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RESEARCH ARTICLE

An instrumentation system for monitoring field performance of agricultural tractor under ballasting and non-ballasting conditions

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ABSTRACT: An instrumentation system was developed and installed on 39 kW agricultural tractor to conduct field performance test of tractor-implement system. The system was intended to be used for compilation of a database for draft requirement of tillage implements. The installed instrumentation on tractor was designed to measure compression and tensile forces of three-point linkage to calculate draft; pulse counter to measure forward speed; depth of the implement and fuel consumption. Microprocessor-based data acquisition system of SoMatEDAQ was linked to –computing device using suitable transducers for recording of field data. Developed instrumentation system was validated in laboratory conditions and field performance parameters were evaluated using 2-bottom and 3-bottom reversible mould board plough under-ballasted and non-ballasted conditions. It was observed that 1–3% less fuel was consumed with 230 kg ballast weight on rear wheels as compared to non-ballasted wheels.

INTRODUCTION

With an increasing demand of high productivity and more tractive performance, high power agricultural tractors become popular in farm operations, haulage, land reclamations and constructions. To meet the demand of the market most of the tractor manufacturing companies are now manufacturing high power tractors (more than 50 hp) in the developing countries. These tractors hold approximately 16% of the total market share in the country (Mehta *et al*., 2014; Tiwari *et al*., 2019a).

Land preparation is one of the most energy consuming operations in the field. Previous studies have shown that about 20 to 55 % of the available tractor energy is wasted at the tyre-soil interface. Along with this loss, it also wears the tyres and compacts the soil, which becomes disadvantageous for crop production (Burt *et al*., 1983) and also reduces the water infiltration inside the soil (Sahu *et al*., 2013; Tiwari *et al*., 2019b). Field performance parameter is one of the most important criteria for defining the tractor under or over used during field operation. The performance of tractors greatly depends upon the various soil-wheel parameters. The performance includes pulling capability, tractive efficiency, optimum slip and minimum fuel consumption. To access the performance of tractor during field operations, several researchers have adopted different methodologies. Cullum *et al*., 1989 developed a data acquisition system using Campbell Scientific 21X data logger, a drawbar dynamometer and a radar-based ground speed sensor and measured the draft of pull type implement effectively Al-Suhaibani and Al-Janobi (1997) developed a data-acquisitions system for mounted type implement using octagonal ring transducer in each lower links and load cell in top links and rotary potentiometer for measuring tillage depth and angular position of three-point linkages. Singh and Singh (2011) developed a computerized instrumentations package using Campbell Scientific CR3000 data logger and suitable transducers to monitor performance parameters of tractor-implement system in field.

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The tractor-implement system is evaluated -in terms of drawbar performance parameter of tractor. In the field, the drawbar performance of tractor can be increased by two methods. First is to use ballast weight for reduction of tyre slippage. It has been reported that adding weights leads to 15% increase in pulling ability at same slip value. The effect of liquid and iron ballast weight was investigated by (Kumar *et al*., 2019). The results of this study shows higher pulling ability and efficiency can be achievable with ballast loads. However, there is an adverse effect of ballast load on tractor tyre wear and soil compaction. Moreover, the soil compaction leads to increase in rolling resistance and more tyre sinkage inside the soil causes increased fuel consumption (Lacour *et al.*, 2014). Second method to increase the drawbar performance of tyre is to increase the soil-tyre contact area. The tyre contact area can be increased by decreasing the inflation pressure of tyre, which leads to increase the deflection of tyre (Kumar and Pandey 2016; Kumar *et al*., 2018 and Kumar *et al*., 2018). Using this method, the weight of tractor is distributed over a large surface area which, reduces the rolling resistance and ground pressure of soil may leads to an increase in traction performance by 8% (Taghavifar and Mardani, 2013). The tractor can be also used economically if there is proper ballast with correct implement matching. With the help of proper ballast the tractive efficiency of a tractor can be improved at reduced specific fuel consumption and increased tractive efficiency and gross traction force. Kumar and Pandey (2015) conducted a field performance test using 32 kW tractors with MB plough and put a ballast of 175 kg on rear wheels to achieve optimum slip. I -Minimum fuel consumption of 30–32 l/ha at 6.9 km/h in L3 gear and 55% throttle open was observed.

The objective of this study was to develop an instrumentation system for 39kW agricultural tractor to monitor the field performance in ballasted and non-ballasted conditions. Ballast requirement for field operation was also determined for maximization of field efficiency.

MATERIAL AND METHODS

Theoretical Consideration

The performance of tractor-implement combination depends on many factors. Important factors related to the tractor are power, speed of operation, hitch height and ballast. For tillage implements, important performance factors are speed, width, and the depth of operation. Soil conditions are important because they affect the performance of both tractor and implements.

Wheel slip

When a tractor pulls a load, the tires are stretched and the soil moves in response to pull to applied drawbar pull, which causes wheel slip. Wheel slip is given by the following Eq. (1)

$$S = \left(1 - \frac{V_a}{V_t}\right) \times 100 \qquad \dots (1)$$

where,
S = Slip, %;
V_a = Actual -speed, km/h and
V_t = Theoretical speed, km/h

Drawbar power

It is the power developed at tractor drawbar to pull implement or trailer with some operating speed. Drawbar power is calculated as Eq. (2)

$$DBP = \frac{D \times V_a}{3.6} \qquad \dots (2)$$

where,
DBP = Drawbar power, kW;
D = Draft , kN and
V_a = Actual speed, km/h

Drawbar Specific Fuel Consumption (dbsfc)

The amount of fuel consumed in unit time per unit drawbar power is known as drawbar specific fuel consumption. Unit of drawbar specific fuel consumption is gm/kW-h.

Gross traction force (GTR)

This is the total force is generated by a tractor and is the sum of the drawbar pull, motion resistance of front and rear wheels and grade resistance. According to Brixius (1987),

$$\text{GTR} = .88(1 - e^{-.1Bn})(1 - e^{-7.5S}) + .04 \qquad \dots (3)$$

where $$B_n = \left(\frac{CI * b * d}{W_d}\right)\left(\frac{1 + 5\frac{\delta}{h}}{1 + 3\frac{b}{d}}\right) \qquad \dots (4)$$

B_n = a dimensionless ratio (Brixius number);
W_d = dynamic wheel load in force units normal to the soil surface, kN;
CI = the cone index for the soil, kPa;
b = unloaded tire section width, m;
d = the unloaded over all diameter, m;
h = the tire section height, m;
δ = tire deflection, m;
s = wheel slip, decimal.

Ballasting of tractor

Ballasting of tractor is a measure by which it determines the betterment of fit of the tractor mass with the implement load. The main purpose of ballasting is to control wheel slip. Tractor ballast influences performance and operating costs, fuel consumption, tire life, and drive train load (transmission).

Required rear axle dynamic weight

The required rear axle dynamic weight can be calculated from Eq. (3)

$$DBP = TE \times AHP \qquad \dots (5)$$

$$DBP = \frac{NTR}{GTR} \times (1 - S) \times AHP \quad \ldots (6)$$

Drawbar power can also be expressed as

$$DBP = \frac{D \times V_a}{3.6} \quad \ldots (7)$$

$$DBP = \frac{NTR \times RWD \times V_a}{3.6} \quad \ldots (8)$$

From eqn. (7) and (8)

$$RWD = \frac{AHP \times 3.6}{GTR \times V_a}(1 - S) \quad \ldots (9)$$

$$RWD = \frac{AHP \times 3.6}{V_t \times GTR} \quad \ldots (10)$$

where,
RWD = rear wheel dynamic weight;
AHP = axle horse power;
GTR = gross traction ratio

The required dynamic weight can be calculated for a given axle power. However, higher travel speed, less dynamic weight is required on the driving wheel. Additional ballast requirement can be calculated as difference of required rear axle dynamic weight and actual rear axle dynamic weight, which includes weight transfer from the front and from the implement.

Instrumented Tractor

The test tractor was instrumented to measure the draft, fuel consumption and forces at horizontal, vertical and side imposed by the implement at three-point linkages. Slip was determined by measuring theoretical and actual speeds of front and rear wheels of tractor. All the data were stored in the laptop through a data logger. The implement draft force and vertical soil reaction force were measured using the tractor three point linkages (Upadhyaya *et al.,* 1985). The instrumentation set-up for measurement of force in tractor three-point linkage is shown in Fig. 1. The electrical strain gauges (NICTECH) each of 350 Ω and 2.6 gauge factor were mounted on the neutral axis of lower links to measure the tensile force and bending force acted on lower links as shown in Fig. 1.

Angular orientation of three-point linkage

The angular orientation of three point linkages are measured with potentiometer (3590S-2-104L potentiometer, Bourns, Mexico), which is mounted for measurement of lower link angle with vertical plane, lower link angle with horizontal plane and top link angle with horizontal plane is shown in Fig. 2.

Depth of operation of implement

Depth of operation of implements was measured using rotary potentiometer (3590S-2-104L potentiometer, Bourns, Mexico) and digital level meter. This rotary

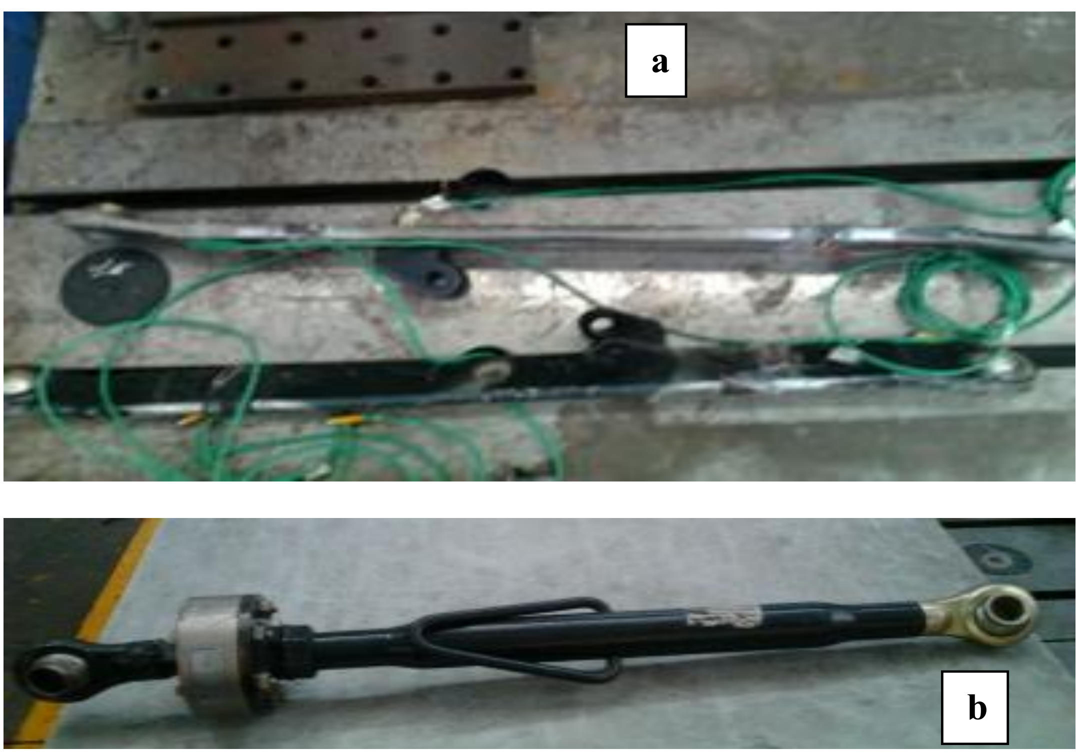

Fig. 1. Instrumentation for measurement of force (a) Strain gauge on lower links (b) Load cell on top link

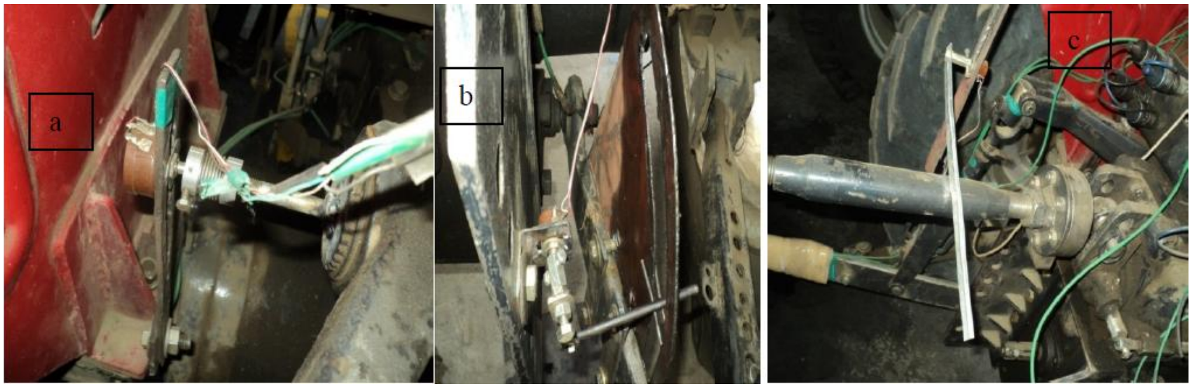

Fig. 2. Arrangements of potentiometers for measurement of (a) lower link angle with vertical plane, (b) lower link angle with horizontal plane and (c) top link angle with horizontal plane

potentiometer was installed on the rocker arm of the tractor hydraulic system (Fig. 3 (a)).

Measurement of fuel consumption

The fuel consumption of the tractor was measured with the help of two differential fuel meter (CONTOIL VZP4 S/N 5270433/2010). For measurement of fuel, the fuel sensor was placed between fuel filter and fuel injection pump (supply line) and other one is placed between overflow line (return line) and the fuel tank. The two fuel meters were connected with the help of adapters and Nylon pipe and placed on the right side of the tractor with the help of L iron sheet, iron plate and bolts.

Fuel consumption (l/h) = Supply line flow rate (l/h) – Return line flow rate (l/h).

In fuel measuring system, an electronic board was used to receive and save digital pulses sent by the flow meter sensors .This flow meter gives 4 to 20 mA current output according to flow rate In this system, a 24Vbattery (as power supply was required. Then the fuel meters are connected to the data logger for storage of signal output. The fuel sensor with display unit was connected for measurement of fuel during field operation is shown in Fig. 3 (b).

Operational speed measuring system

Three proximity switch (Nipponix M30) sensors were used to measure the actual and theoretical velocity of a tractor in dynamic condition. Two proximity sensors were mounted on the final drive housing for measurement of theoretical –speed and one sensor was mounted on the front wheel kingpin rod for actual – speed of tractor.

Data logger

The SoMat EDAQ was a microprocessor-based data acquisition system designed for portable data collection in a variety of test environments. Input power for the system operates in a wide range from 10 to 55 volts DC for the processor. Internal back-up batteries protect the EDAQ from unplanned power losses or low voltage events. It consists of 32 channels, 16 - bridge and 16 HLS channel to collect the data in different modes as shown in Fig. 4.

Fig. 3. Instrumentation for working depth and fuel consumption measurement (a) Digital level meter and potentiometer mounted on rocker shaft, (b) Fuel flow meter installed on the tractor

Fig. 4. SoMat EDAQ data logger

Experimental Plan

For the experiments a 39 kW PTO power tractor was used for heavy field operations. The experimental plan for the field operation is given below in Table 1.

Test Procedure

The 39 kW instrumented tractor used for testing is shown in Fig. 5. For field operation a barren land was selected and divided into 20m x 15m land size for each gear, depth and throttle setting. The operational depth throughout the field operation was maintained 14–30 cm for 3-bottom reversible mb plough and 12 to 27 cm for 2-bottom reversible plough. The test tractor was operated at L2, L3 gears for both reversible mbMB ploughs. The selection of depth of operation of plough was done with the help of depth calibration curve and the depth control lever. Fuel consumption and draft were measured with fuel meters and 3-point linkage dynamometer, respectively. Slip and actual velocity were calculated by measuring number of revolutions of front wheels and rear wheels. All the experiments were replicated thrice.

Table 1.
Research plan for field performance

Independent parameters	Dependent parameters
Depth of operation :12-30 cm	Axial forces on lower link, kgf
Cone Index: 1200–1700 kPa	Bending forces on lower link, kgf
Average Moisture content: 6.5% (db)	Compressive forces on top link, kgf
Forward speed: 2–7 km/h	Position of lower link in Horizontal and Vertical plane, deg
Soil type: Vertisols (17-21.5% sand, 23.5-29.1% silt, and 48-55% clay)	
	Actual forward speed, -kmh^{-1}
	Field capacity, ha-h^{-1}
	Fuel consumption, l-h^{-1}

RESULTS AND DISCUSSION

Drawbar performance with reversible MB ploughs

The actual speed of operation for reversible MB plough varied from 4.20 to 3.23 km-h^{-1}, depending upon type of gear as well as depth of operation. The requirement of drawbar power increased with the increase of depth of implement (Fig. 6 and Fig. 7). When the depth of implement was increased from 14 cm to 30 cm, the required drawbar power increased from 12.05 to 18.57 kW. Fuel consumption of test tractor also increased from 6.74 to 8.81 l- h^{-1} as depth of operation increased from 14 to 30 cm. The draft force required for 3-bottom reversible MB plough for field operation increased from 1053.71 kgf to 2135.00 kgf and speed reduction ratio increased from 13.23 to 29.46%, as depth of operation increased from 13.50 cm to 30.50 cm. The required drawbar specific fuel consumption was more at lower depth and it decreased as per increase of depth of implement. This is because of less use of available power of tractor. Drawbar specific fuel consumption was found to vary from 467 to 396 g-/kW-h.

The drawbar power of 2-bottomreversible MB plough also increased with increase in depth. It varied from 14.26 to 16.06 kW as depth increased from 12 to 27 cm, respectively; whereas fuel consumption of the test tractor varied from 6.26 to 8.10l h^{-1} (Fig. 9) Moreover, the draft force requirement was found to be increased from 1026.56 to 1711.64 kgf and speed reduction ratio 12.65 to 29.85% when the depth of operation increased from 12 to 27 cm. Drawbar specific fuel consumption also increased from 367 to 427 g-/kW-h for the same variation in depth of operation.

Fig. 5. Field operation with 3-bottom and 2-bottom reversible plough

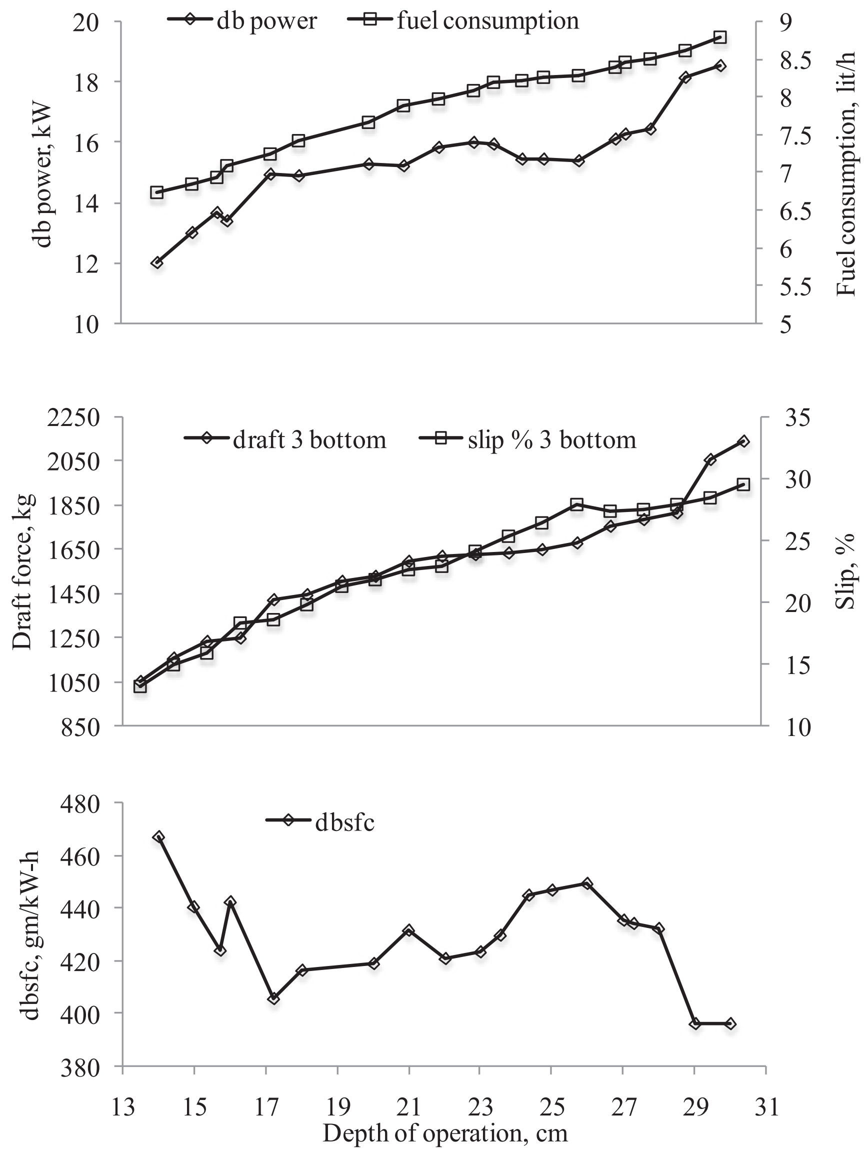

Fig. 6. Variations of draft, slip, db power, fuel consumption and dbsfc with depth of operations for 3-bottom reversible plough before ballasting

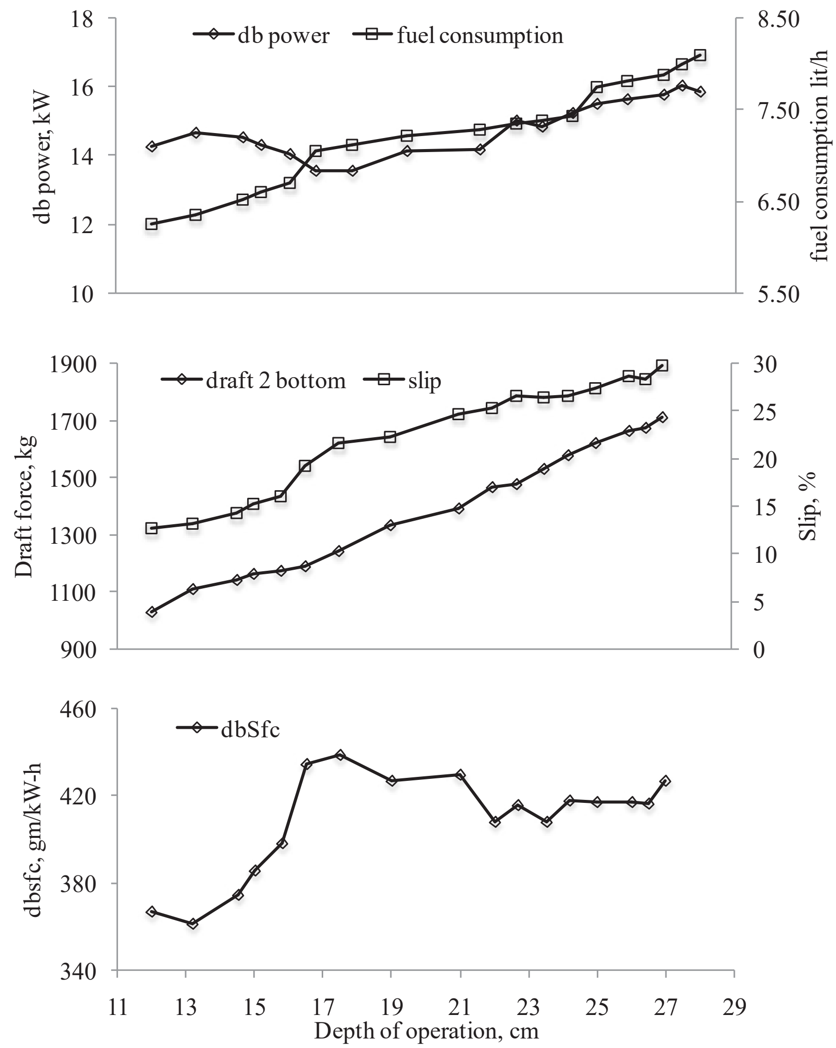

Fig. 7. Variations of draft, slip, db power, fuel consumption and dbsfc with depth of operations for 2-bottom reversible plough before ballasting

Ballast requirement for heavy field operation

Ballasting requirement for the tractor to reduce the wheel slip within 15% was calculated. The calculated values are given in Table 2 for 3-bottom and 2-bottom at different depth of operation.

Fuel consumption before and after ballasting of tractor

An experiment was conducted to determine the fuel consumption before ballasting the tractor at different depths of operation at full throttle in L2. A similar experiment was also conducted under the same gear and throttle positions after ballasting the tractor (average weight 230 kg on each wheel). The results indicated decrease in fuel consumption after ballasting the tractor from 1 to 3 % for both ploughs (Fig. 8 and Fig. 9).

The ANCOVA was carried out (Table 3) with depth considered as a covariate to identify the effect of plough size on fuel consumption. As seen from Table 3 difference of the fuel consumption of 3-bottom and 2-bottom reversible MB plough before ballasting and after ballasting is statistically significant ($P < 0.05$) indicating strong effect of fuel consumption on size of implement. It was also found that depth of operation also significantly affected the fuel consumption ($P < 0.05$) in both ballasted and un-ballasted condition.

CONCLUSIONS

High precision instrumentation system was developed to monitor the performance parameters such as forward speed, rear wheel slip, fuel consumption and forces on three-point linkage-implement and depth transducer for use in field operations. The system was mounted on 39 kW agricultural tractor to monitor field performance parameters in ballasting and non-ballasting condition.

Table 2.
Theoretical ballast requirement for 3-bottom and 2-bottom reversible MB plough.

3-bottom plough				2-bottom plough			
Depth (cm)	Draft (kg)	Slip %	Ballast requirement for 15% slip (kg) on each rear wheel	Depth (cm)	Draft (kg)	Slip %	Ballast requirement for 15% slip (kg) on each rear wheel
14.0	1054	13.23		12.0	1026.56	12.65	
15.0	1154	14.89		13.2	1106.17	13.17	
15.7	1236	15.83		14.5	1139.81	14.26	
16.0	1246	18.34	214	15.0	1160.04	15.17	
17.2	1422	18.64	238	15.8	1170.23	16.09	
18.0	1445	19.78	240	16.5	1190.78	19.26	205
20.0	1507	21.31	234	17.5	1244.03	21.65	233
21.0	1526	21.86	232	19.0	1331.51	22.35	234
22.0	1594	22.59	233	21.0	1389.22	24.75	257
23.0	1615	22.95	224	22.0	1466.20	25.25	222
23.6	1627	24.07	231	22.7	1478.97	26.56	219
24.4	1630	25.27	243	23.5	1532.48	26.38	243
25.0	1646	26.33	227	24.2	1578.55	26.68	244
26.0	1674	27.86	219	25.0	1620.57	27.47	253
27.0	1754	27.35	225	26.0	1663.23	28.73	248
27.3	1780	27.44	234	26.5	1674.68	28.39	239
28.0	1815	27.85	215	27.0	1711.64	29.85	247
29.0	2057	28.36	230				
30.0	2135	29.46	220				

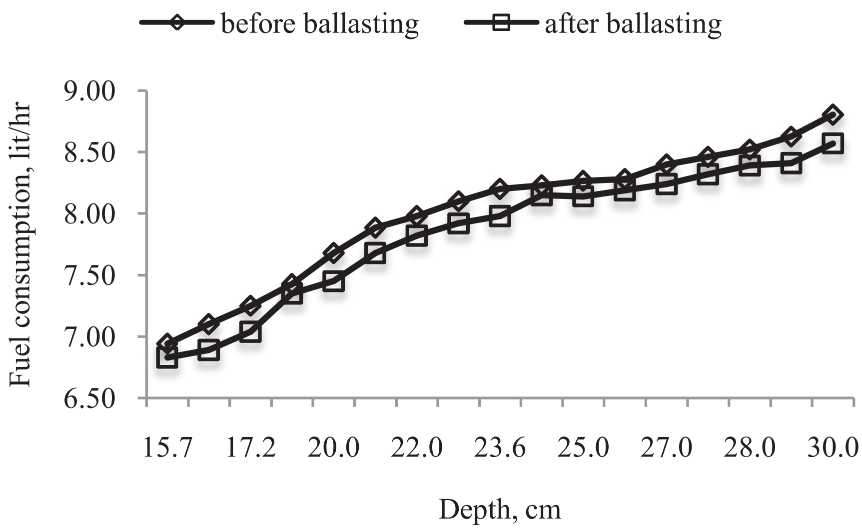

Fig. 8. Variations of fuel consumption with depth of operations for 3-bottom reversible plough

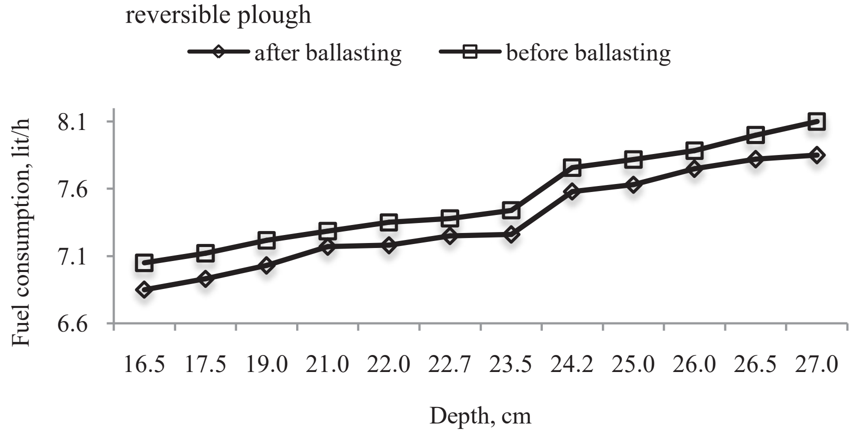

Fig. 9. Varations of fuel consumption with depth of operations for 2-bottom reversible plough

Table 3.
Analysis of covariance to study the effect of plough size and depth on fuel consumption.

Dependent variable		Fuel consumption before ballast			Fuel consumption after ballast		
Source	DF	Type III Sum of Squares	MS	F-Value	Type III Sum of Squares	MS	F-Value
Model	2	7.591[a]	3.795	314.615*	7.630[b]	3.815	336.448*
Intercept	1	23.399	23.399	1939.719*	21.914	21.914	1932.585*
Implement	1	1.192	1.192	98.776*	1.243	1.243	109.652*
Depth	1	6.002	6.002	497.525*	5.982	5.982	527.562*
Error	26	0.314	0.012		0.295	0.011	
Total	29	1778.041			1701.560		
Corrected Total	28	7.904			7.925		
		[a]R Squared = 0.960 (Adjusted R^2 = 0.957)			[b]R Squared = 0.963 (Adjusted R^2 = 0.960)		

DF = Degrees of freedom; MS: Mean sum of square, F-value: index of significance of the coefficient of determination. *Significant at 95 % confidence interval

Observed results shows high precision and accuracy for the data acquisition system and transducer. The system was tested in the field and its performance was found to be excellent. The consistent measurements showed the ability and accuracy of the system in field operations. The field results shows that, theoretical ballast requirement to reduce the wheel slip within 15% was suggested for 3-bottom and 2-bottom reversible MB plough. 1–3% fuel saving was observed with 230 kg ballast weight on rear wheel as compared to non-ballasted wheels.

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