another reservoir-return line to the catch vessel. This plumbing scheme permitted (1)establishment of the proper target flow rate while returning water to the reservoir and (2)rapid diversion of flow into the catch vessel. The catch vessel comprised two 300-gallon galvanized stock tanks. One tank would have provided sufficient volume, but two were used to distribute the load over a larger fraction (23%) of the basket floor area. Flow was split into the two tanks, and baffles were added to minimize water movement.

A reference flow meter provided data used to estimate systematic uncertainty. The device was a single-rotor turbine meter manufactured by Flowdata, Inc. (PN: ES10SS-6FM-DL-110-00) with a specified systematic uncertainty of ±0.1% of the flow rate. This corresponded with a maximum systematic uncertainty of ±0.01 lb/s at the largest flow rate used in the tests. Flow rate uniformity was evaluated for each test using the sample standard deviation. Table 1 contains information used to assess reference flow rate measurements. Flow rates were uniform with a maximum sample standard deviation of 0.014 lb/s. This uniformity allowed an assumption of constant flow rate, and the mean of flow meter measurements was considered the true value for systematic uncertainty evaluation in each test.

Procedure

A 350-ft course was established along the edge of a cotton field, as illustrated in figure 5. The harvester followed the same travel path, and was driven at a constant ground speed of 2 mph along the length of the course during each test. Marker flags were used to designate points along the course where flow was to be diverted to and from the catch vessel. Each test consisted of (1)setting the initial basket load to the appropriate level, (2)setting the proper flow rate, (3)starting harvester travel down the course, (4)diverting flow to the catch vessel and then back to the reservoir-return at the appropriate points, and (5)completing the course. The harvester was operated at normal engine speed of 2150 rev/min during the tests with the cotton conveying fans out-of-gear. Five target flow rates of 0.7, 2.0, 3.4, 4.7, and 6.1 lb/s were used to cover the expected operating range of 750-6750 lb seed cotton per acre. The combination of five flow rates and two initial basket loads of 0 and 500 lb yielded ten tests.

Flow rate measurements from the reference meter and the weighing basket are shown for a typical test in figure 6. Rise time was measured for each test as shown. A 40-observation sample was selected from the steady-flow portion of each test data set, and the mean of reference meter observations from the sample was calculated. Weighing basket systematic uncertainty was determined by finding the difference between the means of weighing basket and reference meter observations. The sample standard deviation of weighing basket flow rate measurements from the 40-observation sample was multiplied by the appropriate coverage factor (Student's $t_{95} \sim 2$, > 30 degrees of freedom) to obtain an estimate of weighing basket random uncertainty. The maximum values of systematic and random uncertainty were combined for each flow rate using the root-sum-square technique. This gave an overall measurement uncertainty estimate for each flow rate.

Test Results

Uncertainty estimates were converted to units of seed cotton yield (lb/ac) assuming a four-row harvester configured for 40-in. rows and a travel speed of 2 mph. Systematic uncertainty estimates are presented in table 2, and random uncertainty estimates are presented in table 3. The maximum estimates of systematic and random uncertainties were ±0.04 lb/s and ±0.4 lb/s, respectively. Maximum values of systematic and random uncertainty were combined for each flow rate using the root-sum-square technique, and resulting uncertainty estimates are shown graphically in figure 7. Maximum weighing basket uncertainty was ±0.4 lb/s (95% confidence) which is equivalent to ±480 lb seed cotton per acre (95% confidence). As shown in figure 7, individual yield estimates generated with the weighing basket can be expected to fall within ±29% of the true value when seed cotton yield is 1500 lb/acre, within ±17% when yield is 3000 lb/acre, and within ±9% when yield is 4500 lb/acre. Rise time from each test is presented in table 4. The maximum value of rise time was 11 seconds.

Summary and Conclusions

Measurement system evaluation techniques were developed for use in evaluating mobile, continuous-weighing flow rate measurement systems. Test objectives included allowing evaluation of uncertainties expected in individual flow rate measurements and describing system dynamic response. Tests were conducted by pumping water into the weighing device at known flow rates while the machine traveled across a course simulating field conditions. Tests were designed to cover the entire range of expected flow rates. Systematic uncertainty was estimated by comparisons with a reference flow meter. Random uncertainty was estimated by measuring scatter in repeated measurements of a constant flow rate. A confidence interval based on combined systematic and random uncertainty terms was developed. Dynamic response was evaluated by measuring system response to a step load.

A cotton weighing basket designed to allow quantification of in-field yield variability was evaluated using the techniques described. Maximum uncertainty for any individual flow rate measurement made with the basket was ±0.4 lb/s (95% confidence). Random uncertainty was dominant (±0.4 lb/s, max) when compared with systematic uncertainty (±0.04 lb/s, max), thus spatial averaging has potential to reduce uncertainty in basket-generated measurements. Uncertainty estimates were converted to units of seed cotton yield (lb/ac) assuming a four-row harvester configured for 40-in. rows and a travel speed of 2 mph. Individual yield estimates generated with the weighing basket can be expected to fall within ±29% of the true value when seed cotton yield is 1500 lb/acre, within ±17% when yield is 3000 lb/acre, and within ±9% when yield is 4500 lb/acre. Rise time measurements indicated that 11 seconds were required for the system to respond to a step load. Based on previously-stated assumptions, the harvester would travel 32 ft in 11 seconds, thus covering 0.01 acres.

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Table 1. Information used to assess reference flow measurements.

Target Flow Rate (lb/s)	Test No.	Initial Load (lb)	Mean Meter Reading (lb/s)	Meter Systematic Uncertainty (lb/s)	Meter Standard Deviation (lb/s)
0.7	1	0	0.67	0.001	0.008
	2	500	0.66	0.001	0.008
2.0	3	0	2.02	0.002	0.014
	4	500	2.01	0.002	0.013
3.4	5	0	3.32	0.003	0.009
	6	500	3.31	0.003	0.008
4.7	7	0	4.89	0.005	0.006
	8	500	4.89	0.005	0.009
6.1	9	0	6.31	0.006	0.009
	10	500	6.32	0.006	0.010

Table 2. Data used to calculate systematic uncertainty.

Target Flow Rate (lb/s)	Test No.	Initial Load (lb)	Mean Meter Reading (lb/s)	Mean Weighing Basket Reading (lb/s)	Systematic Uncertainty (lb/s)
0.7	1	0	0.67	0.66	-0.01
	2	500	0.66	0.63	-0.03
2.0	3	0	2.02	1.98	-0.04
	4	500	2.01	1.98	-0.03
3.4	5	0	3.32	3.31	-0.01
	6	500	3.31	3.29	-0.02
4.7	7	0	4.89	4.89	-0.001
	8	500	4.89	4.88	-0.01
6.1	9	0	6.31	6.29	0.02
	10	500	6.32	6.31	-0.01

Table 3. Data used to calculate random uncertainty.

Target Flow Rate (lb/s)	Test No.	Initial Load (lb)	Weighing Basket Standard Deviation (lb/s)	Random Uncertainty (lb/s)
0.7	1	0	0.057	0.11
	2	500	0.125	0.25
2.0	3	0	0.044	0.09
	4	500	0.215	0.43
3.4	5	0	0.061	0.12
	6	500	0.163	0.33
4.7	7	0	0.110	0.22
	8	500	0.051	0.10
6.1	9	0	0.177	0.35
	10	500	0.132	0.26

Table 4. Rise time measured for each test.

Target Flow Rate (lb/s)	Test No.	Initial Load (lb)	Rise Time (s)
0.7	1	0	11
	2	500	4
2.0	3	0	7
	4	500	10
3.4	5	0	9
	6	500	9
4.7	7	0	10
	8	500	9
6.1	9	0	9
	10	500	9

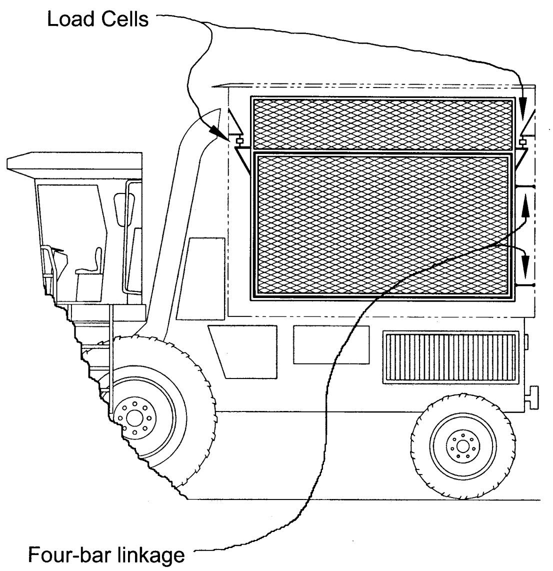

Figure 1. The weighing basket was mounted inside the harvester.

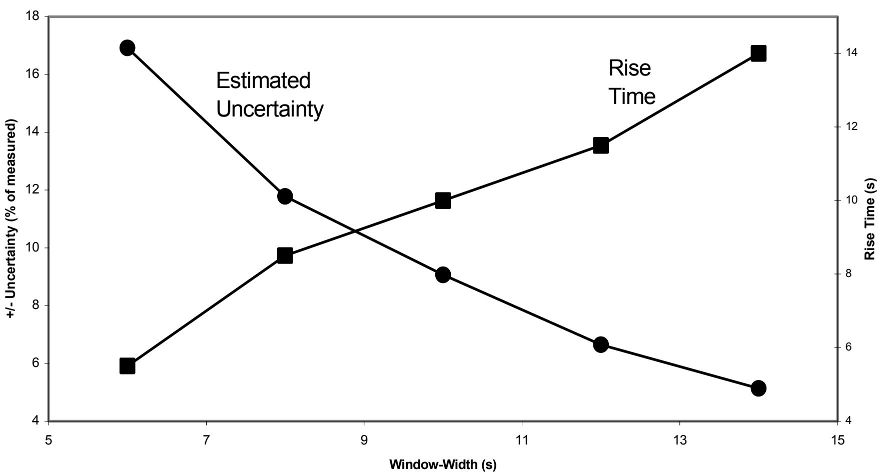

Figure 2. Estimated uncertainty and rise time as a function of window-width for a typical flow rate.

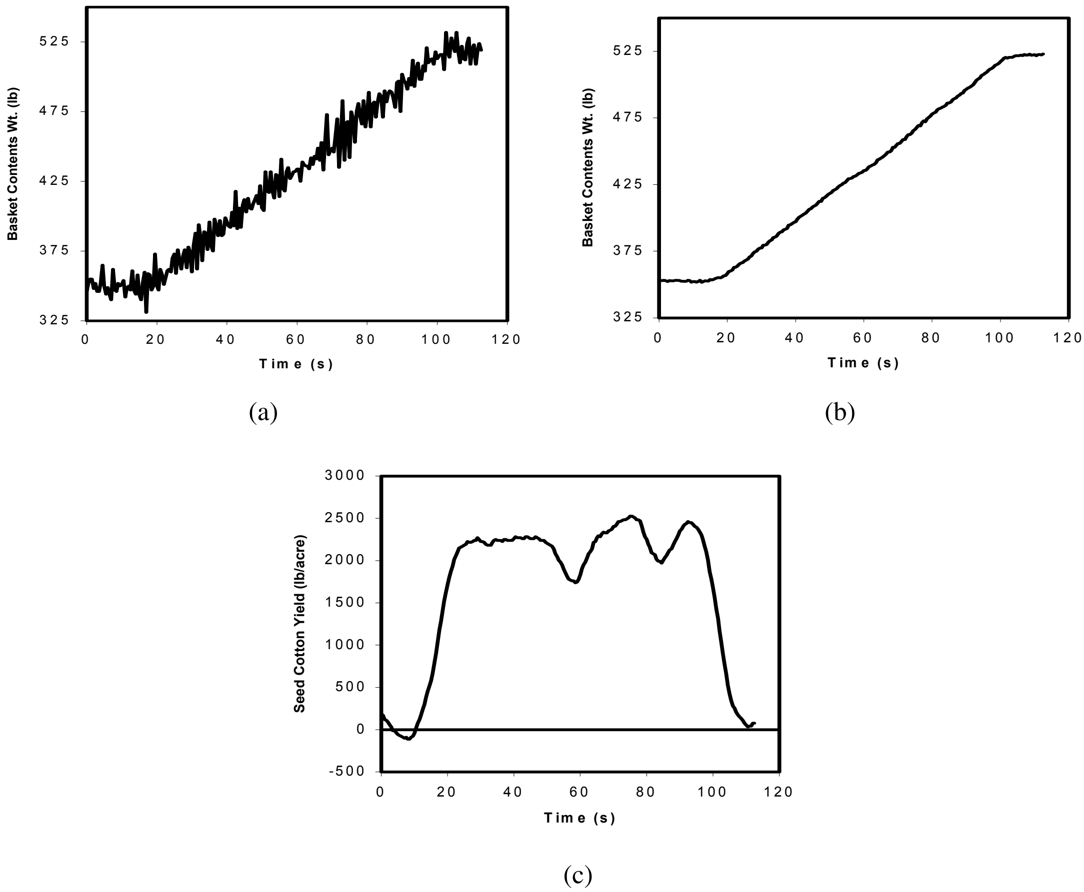

Figure 3. Recorded weights from the basket (a) are processed by first applying a moving average function to produce the data shown in (b). Flow rate measurements from a running regression technique are combined with harvest rate to produce seed cotton yield (c).

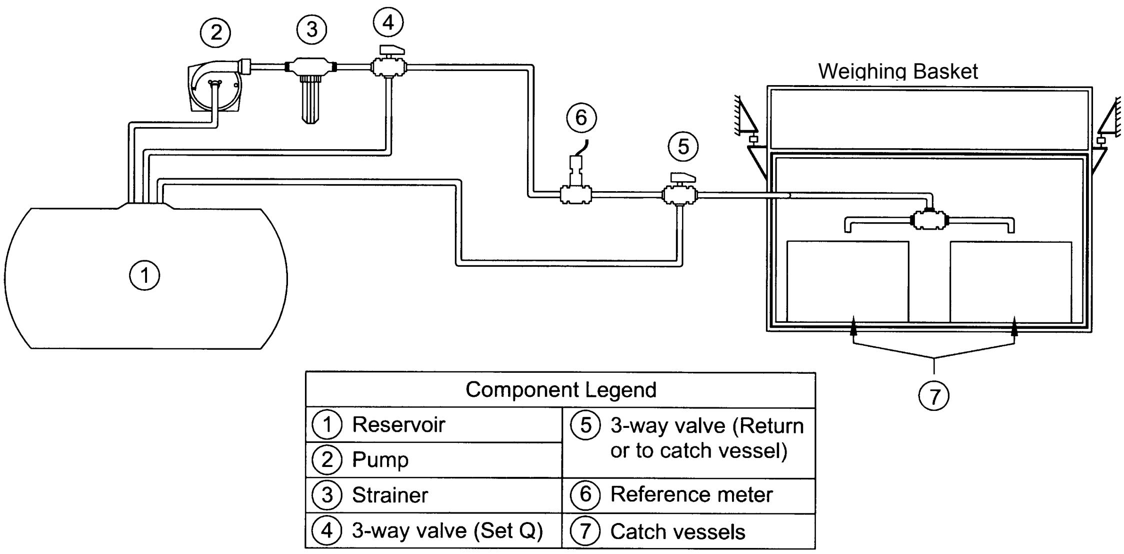

Figure 4. Fluid circuit used to deliver water to the weighing basket during field testing.

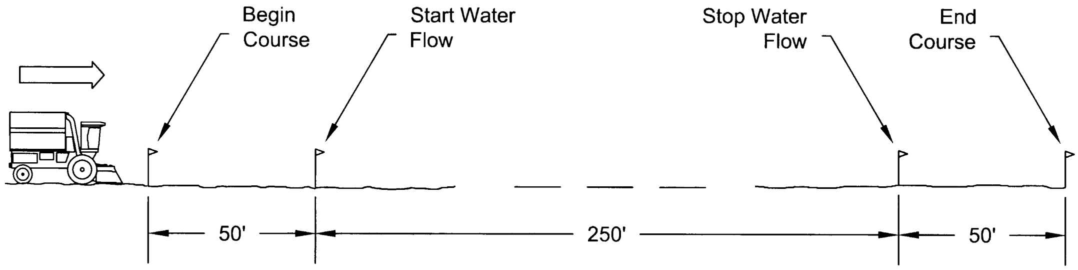

Figure 5. The test course included a 50-ft length with no water flow, a 250-ft length with water flow, and a 50-ft length with no water flow.

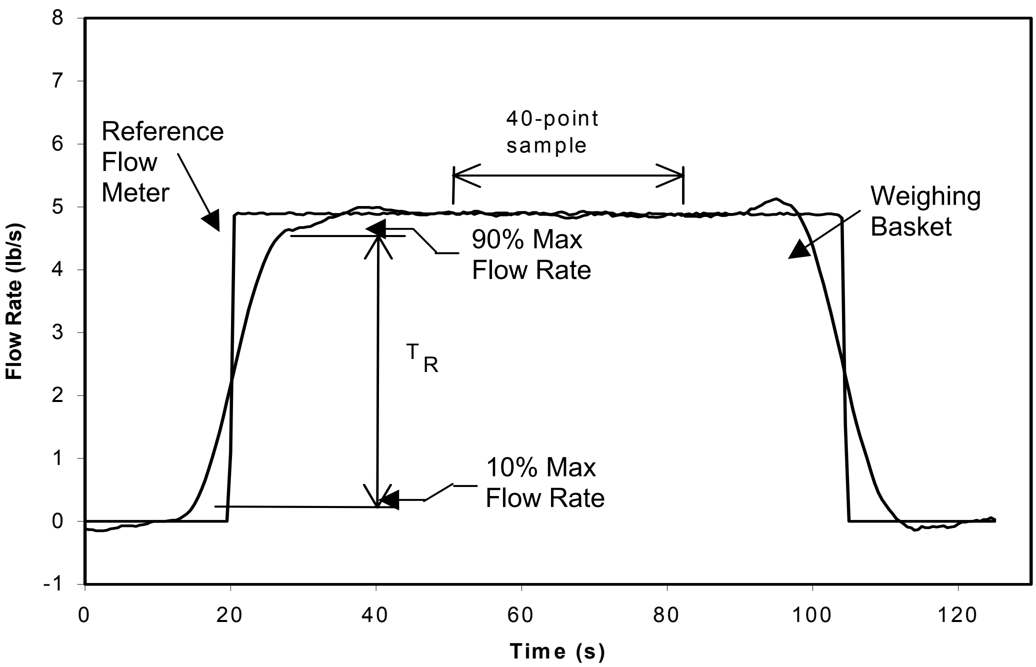

Figure 6. Rise time (T_R) and the 40-point flow rate comparison sample are illustrated.

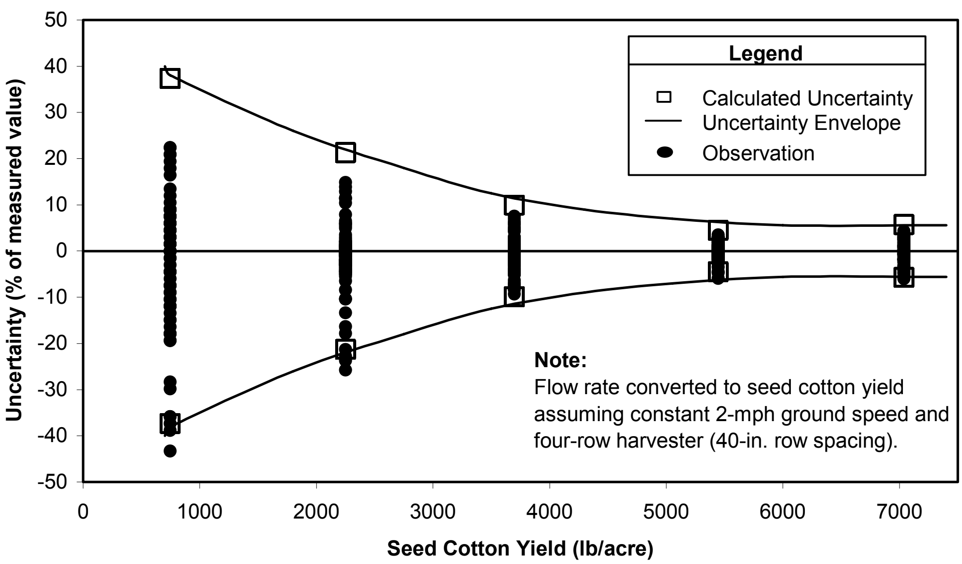

Figure 7. This 95% confidence level uncertainty envelope applies to individual seed cotton yield measurements obtained with the weighing basket.