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A low-cost wheel slip measurement device for agricultural tractors

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ABSTRACT

Tractor wheel slip affects the traction of a tractor, fuel efficiency and tyres adversely, along with compaction of the soil. Tractor operators cannot sense the slip unless it continues for some significant time. In the present study, a low-cost slip measuring device and an indicator were developed at ICAR-IARI, New Delhi (2018) and installed on the tractor dashboard for the operator's information. It warns the operator about slip both by visual and auditory signals to adjust the driving accordingly. In this study, four different sensors (Inductive proximity sensor, IR sensor, Hall effect sensor, and Photo-electric sensor) were tested for measurement of rotational speed under different working conditions of light and dust. Hall effect sensor was found the best for all the operational conditions. So, a low-cost slip measuring device was developed with the Hall effect sensor integrated with a microcontroller as a retrofit for tractors. The device was mounted on the tractor, and field experiments were conducted. The results obtained from the developed device showed that the values were statistically close to actual values.

Keywords: Microcontroller, Proximity sensor, Slip estimation, Slip indicator, Tractor wheel slip

The tractive performance of the tractor depends on soil moisture, normal load on traction wheel, slippage, speed, and inflation pressure (Raper *et al.* 1995). The wheel slip is also affected by soil type, soil moisture, and forward speed. Excessive slippage is associated with loss of energy, tyre wear, variation in working depth, and loss of productivity (Moitzi *et al.* 2014, Janulevicius and Damanauskas 2015, Battiato *et al.* 2015). The tractive efficiency is highest at a wheel slip of 8 and 15% (Keller 2005, Raheman and Jha 2007). Maximum soil compaction was reported at 15–25% wheel slippage. Increasing the mass of the tractor decreased the driving wheel slip but also increased soil compaction (Damanauskas *et al.* 2015). Tractor operators during fieldwork can sense wheel slip only when it is about 30% for at least 6 sec duration (Pranav *et al*. 2010). So, that it can be controlled by reducing speed or depth of operation.

Real-time slip data measurement of front and rear wheel rotation in varying field condition operations is a challenge. Studies had been done for wheel speed determination with pulse generator such as interrupter, optical, inductive, reluctance, and capacitive, but most of these are least reliable under field operation (Pieniazek and Ryba 2017). The Hall effect sensor based rotational speed measurement device was developed (Tisaj 2014, Sreenivasulu and Raghavendra 2016, Negi 2017). Ma *et al.* (2013) and Namaru (2014) developed a microprocessor-based high speed measurement system using an infra-red sensor. Jia *et al.* (2016) developed an Arduino-based real-time tachometer using a pair of Hall-effect sensors. Raheman and Jha (2007) used an inductive proximity sensor for rotational speed measurement of the tractor wheels to assess slip values with error in the actual and measured values in the range of 0–5%. Photo-transducer or encoder type devices require a complete assembly to connect with the shaft. So, these techniques were tractor specific, expensive, and of unproven reliability for instantaneous measurement of slip. The present study was undertaken to develop a tractor wheel slip measurement and indicator device to enable the operator to take steps as the wheel slip exceeds the desired limit.

MATERIALS AND METHODS

Evaluation of sensors for wheel slip measurement device: The experiment was conducted for evaluating four different sensors in the experimental lab setup for suitability in-field operation at the Division of Agricultural Engineering, ICAR-IARI, New Delhi (2018). An experimental setup of size 750 mm × 1000 mm × 650 mm was fabricated with three stepper motors mounted on three corners to simulate two rear and one front wheel of the tractor. A single mounting frame was 3D printed to accommodate four sensors (i.e. inductive proximity sensor (S_1), Infrared sensor (S_2), Hall effect sensor (S_3), and Photoelectric sensor (S_4) facing toward the target to measure the rotational speed and was bolted to the metal frame. A disc of 195 mm diameter was 3D printed and was mounted on one of the stepper motor shaft. Eight hexagonal heads were mounted as target on the

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disc with magnets (Rare earth neodymium magnets- NdFeB magnets or Neo magnets) as to be sensed by each sensor. A 12V DC supply was given to the buck converter and four sensors were supplied 5V output from Arduino Mega. The signal pins of all four sensors were connected to the four interrupt pins (Digital pins 2, 3, 18, and 19). Input wires from the SD memory card module were connected to VCC, GND, Digital pins 50, 51, 52, and 53. Real-time clock (RCT) and I2C display was connected to VCC, GND, and the I2C pins of Arduino (digital pins 20 and 21).

The stepper motor mounted on the experimental frame was run by Arduino Uno through the stepper driver (A4988). All four sensors were mounted close to the bolt head with pasted button magnets. All the four sensors were tested under three different illumination conditions: indoor (78 lux)-clean, outdoor conditions (59 k lux) - clean and dusty conditions. Tractor with farm machines produces a lot of dust, so dusty conditions were created by blowing 2 kg soil dust per hour to assess the efficacy of sensors. The stepper motor speed varied from 10 to 390 rpm; sensor responses were recorded at an interval of two seconds for continuous operation for each revolution, for one minute. The rotation of the disc was also measured with a digital tachometer.

Effect of working conditions on sensors response: The experiment was conducted using a latin square design for four sensors (IR, Inductive proximity, photoelectric, and Hall effect sensor) response in terms of RPM. It showed that the response of the IR sensor and the photoelectric sensor was significantly different from the response of the Inductive proximity sensor and Hall effect sensor. The interaction between the response of Inductive proximity sensor (S_1), IR sensor (S_2), Hall effect sensor (S_3) and Photoelectric sensor (S_4) for conditions and spacing between sensor and target: Indoor 2 mm (IDC2), Indoor 5 mm (IDC5), Outdoor clean 2 mm (ODC2), Outdoor clean 5 mm (ODC5), Outdoor dusty condition 2 mm (ODD2),Outdoor dusty condition 5 mm (ODD5) was analyzed (Fig 1). It indicated that the variation in the interaction was lowest in Hall effect sensor (S_3), followed by an inductive proximity sensor, IR sensor, and photoelectric sensor. The distribution of responses of different sensors in different operating conditions clearly showed that the "Hall effect sensor" had the best response among the four sensors tested, followed by an inductive proximity sensor. However, there was a large number of out-layer values of the IR sensor and the photoelectric sensor (Fig 1).

The observed values were checked for variation in RPM measurement using a t-test. The least-square mean values for the inductive sensor were between -85.61 to 52.12 for different conditions, giving the best result as -1.04 in outdoor conditions without dust for 2 mm spacing. The Hall Effect sensor showed the best results among all the four sensors, where the least square mean was between -0.787 to 0.668, and the minimum variation was 0.095 for outdoor conditions without dust. Based on the comparative study of four different sensors, the Hall effect sensor was selected for the development of a real-time wheel slip measuring device for a tractor.

Development of Wheel slip measurement device: Three Hall effect sensors (the best selected from the lab testing of different sensors) were powered with 5V output of Arduino Mega. The signal pin of each sensor was connected to the VCC pin of a signal using 10 k ohm pull-up resistance, and then the signal pins were connected to the interrupt pins of Arduino Mega (digital pins 2, 3 and 18). Three red, orange and green LEDs were connected to digital pins 4, 5 and 6, and the buzzer was connected to digital pin 7 of Arduino Mega.

Program (code) for wheel speeds and slip calculation: The program in C++ software to calculate the wheel speed and slip from the sensor output was written. The program facilitated receiving interrupts from the sensors counted for two seconds. After three seconds, counting restarts and the number of pulse in these three seconds were processed to assess wheel speed from the number of magnets on the wheel and the rolling radius of the respective wheel as per Eq. 1 and 2.

Wheel RPM calculation;

$$\text{Wheel rpm (N)} = \frac{\text{Number of interrupts}}{\text{Number of magnets}} \times 20 \qquad \text{Eq 1}$$

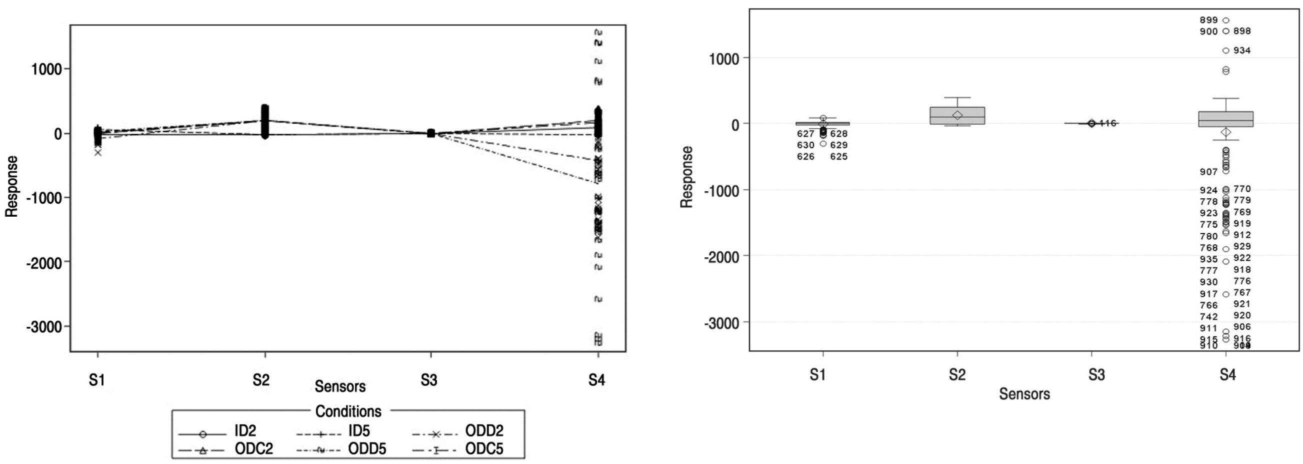

Fig 1 Response of four types of sensor in different working conditions

Wheel speed calculation;

$$\text{Wheel Speed} = \frac{2\pi \times r \times N \times 60}{1000} \text{ km/h} \qquad \text{Eq 2}$$

where r = rolling radius of the wheel.

The wheel slip was calculated using the average speed of both the rear and front wheel as per Eq. 3.

Wheel Slip;

$$\text{Slip \%} = \frac{\text{Average speed of rear wheels} - \text{front wheel speed}}{\text{front wheel speed}} \times 100 \qquad \text{Eq 3}$$

The program was developed using interrupt functions for every sensor; the value of slip and speed was displayed on the LCD. The program was so designed that different lights indicate the operator about the wheel slip status in three categories; for slip >15%-red light slip, <8% –orange and a green light for slip value between 8 and 15%). A buzzer is also provided for an alarm when the slip exceeds 15% to ensure that the operator registers the indication and act.

Evaluation of wheel slip measurement device

Lab test: Three stepper motors and discs were mounted on three corners of the frame to simulate three wheels, two rear wheels and a front wheel of a tractor. Three rotating discs were mounted on the shaft of the stepper motor. Two of them have eight bolt heads, imitating a tractor's rear wheel and a six-bolt head representing the front wheel. The diameter of the discs was equal to the diameter of the respective wheel hub of the tractor. The sensors were tested in the laboratory conditions for the three different rotational speeds. The results obtained during the testing were recorded automatically in the micro SD memory card through the SD card module connected to Arduino Mega.

Field test: Experiments were conducted on the field by mounting the Hall effect sensor on the tractor. The sensor was mounted near each rear wheels hub and one near the right front wheel hub. The developed device was powered by a 12V tractor battery. The slip indicator LED display and the buzzer was installed on the tractor dashboard. The experimental field was divided into three different parts based on soil moisture gradient and bulk density (i.e. 5.4–5.9%; 12.4–13.6% and 15.2–17.1% (Dry Basis) and 1.52–1.59 g/cc, 1.65–1.69 g/cc and 1.71–1.75 g/cc). The average moisture content and bulk density during field evaluation were obtained by oven drying and core cutter method, respectively. Three implements were used for evaluation (Fig 2). The field evaluation of the developed device was conducted by attaching a disc plough. The tractor was operated at three speeds; low first (L_1), low second (L_2), and low third (L_3) gear at 1500 engine rpm. As a standard procedure, distance covered by a tractor in 5 revolutions of rear-wheel was measured along with the time required for it under load and no-load conditions. It was repeated for three speeds and three replications in all three-field moisture conditions. The same procedure was used for disc plough, cultivator and wheat planting by the System of Wheat Intensification (SWI) planter.

RESULTS AND DISCUSSION

Performance of the slip measuring device: The developed device was mounted on an experimental lab setup and on the tractor for field evaluation.

Lab evaluation: The result of paired t-test for the mean of actual and measured front and rear wheel RPM and speed and slip values clearly showed no significant difference between actual values and measured values of all variables at a 5% level of significance. The value for each pair was very close, with standard deviation ranging from 0.027–3.2 for forwarding speed and wheel slip, respectively. Also, all the values of RPM and speed showed a good correlation, with values ranging from 0.994 to 1 (Table 1).

Field evaluation: The developed device was mounted on a tractor for evaluation and observations were recorded. There was an increase in wheel slip with the increased speed at higher soil moisture in the field (17.1% db). The trend was reversed at low and medium soil moisture as slip decreased with an increase in speed. Also, wheel slip increased with an increase in moisture content for speeds L_2 and L_3 at 1500 engine rpm, but in the case of speed L_1 with 1500 engine rpm, there was less slip in the field with medium soil moisture (13.6% db). An increase in wheel slip with the higher forward speed at low and high moisture content fields was observed for a cultivator. However, in the medium moisture content field, there was an increase initially and then a decrease in slip and speed. The wheel slip increased with forward speed of tractor in high moisture

Fig 2 Field experiment for slip measurement with Disc plough, Cultivator and SWI planter.

Table 1 Paired t-test for rear and front-wheel rpm

Pair	Mean	Standard deviation	Std. Error Mean	Correlation	t	df	Significance (2-tailed)
Rear wheel-1 RPM	-0.064	0.533	0.085	0.996	-0.751	38	0.457
Rear wheel-2 RPM	-0.106	0.56	0.09	0.994	-1.185	38	0.243
Front wheel RPM	0.002	0.201	0.032	1.00	0.035	38	0.972
Slip	-0.502	3.246	0.52	0.995	-0.996	38	0.340
Forward speed	0.00015	0.027	0.0044	1.000	0.035	38	0.972

Table 2 Paired t-test for actual and measured wheel slip and forward speed

Factor	Actual speed-Measured speed	Actual slip-Measured slip
Mean	0.0027	-0.821
Standard deviation	0.50393	1.145
Standard error mean	0.5599	0.452
Correlation	0.9	0.852
t-value	0.048	0.085
df	80	80
Significance	0.962	0.093

content (17.1% db) of soil when disc plough was used. Janulevicius and Damanauskas (2015) also reported the slip increase of 2 to 3 times higher with forward speed. This was due to lower traction in high moisture content of soil which restricted the forward speed. Similarly, wheel slip increased with an increase in the moisture content of the soil at low (1.85 km/h) and medium (2.85 km/h) speeds, but for high speed (4.1 km/h), initially slip decreased and then increased with soil moisture. The result obtained from the field evaluation showed the increase in wheel slip with increased moisture content of soil. This was due to low cohesiveness of soil, thus less traction produced. Inchebron *et al.* (2012) also reported that there was increase in wheel slip with increased moisture content of soil. The maximum value of slip was in a high moisture content field for medium speed of cultivator operation. An increase in wheel slip was observed for SWI planter operation with an increase in soil moisture and forward speed. The maximum slip was 10.5% for the SWI planter at a higher moisture content field with high speed. Wheel slip was higher in disc plough operation followed by cultivator and SWI planter for medium (13.6 and 12.4% db) and high moisture content (17.1 and 15.2% db). Wheel slip was minimum in cultivator operation in low moisture content (5.9% db) of soil. The reason was hard soil and low draft requirement for cultivator then disc plough. The paired t-test was performed to compare the means of actual and measured values of wheel slip and forward speed. There was no significant difference between actual and measured values of wheel slip and forward speed (Table 2).

The indicator also displayed different colour lights indicating the slip category and an auditory signal was also buzzing for registration of the operator.

Hall effect sensor was found the best among four selected sensors (R^2 value 0.9999) with 0.095 (minimum) least square mean. Wheel slip and speed measurement device was developed using a Hall effect sensor and tested in the laboratory. There was no significant difference between measured and actual values of RPM, slip, and speed with a t-test. In the field, experiments were conducted for the measurement of slip and forward speed with the developed device; no significant difference was observed between the values measured with the developed device. The device gave warning signals through LEDs and buzzer when wheel slip value exceeded or decreased the adequate range (8–15%). The estimated cost of the developed wheel slip measuring device was □2500, which can be easily fabricated and installed on a tractor by rural youth.

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