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Development and Evaluation of Automated Slip and Draft Control System for Tractor

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A microcontroller-based Automatic Slip Control System (ASCS) and Automatic Draft Control System (ADCS) for 2WD tractors was devised to automatically alter the depth of operation to keep the wheel slip and implement draft within a pre-specified range. An electro hydraulic lift link system was devised to control the depth of the implement's operation. The technology continuously checks wheel slip and draft in the field and notifies the hydraulic system, which changes the implement's depth if the wheel slip and draft exceeds the specified range. Experiments were conducted with defined slip ranges of 10–15, 15–20, and 20–25% for ploughing and cultivating activities. Field capacity and drawbar specific fuel consumption were measured as performance criteria. With the ASCS, the slip was found to range from 15–24%, versus the desired range of 15–20%, while with the current draft control system, it was found to range from 12–48% Tractor Draft Control System (TDCS). Fuel consumption was determined to be 20.13, 21.11, and 22.98 l/ha for ploughing operations with TDCS at initial depth settings of 150, 180, and 220 mm, respectively. However, ASCS resulted in a significant increase in fuel efficiency, with an 11.2% reduction in consumption. When compared to the TDCS, it consumed 4 to 14% less fuel during ploughing operations. Field capacity was increased by 3.4–14.5% due to ASCS and ADCS. The measuring efficiency of the devised system was determined to be greater than 99%.

Keywords: Electro hydraulic, Field efficiency, Microcontroller, Slip control systems

Introduction

Land preparation is one of the most important operations for successful crop establishment and consumes about 30% of the total energy required for crop production. Among the various responsible parameters affecting the energy utilization pattern, mainly soil type and condition, operating depth, travel speed plays an important role. Abundant research has been carried out with various soil, implement and operating conditions to optimize the tractor performance in the field for various tractor implement combinations. In spite of lots of recommendation like determining the best travel speed for a tractor-implement system, development of advanced technology to maximize the traction devices' tractive advantage and maximising the engine and drive train's fuel efficiency, research shows that about 20–55% of the available tractor energy is wasted at the tyre-soil interface. This energy wears the tractive devices and compact the soil.[1]

Tractors lose a substantial amount of energy in the field due to rolling resistance and traction wheel slippage. The best tractive efficiency is achieved by striking a balance between lowering rolling resistance and optimising wheel slip. Increase the area of contact between the tractor wheels and the soil surface, as well as reduce abnormal slippage, to improve tractive effort. Maximum tractive efficiency for a tractor obtained within a specified range of slip for any type of soil condition.[2,3] Operating the tractor in the optimal slip range would help to conserve fuel while also boosting field capacity.

Mechanical draft control systems employed in tractors maintain the constant tractor effort by varying the depth of operation automatically in spite of varying working conditions. But in Indian tractors, these draft control system works in a very narrow range and hence are not so much efficient. When the implement is elevated at an angle, it produces a vertical component that cancels out the downward opposing force and tends to cancel out the original signal of lifting the implement.[4,5] Inefficiency in the draft control system forces the operator to operate the position control lever frequently resulting in uneven depth of operation as well as poor ergonomically exercises of the operator.[6,7] Plenty of research work has been carried out in the past to enhance the

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efficiency of the mechanical draft control system but it has been shown that there is no scope in improvement of the existing draft control systems.[6]

To improve vehicle sub-system reaction and reduce operator physical effort, electronic solutions are necessary to control tractor sub-systems. Controlling the slip and draft by adjusting the depth of operation using an auto depth control device could be a feasible solution to the above-mentioned problem. Despite the fact that numerous techniques have been developed to control slip and draft.[8,9] The system continuously monitors wheel slip and draft in the field and alerts the external hydraulic system, which adjusts the depth if the wheel slip and draft exceeds the specified range. In view of these facts, a study was conducted to design an automatic wheel slip and draft control system for 2WD tractors using a microcontroller.

Materials and Methods

Slip and draft of the tractor was controlled by controlling the depth of operation. An electro-hydraulic lift link system was designed and developed to control the depth of the implement automatically (Fig. 1).

Existing lift link of the tractor was replaced by two hydraulic cylinders. The cylinder actuated by the tractor hydraulic system through a proportional hydraulic directional and flow control valve. A double ended and single ended shear pin type load cell of capacity 20 kN was designed to replace link pins of the tractor to measure the draft force. Two rotary potentiometers were used for measuring vertical angle made by the top link and lower link separately. To measure the vertical angle made by the lower link, rotary shaft of one potentiometer coupled to the rocker arm of tractor hydraulic system was allowed to rotate along with the upward and downward movement of lower link. Horizontal angle of lower link for each implement was measured manually and fed to the microcontroller. For vertical angle of top link, a fixture was fabricated and attached to the back of the tractor. A rotary potentiometer was mounted on that fixture and arrangements were made to rotate their shafts along with the change in position of the top link. A draw wire encoder was fitted at the rear of the tractor just above the implement to measure the depth of operation of the implement.

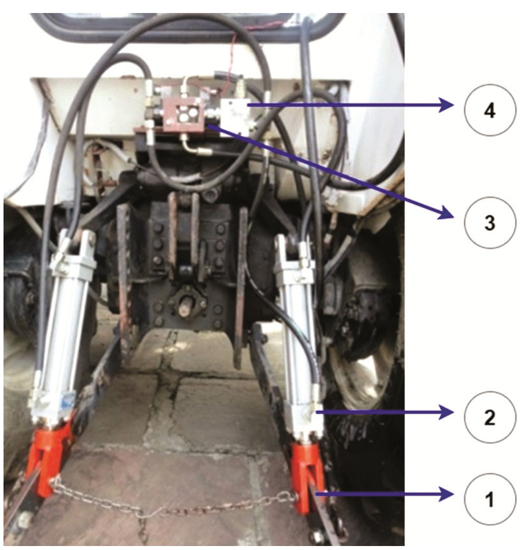

Fig. 1 — Hydraulic arrangement for electro hydraulic lift link (1 = Clevis Joint, 2 = Double acting hydraulic cylinder, 3 = Proportional hydraulic directional and flow control valve, 4 = Counter balance valve)

Slip is not a directly measured value. It is calculated from two other measurements, that is actual forward speed and theoretical speed of the tractor, which can be measured either directly or computed from the rotational speed and the rolling radius of the wheels. In this study, the theoretical speed of the tractor was calculated by measuring the average revolution per minute (RPM) of the rear wheels, while the actual speed was measured by radar sensor. Incremental encoder was used for measuring wheel rpm. It has 1024 lines. It was fixed to a fabricated frame and coupled to the rear axle shaft.

Ground speed sensor based on radar principle was used to record the true forward speed of the tractor during operation. The sensor was mounted in the front of the tractor. For calculation of slip the difference of pulse value between the radar and encoder was observed in zero slip condition. The received pulses were read as P_r for rear and P_f for front wheel. The radar sensor gives constant pulse per km/h. Hence knowing the pulse per second, actual velocity in km/h was calculated. The following equation was used to calculate the theoretical speed and wheel slip from the received signal of pulses.[2]

$$V_t = \frac{\text{Perimeter of wheel, m}}{1023} \times \text{Number of pulse from the encoder/sec} \times 3.6 \quad \ldots (1)$$

$$S = \left(1 - \frac{V_a}{V_t}\right) \times 100 \quad \ldots (2)$$

where, V_a = actual velocity (km/h), V_t = theoretical velocity (km/h), and S = wheel slip (%)

From the forces acting on the links and the angles made by the links in horizontal and vertical planes, the draft of the implement was computed using the following expression:

$$D = F_{L1}\cos\theta\cos\beta + F_{L2}\cos\theta\cos\beta - F_U\, cos\gamma \quad \ldots (3)$$

where, F_{L1} = force in lower link one, F_{L2} = force in lower link two, F_U = compressive force in top link

θ = angle of lower link in vertical plane, β = angle of lower link in horizontal plane, and γ = angle of top link in vertical plane

The layout of the developed slip control system and sequence of calculation in microprocessor is presented through a flow chart (Fig. 2a) and the layout of the draft control system is presented through a flow chart (Fig. 2b).

Microcontroller was uploaded with the lower limit (LL) and upper limit (UL) of optimum wheel slip/draft through the developed computer interfacing. The measured wheel slip/draft was compared by the microcontroller with the UL and LL. If the slip/draft is less than the LL, a signal goes to proportional valve to extend the hydraulic cylinder. Similarly, if the slip/draft is more than the UL, an opposite signal goes to proportional valve to retract the hydraulic cylinder. And if the slip/draft value lies between LL and UL, cylinder remains stationary.

Development of Simulator for Slip Control System Calibration

A simulator was developed to validate the developed slip control system in the laboratory. The facility of soil dynamics laboratory of ICAR-CIAE, Bhopal was used to evaluate the slip control system under controlled soil bin condition. The laboratory facility consisted of a 16.0 × 2.50 × 1.0 m soil bin filled with the locally available clay soil, a soil processing trolley, an instrumented tool carrier and linear transmission system with 20 hp AC variable drive. Linear speed of the carriage is controlled by moving the carriage with a motor having AVS drive. Linear speed of the carriage is determined by an optical laser sensor mounted at the end of soil bin system. In the soil bin the carriage can be operated at a predetermined varying speed. The complete setup was fixed to the tool bar of soil bin carriage. The setup consisted of incremental encoder, 12 V DC low RPM geared motor with RPM controller, radar speed sensor, 12 V DC power supply, slip control system and personal computer. Incremental encoder was coupled to 12 V DC low RPM geared motor to represent rear wheel rotation. Electronics circuit was used for varying the speed of the encoder similar to the speed of the tractor. The main purpose of the simulator was to find out the pulse output from the radar speed sensor and encoder at various slip. For adjusting the slip the radar speed sensor was allowed to move at a constant speed and encoder rotation was varied corresponding to slip of 5 to 40%. This process was repeated with different speed setting to get different values of pulses. The RS232 computer interfacing was provided to the slip control system for transferring the indicated value directly to the computer.

Performance of Slip Control and Draft Control System in Field Condition

The automatic slip control system (ASCS) and automatic draft control system (ADCS) was evaluated under actual field conditions. The soil properties of experimental plot was measured and presented in Table 1.

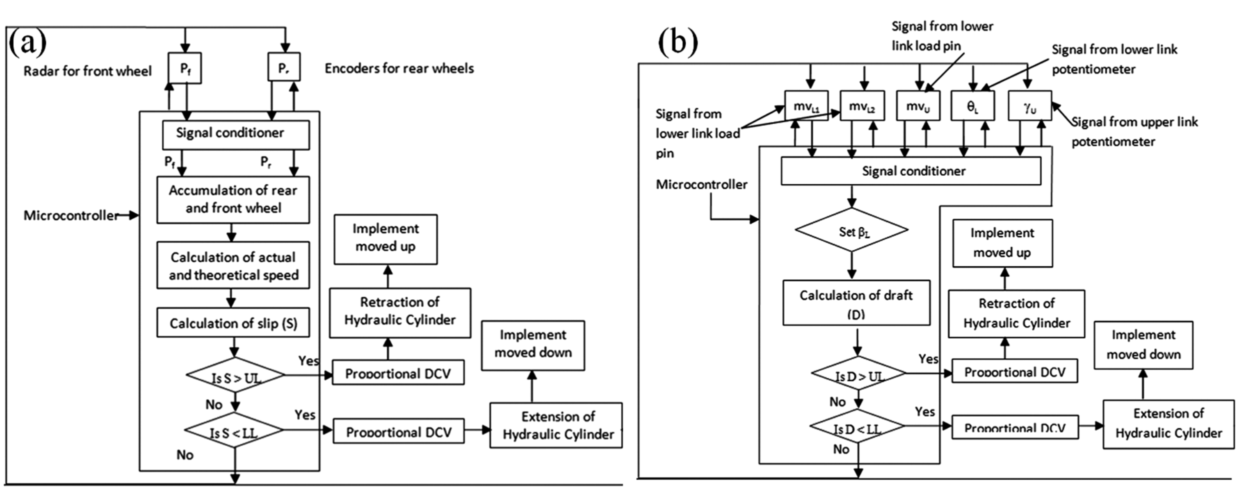

Fig. 2 — Layout of the developed control systems (a) slip control system (b) draft control system

A diesel tractor of 60 hp PTO power was used to conduct drawbar test at different working depth of 250 mm and 150 mm for 2–bottom MB plough and sweep cultivator, respectively. The MB Plough was operated at 2.5–3 km/h and cultivator was operated at 5–6 km/h. The specification of the tractor used in filed evaluation is shown in Table 2.

A 50 m length strip in a field was selected for comparing the performance of ASCS, ADCS and existing Tractor Draft Control System (TDCS). Within the total run of 50 m, three systems were operated in about 10 to 15 m run randomly and observations were recorded. During the operation of ASCS and ADCS, TDCS was made inactive by some special arrangement.

Results and Discussion

Performance of Slip Control and Draft Control System in Field Condition

Within the total run of 50 m, ASCS, ADCS and TDCS were operated in about 10 to 15 m run randomly and observations were recorded. It was observed that slip varied from 14–25% with the ASCS as against the desired range of 15–20%, while it varied from 12–48% with the TDCS. Similarly draft varied from 5.7–10.2 kN with the ADCS as against the desired range of 7–9 kN, while it varied from 5.2–17.9 kN with the TDCS. A large variation in slip and draft in case of the existing draft control system may have been due to longer control time required by the system compared to that required by the designed ASCS and ADCS. It may be seen that the developed system starts controlling the slip by reducing the depth of operation, when it goes beyond 20−25%. Therefore, the system maintains the desired slip and draft range.

Table 1 — Physical and mechanical properties of soil in experimental plot

Soil Order	:	Vertisols
Soil texture	:	Clay soil
Clay,%	:	61.27
Silt,%	:	27.15
Sand ,%	:	11.59
Cohesion (c), kPa	:	11.95
Angle of internal friction ,°	:	26.18
Soil moisture content(db), %	:	15–18
Bulk density, g/cc	:	1.46

Table 2 — Specification of Tractor

Engine make	:	HMT 6522 TC (TREM – III ‘A’)
Hp range	:	60
Rated engine rpm	:	2200
No. of speeds	:	10 forward + 2 reverse with tyre size 16.9/14–28
Steering	:	Re-circulating ball type/hydrostatic power steering

Slip control system was also evaluated in the field in undisturbed and tilled conditions. The indicated slips by the slip control system at varying drawbar pulls and normal loads on undisturbed and tilled condition were compared with the measured slip values. These are shown in Fig. 3a and 3b. The numerical values within the brackets above the bar diagrams indicate percentage deviation. The percentage deviation of measured and indicated slip in undisturbed and tilled soil was within −3.2 to +4%.

The other performance parameters of the slip control system are given in Table 3. The data analysis showed a Root Mean Square Error (RMSE) of 2.48%. The Measuring Efficiency (ME) was found to be 99.5%. The graph shows a very good correlation between the measured and the indicated slip. Comparison was made between the observed and indicated slip control system readings using paired t-test. At 5% level of significance, no difference was observed between the two data.

Calculation of Control Time

The control time of ADCS, ASCS and TDCS were calculated using the real time data. The time required to

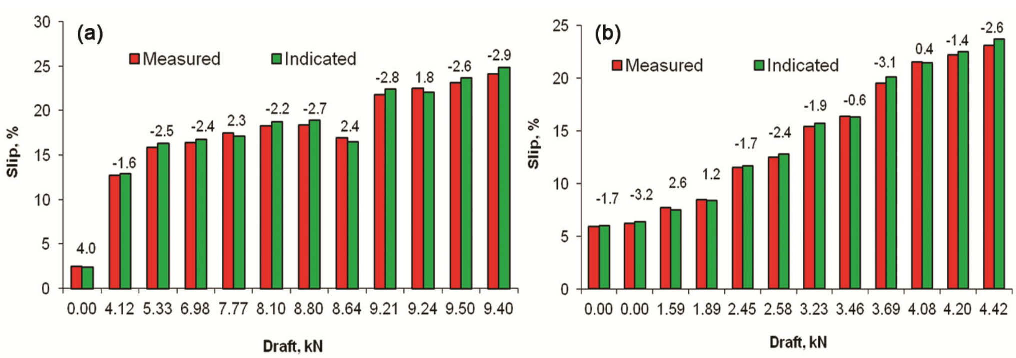

Fig. 3 — Comparison of measured and indicated slip in (a) Undisturbed soil, (b) Tilled soil

regain the set draft close to its initial setting is considered as the control time of the system. The initial setting is represented by the average draft line, which corresponds to approximately 9160 N. Similarly for ADCS and ASCS, the variation of draft is plotted against time are shown in Fig. 4a and Fig. 4b.

The duration in which the slip and draft is controlled by the system within the optimum range is considered as the control time. The calculated control time for all the systems is given in Table 4. The data indicate that the average control time decreased by 32.6% and 43.2% in ADCS and ASCS as compared to the TDCS of the tractor hydraulics.

By adjusting the slip control range in different tillage operations, the performance of the slip control system was examined in the field. Table 5 shows the observed slip's minimum, maximum, and average values in relation to the established slip control range. The average slip values were all within the established slip control range, according to the data. The minimum value, on the other hand, was found below the lower limit, while the maximum value was located above the higher limit. The average slip is usually equal to or close to the higher limit because it crosses the upper limit more frequently than the lower limit during the operation. When the slip increases rapidly owing to soft soil, the system detects the effect and attempts to control it. This could be the reason why slip occasionally exceeds the predefined slip range. Identical outcomes were also reported.[7]

Drawbar Performance of a Tractor with Slip and Draft Control Systems for Different Field Operations

The drawbar performance of a diesel tractor equipped with the developed slip and draft control system was compared with the existing draft control system of tractor hydraulics under actual field condition. The performance data showed that the increase in the desired range of slip from 10–15 to 20–25% resulted in increasing the draft of the implement due to an increase in its depth of operation. With increase in slip beyond the optimum range field capacity were found to decrease while fuel consumption increased. Similar field results were also reported.[10,11] The comparative performance of ASCS, ADCS and TDCS on drawbar performance of the tractor during field operations is discussed below.

Table 3 — Performance parameters of slip control system

Mean slip, % Measured	Mean slip, % Indicated	Accuracy, %	Min and Max Deviation %	RMSE %	r	ME %
15.86	16.05	0.99	−3.2 to 4.0	2.48	0.99	99.5

Table 4 — Control time calculation

Condition	Control time, s		
	In lifting the implement	In lowering the implement	Average
TDCS	7.2, 7.0, 3.5, 5.7, Avg = 5.85	3.4, 7.1, 2.1, Avg = 4.2	5.02
ADCS	3.4, 4.6, 3.3, Avg = 3.76	3.0	3.38
ASCS	4.0, 3.6, 3.2, Avg = 3.6	2.1	2.85

Table 5 — Observed slip value with respect to set slip control range

Operation	Set slip range, %	Observed slip, %			Standard deviation
		Min	Max	Average	
Ploughing	10–15	12	20	15	3.2
	15–20	14	24	19	3.5
	20–25	18	27	24	3.4
Cultivating	10–15	9	16	14	3.2
	15–20	13	22	18	2.9

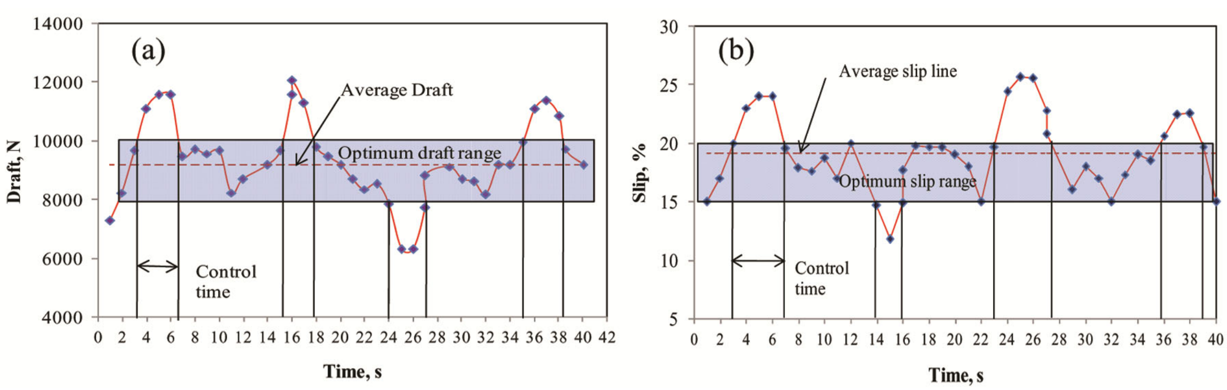

Fig. 4 — Automatic Control System (a) Time versus draft in automatic draft control system, (b) Time versus slip in automatic slip control system

Effect of ASCS, ADCS and TDCS on Field Capacity

The field capacity as influenced by ASCS, ADCS and TDCS is presented in Fig. 5a and 5b for ploughing and cultivating operations at different settings of the initial depth, slip and draft range.

The values at the top of the histogram indicate the percent deviation using the slip and draft control system as against the existing draft control system based on average data recorded. It is observed that the field capacity decreased as slip increased in all the operations. However, as compared to TDCS, a higher field capacity was noticed in ASCS in all the field operations for every selected depth and slip range. During ploughing operation, the field capacity increased by 6.3, 7.4 and 4.0% for the slip control ranges of 10–15, 15–20 and 20–25%, respectively in comparison to the existing tractor draft control system. Similarly, in the case of cultivating operations, the field capacity also increased by 3.7, 6.9 and 9.7%, respectively in the slip control range of 10–15, 15–20 and 20–25% respectively.

Comparison has also been done between ADCS and TDCS and increased field capacity was observed for ADCS. During ploughing operation, the field capacity increased by 6.1, 6.5 and 3.4% for the draft control ranges of 5–6, 7–8 and 9–10 kN, respectively in comparison to the existing tractor draft control system. Similarly, in the case of cultivating operations, the field capacity also increased by 8.7, 8.3 and 14.5%, respectively in the slip control range of 5–6, 7–8 and 9–10 kN respectively.

Effect of ASCS, ADCS and TDCS on Fuel Consumption

The effect of ASCS, ADCS and TDCS on fuel consumption (l/ha) is presented in Fig. 6a and Fig. 6b for different field operations.

During ploughing operations with TDCS, fuel consumption was determined to be 20.13, 21.11, and 22.98 l/ha at beginning depth settings of 150, 180, and 220 mm, respectively. However, including ASCS resulted in a considerable gain in fuel efficiency, with a reduction of 11.2% in fuel consumption. Similarly in case of cultivating operations, the saving in fuel consumption in ASCS was to the tune of 6.4%. The

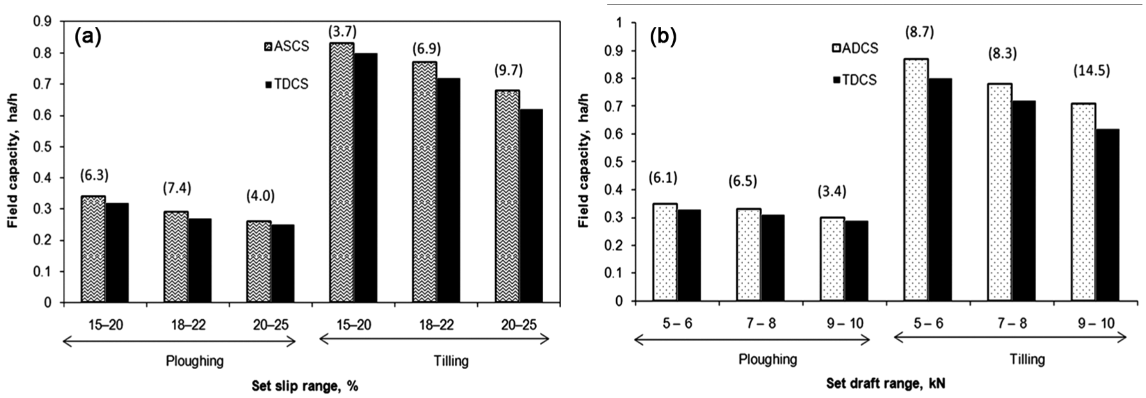

Fig. 5 — Effect of ASCS and TDCS on field capacity (a) field capacity versus slip percentage, (b) field capacity versus draft

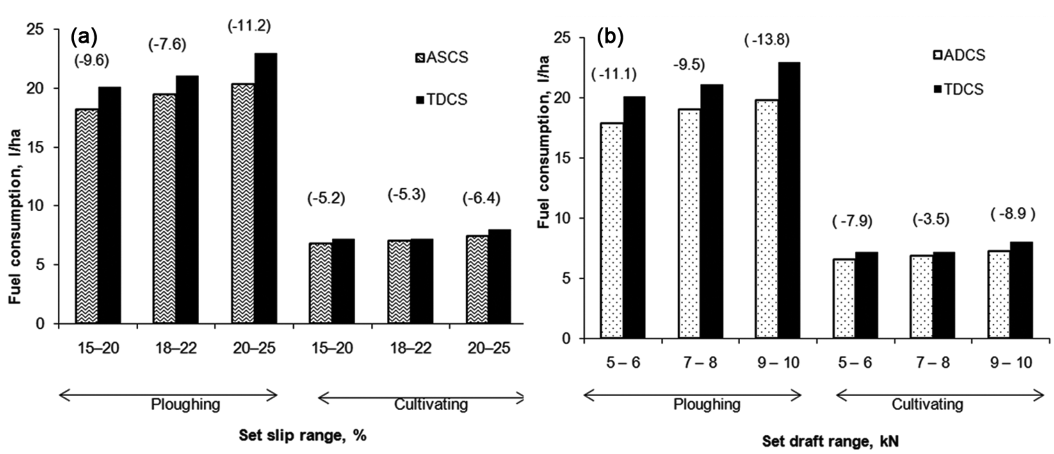

Fig. 6 — Effect of ASCS and TDCS on fuel consumption (a) fuel Consumption versus slip percentage (b) fuel consumption versus draft

reduction in fuel consumption in case of ASCS was mainly due to increase in the field capacity owing to reduced slippage.

Comparison has also been done between ADCS and TDCS and increased fuel efficiency was observed for ADCS. During ploughing operation, the fuel consumption was decreased by 11.1, 9.5 and 13.8% for the draft control ranges of 5–6, 7–8 and 9–10 kN respectively in comparison to the existing tractor draft control system. Similarly, in the case of cultivating operations, the fuel consumption also decreased by 7.9, 3.5 and 8.9%, respectively in the slip control range of 5–6, 7–8 and 9–10 kN respectively.

Effect of ASCS, ADCS and TDCS on Depth of Operation

Three draft, slip and depth setting were considered during the observation. For every length of run ASCS, ADCS and TDCS was operated in sequence and both the ASCS and ADCS was compared with the TDCS individually. Slip range was fixed at 15–20, 18–22 and 20–25% and draft range was at 5–6, 7–8 and 9–10 kN for the initial depth adjustment of 150, 180 and 220 mm, respectively. It may be observed that in ASCS, the average depth of operation was close to the initial depth setting with maximum standard deviation of 3.8, 5.5 and 8.8 mm, and for ADCS the maximum standard deviation is 2.9, 3.8 and 5.9 mm, for the initial depth adjustment of 150, 180 and 220 mm, respectively, whereas in TDCS, the average depth of operation increased by about 6–8% from the initial depth setting with maximum standard deviation of 15 mm.

The rate of variations in depth of operation was increased with increase in depth of operation and is almost same trend for ASCS, ADCS and TDCS. But from the plot it can be concluded that, depth of operation could be managed more effectively in ASCS as compared to TDCS.

Conclusions

Tractors are mostly used for hauling and pulling drawbars. Due to motion resistance and slip, a 20–25% loss has been reported at the soil tyre interface. An attempt has been made to design an embedded system for automatic draft and slip measurement system within a specific range of soil conditions in order to increase the tractive efficiency of off-road vehicles.

The important findings of this research are listed below.

- For 2WD tractors, an automatic slip and draft control system was created for online assessment of wheel slip in real-world conditions. The designed slip control system's measurement efficiency was found to be over 99%.
- To validate the slip control system in the laboratory, a simulator was constructed and developed.
- To manage the depth of operation effectively and efficiently, an electro hydraulic lift link system was created.
- A slip and draft control system was devised to keep the wheel slip and implement draft within a pre-specified range of slip and draft, respectively, by automatically adjusting the depth of operation.
- In vertisol, the designed automatic draft control and slip control system may minimise fuel consumption by 14% while increasing field capacity by 14.5%.
- This control system may be fitted on any 2WD tractor, regardless of make or model.

Declaration of Competing Interest

The authors state that they have no known competing financial interests or personal ties that could have influenced the research presented in this study.

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