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Full Length Research Paper

Design of digital weight transfer display for agricultural tractors

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A microcontroller based digital display unit was developed for 2WD agricultural tractors to measure and display the weight transfer from tractor front axle. The device includes a transducer for measuring the tractor front end reaction, an amplifier to amplify the transducer signal and a microcontroller to calculate and display the weight transfer from the front axle. The developed device can be mounted on any make and model of 2WD tractor. The digital display unit was rigorously tested in the laboratory as well as in the field. A maximum of + 3.5% variation in weight transfer was observed between the theoretically calculated and experimentally observed values.

Key words: Microcontroller, weight transfer, ring transducer, tractor, front axle.

INTRODUCTION

The agricultural tractor is rather a heavy machine and is used for a variety of operations from tillage to haulage under diverse conditions. Whatever the case may be, one of the most important considerations is to ensure safety in operation or in other words, a hazard free operation. This is possible when a tractor is stable during a static as well as a dynamic situation. Historical data shows the fatality rate in agriculture remained about 22/100,000 workers through the 1990s, while tractor-related accidents cause approximately 300 fatalities each year (Rautiainen and Reynolds, 2002). Tractor rollovers cause over 50% of fatalities from agricultural accidents each year (Hard et al., 1999). Even with enormous efforts to improve tractor safety designs, the rate of tractor-related fatalities has shown a slight increase mainly due to the inadequate maneuvering of the tractor (Myers et al., 1998).

Tractive ability of a tractor is normally affected by soil reactions against the front and rear wheels. Weight transfer is reaction transfer of front and rear wheels of the tractor. Because of drawbar loading, weight transfer decreases soil reaction against the front wheels while it increases in the rear wheels. This causes a significant increase in the dynamic load on the drive tires. Weight transfer for a tractor operating with mounted implements can be up to 65% of the drawbar pull (Zoz, 1970).

Habarta (1971) investigated the problems involved in steering ability of a tractor with implements. He analyzed the minimal values of the load on the front axle of a tractor and quoted that regardless of the load of the tractor, the load transferred by the front wheels of the tractor on to the road should not be less than 20% of the weight of the tractor. To achieve longitudinal stability and manoeuvrability of the tractor, he emphasized that the load of the controlled axis of the tractor in static condition on plane ground should be at least 25% of the instantaneous weight of the tractor. Gravalos et al. (2011) conducted the experiments to study the impact of the rear track width on the stability of agricultural tractors using a test bench and found that, the static limit of overturn was considerably improved when the width of the rear track was 1650 mm and an additional weight had been used for the uphill wheel.

It has been reported earlier that rearward overturnings are more likely to be fatal than the sideways overturnings (National Safety Council, 1968). Rearward overturning takes place when dynamic front wheel reaction is

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reduced to zero due to excessive drawbar loading or rear wheel slippage. If this reaction could be measured and displayed near tractor seat the operator can take precautionary measure to avoid overturn. The analytical mechanics of farm tractors have been studied by several researchers in the past (Sack, 1956; Koch et al., 1970; Smith and Liljedahl, 1972; Mitchell et al., 1972) with a view to develop mathematical models for predicting their rearward overturning behavior. Rowe and Spencer (1976) developed an instrumented tractor to measure the weight transfer by mounting strain gauges on the front and rear axles of the tractor, however, the dimensions of the axle resulted in very small strains induced by wheel loads. Some studies have also been made to develop devices for measuring the critical slopes at which tractor accidents may occur when they are out of control while sliding downhill (Spencer and Owen, 1981; Spencer et al., 1983). However, the development and use of a suitable device to measure the dynamic front wheel reaction to prevent rearward overturning of farm tractors is not well documented. A study was therefore, undertaken to address this issue with the following objectives:

1. To design and develop a suitable ring transducer for sensing tractor front end reaction.
2. To design and develop a microcontroller based circuit for processing and displaying the transducer signal near the tractor operator.
3. To evaluate the developed digital display unit under laboratory and field conditions.

THEORETICAL CONSIDERATIONS

The following theoretical and empirical equations were used to calculate various parameters for predicting weight transfer in this study.

Draft (D)

The horizontal component of resultant force required to pull a machine in the field is draft. According to ASAE standard (1997) D497.3, it can be calculated by:

$$D = F_j\,(A+BV_a+CV_a^2)*W*d \qquad (1)$$

Where F_j is dimensionless soil texture adjustment parameter (j = 1 for fine, 2 for medium and 3 for course textured soils), and A, B and C are machine specific parameters.

Wheel slip (S)

When a tractor pulls a load, there is a reduction in distance travelled and/or speed that occurs because of flexing of the tractive device and shear within the soil. Slip occurs any time a wheel or traction device develops pull (net traction). It is expressed as the ratio of the decrease in the actual speed to the theoretical speed and is given by:

$$S = \left(1 - \frac{Va}{Vt}\right) \qquad (2)$$

Motion resistance ratio (MRR)

Coefficient of motion resistance or motion resistance ratio (MRR) is defined as the ratio of rolling resistance to the dynamic weight on a wheel.

Gross traction ratio (GTR)

The gross traction ratio is the ratio of the gross thrust developed by the tractor to the dynamic weight on the traction wheels (powered wheel). Brixius (1987) developed the following expressions for GTR and MRR as a function of mobility number (B_n) and wheel slip(S).

$$GTR = 0.88(1-e^{-0.1B_n})(1-e^{-7.5S}) + 0.04 \qquad (3)$$

$$MRR_r = \frac{1}{B_n} + 0.04 + \frac{0.5 \times S}{\sqrt{B_n}} \qquad (4)$$

$$MRR_f = \frac{1}{B_n} + 0.04 \qquad (5)$$

$$B_n = \frac{CI \times b \times d}{R_r}\left(\frac{1+5\frac{\delta}{h}}{1+3\frac{b}{d}}\right) \qquad (6)$$

Net traction ratio (NTR)

Net traction ratio is defined as the ratio of draft to the dynamic weight on the driving wheels and is given by:

$$NTR_1 = D/R_r \qquad (7)$$

$$NTR_2 = GTR - MRR \qquad (8)$$

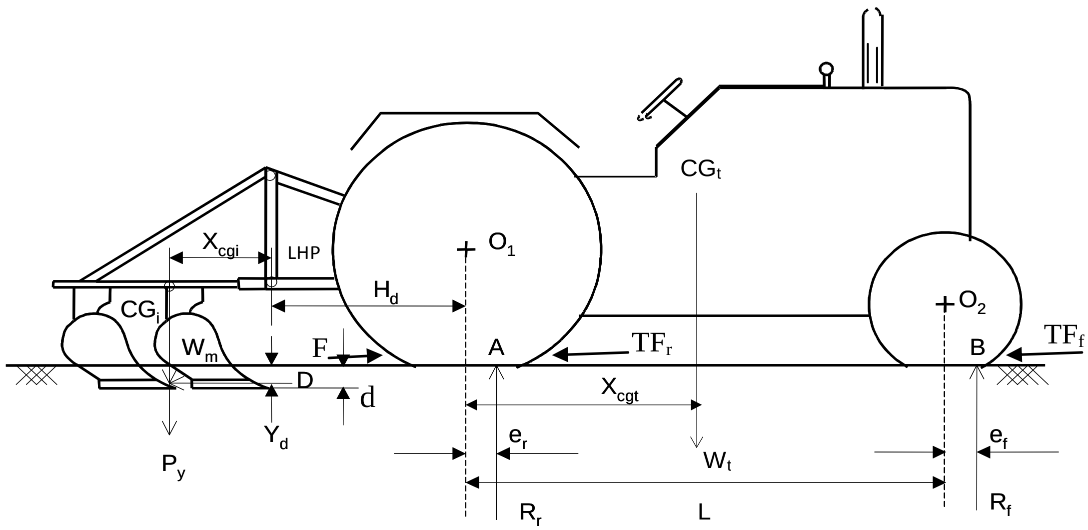

Figure 1. Forces acting on tractor- mould board plough combination.

Weight transfer (WT)

The dynamic weight on tractor axles is required to determine weight transfer from the front as well as from the implement. Considering force and moments in Figure 1 (Sahu and Raheman, 2008), the dynamic reaction on tractor rear wheel, R_r, and front wheels, R_f can be expressed as follows:

$$R_r = \frac{W_t(L + e_f - X_{cgt}) + (W_m + P_y)(X_{cgi} + H_d + L + e_f) - DY_d}{L - e_r + e_f} \quad (9)$$

$$R_f = (W_t + W_m + P_y) - R_r \quad (10)$$

The rear and front wheel eccentricities were calculated by:

$$e_r = MRR_r \times r_r \quad (11)$$

$$e_f = MRR_f \times r_f \quad (12)$$

For simplicity, the CG of the implement and centre of resistance, CR were assumed to lie in the same vertical plane. Also, the distance of CR from the ground surface was assumed to be two-third of the operating depth. Weight transfer from the front end of the tractor and from the implement side is given by:

$$WTF = FWS - R_f \quad (13)$$

$$WTI = R_r - RWS - WTF \quad (14)$$

$$\text{Percent weight transfer from front axle (PWTF)} = \frac{WTF}{W_t} \times 100 \quad (15)$$

Software development

A software was developed in visual basic© to calculate the theoretical weight transfer for a given soil type, implement and tractor parameter is shown in Figure 2. Equation 1 was used to calculate the draft of the implement, and (Equations 3 to 6), were used for predicting GTR and MRR. The motion resistance ratio was calculated by iteration process by initially fixing the motion resistance ratio equal to 0.04 and comparing it with that derived from Brixius equation (Equation 4). The slip was also calculated by iteration process (assuming initial value equal to 2%) by comparing the net traction ratio from Equation (7) with that derived from Brixius equation (Equation 8). The dynamic rear wheel reaction of the tractor was calculated by using Equation 9. Finally, the weight transfer was calculated by using Equations 10 and 13.

Development of force transducer and digital display unit

Force transducer

A diesel tractor (Ford 3630 with rated PTO power 33.8 kW) with a static weight of 19600 N was used as a test tractor in the study. The front axle of the test tractor consists of a hollow centre beam with a telescopic section at each end. Seven holes at 50 mm intervals

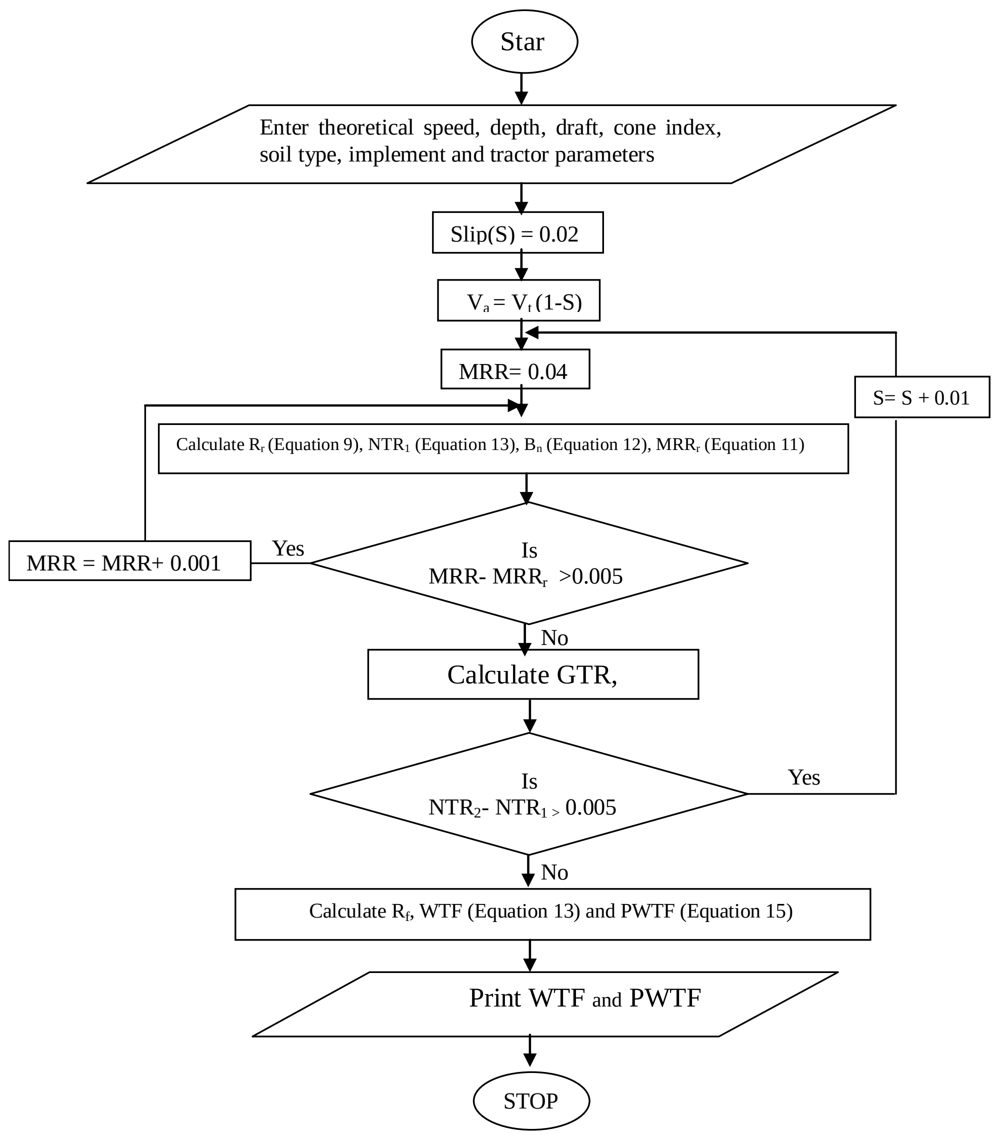

Figure 2. Flow chart for calculating the theoretical weight transfer.

were provided in the telescopic sections for increasing or decreasing the length of the axle. The static weight coming on the tractor's front axle is 6566 N. The front axle experiences a bending force between centre pivot point and stub axle at each end. A ring transducer was developed and attached to the front axle to measure part of this bending force transmitted through the two fixing brackets. The ring was made of special steel, carefully forged to give maximum strength and individually tailored to give high sensitivity combined with stability to ensure life and accuracy. The loading abutments were integrally forged to the ring and were threaded internally on the diametrical opposite loading axis. Four electrical strain gauges each of 350 Ω and 2.6 gage factor were oriented in full bridge pattern which formed a Wheatstone bridge as shown in Figure 3 to determine the tensile and compressive forces coming in the ring transducer due to corresponding tractor weight on the front axle. The design dimensions of this transducer were finalized considering a maximum of 30% of the front axle weight to be sensed by the transducer. The developed transducer was calibrated for both the tensile and compressive forces. A good correlation (R^2=0.99) was found between the applied load and transducer bridge output for the whole range of front axle loading.

Processing and digital display unit

Processing digital display unit includes a signal amplifier and a microcontroller unit. During the calibration of ring transducer, it was observed that the maximum signal

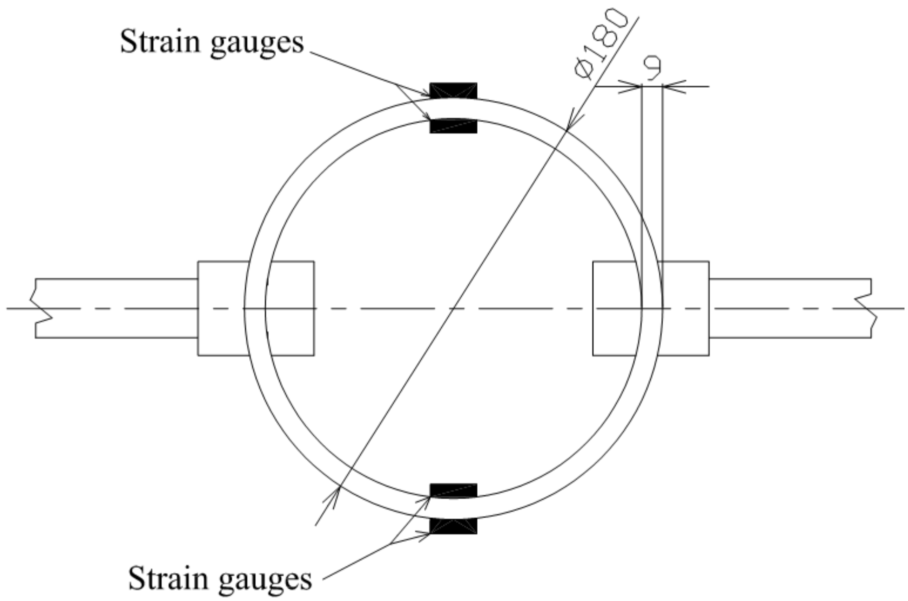

Figure 3. Ring transducer with position of strain gauges. All dimensions are in mm.

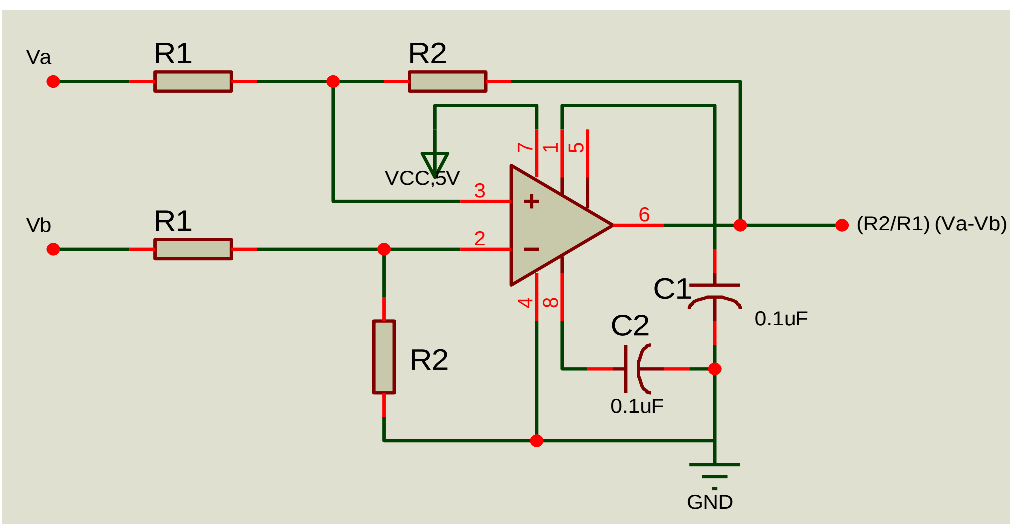

Figure 4. Circuit diagram of difference amplifier.

output from the transducer was 0.1 to 0.7 mV, which is too low a signal value to be fed to the Analog to Digital Converter (ADC) of the microcontroller unit. To amplify the signal from transducer output, an amplifier with an IC (TLC 2654A) was used. The overall circuit diagram of difference amplifier is shown in Figure 4.

Data processing and display

The data processing and display unit has the following three main functions:

I. To calculate the weight transfer from the front axle of the tractor for the corresponding depth of operation.
II. To give audible and visual warnings to the driver of the vehicle when the weight transfer from the front axle of the vehicle approaches the critical value.

The output of the amplifier was fed to the AT Mega32 microcontroller unit of ADC to convert the analog values into digital values through a single channel. The microcontroller program was written in C language (Code Vision AVR V1.23.8a) and the flow chart of the program is shown in Figure 5. The microcontroller processes the

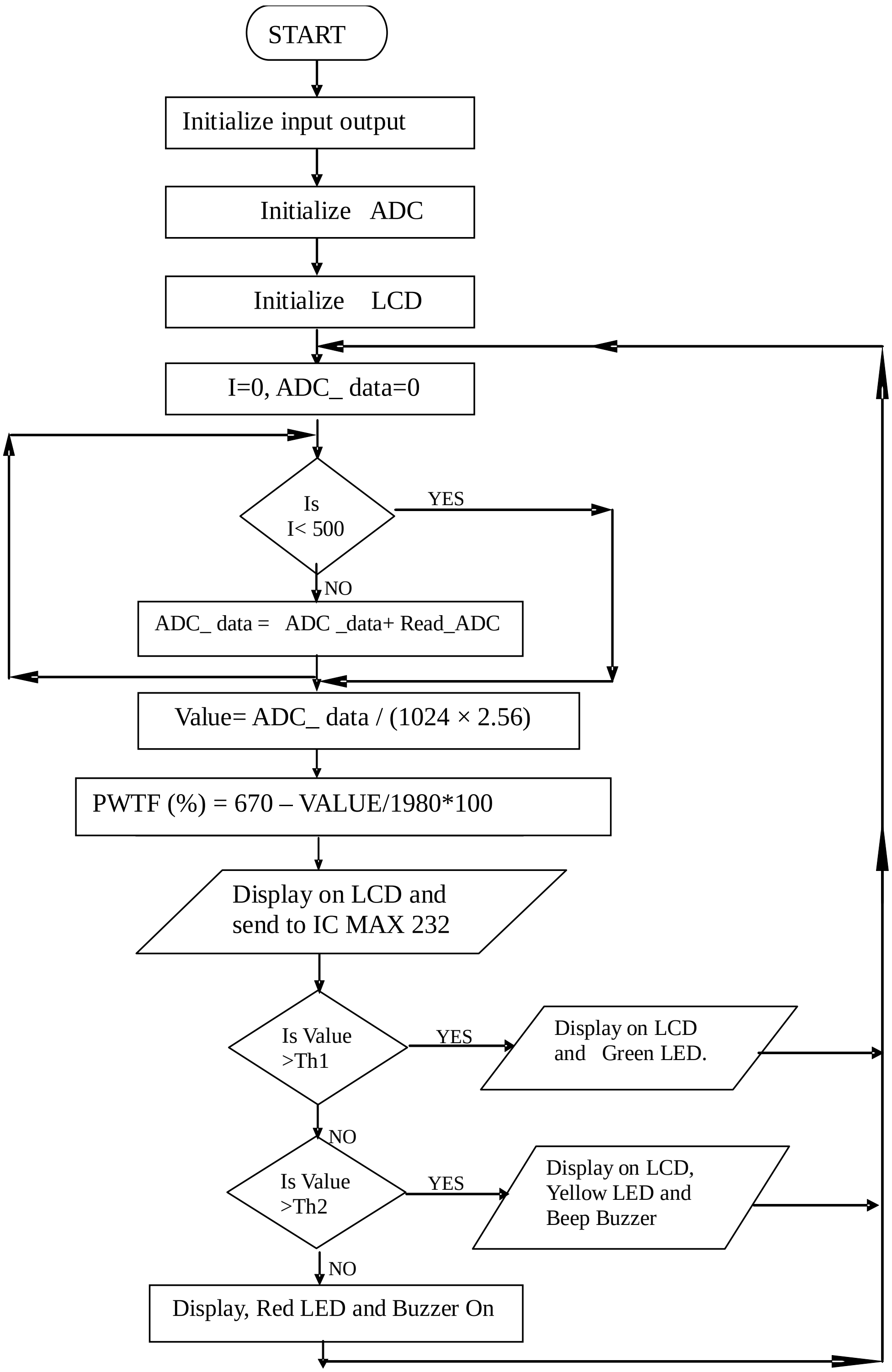

Figure 5. Flow chart for the tractor front end reaction measurement.

signal received from the amplifier and displays in terms of percent weight transfer from the front axle (PWTF).

In addition to the display, an alarm and three LEDs, namely the Green LED, Yellow LED and Red LED were used. The Green LED indicates the safe zone of operation if the load on the front axle is more than 25% of the total tractor static weight. The Yellow LED accompanied with a loud intermittent beep indicates the

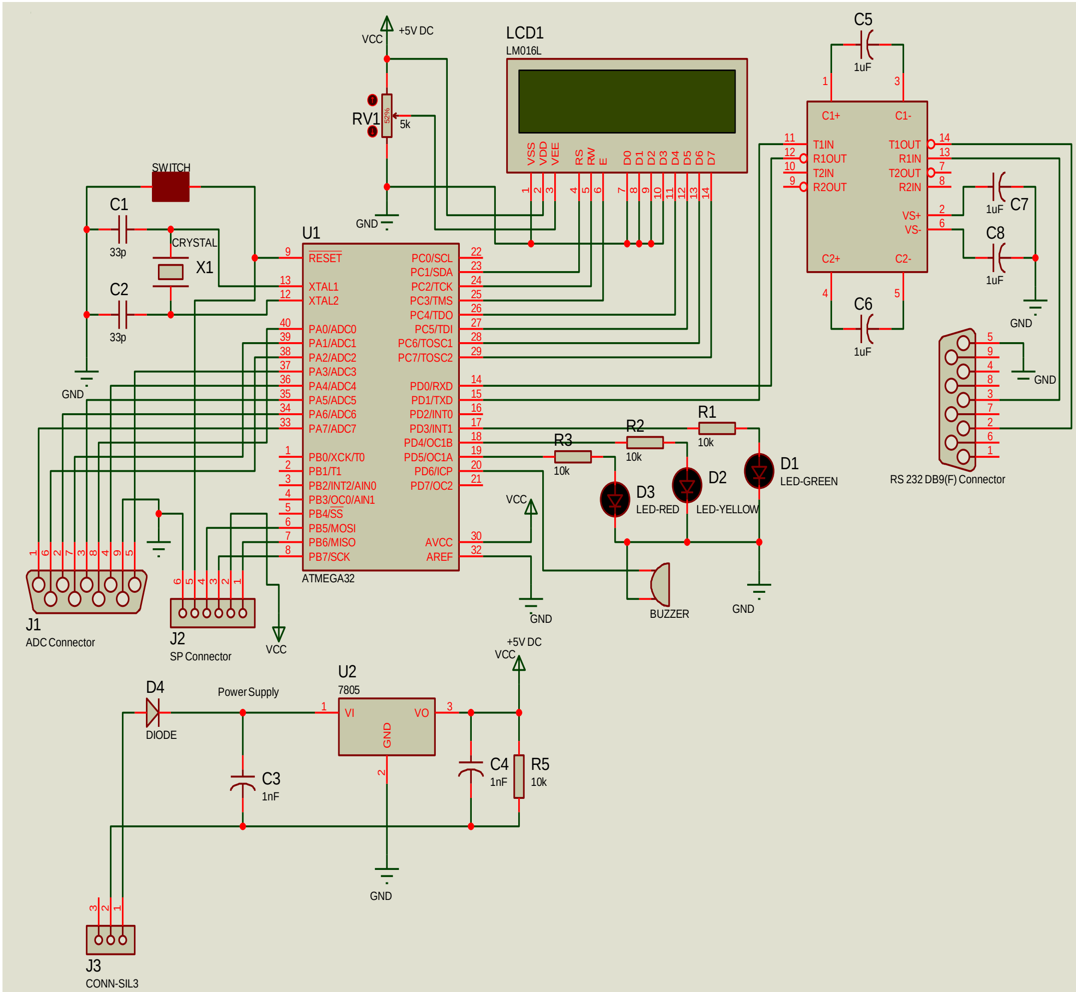

Figure 6. Circuit diagram of the processing and display unit with pin configuration.

warning zone of operation when the load on the front axle is 20 to 25% of the total tractor static weight. The Red LED accompanied with a loud continuous beep indicates the danger zone of operation when the weight retained on the front axle is less than 20%. These values were fixed based on the recommendations of Habarta (1971). The output voltage in safe, warning and danger zones is taken as Threshold voltage Th1, Threshold voltage Th2, and Threshold voltage Th3 respectively.

When the meter is switched on, the controlling microprocessor performs a self-test. If the self-test is satisfactory then, Green LED glows and the indicator displays the current weight retained on the front axle. If an error is detected, the display will show the number as 40%. The developed device completes the entire process in a time of 0.5 ms, and for every one second, it sends the signal to the computer for storage of voltage values. The detailed circuit diagram for measuring the tractor front end reaction and displaying it on the LCD is shown in Figure 6.

Testing of the developed device

Laboratory condition

Initial tests were conducted under laboratory condition to determine the suitability of the developed device for the purpose of indicating the weight transfer from the tractor front axle (Figure 7 and Table 1). The output of the transducer was connected to the developed device and the power supply to the device was given from the tractor 12V battery. An electronic platform balance was used to support the weight of the front axle. The front end of the tractor was lifted slowly with the help of a hydraulic jack for unloading the axle. The output of the transducer bridge (Wheatstone full bridge) and the corresponding balance reading were measured. The blinking of Green LED, Yellow LED and Red LED were observed when the weight on the front axle was more than 25%, between 20 to 25%, and less than 20% respectively. The intermittent and continuous beeps were also produced with the

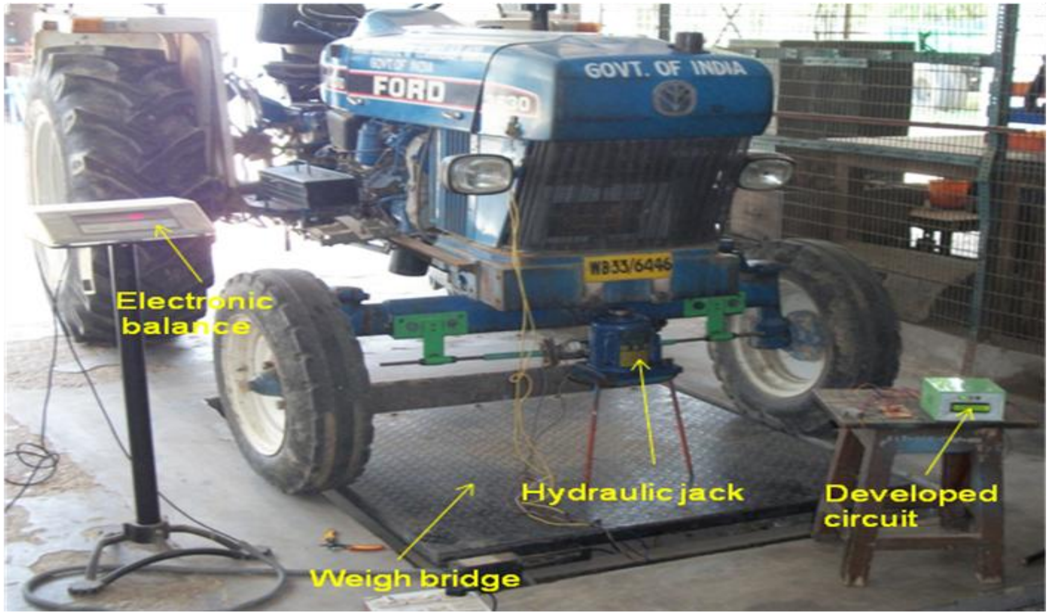

Figure 7. Evaluation of developed device under laboratory condition.

Table 1. Comparison between the actual and observed values of weight transfer under laboratory condition.

Initial load on front axle (N)	Weight removed on the front axle by using hydraulic jack (N)	Weight transfer measured with electronic plat form (%)	Weight transfer measure using developed device (%)	Difference between the observed and actual value (%)	Zone of operation
6566	0	0.00	0.00	0.00	Safe
	980	5.05	5.86	0.81	Safe
	1568	8.08	8.93	0.85	Safe
	1960	10.10	11.05	0.95	Warning
	2450	12.63	13.21	0.58	Warning
	3430	17.67	18.35	0.68	Danger
	4410	22.72	23.43	0.71	Danger
	5390	27.78	28.71	0.93	Danger

blinking of Yellow LED and Red LED respectively. The maximum difference in the dynamic weight on the front axle was obtained using the developed circuit from that recorded using the electronic balance that was less than 1% in all the three zones.

Field condition

To evaluate the developed processing and display

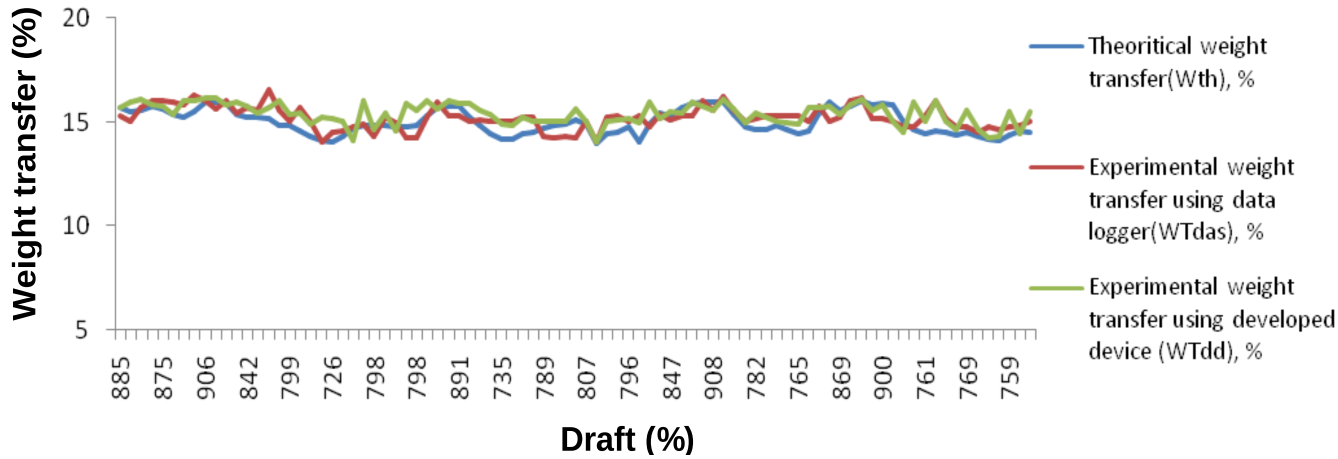

Figure 8. Comparison between the theoretical and experimental weight transfer for ploughing operation at 15 cm depth.

unit in actual field condition, the test tractor was used with 11 tine cultivators. The depth of operation was varied from 10 to 20 cm. The draft requirement of the implement was measured by using an instrumented three-point linkage and a data acquisition system (DAS). The weight transfer of the tractor (WT_{dd}) at different depths was measured by connecting the output of the ring transducer to the developed processing and display unit. For the same operating conditions, the weight transfer of the tractor (WT_{das}) was also measured without using the developed device, but by connecting the ring transducer output to DAS. The experimental results obtained by these two methods at different depths were then compared with the theoretical results (W_{th}) calculated by Equation 15. The comparative results are shown in Figure 8. The range of variation in weight transferred from the front axle between WT_{dd} and W_{th} was found to be -1.5 to 2.50% with SD=1.28, while that between WT_{das} and W_{th} was -2.3 to 2.24% with SD=1.13. The observed experimental data were also compared with theoretical results using a statistical term, relative deviation (RD), which is defined as follows (Kumar and Pandey, 2009):

$$RD = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{WRF_e - WRF_t}{WRF_t}\right)100 \quad (14)$$

Where WRF_e is the experimental value measured either by using developed device or data acquisition system, and N the number of observations. The RD values for the entire test observations were found less than ± 0.4%.

The analysis of the test results was done using the Duncan Multiple Range Test (DMRT) (Montgomery and Douglas, 2008). The analysis showed that the difference in weight retained on the front axle using the developed device and that with the data acquisition system was not significant at 1% level of significance. However, the difference between the theoretical and experimental results was found to be significant at 1% level of significance. This shows that the developed device can provide a longitudinal stability data as reliable as one would expect from using costly equipment like DAS.

Conclusion

A processing and digital weight transfer display unit was developed for 2WD tractors to measure the weight transfer from the front axle to the rear axle. The display unit provides a safe green zone, warning yellow zone and danger red zone to the operator. These zones will help the operator to operate the tractor without any hazardous condition. The output of the developed device was found very close to the theoretical results under field conditions. The developed ring transducer along with the display unit is simple in construction and provides ease of mounting on any make of 2WD tractors by uploading the total static weight of the tractor through computer interface of the microcontroller program.

Abbreviations: B, Wheel width (cm); **B_n,** mobility number; **CI,** cone index (kPa); **D,** wheel diameter (m); **D,** draft (kg); **DAS,** data acquisition system; **d_1,** depth of operation (cm); **e_r,** rear wheel eccentricity; **e_f,** front wheel eccentricity; **F,** tractive effort; **GTR,** gross traction ratio; **H_d,** horizontal distance of tractor lower hitch point from the rear axle center (m); **H,** tyre section height (m); **L,** wheel base (m); **MRR,** motion resistance ratio; **MRR_r,** motion resistance ratio of rear tyre; **MRR_f,** motion resistance ratio of front tyre; **NTR,** net traction ratio; **P_y,** vertical component of resultant soil force (kg); **RD,** relative deviation (%); **R_r, R_f,** dynamic reaction on tractor rear wheel and tractor front wheel (kg); **r_r,** rolling radius of rear wheel (m); **r_f,** rolling radius of front wheel (m); **S,** wheel slip (%); **SD,** standard deviation; **TF_f,TF_r,** towed force of front and rear wheel; **V_a,** actual velocity (m/s); **V_t,**

theoretical velocity (m/s); **W,** width of cut (m); **WRF,** weight retained on the front axle (%); **WRF_t,** theoretical weight retained on the front axle (%); **WRF_{das},** experimental weight retained on front axle measured with DAS (%); **WRF_{dd},** experimental weight retained on front axle measured with developed device (%); **W_t,** static weight of tractor (kg); **W_m,** weight of implement (kg); **X_{cgt},** horizontal distance of CG of tractor from the rear axle center (m); **X_{cgi},** horizontal distance of CG of implement from tractor lower hitch point LHP (m); **Y_d,** distance of centre of resistance from ground surface (m); **δ,** tyre deflection.

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