EVALUATION OF GROUND SPEED SENSING DEVICES UNDER VARYING GROUND SURFACE CONDITIONS

By

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EVALUATION OF GROUND SPEED SENSING DEVICES UNDER VARYING GROUND SURFACE CONDITIONS

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INTRODUCTION

The determination of accurate tractor ground speed is imperative for many agricultural operations. Ground speed is used as an input for varying the quantities of fertilizer, pesticides, or herbicides applied. It forms the basis for optimum application of chemicals thus resulting in minimizing crop inputs and maximizing profits. In addition, ground speed is also used for controlling the laying of seeds at optimum distance to improve planting efficiency. Therefore, determination of accurate and precise tractor speed is critical to optimize the application of high cost farm inputs. Many speed sensing methods have been developed to achieve this objective.

In the past, wheel speed sensors were used to measure tractor speed. These were inaccurate because of low resolution, wheel slip, and loss of surface and wheel contact. Radar speed measurement systems are commonly used due to their reasonable cost and acceptable accuracy. However, empirical field observations indicate that radar ground speed measurements contain increased error as crop vegetative height increases. A GPS based velocity sensor has been recently developed that can be used instead of radar sensors and wheel speed sensors.

In this study, two radar sensors and a GPS based velocity sensor were used for ground speed measurements under varying ground surface conditions. The responses of these sensors were evaluated compared to a reference speed. The issues pertaining to measurements of true ground speed were identified and evaluated with emphasis on addressing the accuracy and precision of these devices.

1.1 Objectives

The main objectives of this study were to assess:

a) The accuracy and precision of four speed measuring devices under constant velocity conditions on four different surfaces.
b) The velocity error of three measuring devices during acceleration of the tractor.

CHAPTER II

REVIEW OF LITERATURE

Due to the importance of determining true ground speed for agricultural applications, numerous studies have been conducted on the subject for more than three decades. A study by S.S Stuchly et al., (1978) identified the need for an accurate method of determining the true ground speed of agricultural and other off-highway equipment. The fifth wheel and free-rolling wheels were predominantly used to measure ground speed relative to the ground surface (Luth et al., 1978, Garner et al., 1980, Lin et al., 1980). The ground speed measurement was also determined by measuring the rotation of tractor front wheel itself (Grevis-James et al., 1981).

However, the problems associated with measurements of ground speed using rear or un-driven wheels were identified by Tsuha et al., (1982). The main problems were:

a) Slippage of rear wheel relative to ground surface.
b) Lifting of un-driven wheels off the ground, thereby resulting in erroneous measurements in the ground speed.
c) Poor accuracy and resolution.
d) Wheel slip associated with un-driven wheels due to steerage.

Therefore, a non-contact ground speed measuring technique was proposed by using a radar sensor. The absolute accuracy of the radar sensor was between 1-4% over a variety of surface conditions such as concrete, sand, mud, asphalt, grass, tiled soil, and moist surfaces. The accuracy of the sensor was between ± 2% and ± 5% both during controlled field conditions and in actual working conditions (Tsuha et al., 1982).

N.A. Richardson et al., (1983) identified the limitations on the use of low cost optical and acoustical sensors. It was concluded that there is very close correlation between fifth wheel speed measurements and un-driven tractor wheel measurements, when the tractor is driven on smooth, and firm soil conditions. The dual beam radar sensor was found to be less sensitive to vehicle motion as compared to single beam radar sensor.

Tompkins et al., (1985) compared three different type of ground speed measurement techniques viz., using fifth wheel, front (un-driven wheel), and radar sensor. The trials were conducted on different surface conditions which included a smooth, non-deformable surface, various levels of tillage conditions, and vegetative covers. It was concluded that:

a) There was less slippage of un-driven front wheel compared to fifth wheel.
b) Both front and fifth wheel measurement were in agreement on firm surfaces.
c) Radar tended to produce accurate results based on a single calibration as compared to fifth wheel or front (un-driven) wheel.

d) The coefficient of variation for ground contacting speed measuring devices was greater as compared to radar sensors on all test surfaces except for tall vegetation. It was proposed to calibrate the sensors attached to ground contacting wheels for specific surface conditions.

G. R. Mueller (1985) did a similar study and concluded that the effect on accuracy of radar sensors is less due to dense and uniform vegetation as compared to non-uniform vegetation, for instance corn crops. A dual beam device was proposed to reduce the variations. Sokol (1985) discussed the use of a Dickey-John RVS-II radar velocity sensor for agricultural applications and concluded that the sensor's accuracy is within ± 2% over variety of terrain conditions and test course lengths.

Hassan and Sirois (1985) tried a different approach to measure ground speed by using the stake and stopwatch method. The accuracy and the resolution improved but had the limitation of preplanned vehicle path. R.D. Munilla et al., (1988) developed an optical encoder system for wheel rpm and ground speed. The ground speed encoder had the following drawbacks:

a) The speed measurements were inconclusive.

b) The ground speed encoder accuracy ranged from 10% to 14%.

Stone and Kranzler (1992) developed a prototype of image based ground velocity sensor. This sensor outperformed both the un-driven wheel-based measurement and radar system at low speeds but had limitations at higher speeds. The accuracy of the instrument depended on the optical alignment. The limitations of this system were:

a) Errors or false reading could be generated in case of non-stable ground reference.

b) Not practically suitable for dusty environment.

c) Increased errors due to unaccountability of pitch and roll changes.

Serrano et al., (2004) investigated the feasibility of low-cost GPS velocity sensor for vehicle testing application. It was concluded that:

a) The knowledge of satellite position with accuracy level better than 10 meters was necessary to determine vehicle velocity at mm/s level.

b) The error in velocity determination can be due to receiver clock bias that can be affected by residual atmospheric, multi-path receiver system noise, and user dynamics as against static mode.

c) The velocity can be estimated better than 1 cm/s in static mode while in kinematic mode, there was increasing effect of user (receiver) dynamics in residuals.

2.1 Summary

There is an increasing demand for accuracy and precision in many agricultural applications due to the desire to carefully control the application of chemicals. Therefore, it is important to investigate the inaccuracies and imprecision associated with commercially available speed measurement devices. This study was different from previous works in following aspects:

a) The GPS Velocity sensor was recently developed and was incorporated for real time speed measurement.

b) All the sensors were calibrated for specific surface conditions as proposed by Tompkins et al. (1985).

c) Performance of different speed sensors were evaluated for both steady state and transient conditions.

d) The shaft encoder coupled with un-driven front wheel was considered as a reference speed as Tompkins et al., (1985) identified that the speed measurements by using un-driven wheel was in general agreement with fifth wheel measurement on hard surfaces.

The scope of this work was to assess the precision and accuracy of different speed measurement techniques as compared to a reference speed sensor under varying surface conditions.

CHAPTER III

HARDWARE OVERVIEW

3.1 Radar sensor

The typical radar speed sensor operates by generating and transmitting microwaves, which are reflected back with a frequency shift due to movement between the transmitter / receiver and the target object. This difference in frequency between the transmitted and the reflected frequency is known as the Doppler effect (Sokol, 1985). The sensors compare the frequency of reflected energy with that of emitted energy and this difference is proportional to the vehicle speed.

The Doppler frequency can be calculated as shown (Sokol,1985):

$$f_d = \frac{2 \times V_G \times \cos\theta}{\lambda} \quad \text{……………………………………………………….(1)}$$

f_d = doppler frequency (Hz)

V_G= Velocity of the vehicle (miles per second)

λ = Wavelength of transmitted signal (miles)

θ = Angle between ground and sensor (degrees)

The Dickey-John Radar Velocity Sensor-II (DJ RVS-II) works on 24.125 GHz ± 25 MHz microwave frequency with micro power level of 5mw (nominal) (Sokol, 1985).Two radars of different brands were used for this study as shown in figures 3.1 and 3.2.

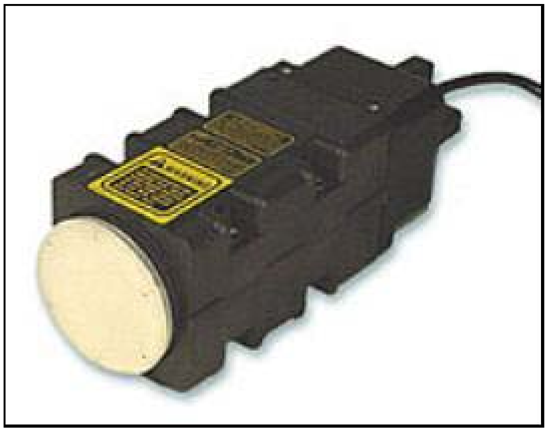

Figure 3.1 Radar II ground speed sensor (Source: Dickey-John Corp.)

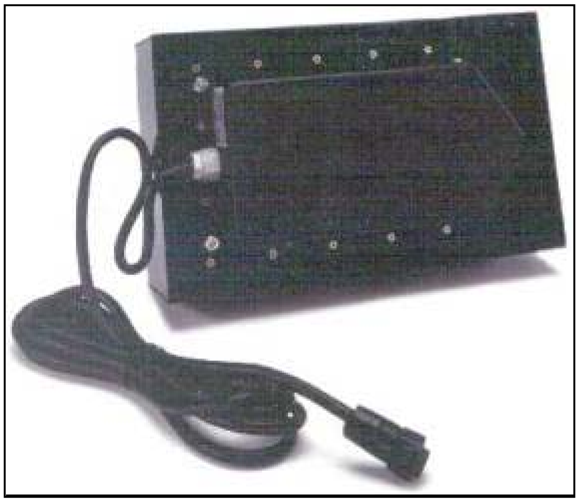

Figure 3.2 Raven radar sensor (Source: Raven Industries)

3.2 GPS based velocity sensor

A GPS velocity sensor determines speed by either using the carrier phase derived Doppler measurement or receiver generated Doppler measurement (Serrano et al., 2004). A GPS velocity sensor is a cheaper alternative to radar sensors and is easy to install. An AgExpress GVS-GPS based velocity sensor was used as shown in figure 3.3 having update frequency of 4 Hz. The sensors works only when at least 4 or more satellites are in view.

Figure 3.3 AgExpress GVS-GPS based velocity sensor
(Source: AgExpress Electronics)

3.3 Shaft encoder

A shaft encoder is an optical encoder that converts the shaft rotations to pulses from which distance or speed can be calculated. There are two types of optical encoders, incremental and absolute encoder. The incremental type shaft encoder was used for this study as shown in figure 3.4.

Figure 3.4 Incremental type shaft encoder
(Source: Danaher Industrial Controls)

In addition, the direction of rotation of shaft encoder was determined by including an electronic circuit comprising of two D-flip flops. The schematic diagram of the circuit is shown in figure 3.5.

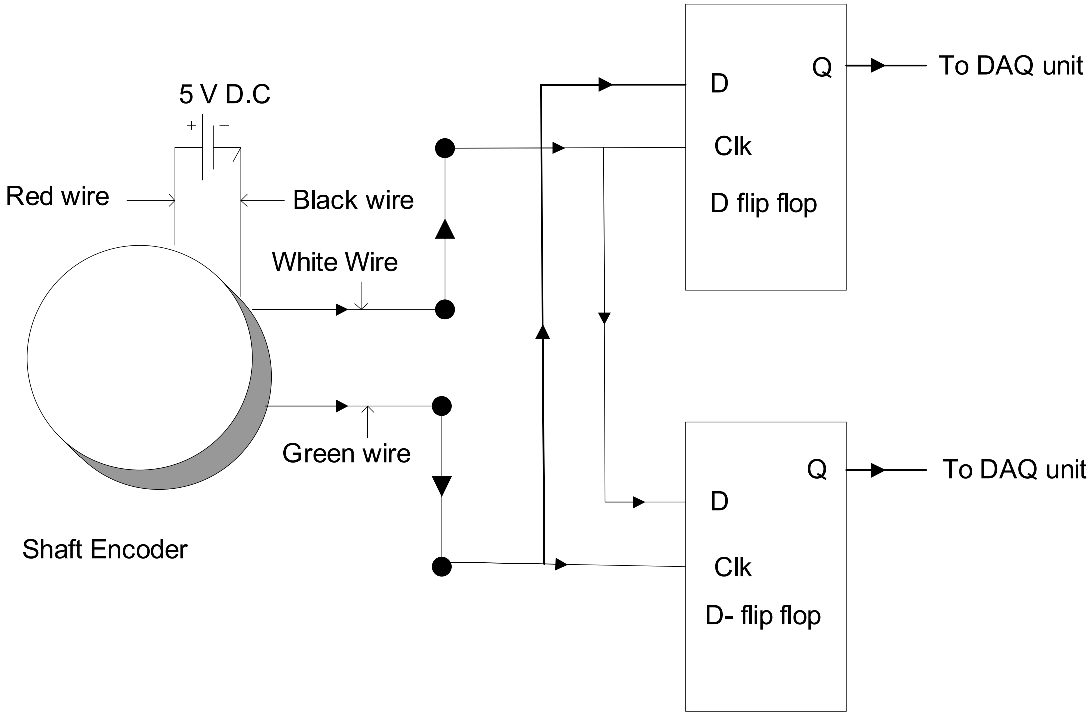

Figure 3.5 Schematic diagram of the D-flip flop circuit (Source: Horowitz and Hill)

This was useful in elimination of ambiguity in the measurements due to vehicle vibrations to calculate net pulses generated by the encoder during forward motion of the vehicle.

3.4 Photoelectric sensor

A photoelectric sensor was used to time the intervals of distance traversed by the vehicle over the test track. The wooden boards were painted black in color to provide contrast for the photoelectric sensor. The boards were placed at desired intervals of distance over the asphalt surface as shown in figure 3.6.

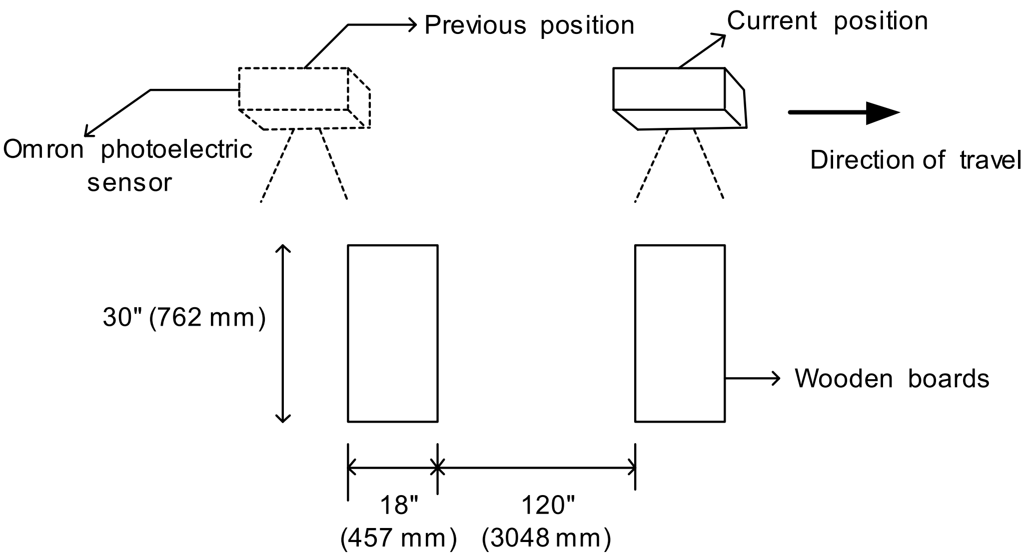

Figure 3.6 Schematic representation of boards and photoelectric sensor

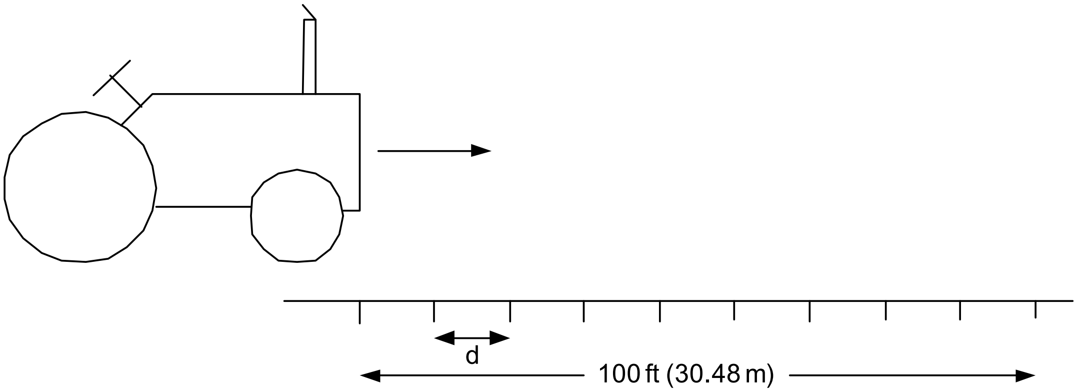

Figure 3.7 Schematic representation of the test track

The time was recorded for each interval in the computer. This method was used for calculating the average speed of the tractor traversed within the intervals of distance over 100 feet (30.48 m) test track. The preliminary results of this method are discussed in detail in Chapter V.

3.5 Materials used

The materials used for this project and their technical specifications are discussed in detail in following sections.

3.5.1 Ground speed sensors

The sensors used for this project were Dickey-John radar (DICKEY-John Corporation, Auburn, IL), Raven radar (Raven Industries Inc., Sioux Falls, SD), AgExpress GVS-GPS based velocity sensor (AgExpress Electronics, Grand Island, NE), Dynapar shaft encoder (Danaher Industrial Controls, Gurnee, IL), and Omron photoelectric sensor (Omron Electronics Components, Schaumburg, IL)

3.5.2 Technical details

a) Dickey-John radar velocity sensor (Model Dj RVS-II)

Velocity range: 0.53 to 107 km / hr (0.33 to 67 mph)

Accuracy: ≤± 5% for speed from 0.53 to 3.2 Km / hr (0.33 to 2 mph)

≤± 3% for speeds from 3.2 to 107 Km / hr (2 to 67 mph)

Output frequency: 26.11 Hz / Km / hr (44.21 Hz / mph)

Microwave frequency: 24.125 GHz ±50 MHz

b) Raven radar gun / cable

Velocity range: 8.05 to 112.65 km / hr (5 to 70 mph)

Accuracy: Depends on type of console used

Output frequency: 58.12 Hz / mph

Microwave frequency: 24.125 GHz

c) AgExpress GVS-GPS based velocity sensor

No. of channels: 16 channel GPS receiver

Accuracy: 0.1mph for speeds from 0.5 to 50 mph

Output frequency: 58.94 Hz / mph

GPS update rate: 4 Hz (4 updates / second)

d) Dynapar Shaft encoder

Resolution: 200 PPR (pulses per revolution)

Accuracy: ± 3 x (360° ÷ PPR) or ± 2.5 arc-min worst case pulse to any other pulse, whichever is less

e) Photoelectric sensor

Sensing distance: 0 to 70 cm (27.56 inches)

Variation in sensing distance: ± 10% (maximum)

Variation in optical axis and mounting direction: ± 2% (maximum)

Light source: Pulse modulated infrared LED (880nm)

Response time: 1 ms. (maximum)

Standard object: Opaque and transparent materials

Sensitivity: Adjustable

3.5.3 Test vehicle

A John Deere 4100 tractor, owned by the OSU-BAE department, was used for this project and was instrumented with the sensors and USB based data acquisition unit as shown in figure 3.8.

Figure 3.8 John Deere 4100 tractor instrumented with sensors

3.5.4 Data acquisition and computing equipment

The USB based IOtech DAQ book was installed on the tractor along with a pentium-based laptop computer to collect sensor information. The IOtech DAQ book-Personal Daq 56 (IOtech, Inc., Cleveland, Ohio) has 4 frequency / pulse input channels and 16 digital I/O lines. Figure 3.9 shows the schematic of wiring diagram.

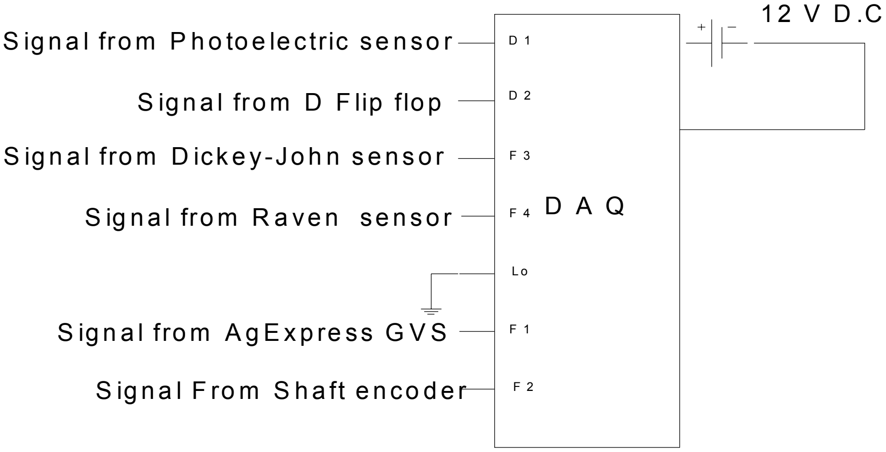

Figure 3.9 Schematic of wiring diagram

3.6 Installation of ground speed sensors

The Dickey-John RVS-II, radar sensor was mounted in the center, at the front of the tractor. The sensor was mounted on an adjustable frame, so that the height of the sensor could be varied depending on the surface conditions. The location of the sensor is shown figure 3.9.

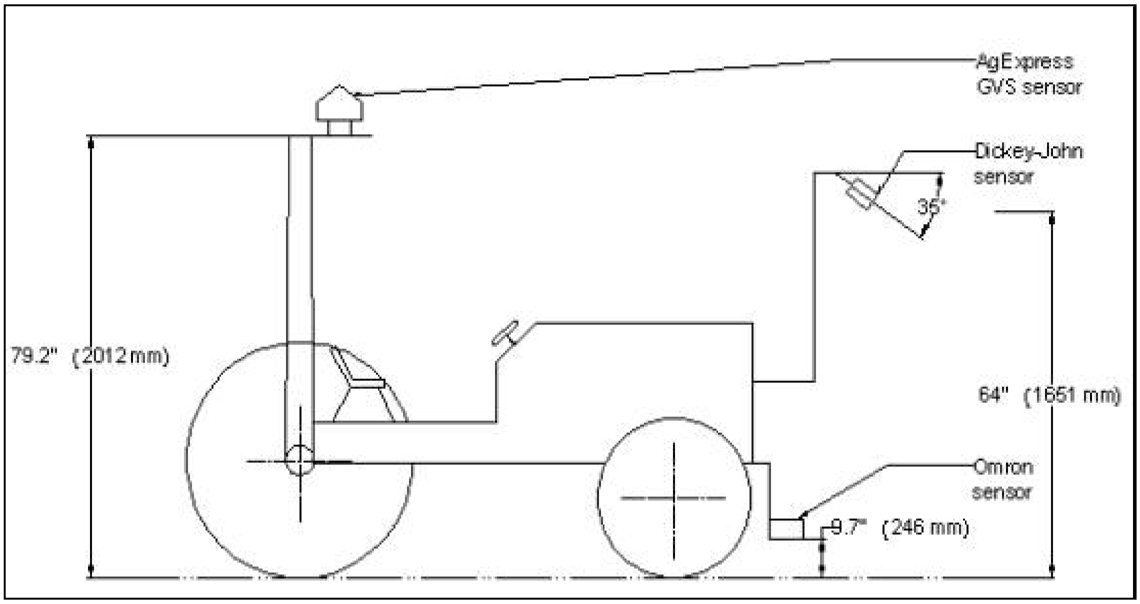

Figure 3.10 Schematic showing location of sensors

The Dickey-John radar sensor was mounted at an angle of 35 degrees (depressed from the horizontal) according to the manufacturer's recommendation to be clear of any obstruction. The radar sensor operates on Doppler radar technology that generates an output of +12 volt dc square wave signal whose frequency is proportional to ground speed. Similarly, the Raven radar gun was mounted at an angle of 10 degrees (as shown in figure 3.11) that was within the manufacturer's recommendation of 0 degrees to 15 degrees from the horizontal on the right side of the operator seat as shown in the figure 3.10. The Raven radar sensor also generated a +12 volt dc square wave signal proportional to ground speed.

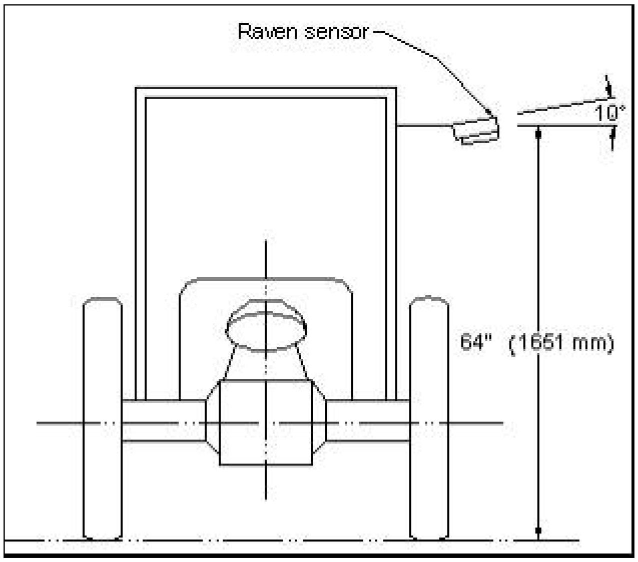

Figure 3.11 Schematic diagram showing location of Raven radar sensor

The Dynapar incremental optical shaft encoder (Model # E14020000303) was mounted on the left front wheel of the tractor and was driven by a belt as shown in the figure 3.12. The shaft encoder generated 200 pulses per revolution. The number of revolutions of shaft encoder for one revolution of front wheel was determined by taking the ratio of diameter of pulley attached to left front wheel to the diameter of pulley attached to the shaft encoder. The number of revolution of shaft encoder for one revolution of wheel was 5.007:1. The specification of front tire was 7X12 R-1, 4 ply rating deep traction tire that provided maximum traction.

Figure 3.12 Location of Dynapar shaft encoder

The AgExpress GVS was mounted on the top of the tractor to have clear unobstructed view of satellites on all sides as specified by the manufacturer. Figure 3.10 shows the location of the sensor on the tractor. The output of all the sensors were routed to the DAQ book and then recorded in the laptop computer in ASCII format.

CHAPTER IV

EXPERIMENTAL DESIGN

4.1 Preliminary tests

The initial trial runs were done on an asphalt surface. The optical sensor was used for sensing the wooden boards placed at specific intervals of 10, 15, 20, 25, 30, and 35 feet (3.05, 4.57, 6.10, 7.62, 9.14, and 10.67 m) respectively over the test track. The tractor was driven to maintain a speed of 5 mph (8.05 kmph). The time elapsed for the distance traversed through the intervals was taken from the computer clock and average speed was calculated for each interval within the 100 feet (30.48 m) track as shown in figure 3.6. The purpose of these trials were to determine the practical minimum distance interval within the 100 feet (30.48 m) course to calculate the average speed for these intervals and then compare them with measurements made by other speed sensors. The results are discussed in Chapter V.

4.2 Test procedure

The four test surface conditions selected were:

a) Asphalt.
b) Vegetative cover with crop height ranging from 0.3-0.5 m.
c) Vegetative cover with crop height ranging from 0.5-1.0 m.
d) Tilled soil conditions where secondary tillage was done.

The experiments were conducted as per the design shown in the table 4.1.

Table 4.1 Experimental design

Test condition	Surface type	Sensors	Speeds mph (kmph)
Constant speed	Asphalt	Shaft encoder	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		AgExpress GVS	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Dickey-John	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Raven	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
	Canola	Shaft encoder	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		AgExpress GVS	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Dickey-John	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Raven	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
	Wheat	Shaft encoder	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		AgExpress GVS	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Dickey-John	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Raven	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
	Tilled	Shaft encoder	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		AgExpress GVS	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Dickey-John	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)
		Raven	3, 5, 7, 9 (4.83, 8.05, 11.26, 14.48)

Acceleration condition	Asphalt	Shaft encoder	
		AgExpress GVS	
		Dickey-John	
		Raven	
	Canola	Shaft encoder	
		AgExpress GVS	
		Dickey-John	
		Raven	
	Wheat	Shaft encoder	
		AgExpress GVS	
		Dickey-John	
		Raven	
	Tilled	Shaft encoder	
		AgExpress GVS	
		Dickey-John	
		Raven	

4.2.1 Under steady state conditions

After instrumentation of the tractor, the bare tractor was driven on 100 feet (30.48 m) track on each surface condition at a ground speed of 3, 5, 7, and 9 mph (4.83, 8.05, 11.26, and 14.48 kmph) by setting the throttle at the required position.

The tractor with all the speed sensors was brought up to the specified speed before entering the test track. The sensors were connected to a USB based DAQ book (IOtech Personal DAQ 56). The DAQ unit was triggered just before entering the 100 feet (30.48 m) track, and the measurements were recorded in the computer connected to data acquisition unit until the tractor went past the end point of the track. The start points, the intermediate points, and the end points were sensed by a photoelectric sensor on the asphalt track to get the information of the distance traversed by the tractor at regular intervals during the elapsed time. The time was recorded both by the computer clock and by a stop watch (having a least count of 0.01 seconds). The pulses from the sensors were sampled at an interval of 119 ms. All the sensors were calibrated for specific surface condition as explained in calibration procedure section in this chapter.

4.2.2 Under transient conditions

a) Vehicle under rapid acceleration

The tractor was driven at approximately 4 mph (6.44 kmph) in high gear and then rapidly accelerated by increasing the throttle so that the tractor was driven at maximum achievable speed without drawbar loading on different surface conditions. The measurements were recorded using the data acquisition system.

b) Vehicle under rapid deceleration

Similarly, the tractor was decelerated from maximum achievable speed in high gear to 4 mph (6.44 kmph) (approximately) speed by reducing the throttle to the desired position. The measurements were recorded using the data acquisition system and the results are discussed in detail in chapter V.

The trials were replicated six times. This was done to study the transient behavior of all speed measuring devices during velocity ramp up and ramp down conditions in addition to assessing the accuracy of all the devices.

4.2.3 Under varying vegetative conditions

The tractor was driven in an agricultural field on a 100 feet (30.48 m) track following the same procedure as explained in steady state condition but without the wooden boards. The responses from the speed measuring devices were recorded under varying crop height conditions ranging from 1 feet (~0.30 m) to 3 feet (~0.91 m). Figures 4.1 and 4.2 show the canola and wheat crop chosen for this study. The crop height of canola and wheat crop was around 47 inches (1.19 m) and 20 inches (0.508 m) respectively.

Figure 4.1 Canola crop field

Figure 4.2 Wheat crop field

4.2.4 Tilled soil condition

Figure 4.3 shows the tilled field condition used for this study. The tractor was driven on tilled field conditions over a 100 feet (30.48 m) track as explained in the steady state condition section test procedure but without the wooden boards.

Figure 4.3 Tilled soil surface

Tompkins et al., (1985) concluded that the ground speed sensor having a ground contacting wheel should be calibrated for a specific surface for accurate speed measurements. Therefore, shaft encoder mounted on the tractor as shown in figure 3.11 having ground contacting wheel was calibrated for specific surface conditions to minimize the error caused due to slip between the tire and surface. The radar sensors and GPS based velocity sensor were also calibrated for specific surface conditions.

4.3 Calibration procedure

The calibration procedure for all the sensors is discussed in detail.

4.3.1 Shaft encoder calibration

The instrumented tractor was driven over a measured distance of 100 feet (30.48 m) at 3, 5, 7, and 9 mph (4.83, 8.05, 11.26, and 14.48 kmph) speed respectively without any drawbar load. The total pulses generated by the shaft encoder were counted for each trial using IOtech DAQ 56 and was recorded in the computer.

The following formula were used to calibrate the shaft encoder:

P = Total number of pulses for traversing 100 feet (30.48 m)

A = Pulses / revolution of shaft encoder

R_{se} = Total no. of revolutions of shaft encoder

C = Reduction Ratio

D_w = Diameter of pulley attached to the wheel hub

D_{se} = Diameter of pulley attached to shaft encoder

t = time elapsed

Total number of revolutions of shaft encoder (n_{se}) = P / A……………………..(2)

No. of revolutions of wheel for 100 feet (30.48 m) distance (n_w) = R_{se} / C…….(3)

Where,

$C = D_w / D_{se}$…………………………………………… ……………..…..(4)

Distance traveled for one revolution of wheel (d_w) = $\frac{100 \text{ feet}}{n_w}$………..… …(5)

Speed was calculated by

$$\text{Speed (mph)} = \frac{P \times d_w \times K}{C \times t \times A} \quad \text{……………………………………………..(6)}$$

Where,

K = 0.6804 (constant) to express values of speed in miles per hour

K = 1.0950 (constant) to express values of speed in kilometers per hour

This method was followed for all surface conditions.

4.3.2 Radar sensors calibration

The radar sensors were calibrated by driving the tractor over a measured distance of 100 feet (30.48 m). The calibration value was determined by comparing the theoretical output with actual output signal for each surface condition.

The output signal for Dickey-John radar sensor was 30.08 pulses / feet (99 pulses / meter) and for Raven radar sensor was 39.6 pulses / feet (130 pulses / meter). The actual signal output was measured and compared with theoretical output signal for determining the calibration value for each surface condition.

4.3.3 GVS-GPS based velocity sensor calibration

The instrumented vehicle was driven over a measured distance of 100 ft (30.48 m). The output signal from the GVS was compared with theoretical output signal for the determination of calibration value. The output signal for GVS sensor was 40.10 pulses / feet (132 pulses / meter).

4.4 Sample size determination

The sample size was determined statistically as explained by Steel et. al, 1997. The number of trials or replications for each treatment depends on:

a) Estimate of σ^2

b) Size of the difference to be detected

c) Assurance to detect the desired difference (Power of the test equals 1-β)

d) Level of significance in actual experiment (Type I error)

e) Type of test, whether single or two-tailed

Practically, the estimation of σ^2 can be obtained from previous experiments or by expressing δ as multiple of true standard deviation, σ.

Mathematically, the number of sample size to be replicated for two tailed test can be calculated by the given formula (Steel et. al, 1997)

$$r \geq 2 \times (t_{\alpha/2} + t_{\beta})^2 \times (\sigma / \delta)^2 \qquad \text{...(7)}$$

Where,

r = number of observations on each treatment

σ = estimate of standard deviation

δ = differences in mean

The subscripts of ‘t’ are based on Type I and Type II error and the values can be referred to the probability in a single tail of the t distribution.

In this study, the desired significance level α was 1% and β was 10% with 90 percent assurance of detecting the differences. Thus, the value of $t_{\alpha/2} = 2.015$ and the value of $t_{\beta} = 1.28$. The value of ‘σ’ as estimated conservatively from initial trial runs was 0.1 and the desired value of $\delta = 0.1$ mph. Replacing the values of t

$_{\alpha/2}$, t_{β}, σ, and δ in the equation (7), we get the number of observations for each treatment ‘r’ equal to 6. Based on this calculation, all the trials were replicated six times under different surface conditions to evaluate the precision of the speed measuring devices. The results of precision errors and the accuracy of these devices are discussed in chapter V.

CHAPTER V

RESULTS AND DISCUSSIONS

5.1 Determination of a “reference” speed sensor

It was important to determine a true reference speed for comparing measurements by different speed measuring devices. The initial trials were conducted on an asphalt surface with a photoelectric sensor mounted on the tractor. The following steps explain the method for measurement of true ground speed using the photoelectric sensor.

a) The 100 feet (30.48 m) track was subdivided into different intervals of 10, 15, 20, 25, 30, and 35 feet (3.05, 4.57, 6.10, 7.62, 9.14, and 10.67 m).

b) The tractor mounted with the speed sensors was driven at a speed of 5 mph on asphalt surface.

c) The time elapsed for traversing each intervals within 100 feet (30.48 m) (as shown in figure 3.6) was recorded using a laptop computer.

d) The average speed was calculated for each interval.

e) This method was used to calculate the average speed over the specified intervals and then compare the average speed measured by other devices for the same stretch. The advantage of using photoelectric sensor was that it had no effect of factors like wind or wheel slip.

It was observed that the average speed calculated by the above method had significant errors. This error was due to the inaccuracy in sensing the wooden boards each time at the beginning of the mark. This method necessitated accurate triggering of the photoelectric sensor at the beginning of each board, which was difficult to ensure. Due to this reason, the error was more predominant when the frequency of triggering was high as in the case of 10 feet (3.048 m) intervals as shown in figure 5.1. As the interval increased the error seems to get distributed as shown in figure 5.2. The standard deviation was 0.108 mph (0.174 kmph) and 0.048 mph (0.077 kmph) for 10 feet (3.05 m) and 35 feet (10.67 m) respectively and was the highest as compared to other sensors. The values can be referred in table 5.1. In addition to this, the use of the photoelectric sensor required good or high contrast to sense the boards, and that was not possible to maintain on vegetative surface conditions. The photoelectric sensor sensed the crop besides the boards that caused ambiguity in separating the signals due to the wooden boards and the crop. Hence, the use of photoelectric sensor as a reference speed sensor was not feasible.

Table 5.1 Standard deviation of sensors at different intervals

Standard deviation ↓	Omron mph (kmph)	AgExpress mph (kmph)	Shaft encoder mph (kmph)	Dickey-John mph (kmph)	Raven mph (kmph)
at 10 feet (3.048 m)	0.108 (0.174)	0.015 (0.024)	0.014 (0.023)	0.020 (0.032)	0.037 (0.060)
at 35 feet (10.67m)	0.048 (0.077)	0.037 (0.060)	0.034 (0.054)	0.032 (0.051)	0.033 (0.053)

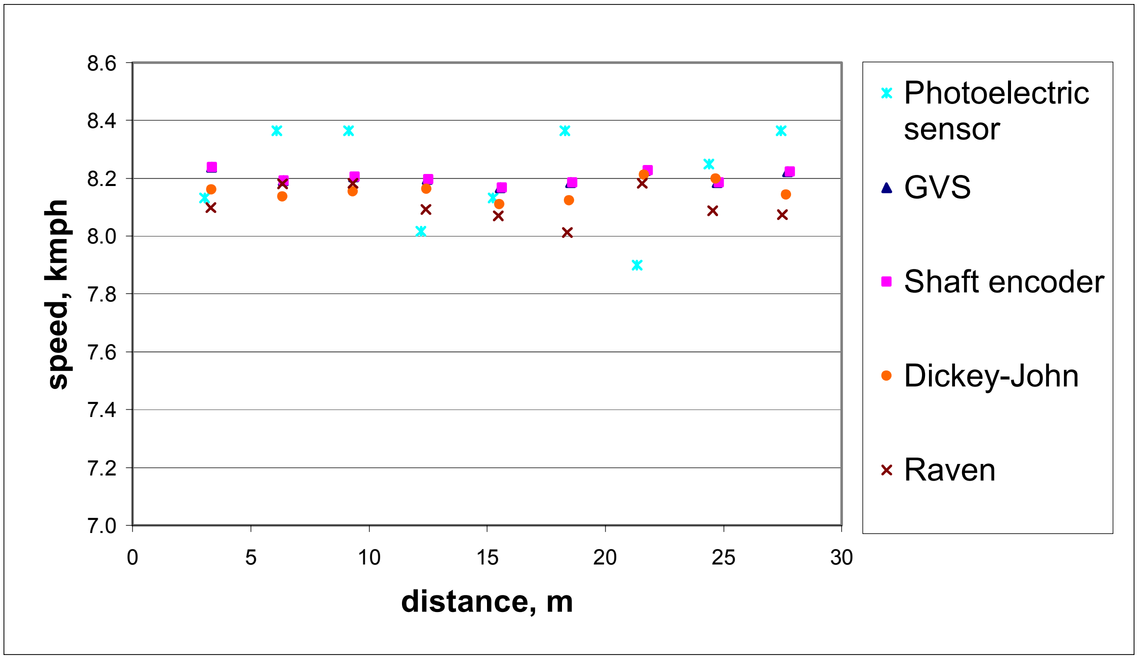

Figure 5.1 Comparison of sensors on asphalt surface at 10 feet intervals

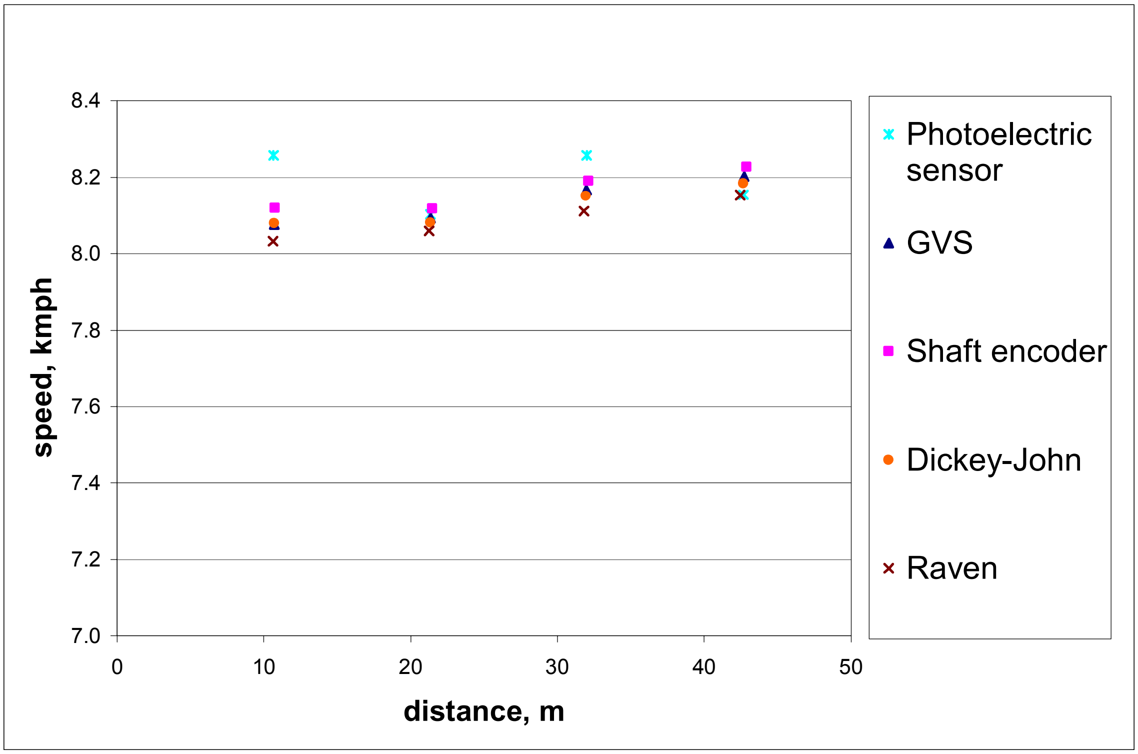

Figure 5.2 Comparison of sensors on asphalt surface at 35 feet intervals

An alternative strategy was adopted using a sensor attached to a ground contacting wheel. The shaft encoder was coupled to the left front tire of the tractor as shown in the figure 3.11. Speed measurements obtained by the shaft encoder on the asphalt and tilled surface were analyzed. The sensor was calibrated for specific surface condition as proposed by Tompkins et. al, (1985). The average speed was also calculated by measuring the time elapsed for traversing the measured distance of 100 feet (30.48 m) with the help of stop watch. The figure 5.3 and 5.4 show that the average speed measured by the shaft encoder on both asphalt and tilled surface were in general agreement with the average speed calculated by stop watch method. Therefore, the shaft encoder speed measurements could be considered as a reference speed for comparison of different speed sensors at varying surface conditions.

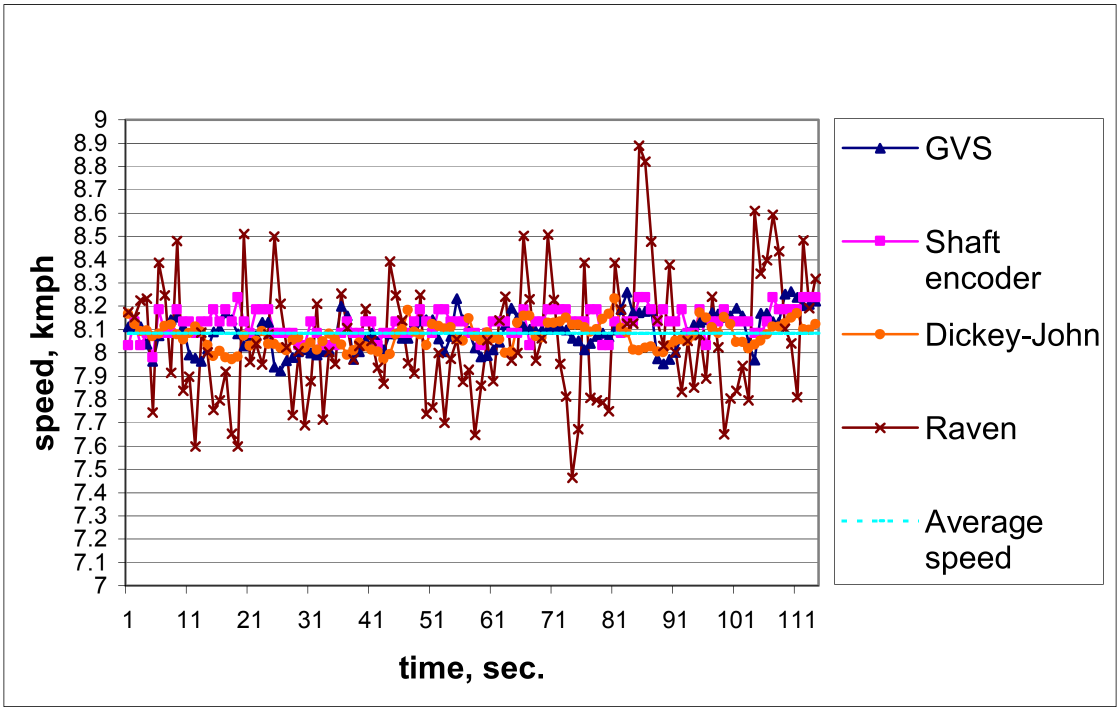

Figure 5.3 Speed Vs. Time graph on asphalt surface

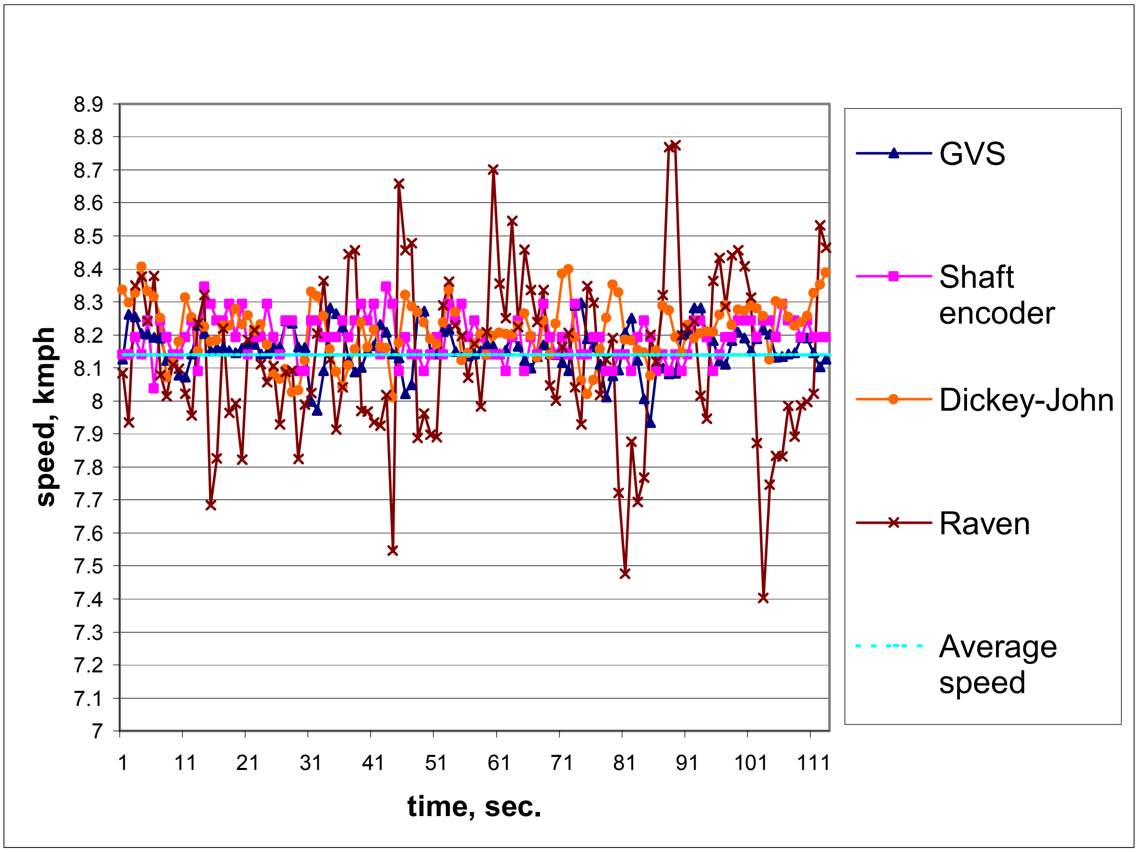

Figure 5.4 Speed Vs. Time graph on tilled surface

5.2 Minimum speed measurements

The minimum speed that can be measured by the Raven sensor was not provided by the manufacturer’s information brochure. Some trials were done to estimate the minimum threshold speed measurable by the Raven radar sensor. The tractor was driven at minimum achievable speed and the signals from all the sensors were recorded as shown in the graph 5.5.

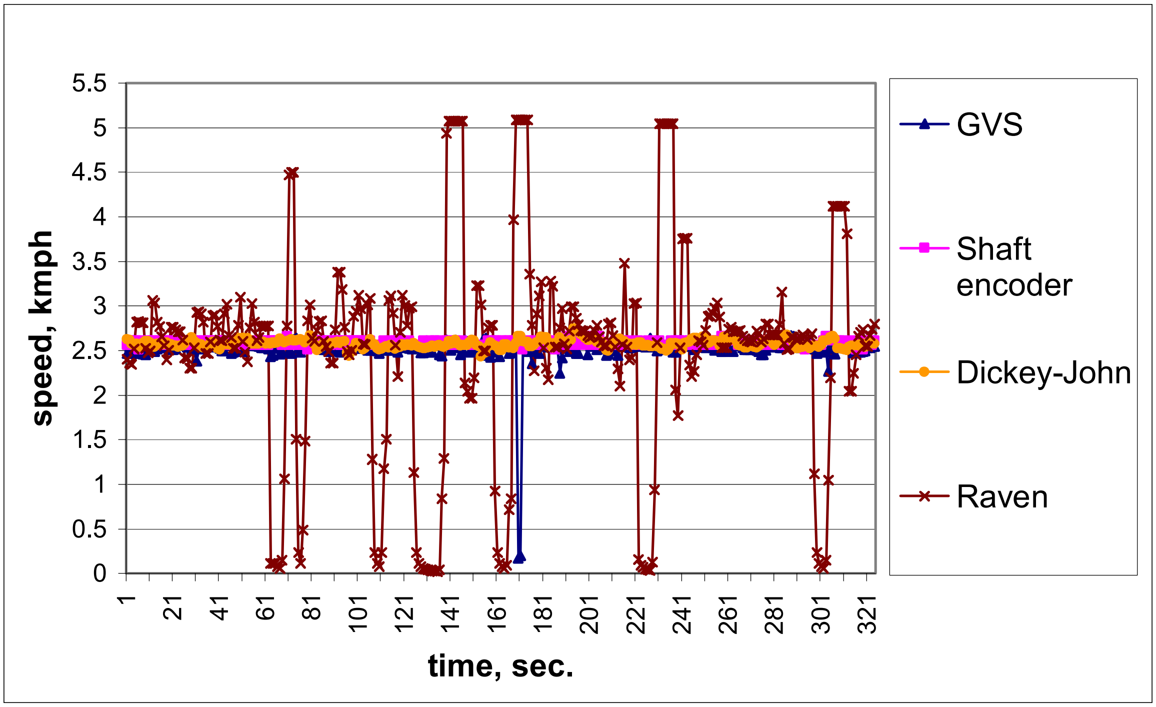

Figure 5.5 Speed Vs. Time graph at minimum speed on asphalt surface

This graph shows that speed measured by the Raven radar sensor varied from 0 mph (0 kmph) to little over 3 mph (4.83 kmph) when the actual forward speed of the vehicle was close to 1.6 mph (2.57 kmph). This was probably due to the inherent design characteristics of the device. On further investigation during transient conditions, it was observed that there was a minimum threshold speed of 2.5 mph (4.02 kmph) and the sensor did not work well below this speed. This is shown in the figure 5.6.

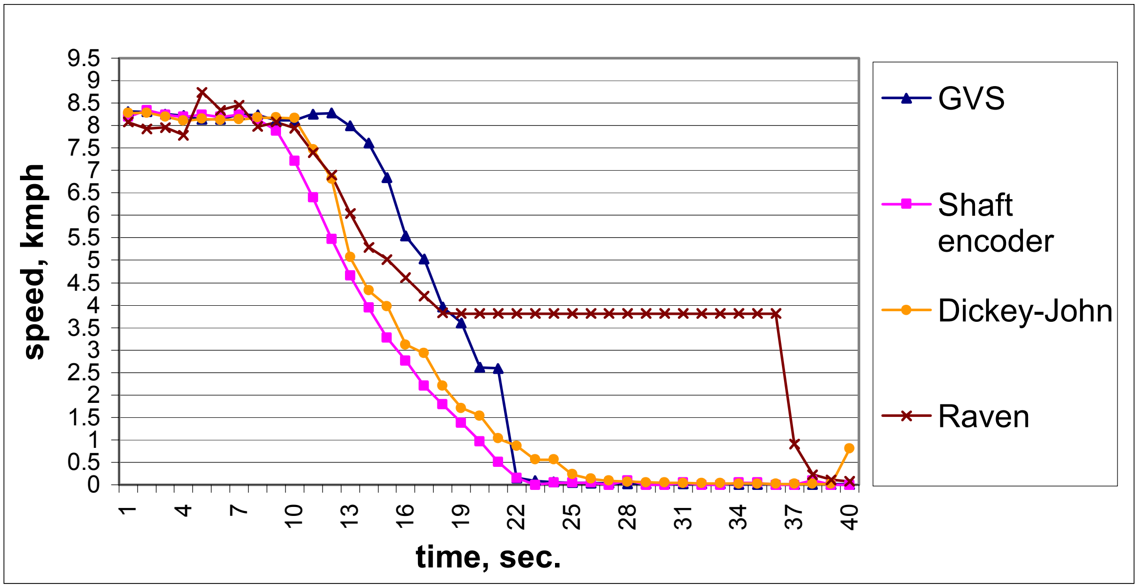

Figure 5.6 Graph showing minimum threshold speed for Raven sensor

5.3 Steady state condition analysis

The performance characteristics of all speed sensors at 3, 5 , 7, and 9 mph (4.83, 8.05, 11.26, and 14.48 kmph) at steady state conditions averaged for six replications were tabulated in tables A-1 to A-4 in appendix A. Statistical analysis was performed to determine whether the values measured by the speed sensors were equivalent at different speeds for a specific surface condition. By performing ANOVA on means of six replications for specific surface condition, it was observed that the speed measurements by different sensors at different speeds were statistically significant at $\alpha = 0.01$. In addition, it was found that there was interaction between speed level and the sensors for all surface conditions. The ANOVA and the interaction of factors for each surface at $\alpha = 0.01$ are tabulated in tables A-5 to A-8 in appendix A.

The sensors were compared at specific speed using Least Significant Difference (commonly known as LSD) multiple comparison method due to the interaction between speed level and sensors. The results of the comparison of different speed sensors at each speed for specific surface conditions relative to shaft encoder are summarized in table 5.2.

Table 5.2 Summary of Least Significant Difference (LSD) comparison

Asphalt surface	**Sensors**		
Speed ↓	GVS mph (kmph)	Dickey-John mph (kmph)	Raven mph (kmph)
3 mph (4.83 kmph)	3.005 (4.836)	3.009 (4.842)	3.096* (4.982)
5 mph (8.05 kmph)	5.039 (8.109)	5.031* (8.096)	5.008* (8.059)
7 mph (11.26 kmph)	7.085* (11.402)	7.066 (11.371)	7.049 (11.344)
9 mph (14.48 kmph)	8.890* (14.307)	8.864* (14.265)	8.838* (14.223)
Canola surface			
3 mph (4.83 kmph)	2.993 (4.817)	3.036 (4.886)	3.157* (5.081)
5 mph (8.05 kmph)	4.986 (8.024)	5.008 (8.059)	5.105* (8.215)
7 mph (11.26 kmph)	6.940 (11.169)	6.985* (11.241)	7.112* (11.445)
9 mph (14.48 kmph)	9.142* (14.712)	9.154* (14.732)	9.402* (15.131)
Tilled surface			
3 mph (4.83 kmph)	3.025 (4.868)	3.062* (4.928)	3.069* (4.939)
5 mph (8.05 kmph)	5.064* (8.149)	5.121 (8.241)	5.074* (8.166)
7 mph (11.26 kmph)	7.066* (11.371)	7.115 (11.450)	7.015* (11.289)
9 mph (14.48 kmph)	9.023 (14.521)	9.117* (14.672)	9.023 (14.521)
Wheat surface			
3 mph (4.83 kmph)	3.007 (4.839)	3.027 (4.871)	3.150* (5.069)
5 mph (8.05 kmph)	5.020 (8.079)	5.088 (8.188)	5.166* (8.314)
7 mph (11.26 kmph)	7.142 (11.494)	7.158 (11.519)	7.253* (11.672)
9 mph (14.48 kmph)	9.080* (14.612)	9.069* (14.595)	9.275* (14.926)

Note: Figures with '' are statistically different from shaft encoder measurement*

In general, AgExpress GVS and Dickey-John sensor were in agreement with shaft encoder measurements under vegetative conditions except at higher speeds. Raven radar was significantly different in most of the cases from the shaft encoder speed measurements due to higher variability in the speed measurements. The Raven radar measurements for 3 mph (4.83 kmph) were documented though it was later communicated by Raven's representative that the minimum speed that can be measured by the sensor is 5 mph (8.05 kmph).

The performance of the ground speed sensors at 5 mph (8.04 kmph) is shown in the figure 5.7. It was evident from this graph that there were large variations in the measurement of speed by Raven radar sensor at each instant compared to the other speed sensors. The coefficient of variation for different speed sensors are tabulated in table 5.3.

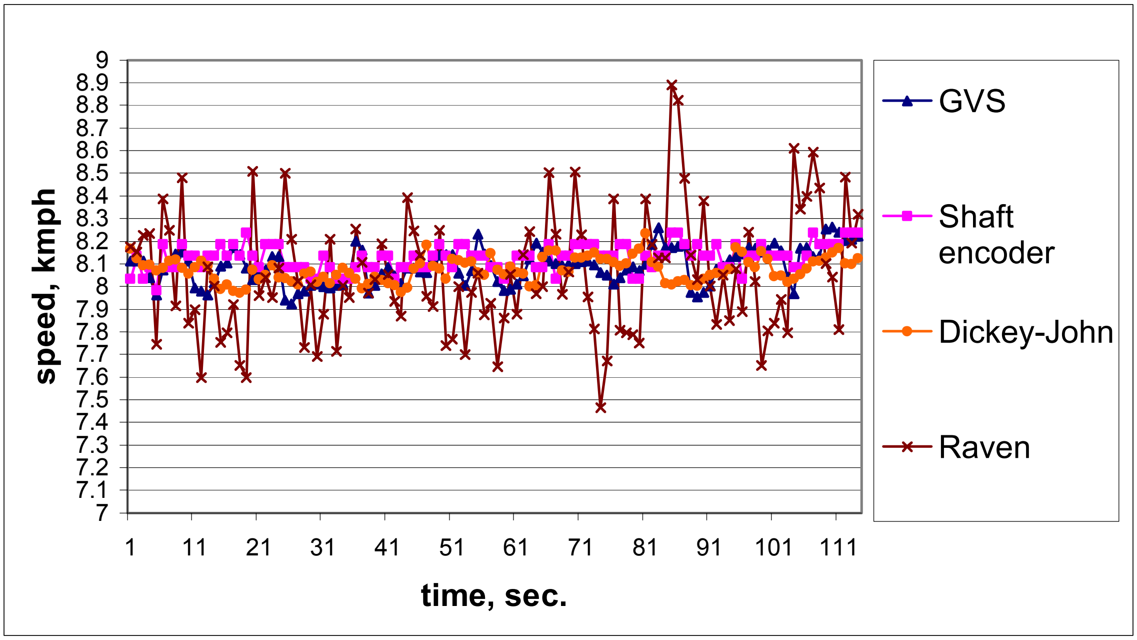

Figure 5.7 Graph showing large variations measured by Raven sensor

Table 5.3 Values of coefficient of variations of sensors at constant speed

Sensor type	**Coefficient of variation**
AgExpress GVS	0.25 % - 2.2 %
Dickey-John	0.2 % - 1.7 %
Raven	0.61 % - 1.78 %

Similarly, the results of ANOVA at α = 0.01 revealed that the standard deviation of AgExpress GVS and Dickey-John speed sensor were in general agreement with the shaft encoder except at 9 mph (14.48 kmph) speed. The standard deviation of Raven radar data was significantly different from that of the shaft encoder as well.

The inaccuracy of the speed sensors were calculated by taking difference between the mean of speed measurement of six replications and the test unit at each speed for specific surface conditions. The values are tabulated in table 5.4. Similarly, the imprecision values were the twice the standard deviation of six replications at each speed for specific surface conditions as mentioned in the NIST Guideline (1994) and are tabulated in table 5.5. The tables A-1 to A-4 in appendix A can be referred for the speed and the standard deviation values of each device at each speed for specific surface condition.

Table 5.4 Inaccuracy of speed sensors at each speed at specific surface

Asphalt Surface	Inaccuracy at 3mph, **mph (kmph)**	Inaccuracy at 5 mph, **mph (kmph)**	Inaccuracy at 7 mph, **mph (kmph)**	Inaccuracy at 9 mph, **mph (kmph)**
Dickey-John	0.008 (0.013)	- 0.024 (-0.039)	0.011 (0.018)	- 0.052 (-0.084)
Raven	0.095 (0.153)	- 0.048 (-0.077)	- 0.006 (0.010)	- 0.078 (-0.126)
GVS	0.005 (0.008)	- 0.016 (-0.026)	0.030 (0.048)	- 0.026 (-0.042)
Canola surface				
Dickey-John	0.027 (0.043)	0.020 (0.032)	0.075 (0.121)	0.095 (0.153)
Raven	0.148 (0.238)	0.117 (0.188)	0.202 (0.325)	0.343 (0.552)
GVS	- 0.015 (-0.024)	- 0.002 (-0.003)	0.003 (0.005)	0.083 (0.134)
Tilled surface				
Dickey-John	0.037 (0.060)	0.018 (0.029)	- 0.023 (-0.037)	0.094 (0.151)
Raven	0.044 (0.071)	- 0.029 (-0.047)	- 0.123 (-0.198)	0.000 (0.000)
GVS	0.000 (0.000)	- 0.039 (-0.063)	- 0.072 (- 0.116)	0.000 (0.000)
Wheat surface				
Dickey-John	0.019 (0.031)	0.041 (0.066)	0.059 (0.095)	0.074 (0.119)
Raven	0.142 (0.229)	0.119 (0.192)	0.154 (0.248)	0.280 (0.451)
GVS	0.000 (0.000)	- 0.027 (-0.043)	0.043 (0.069)	0.085 (0.137)

Table 5.5 Imprecision of speed sensors at each speed at specific surface

Asphalt Surface	Imprecision at 3mph, **mph (kmph)**	Imprecision at 5 mph, **mph (kmph)**	Imprecision at 7 mph, **mph (kmph)**	Imprecision at 9 mph, **mph (kmph)**
Dickey-John	± 0.014 (± 0.023)	± 0.028 (± 0.045)	± 0.038 (± 0.061)	± 0.018 (± 0.029)
Raven	± 0.022 (± 0.035)	± 0.038 (± 0.061)	± 0.054 (± 0.087)	± 0.054 (± 0.087)
GVS	± 0.012 (± 0.019)	± 0.024 (± 0.039)	± 0.030 (± 0.048)	± 0.022 (± 0.035)
Canola surface				
Dickey-John	± 0.018 (± 0.029)	± 0.086 (± 0.138)	± 0.040 (± 0.064)	± 0.054 (± 0.087)
Raven	± 0.036 (± 0.058)	± 0.086 (± 0.138)	± 0.052 (± 0.084)	± 0.104 (± 0.167)
GVS	± 0.066 (± 0.106)	± 0.060 (± 0.097)	± 0.056 (± 0.090)	± 0.154 (± 0.248)
Tilled surface				
Dickey-John	± 0.014 (± 0.023)	± 0.030 (± 0.048)	± 0.024 (± 0.039)	± 0.048 (± 0.077)
Raven	± 0.024 (± 0.039)	± 0.054 (± 0.087)	± 0.028 (± 0.045)	± 0.048 (± 0.077)
GVS	± 0.014 (± 0.023)	± 0.026 (± 0.042)	± 0.016 (± 0.026)	± 0.060 (± 0.097)
Wheat surface				
Dickey-John	± 0.020 (± 0.032)	± 0.058 (± 0.093)	± 0.044 (± 0.071)	± 0.058 (± 0.093)
Raven	± 0.016 (± 0.026)	± 0.092 (± 0.148)	± 0.082 (± 0.132)	± 0.096 (± 0.154)
GVS	± 0.022 (± 0.035)	± 0.048 (± 0.077)	± 0.184 (± 0.296)	± 0.160 (± 0.257)

The AgExpress GVS sensor closely agreed with the shaft encoder in steady state conditions and could be an inexpensive alternative to radar sensors. The error in the speed measurements by the Raven radar sensor increased with increasing speed over canola and wheat surface conditions which might be due to the canopy effect of the crop. The Dickey-John radar sensor was relatively accurate on all surface conditions with accuracy level of 0.095 mph (0.153 kmph) whereas accuracy of the Raven radar sensor was within 0.343 mph (0.552 kmph).

The speed measurements by AgExpress GVS sensor were more precise except at 9 mph (14.48 kmph) which might be due to the uneven vehicle motion under vegetative conditions. The Raven sensor on the other hand was least precise under vegetative conditions as compared to the Dickey-John radar sensor. This could be due to the waving of crop canopy cover caused by high wind speeds of 41.0 mph (65.98 kmph). The values of wind speed were taken from Oklahoma Mesonet website. It was observed that the Dickey-John radar sensor was consistent in terms of precision across all surfaces.

5.4 Transient state condition analysis

The acceleration and deceleration trials were conducted to analyze the transient behavior of speed sensors. The Raven radar sensor had limitation of measuring ground speed below 3 mph (4.83 kmph) as discussed earlier. Therefore, all the acceleration trials were carried out from 4 mph (6.44 kmph) to maximum achievable speed, and the deceleration trials were carried out from maximum achievable speed by the vehicle to 4 mph (6.44 kmph) (approximately).

The data were recorded on time domain as shown in the figure 5.8. The speed measured by the shaft encoder was accurate enough to compare the behavior of other speed sensors with respect to shaft encoder speed measurements as discussed before. Table Curve 2D (Aspire Software International, Leeburg, VA) software was used to process the raw data by fitting a curve through the shaft encoder speed measurements. The sigmoid function was selected as the curve model to fit the shaft encoder data thereby eliminating noise in the shaft encoder measurements.

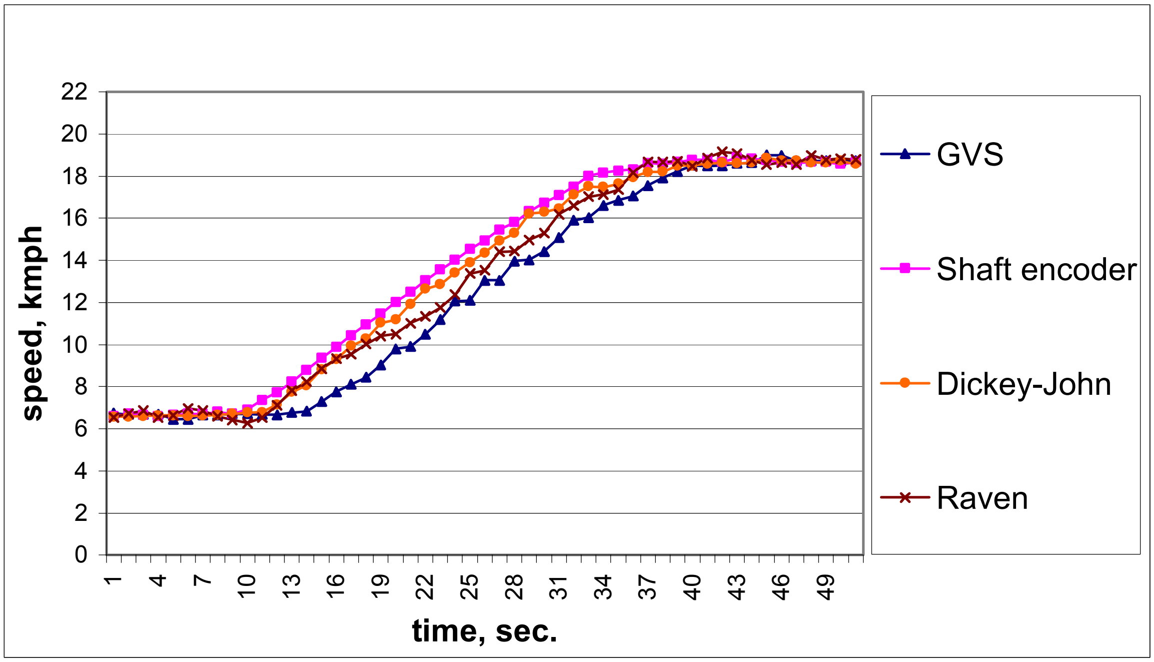

Figure 5.8 Graph showing speed measurements during rapid acceleration

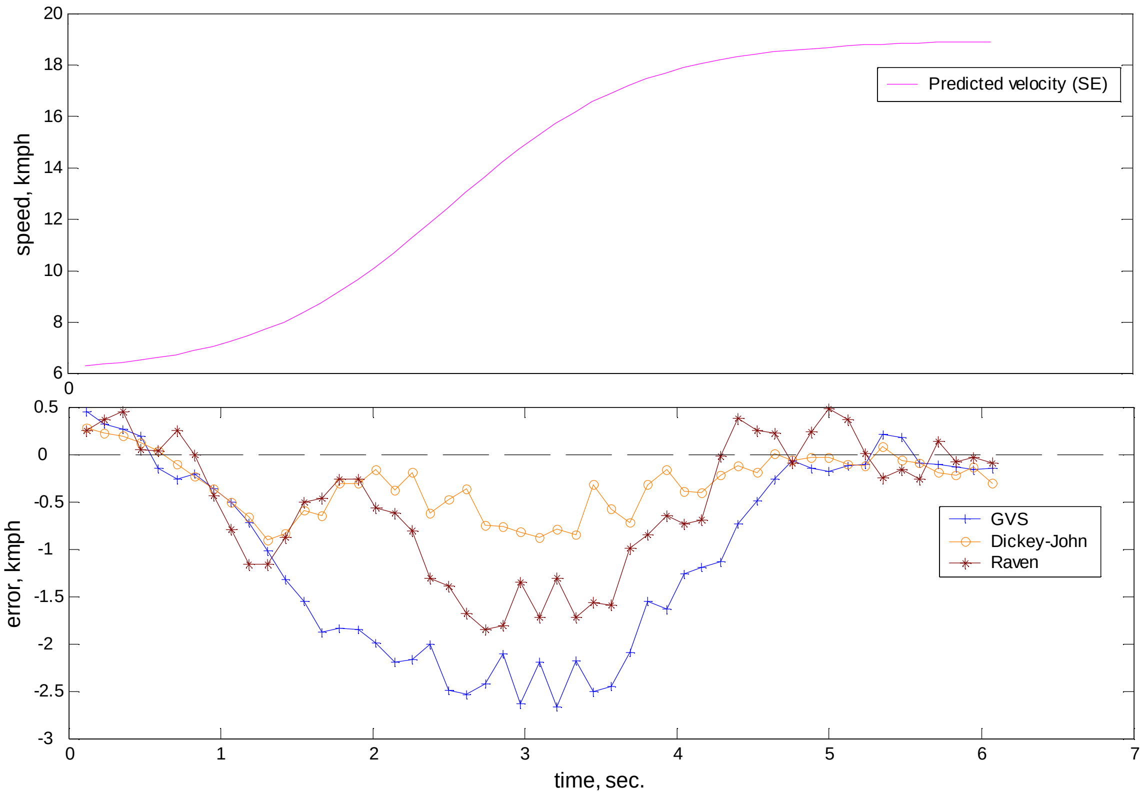

Figure 5.9 Error due to different speed sensors during acceleration

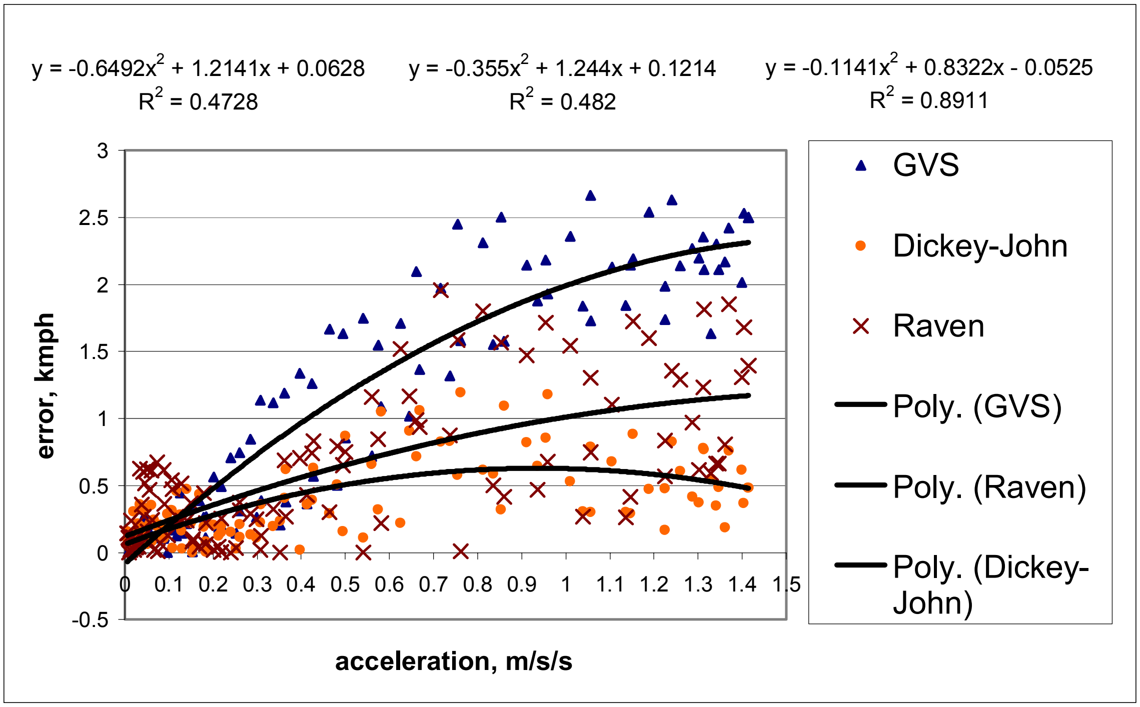

Figure 5.10 Error Vs. Acceleration graph on asphalt surface

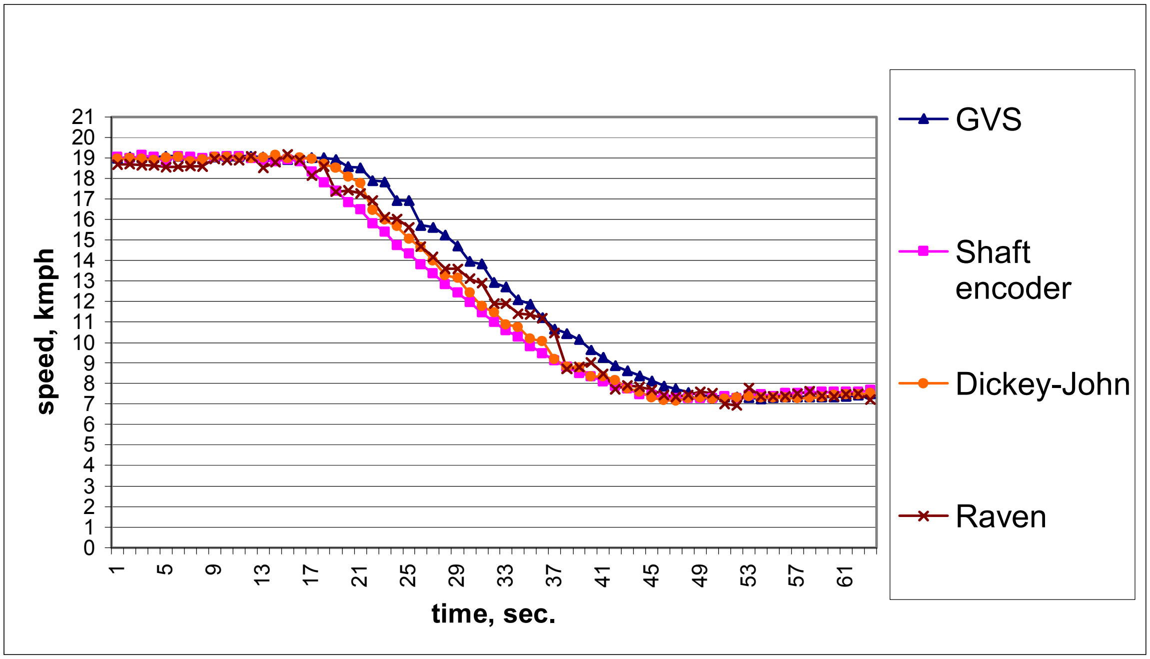

Figure 5.11 Graph showing speed measurements during rapid deceleration

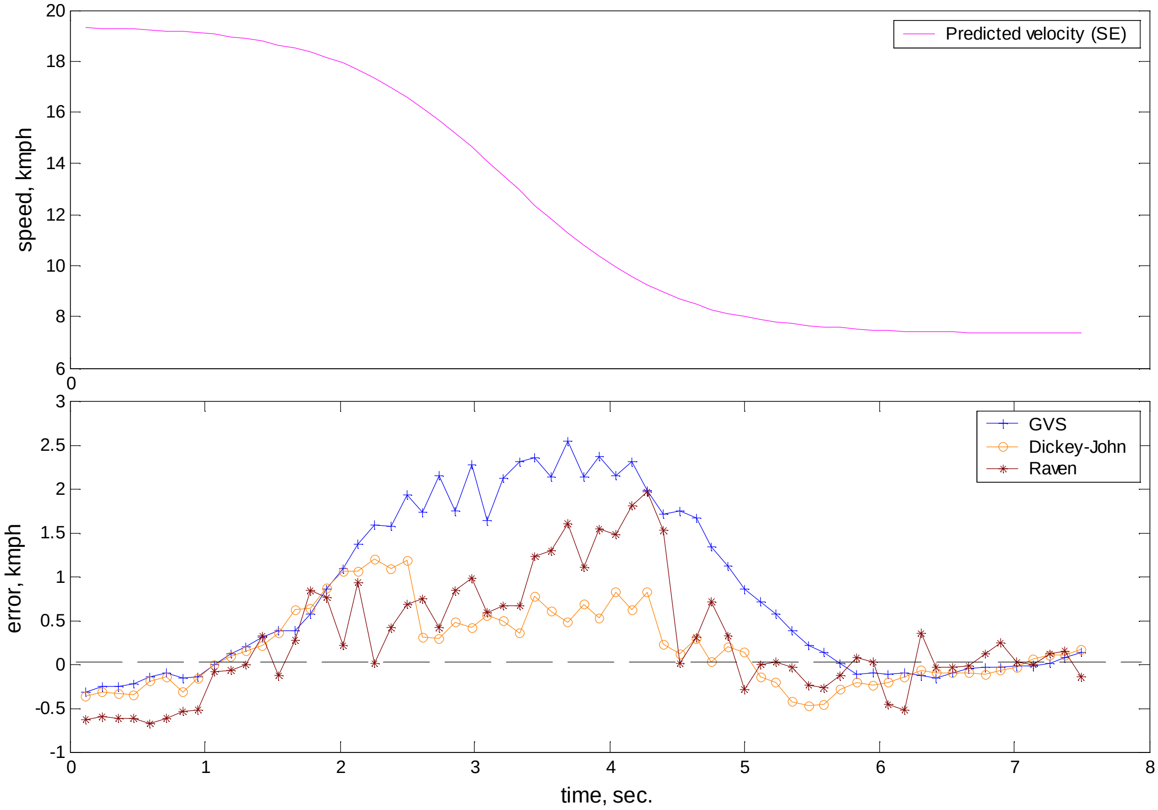

Figure 5.12 Error due to different speed sensors during rapid deceleration

The relative error was calculated based on the difference between the predicted velocity of shaft encoder and the speed measured by each sensor. This is also shown graphically in figures 5.10. It can be noted from figures 5.9 and 5.12 that there was increase of error due to increase in acceleration and deceleration respectively.

The error for AgExpress GVS was the highest across all surfaces due to the latency which can be clearly noticed. The error on asphalt surface was within 1.65 mph (2.66 kmph) whereas for radar sensors, it was within 1 mph (1.61 kmph) during acceleration. Similarly, during deceleration, the error was within 1.57 mph (2.53 kmph) on asphalt surface. The trend was similar on all surfaces, though the error in speed measurement by AgExpress was within 2.75 mph (4.43 kmph) (maximum) during acceleration whereas it was within 4.0 mph (6.44 kmph) during deceleration. The graphs for acceleration and deceleration trials can be referred to the B-1 to B-34 in appendix B.

CHAPTER VI

CONCLUSIONS AND SUMMARY

6.1 Conclusions

The following conclusions can be drawn based on this study:

a) The Dickey-John radar was more precise and consistent as compared to other speed sensors across all surface conditions. The maximum imprecision of speed sensors across all surfaces and speeds are summarized below:

Dickey-John radar sensor → ± 0.044 mph (± 0.071 kmph)
Raven radar sensor → ± 0.096 mph (± 0.154 kmph)
AgExpress GVS sensor → ± 0.184 mph (± 0.296 kmph)

The accuracy of Dickey-John and AgExpress GVS sensors were in close agreement but significantly different from Raven sensor. The Raven sensor was more sensitive to vegetative conditions across all speeds. The maximum inaccuracy of the speed sensors across all surfaces and speeds were:

Dickey-John radar sensor → 0.09 mph (0.151 kmph)
Raven radar sensor → 0.34 mph (0.552 kmph)
AgExpress GVS sensor → 0.08 mph (0.134 kmph)

b) The maximum error in speed measurement during transient conditions for radar sensors were within 1.0 mph (1.61 kmph) whereas the GPS based sensor has maximum error within 4.0 mph (6.44 kmph) during acceleration because of the latency.

6.2 Summary

a) In general, AgExpress GVS and Dickey-John radar sensor were in general agreement with shaft encoder measurements under vegetative conditions except at higher speeds.

b) The Raven radar sensor was statistically different from the shaft encoder The error increased with increase in vehicle speed over wheat and canola surface. This was due to the effect of wind and waving of crop canopy. The Dickey-John was less sensitive to crop canopy effect when compared with Raven radar. It was observed that the Raven radar was least accurate.

c) The Raven radar can be used for measuring speeds on an average from 3 mph (4.83 kmph) onwards though large variations were observed in speed measurements.

d) On the other hand, the AgExpress GVS sensor was consistent except at higher speeds on vegetative surfaces. This might be due to the uneven vehicle motion and user dynamics. The AgExpress GVS sensor showed promising results and could be used for speed measurements for steady state conditions because of its cost advantage.

e) During transient conditions, both the radar sensors followed the same trend. The maximum error in speed measurements by the radar sensors was close to 1 mph (1.61 kmph) during acceleration and deceleration conditions across all surfaces whereas the error in speed measurements by the AgExpress GVS was 2.75 mph (4.43 kmph) (maximum) on the lower side during acceleration and close to 4 mph (6.44 kmph) during deceleration. Therefore, it was not suitable for transient condition applications due to the latency.

6.3 Suggestions for future research

The GPS based speed measuring device shows promising results for use in agricultural applications under steady state conditions. However, additional research needs to be done for improving the GPS system under transient conditions for precision agriculture applications.

The Raven radar sensor had large variations in speed measurements across all surface. Therefore, it is recommended to reinvestigate the inherent design of the sensor and improve it for making it insensitive to errors due to canopy effect or due to pitch, yaw or roll motion of the vehicle. The reference speed could be measured using an advanced technique such as a laser sensor for accurate triggering and then recording the time elapsed for specific intervals using computer.

Further information can by unraveled by conducting the experiment under different wind speed conditions over the vegetative surface. It is also suggested to chose the vegetative crop based on distribution of the crop density for future study which might produce useful information on parameters that affect the speed measurements by radar sensors.

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APPENDIX A

Table A-1 At 3 mph approximately

Surface conditions →	Asphalt	Std. dev.	Tilled soil	Std. dev.	Wheat crop	Std. dev.	Canola crop	Std. dev.
Dickey-John, mph	3.009	0.007	3.062	0.007	3.027	0.010	3.036	0.009
Raven , mph	3.096	0.011	3.069	0.012	3.150	0.008	3.157	0.018
AgExpress, mph	3.006	0.006	3.025	0.007	3.008	0.011	2.994	0.033
Shaft encoder, mph	3.001	0.007	3.025	0.007	3.008	0.005	3.009	0.006

Table A-2 At 5 mph approximately

Surface conditions →	Asphalt	Std. dev.	Tilled soil	Std. dev.	Wheat crop	Std. dev.	Canola crop	Std. dev.
Dickey-John, mph	5.031	0.014	5.121	0.015	5.088	0.029	5.008	0.043
Raven , mph	5.007	0.019	5.074	0.027	5.166	0.046	5.105	0.043
AgExpress, mph	5.039	0.012	5.064	0.013	5.020	0.024	4.986	0.030
Shaft encoder, mph	5.055	0.009	5.103	0.011	5.047	0.015	4.988	0.052

Table A-3 At 7 mph approximately

Surface conditions →	Asphalt	Std. dev.	Tilled soil	Std. dev.	Wheat crop	Std. dev.	Canola crop	Std. dev.
Dickey-John, mph	7.066	0.019	7.115	0.012	7.158	0.022	6.985	0.020
Raven , mph	7.049	0.027	7.015	0.014	7.253	0.041	7.112	0.026
AgExpress, mph	7.085	0.015	7.066	0.008	7.142	0.092	6.940	0.028
Shaft encoder, mph	7.055	0.015	7.138	0.005	7.099	0.018	6.910	0.024

Table A-4 At 9 mph approximately

Surface conditions →	Asphalt	Std. dev.	Tilled soil	Std. dev.	Wheat crop	Std. dev.	Canola crop	Std. dev.
Dickey-John, mph	8.864	0.009	9.117	0.024	9.069	0.029	9.154	0.027
Raven , mph	8.838	0.027	9.023	0.024	9.275	0.048	9.402	0.037
AgExpress, mph	8.890	0.011	9.023	0.030	9.080	0.080	9.142	0.077
Shaft encoder, mph	8.916	0.011	9.023	0.021	8.995	0.031	9.059	0.030

Table A-5 ANOVA table for asphalt surface

Source	DF	SS	MS	F	Pr > F
Model	15	460.308	30.687	132106	< 0.0001
Error	80	0.0186	0.0002		
Corrected Total	95	460.326			

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
speed	3	460.2388607	153.4129536	660432	<.0001
sensor	3	0.0029964	0.0009988	4.30	0.0073
speed*sensor	9	0.0662213	0.0073579	31.68	<.0001

Table A-6 ANOVA for canola surface

Source	DF	SS	MS	F	Pr > F
Model	15	499.837	33.322	26231.2	< 0.0001
Error	80	0.1016	0.0013		
Corrected Total	95	499.938			

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
speed	3	499.1443652	166.3814551	130974	<.0001
sensor	3	0.5950839	0.1983613	156.15	<.0001
speed*sensor	9	0.0976021	0.0108447	8.54	<.0001

Table A-7 ANOVA for tilled surface

Source	DF	SS	MS	F	Pr > F
Model	15	479.984	31.999	114601	< 0.0001
Error	80	0.02234	0.0003		
Corrected Total	95	480.006			

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
speed	3	479.8685761	159.9561920	572866	<.0001
sensor	3	0.0559885	0.0186628	66.84	<.0001
speed*sensor	9	0.0593071	0.0065897	23.60	<.0001

Table A-8 ANOVA for wheat surface

Source	DF	SS	MS	F	Pr > F
Model	15	492.782	32.852	20588.9	< 0.0001
Error	80	0.1276	0.0015		
Corrected Total	95	492.909			

Source	**DF**	**Anova SS**	**Mean Square**	**F Value**	**Pr > F**
speed	3	492.2898338	164.0966113	102842	<.0001
sensor	3	0.4305056	0.1435019	89.93	<.0001
speed*sensor	9	0.0618092	0.0068677	4.30	0.0001

Appendix B

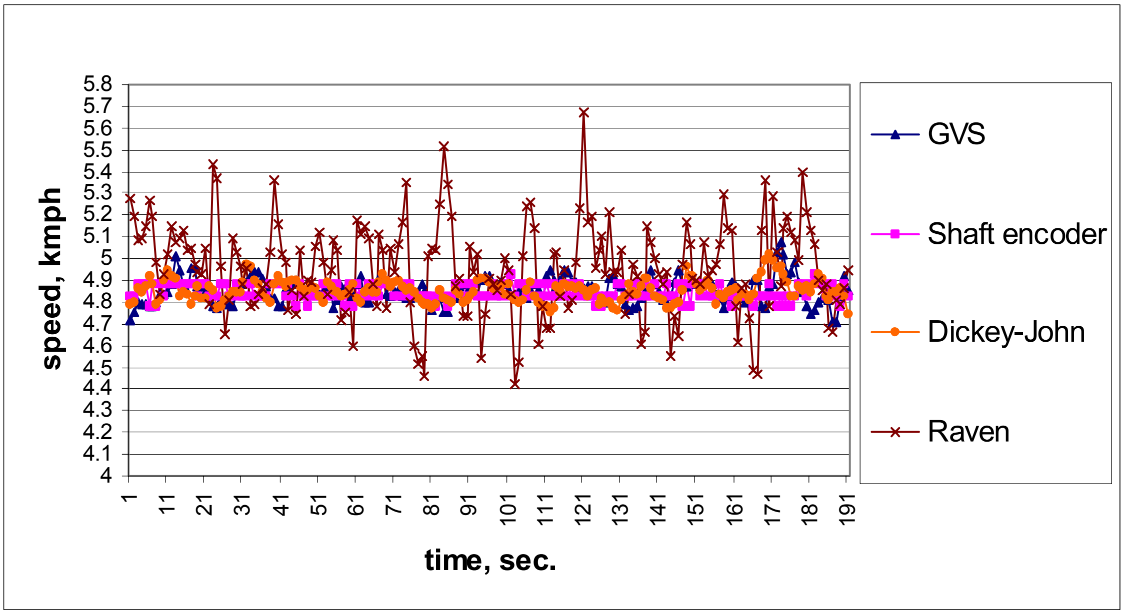

Figure B-1 Graph depicting speed vs. time on asphalt surface at 5 kmph

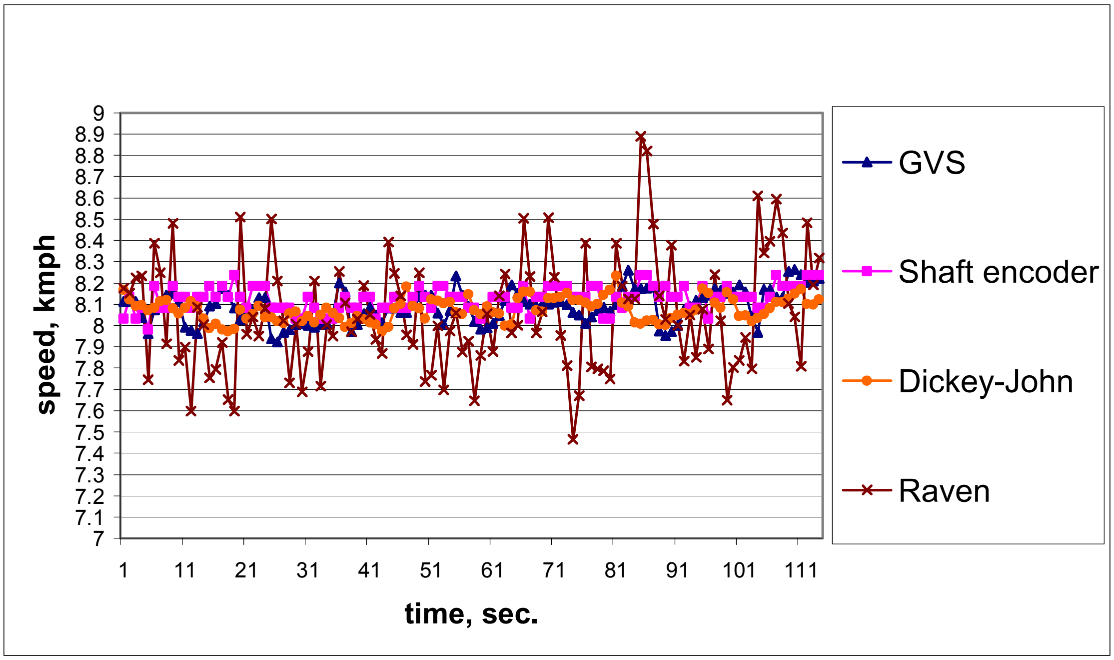

Figure B-2 Graph depicting speed vs. time on asphalt surface at 8 kmph

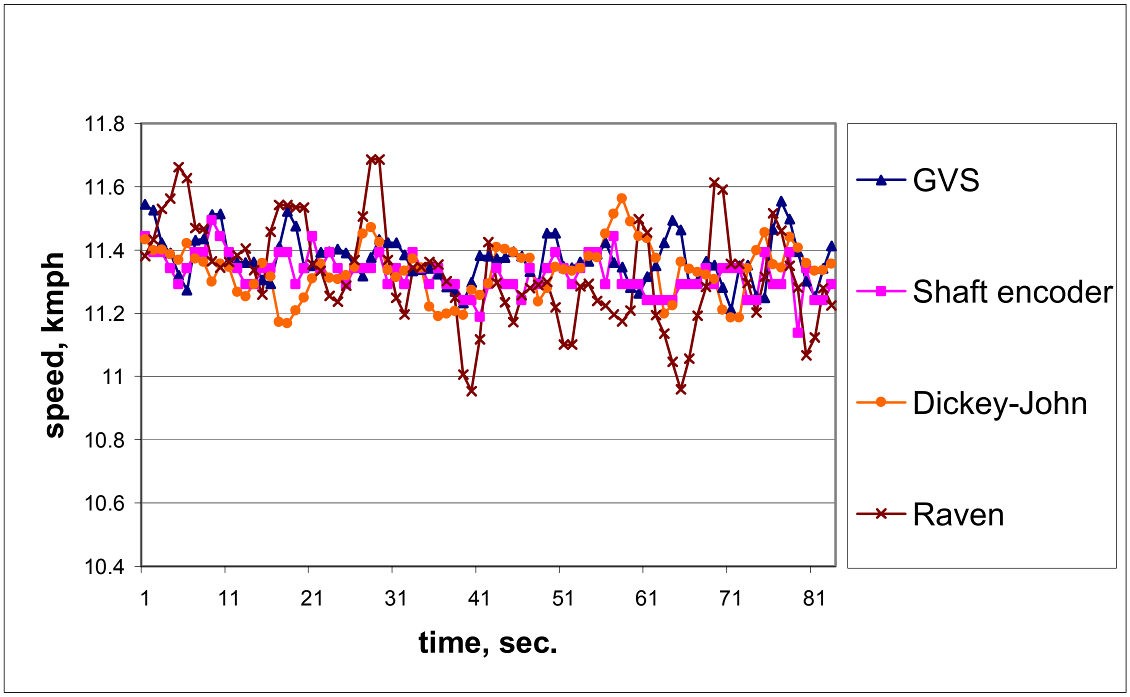

Figure B-3 Figure depicting speed vs. time on asphalt surface at 11 kmph

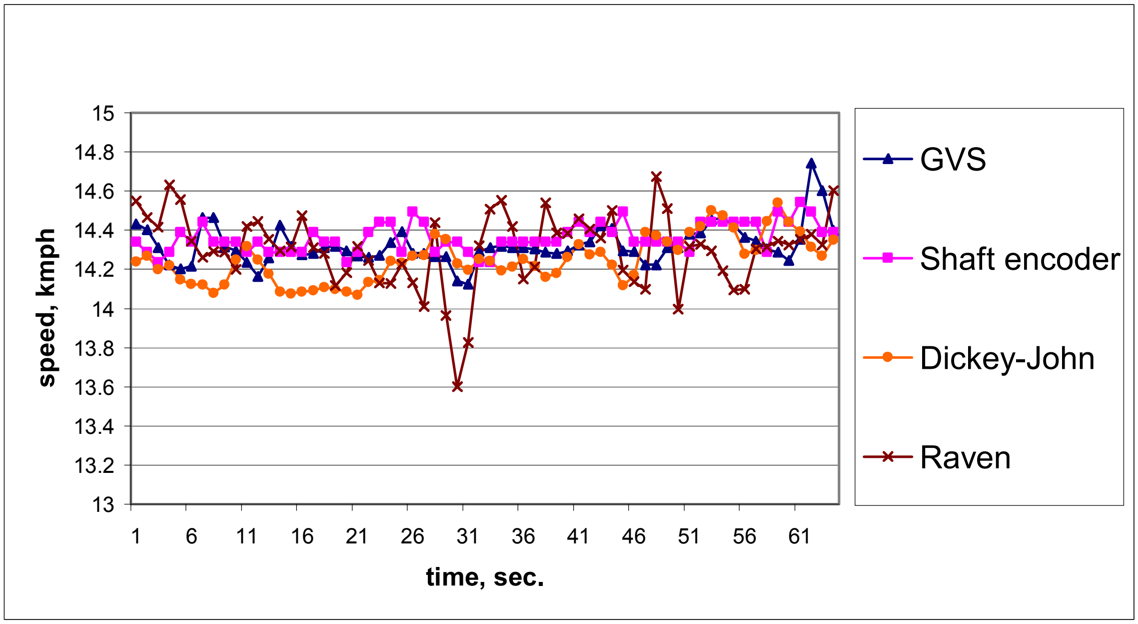

Figure B-4 Figure depicting speed vs. time on asphalt surface at 14 kmph

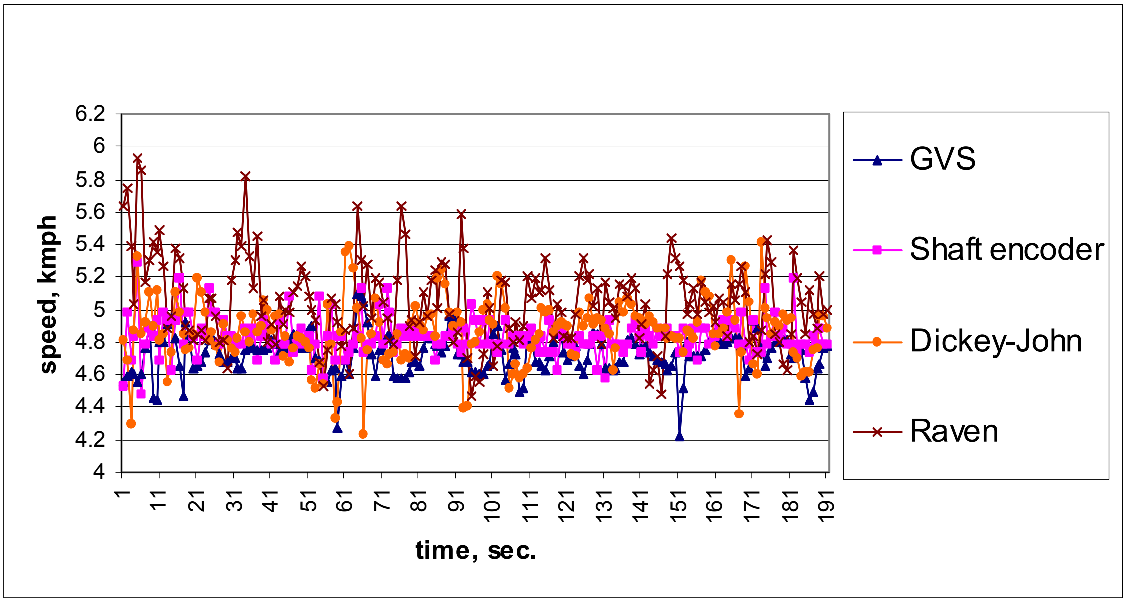

Figure B-5 Figure depicting speed vs. time on canola surface at 5 kmph

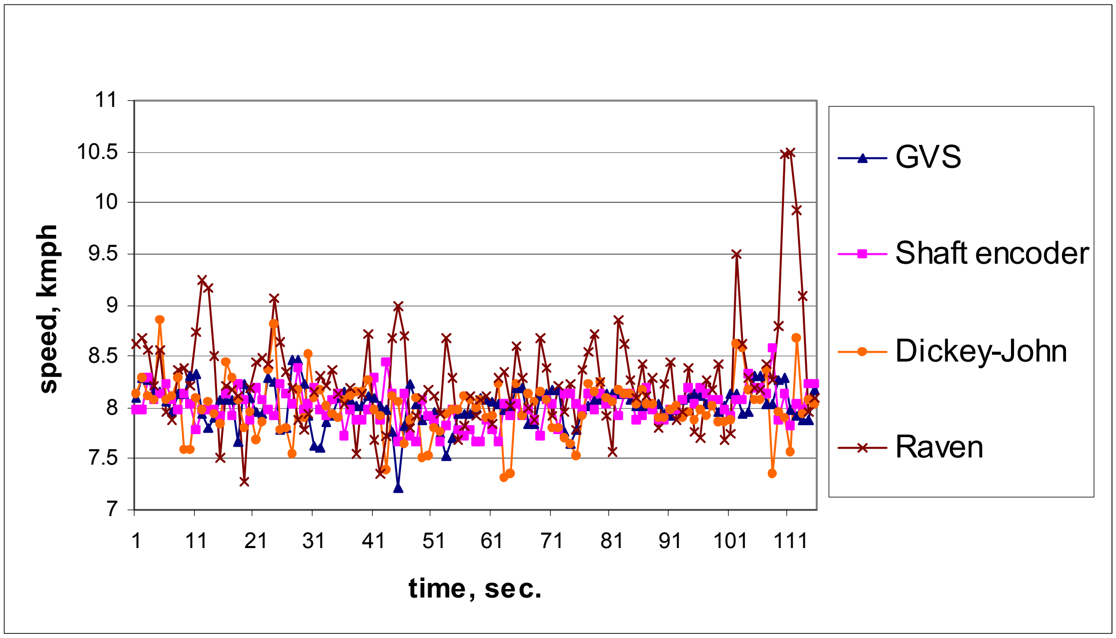

Figure B-6 Figure depicting speed vs. time on canola surface at 8 kmph

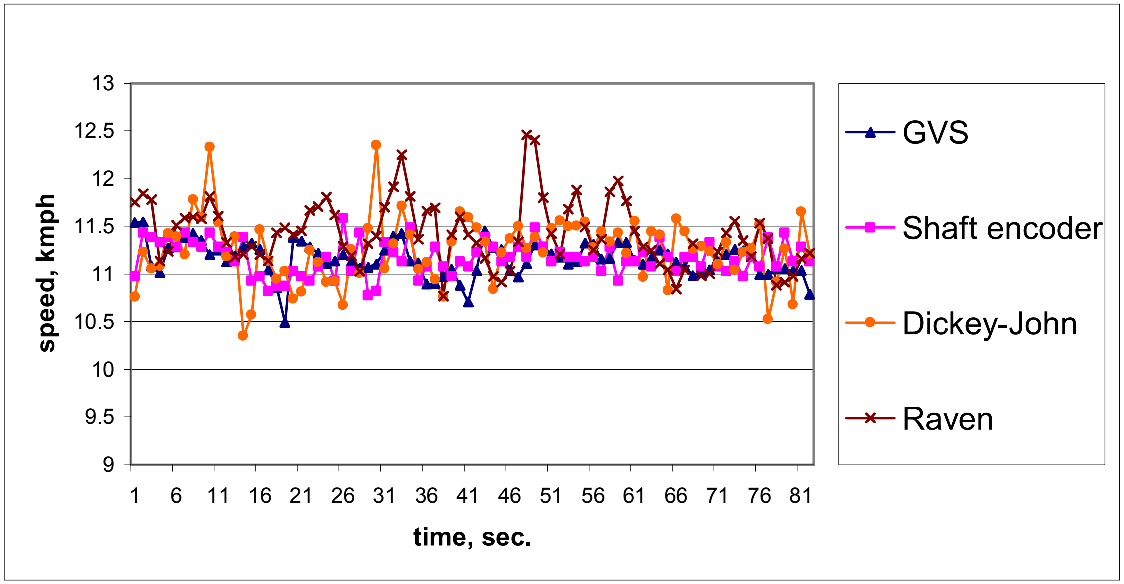

Figure B-7 Figure depicting speed vs. time on canola surface at 11 kmph

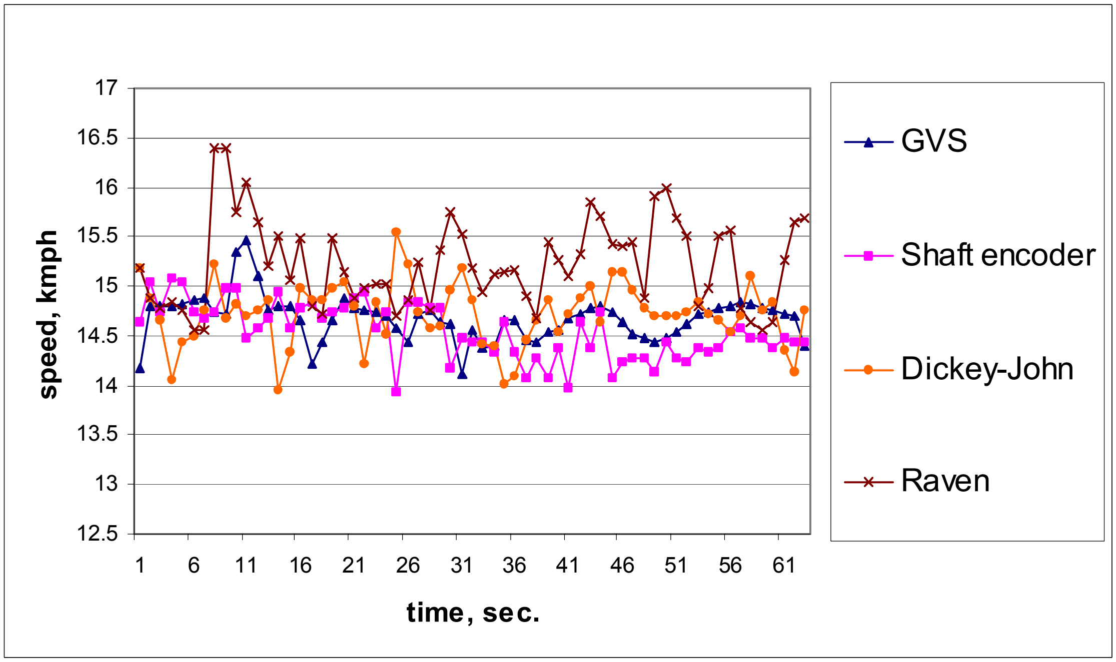

Figure B-8 Figure depicting speed vs. time on canola surface at 14 kmph

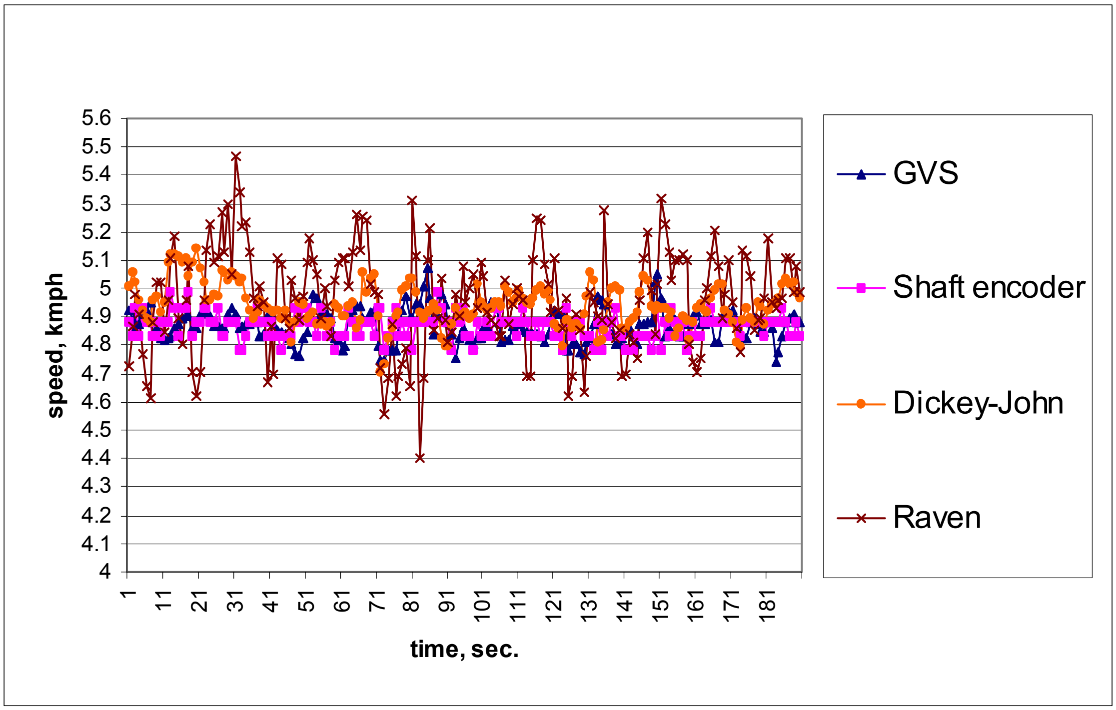

Figure B-9 Figure depicting speed vs. time on tilled surface at 5 kmph

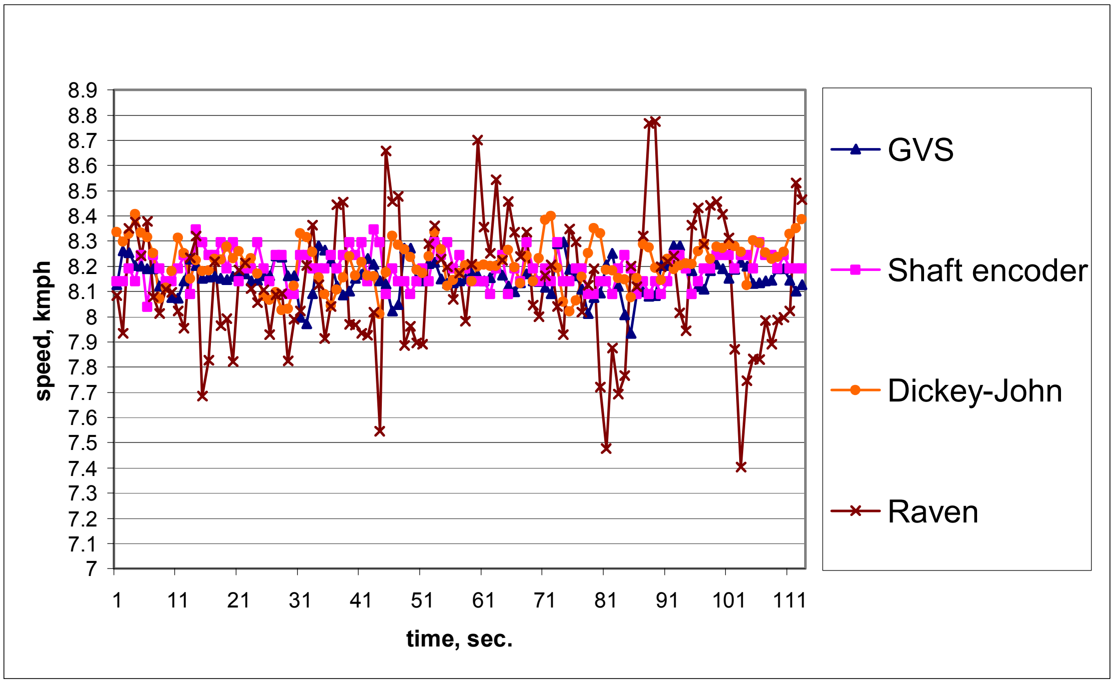

Figure B-10 Figure depicting speed vs. time on tilled surface at 8 kmph

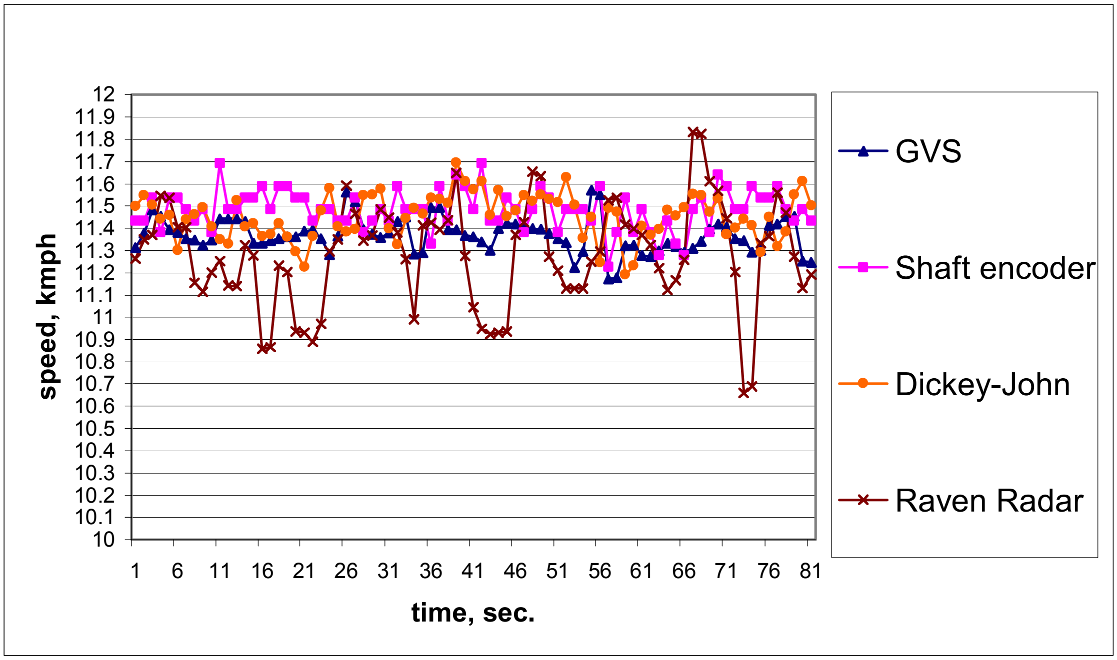

Figure B-11 Figure depicting speed vs. time on tilled surface at 11 kmph

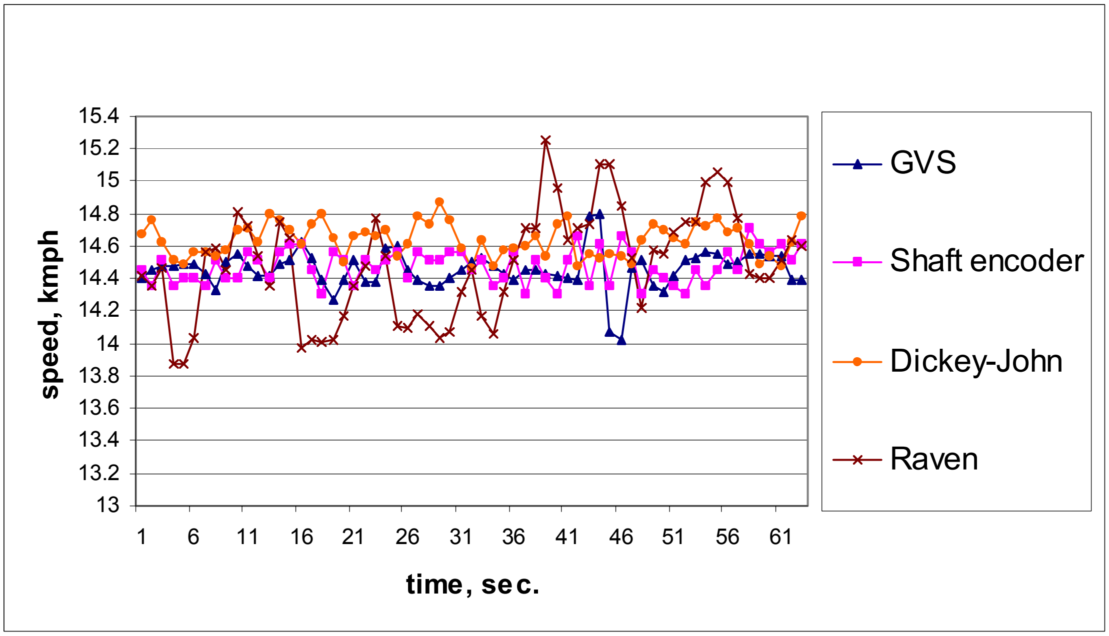

Figure B-12 Figure depicting speed vs. time on tilled surface at 14 kmph

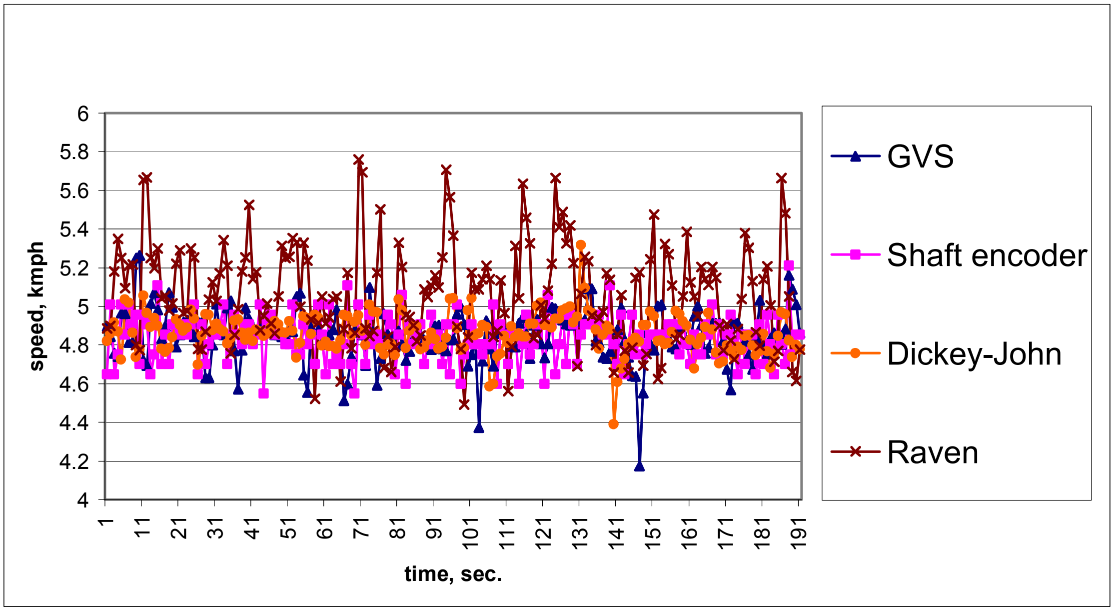

Figure B-13 Figure depicting speed vs. time on wheat surface at 5 kmph

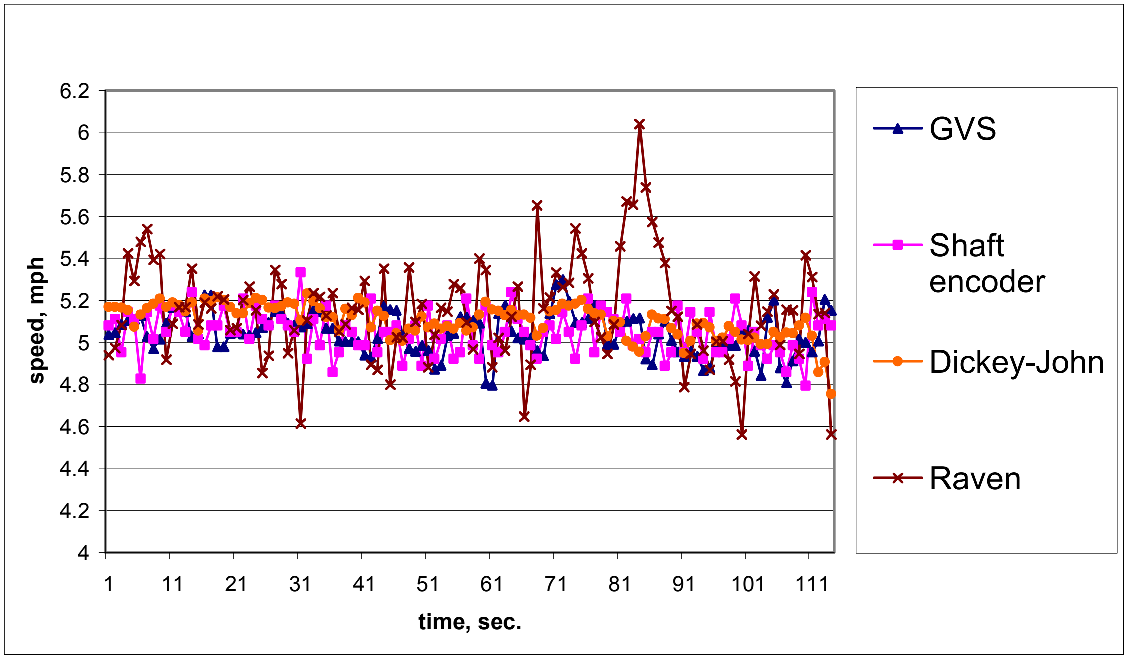

Figure B-14 Figure depicting speed vs. time on wheat surface at 8 kmph

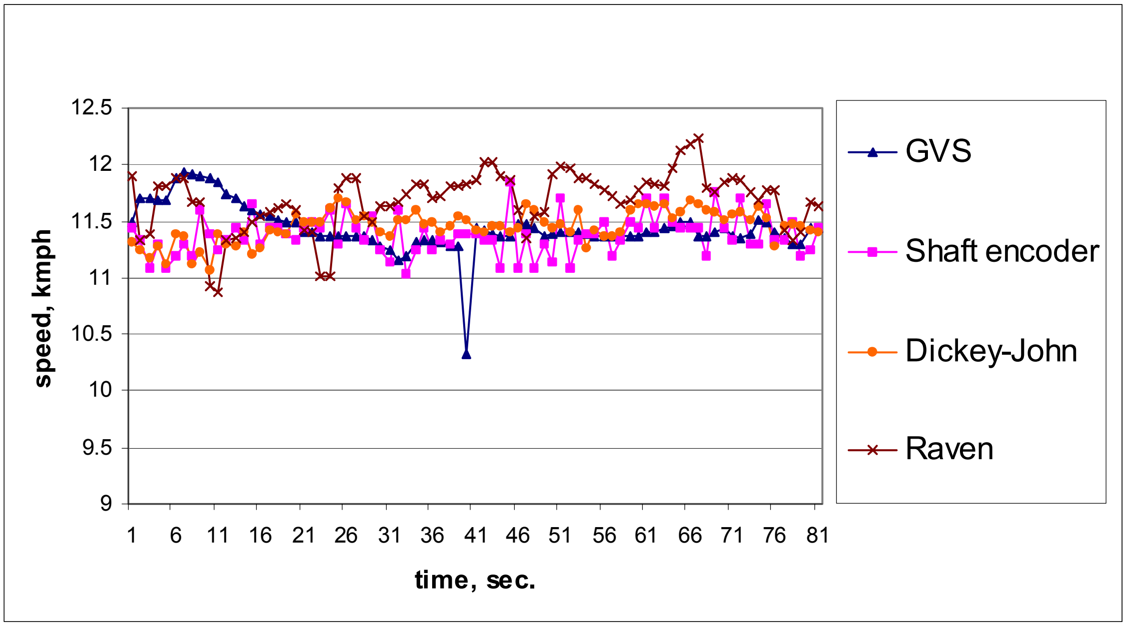

Figure B-15 Figure depicting speed vs. time on wheat surface at 11 kmph

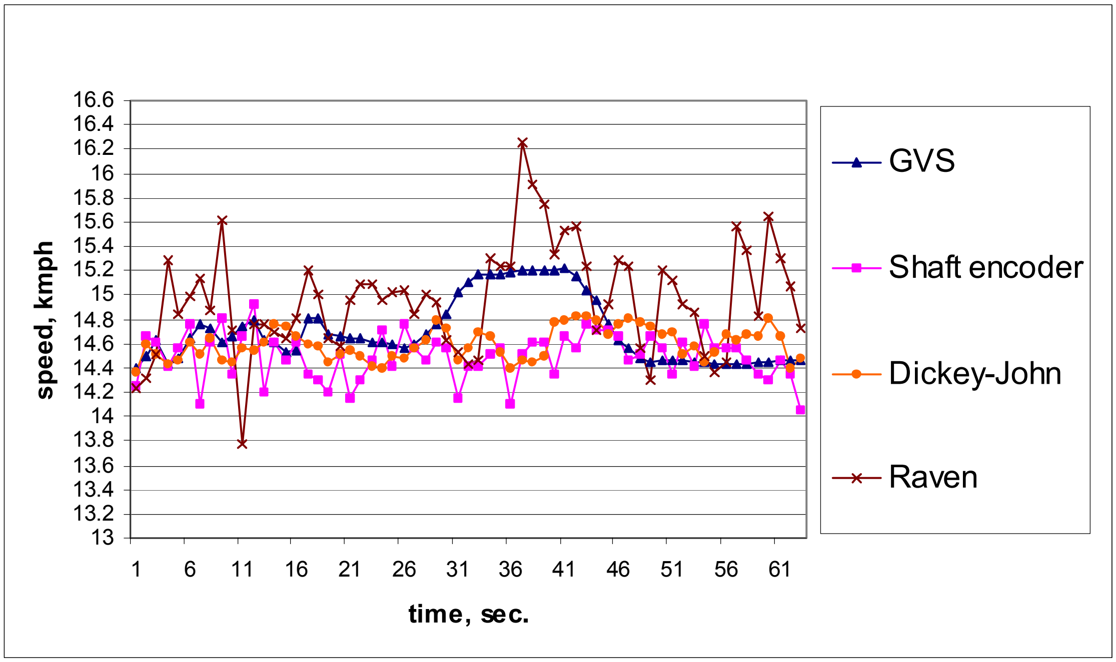

Figure B-16 Figure depicting speed vs. time on wheat surface at 14 kmph

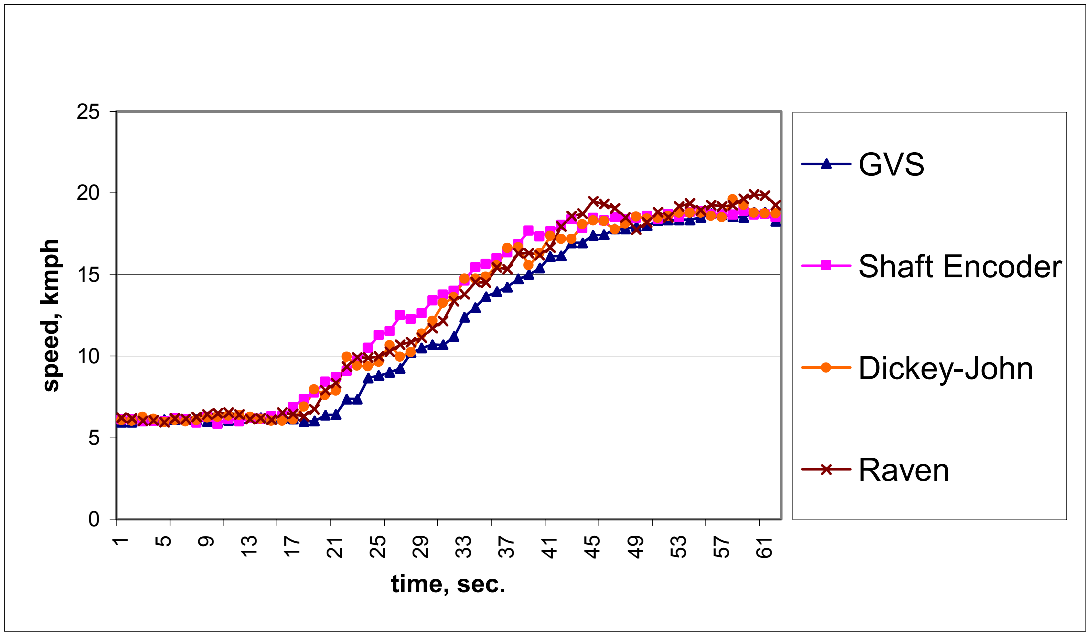

Figure B-17 Speed Vs. Time on canola surface during acceleration

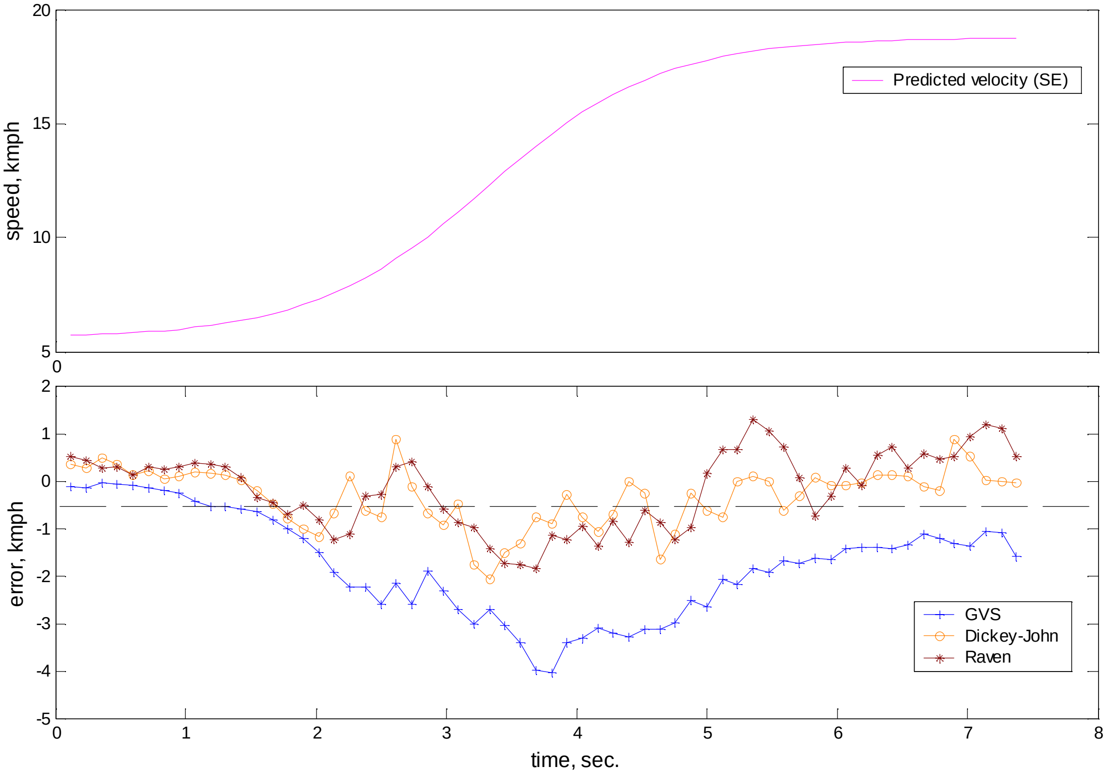

Figure B-18 Speed, Error Vs. Time on canola surface during acceleration

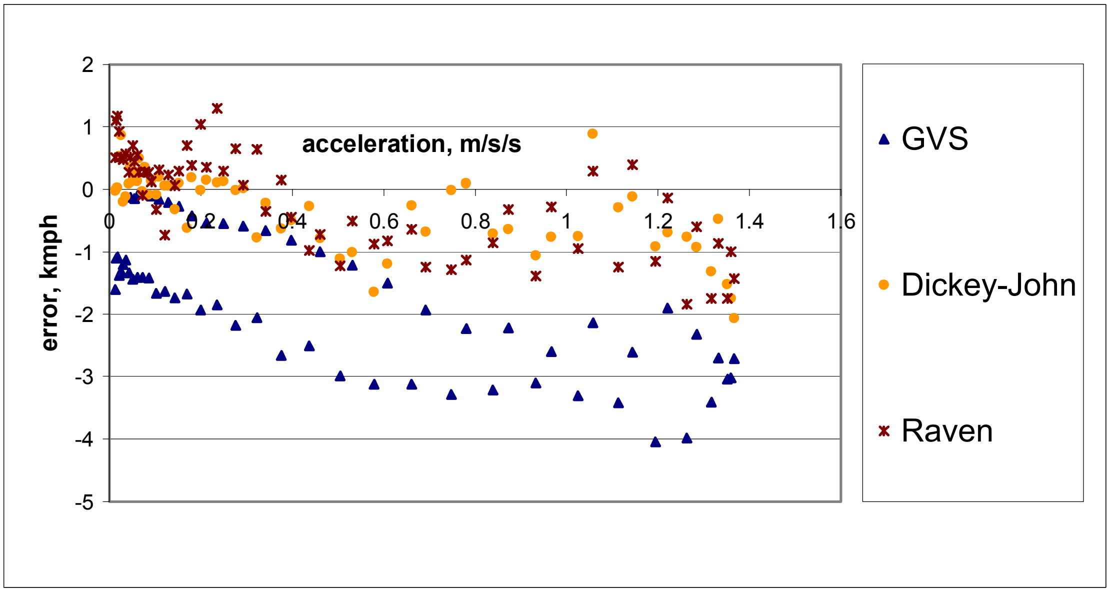

Figure B-19 Error Vs. Acceleration on canola surface during acceleration

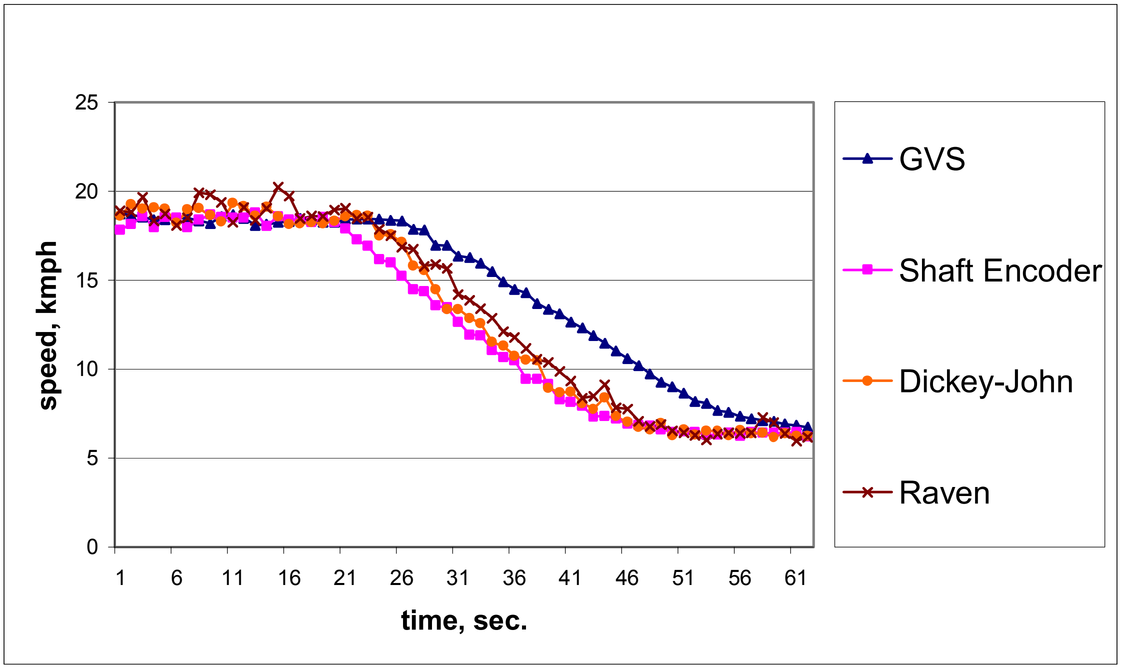

Figure B-20 Speed Vs. Time on canola surface during deceleration

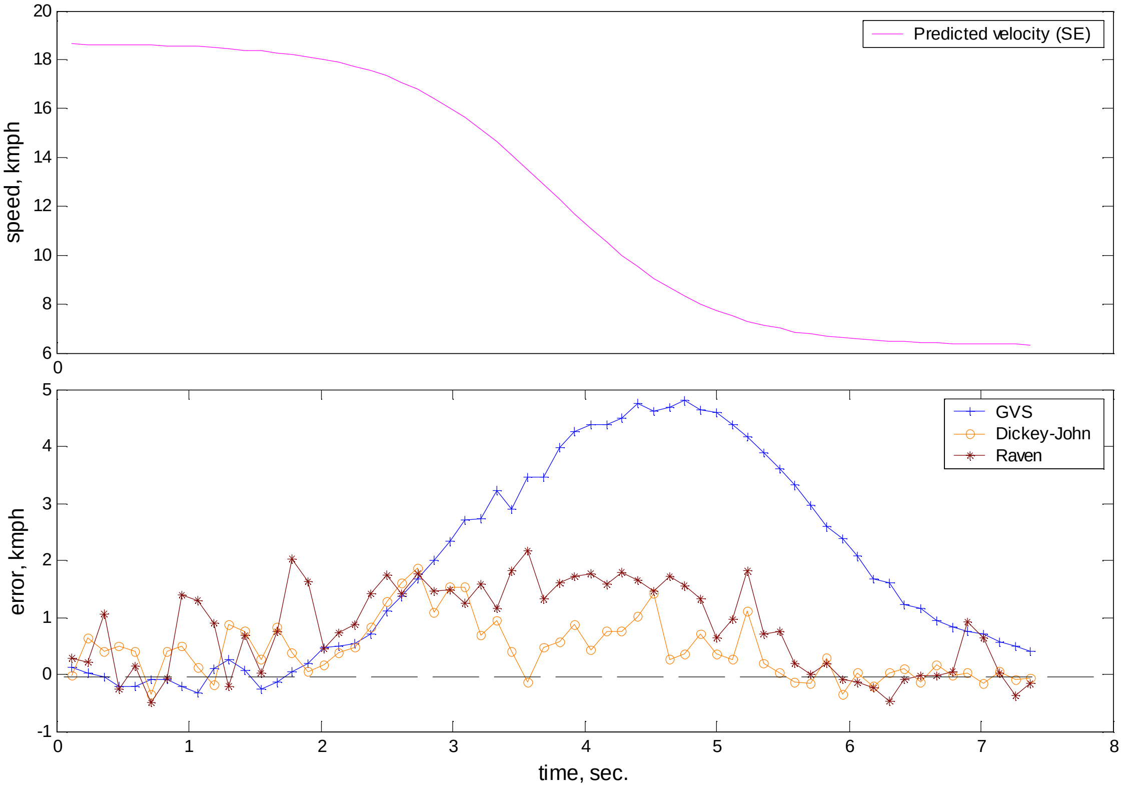

Figure B-21 Speed, Error Vs. Time on canola surface during deceleration

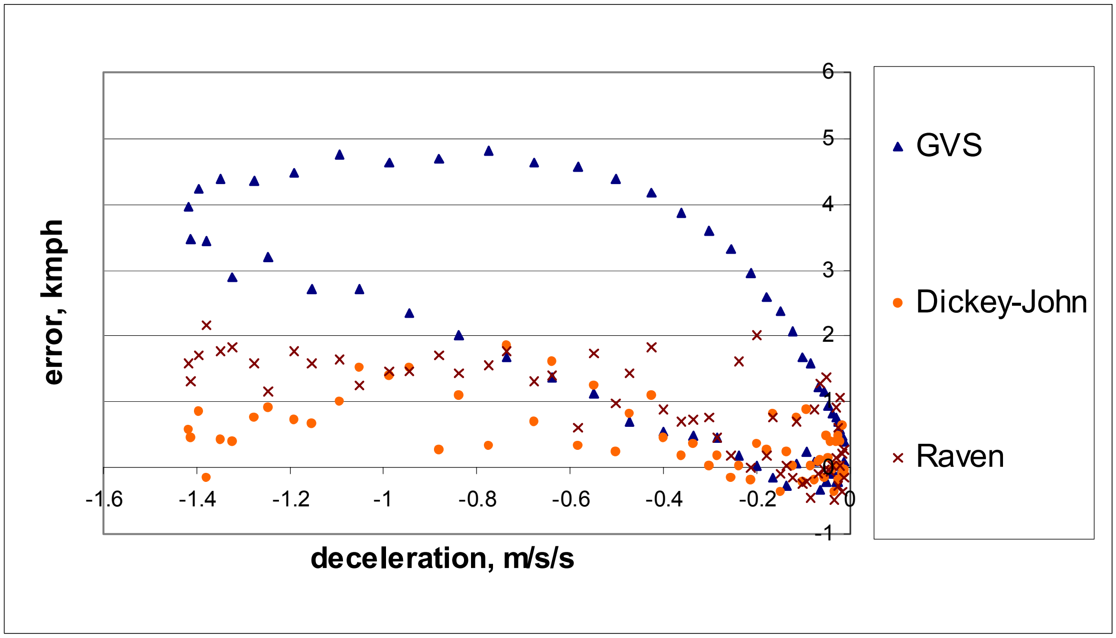

Figure B-22 Error Vs. Deceleration on canola surface during deceleration

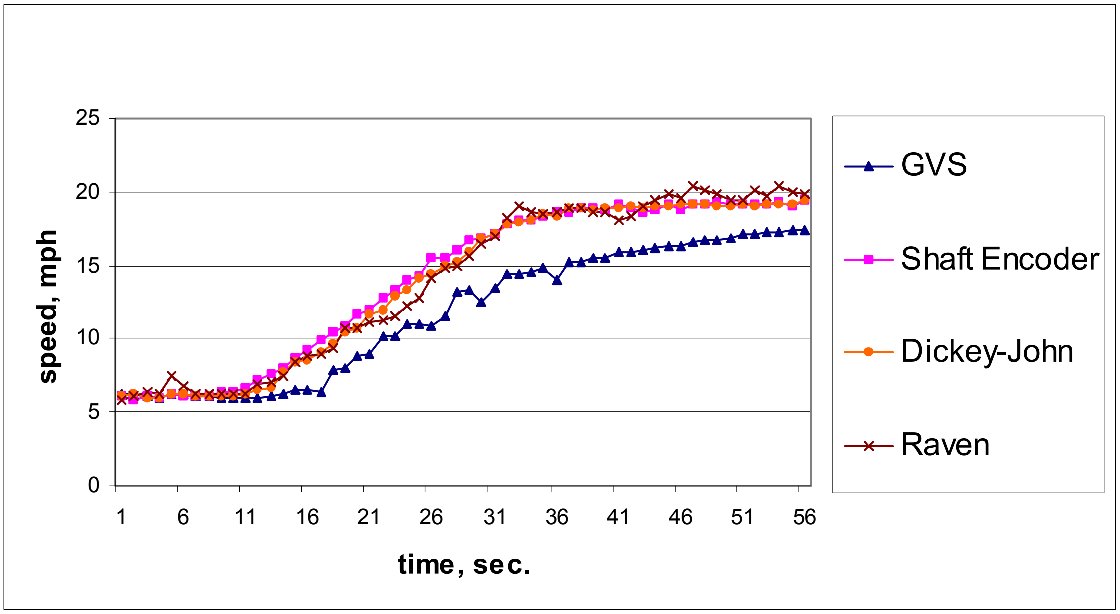

Figure B-23 Speed Vs. Time on wheat surface during acceleration

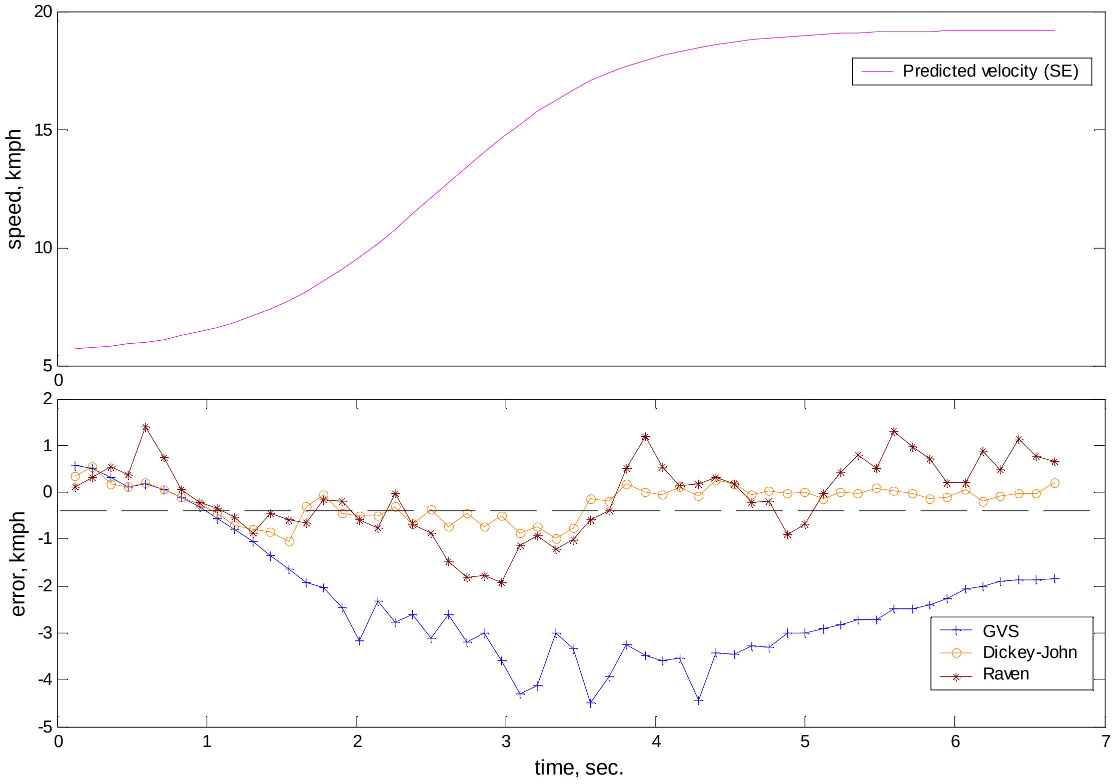

Figure B-24 Speed, Error Vs. Time on wheat surface during acceleration

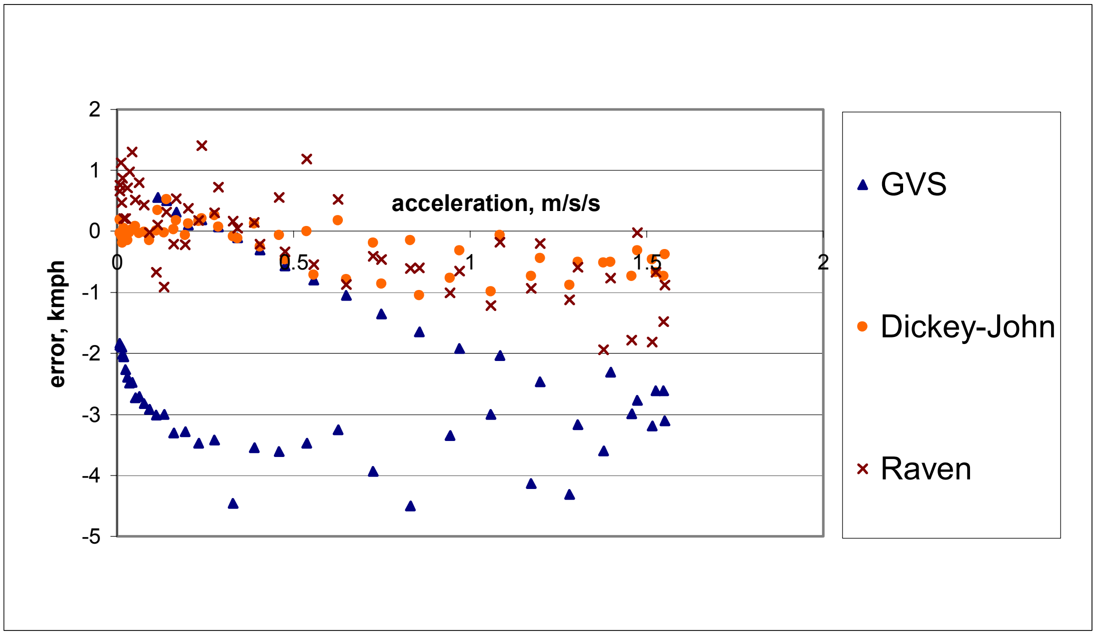

Figure B-25 Error Vs. Acceleration on wheat surface during acceleration

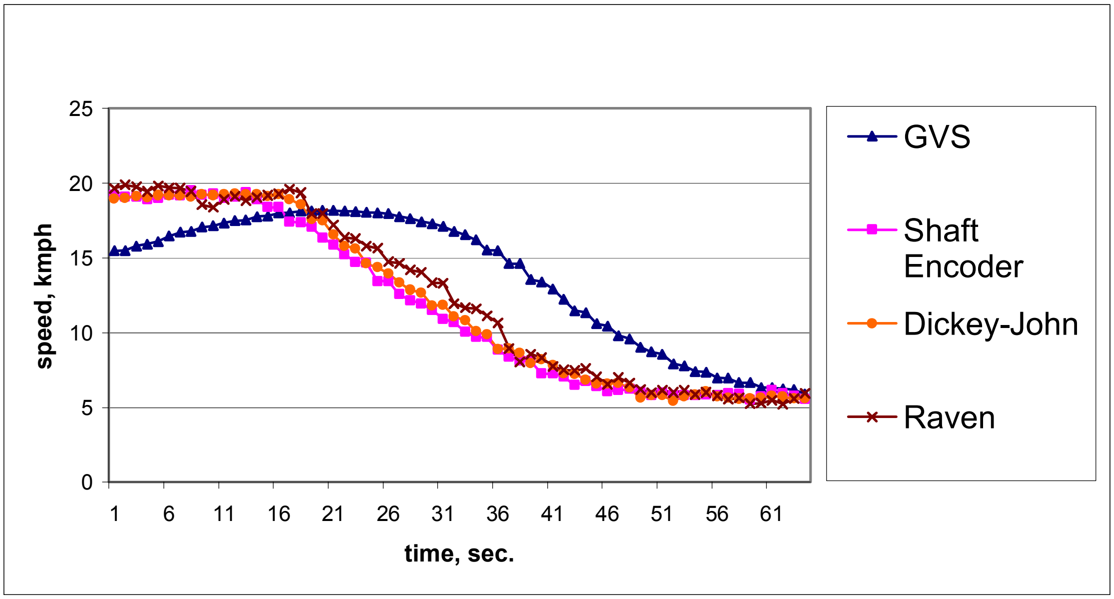

Figure B-26 Speed Vs. Time on wheat surface during deceleration

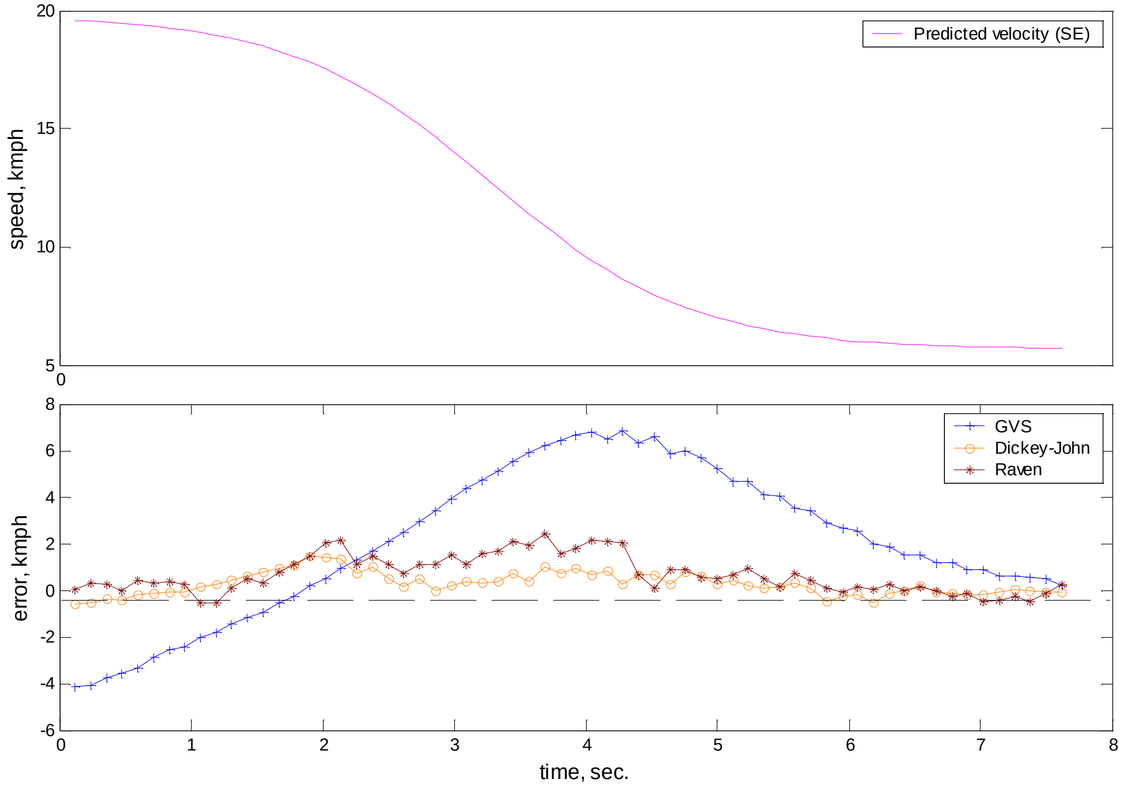

Figure B-27 Speed, Error Vs. Time on wheat surface during deceleration

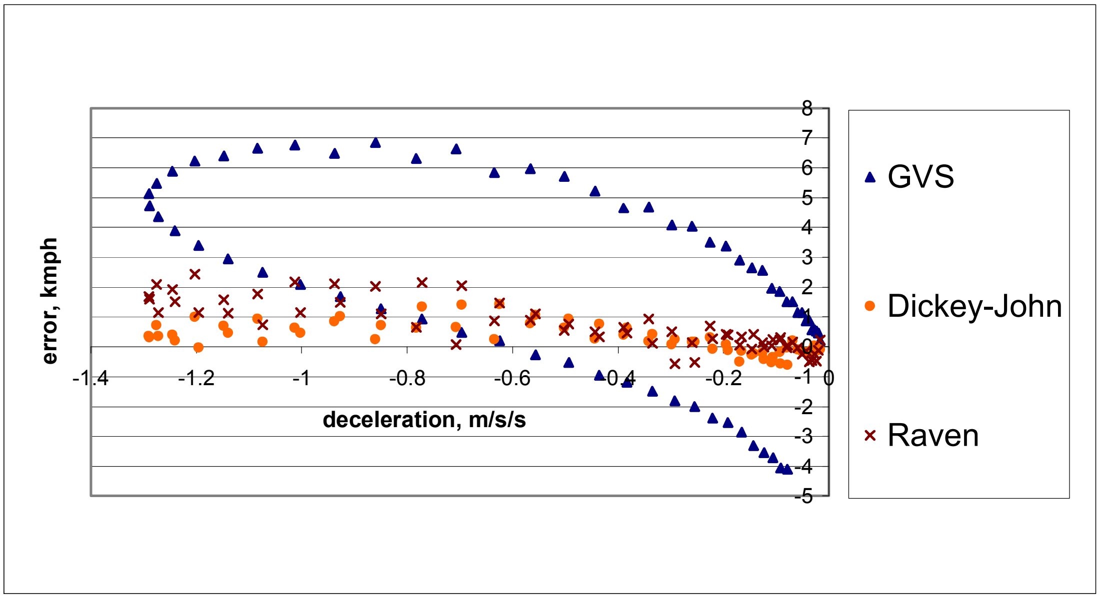

Figure B-28 Error Vs. Deceleration on wheat surface during deceleration

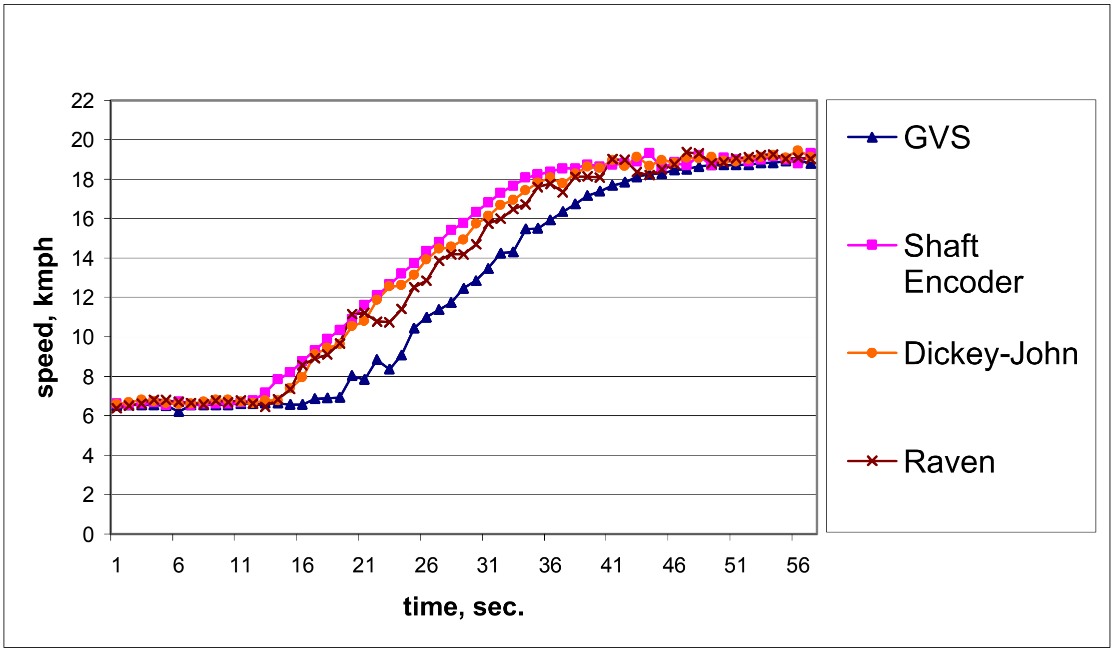

Figure B-29 Speed Vs. Time on tilled surface during acceleration

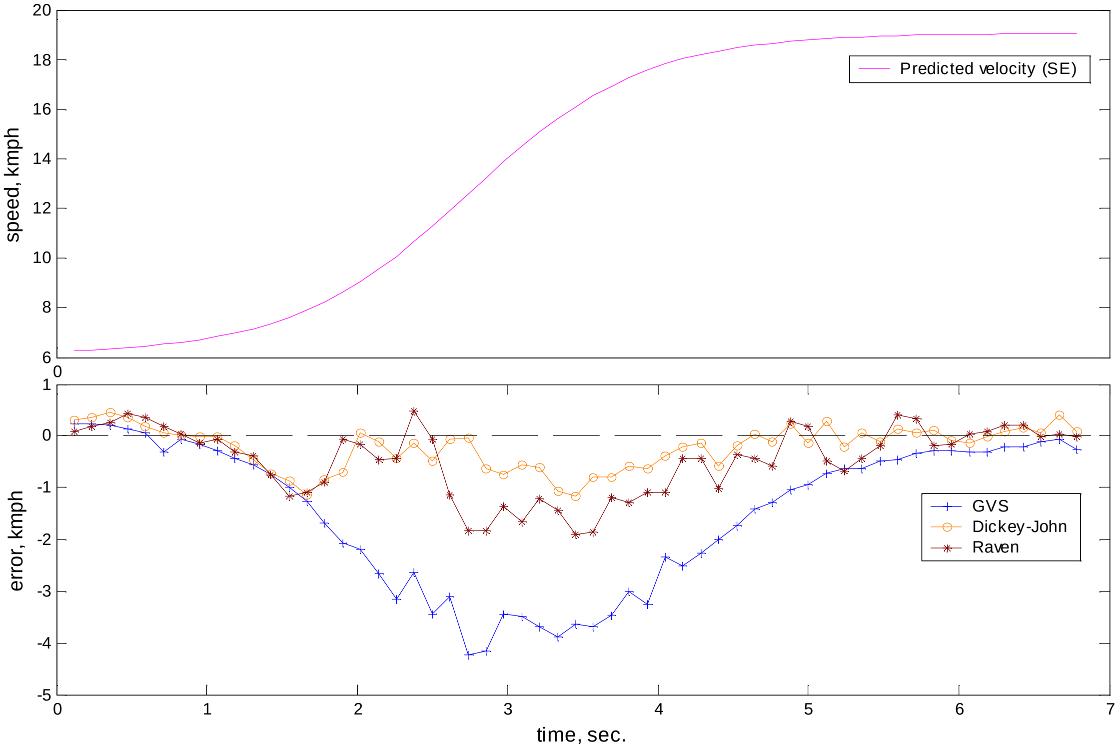

Figure B-30 Speed, Error Vs. Time on tilled surface during acceleration

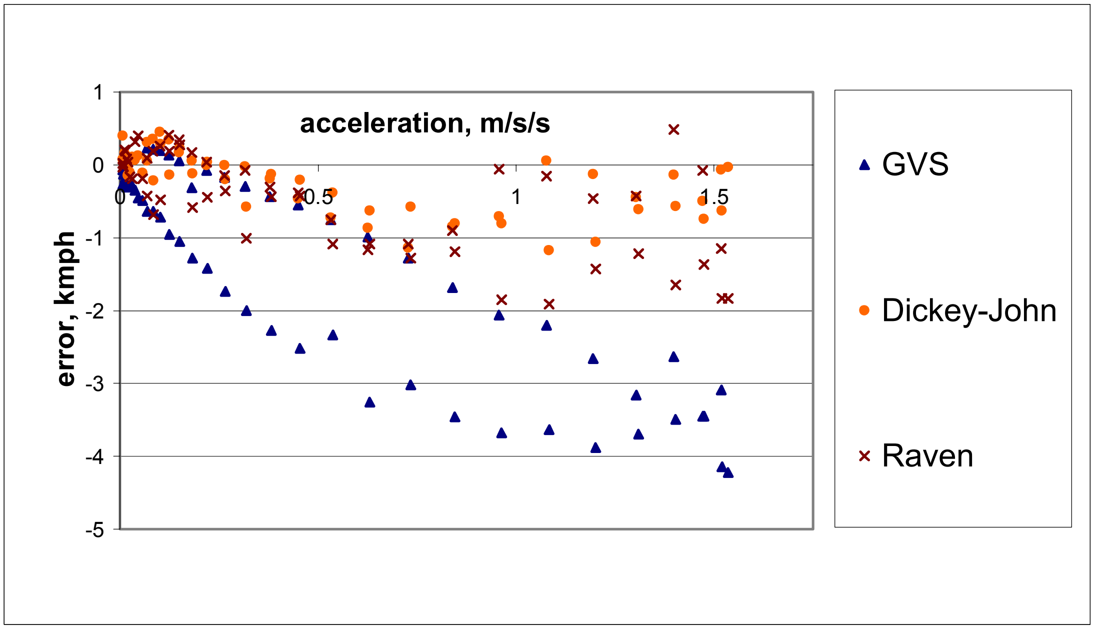

Figure B-31 Error Vs. Acceleration on tilled surface during acceleration

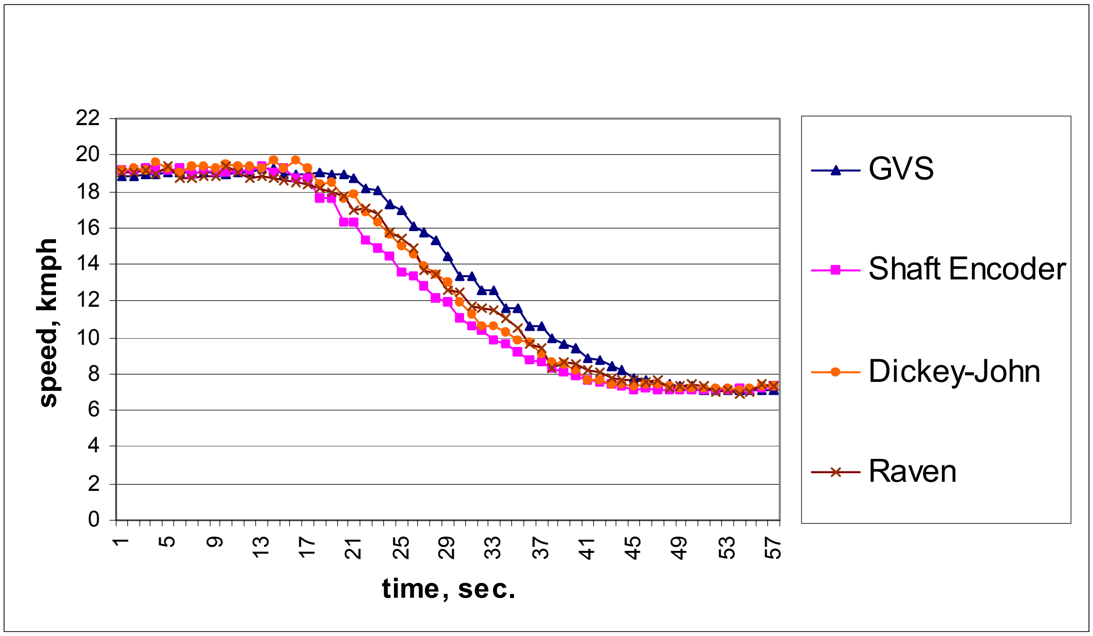

Figure B-32 Speed Vs. Time on tilled surface during deceleration

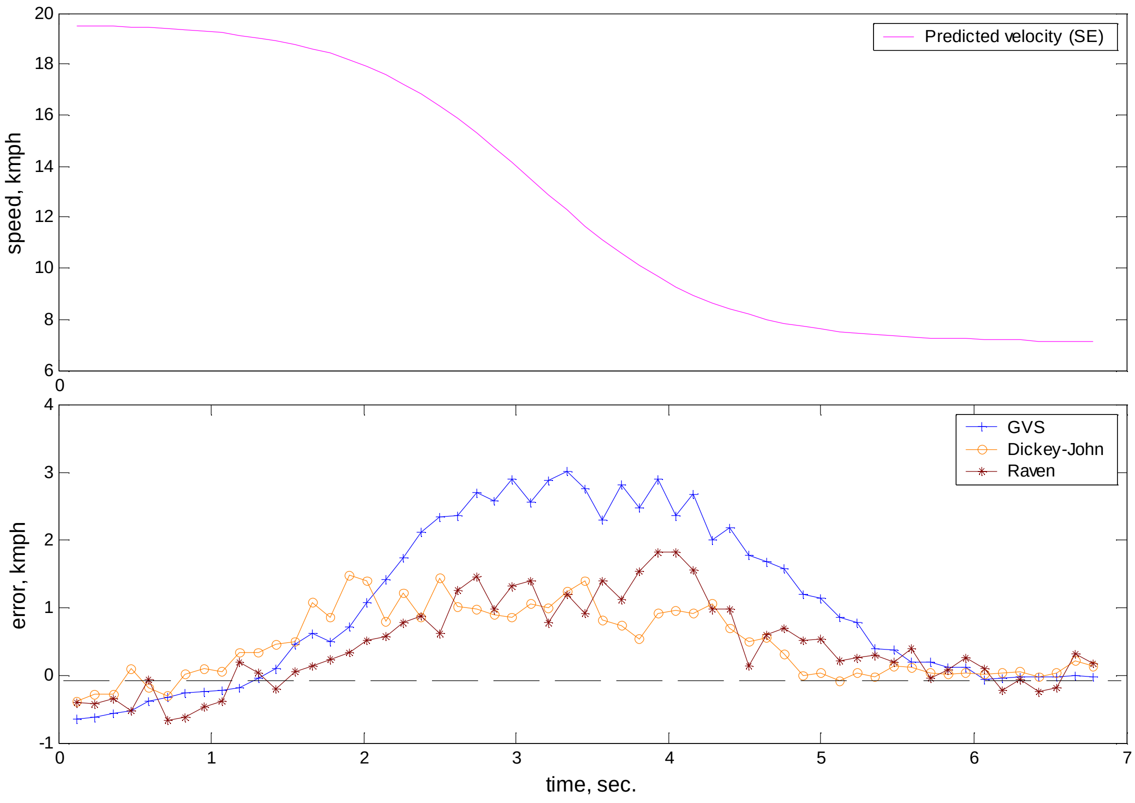

Figure B-33 Speed, Error Vs. Time on tilled surface during deceleration

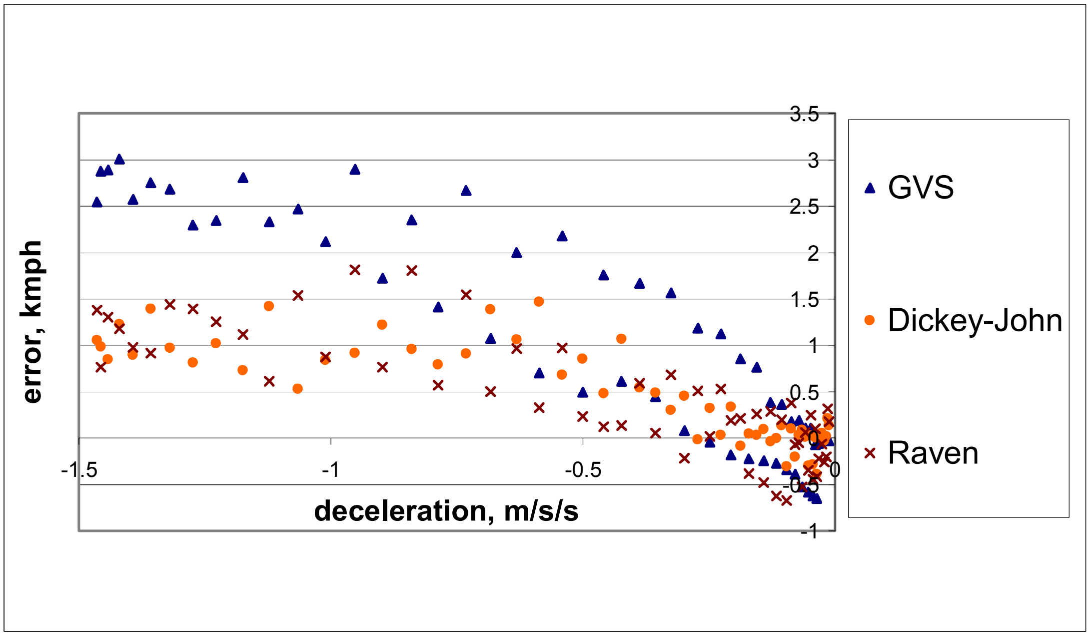

Figure B-34 Error Vs. Deceleration on tilled surface during deceleration

VITA

Ramesh Vishwanathan

Candidate for the Degree of

Master of Science

Dissertation: EVALUATION OF GROUND SPEED SENSING DEVICES UNDER VARYING GROUND SURFACE CONDITIONS

Major Field: Biosystems Engineering

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Education: Bachelor of Engineering in Agricultural Engineering from Rajasthan Agricultural University, Rajasthan, India (1997). Completed the requirements for the Master of Science degree with major in Biosystems and Agricultural Engineering at Oklahoma State University, July, 2005.

Experience: Worked as Field Engineer in Rajasthan Agriculture Drainage research project, Rajasthan, India (1997-1999). Worked for Tractor and Farm Equipment Limited (TAFE), Chennai, India (1999-2003). Graduate Research Assistant at Biosystems Engineering department, Oklahoma State University, Stillwater, OK (Aug 2003-July 2005).

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Name: Ramesh Vishwanathan Date of Degree: July, 2005

Institution: Oklahoma State University Location: Stillwater, Oklahoma

Title of Study: EVALUATION OF GROUND SPEED SENSING DEVICES UNDER VARYING GROUND SURFACE CONDITIONS

Pages in Study: 73 Candidate for Degree of Master of Science

Major Field: Biosystems Engineering

Abstract:

The objective of this study was to compare several commercially available methods of ground speed measurement under varying vegetative covers and ground conditions. Empirical field observations indicated that radar ground speed measurements show increased error as crop vegetative cover/ height increases. A low cost GPS based ground velocity sensor has been recently developed, and that system was compared to the other speed sensors as well. These systems were compared to a reference (true) ground speed. The experimental study included instrumentation of a tractor with speed sensors and a data acquisition system.

Findings and Conclusions:

GPS based velocity sensor can be an inexpensive alternative to radar sensors for steady state applications, however further refinements in the system are required for its intended use in transient speed conditions. The speed measurements obtained from radar sensors were within the acceptable accuracy range, although further refinements in Raven radar data are necessary to make it insensitive towards canopy effect of the crops. Results included validation of GPS and radar sensors for true ground speed measurements in terms of their accuracy and reliability.

Advisor's Approval: Dr. Paul R. Weckler