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AUTOMATIC CONTROL OF WHEEL SLIP IN SOIL TILLAGE

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ABSTRACT

In this study, a control system that automatically adjusts the working depth of the tractor tillage equipment has been developed in order to keep the wheel slip occurring in agricultural tractors during the tillage activities at the determined limit value. The developed automatic control system continuously measured the wheel slip on the tractor drive wheels and reduced the tillage depth adjusted for the wheel slip increase. While the amount of wheel sip was at the allowed level, the tillage equipment worked at the set depth value. In the study, a driver warning system is also designed to alert the driver to reduce the tillage depth when the amount of wheel slip exceeds the specified limit value. The driver warning system warns the driver visually with the help of colored LEDs and audibly with a buzzer according to the measured wheel slip value. The developed automatic control system was compared separately with the designed driver warning system and the operator's own control. The wheel slip value was calculated by comparing the forward speed of the tractor with the speed of the drive wheels. The automatic control system and driver warning system were installed on a New Holland TD110 agricultural tractor and trials were carried out in real field conditions. As a result of the trials, according to the driver warning system and operator control, it was determined that there was a 3-29% reduction in wheel slip and a 22-30% reduction in fuel consumption in soil tillage activities carried out with automatic control system. On the other hand, the draft force decreased by more than 5% compared to the operator control in the automatic control system. However, it was observed that there was almost no change in the average tillage depth between the control methods.

Keywords: Agricultural tractors, Automatic control systems, Fuel efficiency, Plowing depth, Wheel slip

TOPRAK İŞLEMEDE PATİNAJIN OTOMATİK KONTROLÜ

ÖZET

Bu çalışmada, toprak işleme faaliyetleri esnasında tarım traktörlerinde oluşan patinajı, belirlenen sınır değerde tutmak için, traktöre bağlı toprak işleme ekipmanının çalışma derinliğini otomatik olarak ayarlayan bir kontrol sistemi geliştirilmiştir. Geliştirilen otomatik kontrol sistemi traktör tahrik tekerleklerinde oluşan patinajı sürekli olarak ölçmüş ve patinaj değerindeki artış miktarına göre ayarlanan toprak işleme derinliğini azaltmıştır. Patinaj miktarı izin verilen seviyede iken toprak işleme ekipmanı ayarlanan derinlik değerinde çalışmıştır. Çalışmada ayrıca, patinaj miktarı belirlenen sınır değeri aştığında, sürücüyü toprak işleme derinliğini azaltması için uyaran bir de sürücü uyarı sistemi tasarlanmıştır. Sürücü uyarı sistemi, ölçülen patinaj değerine göre sürücüyü renkli LED (Light Emitting Diode)'ler yardımıyla görsel olarak ve bir siren yardımıyla da sesli olarak uyarmaktadır. Geliştirilen otomatik kontrol sistemi, tasarlanan sürücü uyarı sistemi ile ve operatörün kendi kontrolü ile ayrı ayrı karşılaştırılmıştır. Patinaj değeri, traktörün gerçek ilerleme hızı ile tahrik tekerleklerinin dönüş hızı karşılaştırılarak hesaplanmıştır. Otomatik kontrol sistemi ve sürücü uyarı sistemi New Holland TD110 model bir tarım traktörüne monte edilmiş ve gerçek tarla koşullarında denemeler yapılmıştır. Denemeler sonucunda, sırasıyla sürücü uyarı sistemi ve operatör kontrolüne göre, otomatik kontrol sistemi ile gerçekleştirilen toprak işleme faaliyetlerinde, patinaj değerlerinde %3-29 ve yakıt tüketiminde %22-30 azalma olduğu belirlenmiştir. Traktörle toprak işleme ekipmanı arasında oluşan çeki kuvvetinde ise, otomatik kontrol sisteminde operatör kontrolüne göre %5'ten fazla azalma olduğu görülmüştür. Bununla beraber, toprak işleme derinliğinde, kontrol yöntemleri arasında neredeyse hiç değişiklik olmadığı gözlenmiştir.

Anahtar kelimeler: Otomatik kontrol sistemi, Patinaj, Tarım traktörleri, Toprak işleme derinliği, Yakıt verimliliği

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1. INTRODUCTION

Tillage operations are main farm operations required to prepare soil conditions for seed germination. Operations play a very important role in the production of agricultural products. Incorrect tillage operations lead to reduced productivity and, consequently, increased production costs [1].

In tillage operations, differences in soil conditions of the field lead to changes in draft force required to pull implement within soil in any forward speed and plowing depth. Lack of draft force in a certain soil condition results in decrement of tractive efficiency. This also increase the wheel slip and fuel consumption. Therefore, to obtain the optimum draft force, a draft control system was considered for tractors. The available draft control systems regulate draft force in a specific bound on the basis of the first adjustment of plowing depth by operator. The control procedure is continuously performed by plowing depth changes. Therefore, variations in plowing depth are obtained in primary tillage operations [1].

The efficiency of traction depends mainly on tractor related factors (weight of the tractor, number of driven axles, kind of tire, inflation pressure) and soil related factors (surface hardness, soil moisture content) [2]. The requirement of drawbar power in soil tillage depends mainly on the working depth. Approximately 100 m^3 or 150 tons (soil density: 1.5 kg/dm^3) of soil per hectare is moved if 1 cm soil is ploughed. Depending on soil constitution the fuel consumption increases per cm ploughing depth between 0.5 and 1.5 L/ha [3].

Wheel slip was defined as the difference between the actual forward speed of the tractor and the drive wheel speed [4]. The maximum tractive efficiency occurs at a lower wheel slip and starts decreasing with an increase in the slip [5, 6]. If the wheel slip is maintained within an optimum range the tractor operates at maximum efficiency [7]. In previous studies, it has been proposed to optimize the tractor's wheel slip range in the range of 10-15% for better traction performance. It also stated that, wheel slip less than 7% is undesirable because the draft efficiency is reduced, and the power is wasted. However, it has been observed that wheel slip greater than 20% results in inefficiency [8, 9].

Agricultural tractors generally have a hydro-mechanical draft control system where the draft is sensed mechanically, and a hydraulic valve is actuated for operational depth control.

The draft control systems engaged in tractors are found to be inefficient in keeping the draft control in line with the slip [10-15]. Researchers have also concluded that commercial draft control systems force the operator to control the depth control lever frequently for achieving the optimum draft, resulting in poor efficiency [13, 16]. The frequency of operation of hydraulic control lever has been found to be 3 times/min [17] and about 40% of such adjustments were to prevent excessive slip [18, 19]. However, the utilization of this information depends upon operator's experience and fatigue level [11].

In Turkey, 15.5 million ha area is used for the field-agriculture. Depending on tillage methods, 620 million liters of fuel are consumed annually. Approximately $6.2 million will be saved with a 1% saving in fuel consumption. [20].

It is therefore an absolute necessity to measure and indicate slip for getting maximum drawbar output from the tractor.

In this study, it is aimed to develop an embedded system with simple, cheap and reliable materials to digitally measure and display the wheel slip. If the wheel slip exceeds the optimum values, the system is aimed to give audible and visual warnings. In addition, an automatic wheel slip control system for optimum tractive efficiency by altering the depth of tillage was developed and compared with warning system.

2. MATERIAL AND METHOD

The developed warning system and the automatic control system consist a slip measurement unit, a fuel measurement unit, a hydraulic lever adjustment mechanism, a Bluetooth communication unit, a SD card data logger, a draft force measurement unit, a depth measurement unit, and a data collection/processing unit.

In order to determine the actual forward speed, and speeds of the rear driving wheels, hall effect sensors and magnets were used. Magnets placed to left front wheel and rear wheels. The hall effect sensors that would detect magnets were fixed to the apparatus mounted on the tractor (Fig. 1) [21, 22, 32].

The magnets passed in front of the hall effect sensors is counted by using the Arduino Due microcontroller. The actual forward speed, and the speeds of the rear driving wheels were calculated as:

$$V = \frac{a * C * 3.6}{n} \quad (1)$$

where V - Tractor forward speed, [km/h]; a - The number of magnets counted in one second; C - Wheel circumference, [m]; n - The number of magnets found in the wheel [32].

Amount of the slip occurring on the wheels was calculated as:

$$\%S = \frac{V_r - V_f}{V_r} * 100 \tag{2}$$

where %S - Slip [%]; Vr - Rear wheel speed [km/h]; Vf - Front wheel speed [km/h] [29]

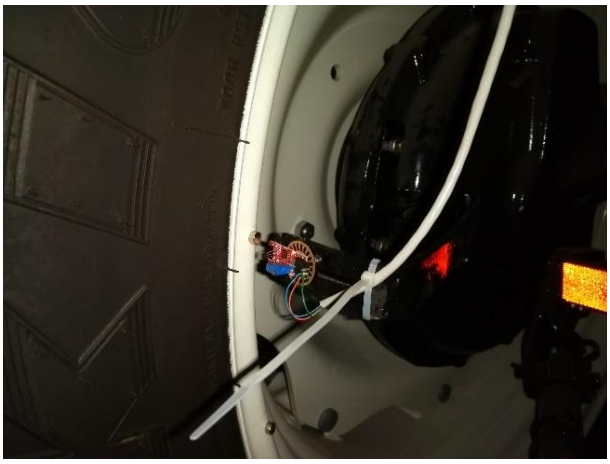

Figure 1. Hall effect sensors and neodymium magnets

Two flowmeters (Sea YF-S201) were used to determine the fuel consumption (Fig.2). The first flowmeter was mounted on the fuel line leading from the tank to the engine, and the second was mounted on the fuel line going back to the tank from the engine [2, 31]. An Arduino Nano microcontroller was used to calculate fuel consumption in L/ha. Finally, calculated values were transferred to the Arduino Due microcontroller board via serial communication ends.

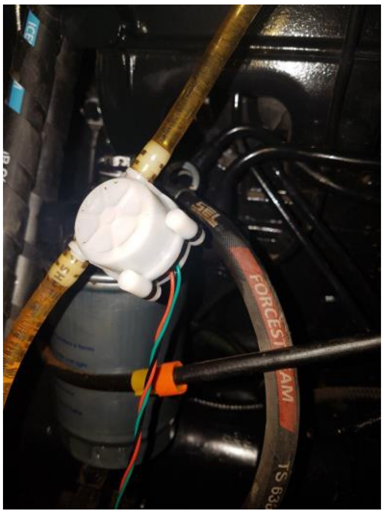

Figure 2. Flowmeter mounted on fuel line

Three 30-kN force-measuring pins (Lorenz Messtechnik GmbH K-2562) were used to measure the draft forces (Fig. 3). The pins were connected to the 3-point hitch system [33]. HX711 modules designed for Arduino microcontrollers were used to convert signals, and then the outputs were transferred to the Arduino Due microcontroller board.

Figure 3. Force-measuring pins to measure the draft forces

To measure the tillage depth, a moving wheel was attached to the plough. A potentiometer (1 kΩ) was placed between the plough and moving wheel (Fig. 4). When the wheel contacts with the soil, the potentiometer rotates according to the sinking amount of the plough into the soil. Thus, the resistance of the potentiometer changes and the tillage depth is calculated by Arduino Due microcontroller board [23-25].

Figure 4. Depth control wheel and potentiometer

In the designed automatic control system, the movement of the hydraulic control lever is ensured by a servo motor (12V, 380kg.cm) mounted on the control lever at the back of the tractor (Fig. 5). For the hydraulic control lever's level setting, the servo motor was controlled between 0-100°. 12V DC voltage for servo motor was taken from the tractor battery and the control pin was connected to the digital output of the Arduino Due microcontroller board.

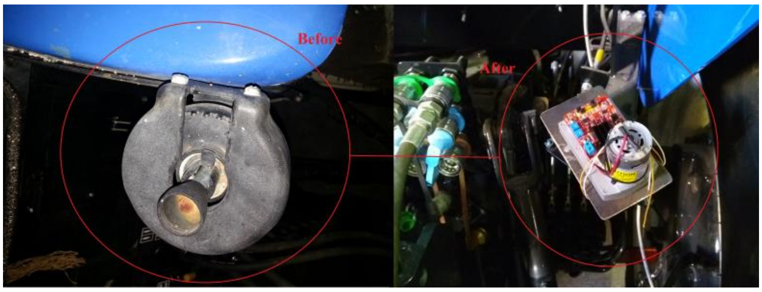

Figure 5. Servo motor mounted on the control lever

The warning system is provided with three LEDs, namely red, yellow, green. A buzzer is also provided to alert the operator. The green led glows continuously to indicate the working of developed system and show that slip value is less then %15. Yellow led glows when the slip value exceeds %15. Red led glows and buzzer starts when the slip value exceeds the value 25%. The flow diagram of the developed warning system is shown in Fig. 6. In the studies carried out with the warning system, the operator was asked to adjust the depth according to the information from the LEDs and buzzer.

For the designed warning system, the amount of slip occurring on the left and right rear wheels was averaged, and LEDs were glowed according to this average slip value. The average slip amount was calculated as:

$$S_{avg} = \frac{S_{lr}+P_{rr}}{2} \tag{3}$$

where S_{avg} - Average amount of slip, [%]; S_{lr} - Left rear wheel slip amount, [%]; S_{rr} - Right rear wheel slip amount, [%].

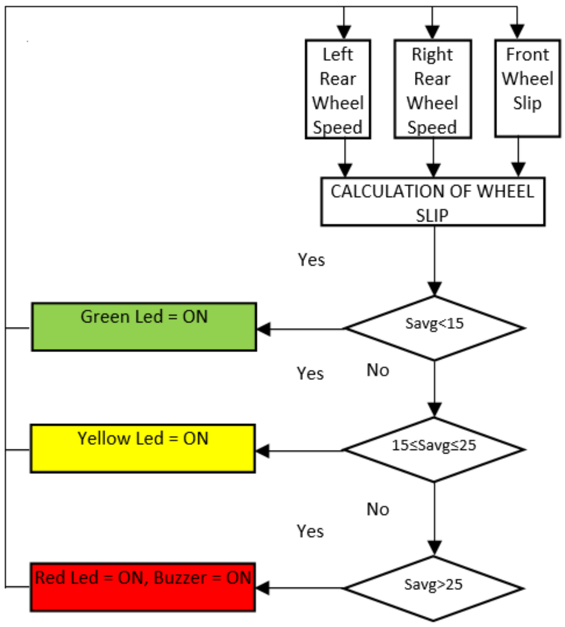

Figure 6. Developed warning system

In this study, an on-off based automatic control system was also developed to compare it with the warning system. A servo motor is added to control hydraulic control lever and the software on the Arduino Due microcontroller board was updated. For the designed automatic control system, the position of the hydraulic control lever was set according to average slip value.

An Android application was developed to set the tillage depth of the tillage equipment. The communication between phone/tablet and the Arduino Due microcontroller card was done via Bluetooth. With the application, the tillage equipment can be lifted up and down with an accuracy of 1cm (+/-). There are also buttons for the tillage equipment to be lifted up and down completely (Lift UP/Lift DOWN). With this application the desired depth of tillage can also be directly set (Fig. 7).

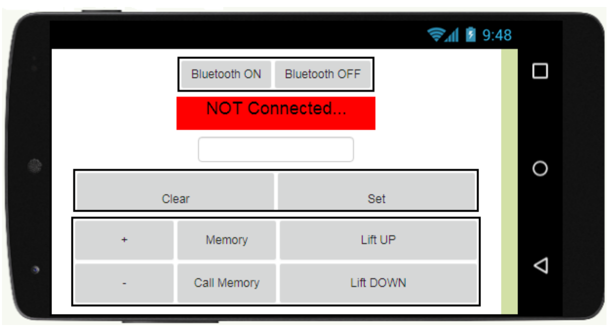

Figure 7. Screen of Android App

The flow diagram of the automatic control system is given in Fig. 8. The rules that are valid for the operation of the automatic control system were established as follows:

IF S_{avg}<15, THEN Depth=SAME
IF S_{avg}≥15, THEN Depth=REDUCE by 50%

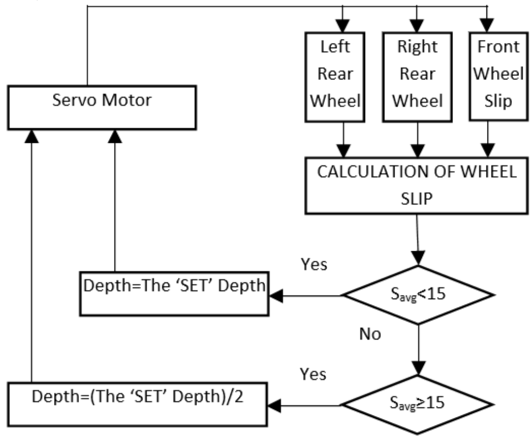

Figure 8. Developed automatic control system

The field tests were conducted at the Sarıcalar Application Farmland of the Faculty of Agriculture of Selcuk University (41°82'27"N ve 45°60'15"E). A New Holland TD110D model tractor was used and the tillage equipment was a 5-furrow plough. The operating width was 1.66 m.

A HC-06 Bluetooth module for Bluetooth communication and a MicroSD card module for data recording were also added to designed systems.

In the trials, the average slip amounts, fuel consumption, total draft force, and tillage depth values were measured. These data were recorded on a SD card (Fig. 9). To reduce experimental errors, trials were conducted in the form of three repetitions.

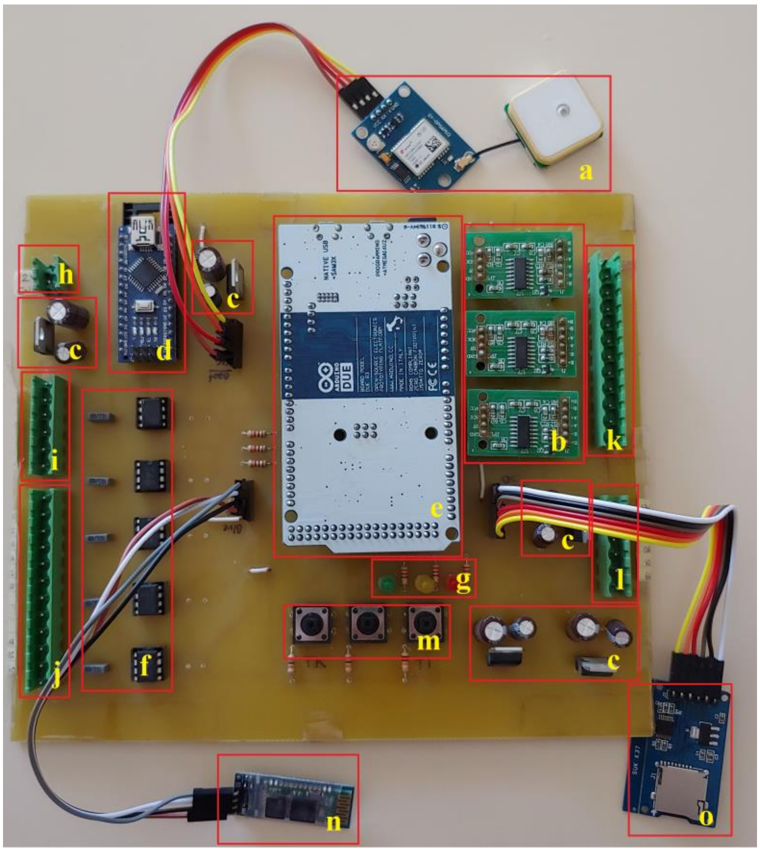

Figure 9. Electronic control board (a. Neo-6M GPS Module, b. HX711 modules, c. 7805 Voltage Regulators, d. Arduino Nano fuel measurement unit, e. Arduino Due data collection/processing unit, f. LM741 OPAMPs for filtering, g. LEDs for warning,

h. +12V Power connection, i. flow meter connection pins, j. Hall effect sensor connection pins, k. Loadcell connection pins, l. Servo motor connection pins, m. Shortcut program buttons, n. Bluetooth module, o. MicroSD card module)

3. RESULTS AND DISCUSSIONS

A total of nine tests were carried out to compare the results; three repetitions for warning system, three repetitions for automatic control system and three repetitions for the operator's own control. Forward speed was set to 4.6 km/h and the tillage depth was set to 25 cm.

The result graphics obtained from automatic control system are given in Figure 10. In studies conducted with the automatic control system, the actual forward speed varied between 3.7 and 4.6 km/h. The drop in actual forward speed can be explained by the increased amount of wheel slip. Wheel slip was changed between %4 and %32 and fuel consumption was changed between 8 and 13.7 L/ha. The minimum draft force was 20 kN while the maximum draft force was 28 kN. The minimum tillage depth measured was 20.5 cm. Similar results have been reported in past studies [1, 8, 26].

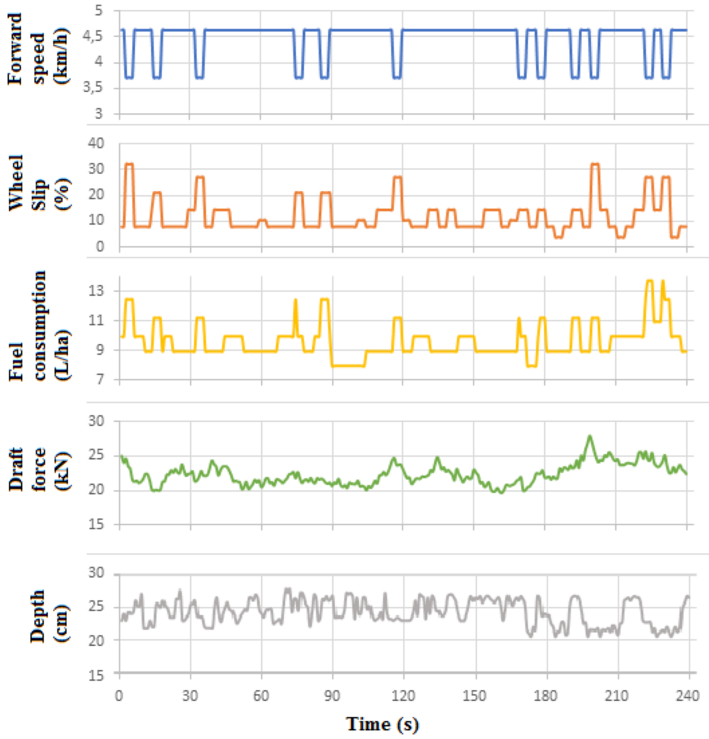

Figure 10. Results of automatic control system

The result graphics of warning system are given in Figure 11. The actual forward speed varied between 3.7 and 5.5 km/h in this study. The minimum wheel slip was %4 and the maximum wheel slip was %37. Fuel consumption was changed between 7.5 and 12.5 L/ha. Draft force changed between 14 – 29 kN. The minimum tillage depth measured was 18 cm. Researchers reported similar results with the warning systems they designed [28, 29].

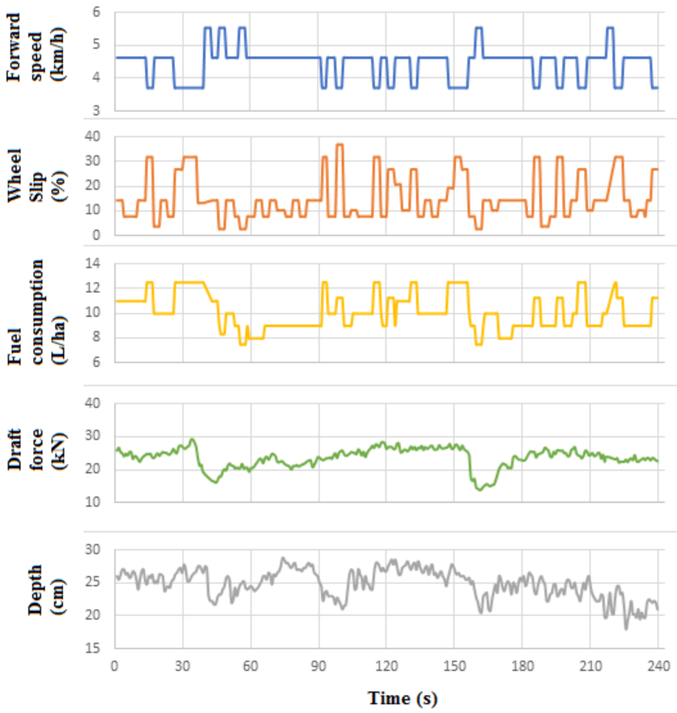

Figure 11. Results of warning system

The result graphics of operator control are given in Figure 12. The minimum actual forward speed was 2.8 and the maximum forward speed was 4.6 km/h. The wheel slip was changed between %4.5 and %53. Minimum fuel consumption was measured as 9 L/ha and maximum fuel consumption was measured as 23 L/ha. Draft force changed between 20 – 29 kN. The minimum tillage depth measured was 19 cm. Similar results have been reported by researchers in previous studies [11, 32, 33].

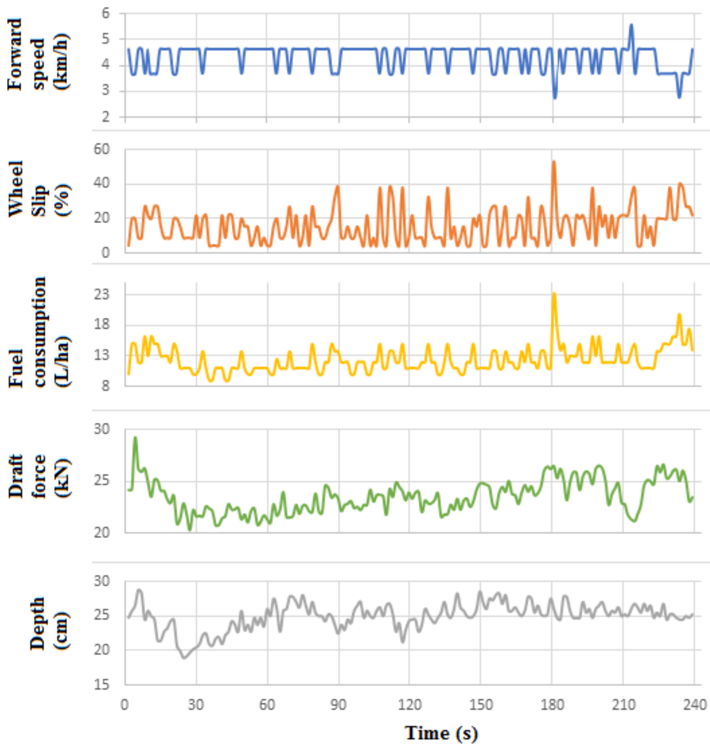

Figure 12. Results of operator control

In all control methods, the minimum and maximum slip values obtained according to operating conditions were found to be above the 10-15% optimum value range. In the trials conducted with the automatic control system, the average slip values remained within the optimum operating range.

Table 1. Average value table for different control methods

	Slip (%)			Fuel consumption (L/ha)			Total draft force (kN)			Tillage depth (cm)		
	Min	**Max**	**Avr**	**Min**	**Max**	**Avr**	**Min**	**Max**	**Avr**	**Min**	**Max**	**Avr**
Warning System	3.0	37.0	15.20	7.48	12.47	10.05	13.92	29.27	23.77	18.00	28.75	24.93
Automatic Control System	4.0	32.0	12.09	7.98	13.73	9.45	19.66	28.04	22.38	20.50	27.75	24.27
Operator	4.5	53.0	15.60	8.96	23.23	12.31	20.26	29.25	23.53	19.00	28.75	24.97

When the results of the trials were examined, it was seen that the minimum average wheel slip (12.09%) was in the trial conducted by the automatic control system and the maximum average wheel slip (15.60%) was in the trial performed by operator control. When the values were compared, it was observed that the average wheel slip values decreased by 2.6% in the warning system and by 29.03% in the automatic control system compared to the trials conducted in operator control.

Minimum average fuel consumption (9.45 L/ha) has measured in the trial conducted by the automatic control system and the maximum average fuel consumption (12.31 L/ha) was in the trial performed by operator control. When the values were compared, it was observed that the fuel consumption values decreased by 22.49% in the warning system and by 30.26% in the automatic control system compared to the trials conducted in operator control.

It was seen that the minimum average total draft force (22.38 kN) and the maximum average total draft force (23.77 kN) was in the trial performed by warning system. It was observed that the total draft force values were almost same in warning system and operator control. But the total draft force decreased by 5.14% in the automatic control system compared to the trials conducted in operator control.

When the results of the tillage depth are analyzed, the values of minimum 18.00 cm (in the experiments carried out with the warning system) and maximum 28.75 cm (in the experiments carried out with the automatic control system and by the operator when no system was active) are obtained. Values below 25 cm seen here were caused by the tillage implement being lifted in case of strain. On the other hand, values over 25 cm emerged when the depth measuring wheel connected to the tillage machine encountered a protrusion (stone, clod, grass cluster, etc.) on the soil surface. When the average soil tillage depth values obtained were compared, it was observed that almost equal values appeared in all different control methods.

4. CONCLUSION

When the data obtained were analyzed, it was seen that the operator could not feel the small values of the wheel slip that occurred during the tillage activities. They could feel the wheel slip after the value %30-35. With the warning system that informs operator about the magnitude of wheel slip, it was observed that the operators intervened more in the tillage depth during the tillage activities, but the time for their interventions was quite long. In the experiments carried out with the automatic control system, it was observed that the automatic control system intervened with the tillage depth as soon as the wheel slip value rises above the optimum value. The intervention to the tillage depth of the automatic control system was faster than the operator and it did not miss the excess of optimum wheel slip. In the tillage operation carried out by the automatic control system, the operator did not need to make any additional effort. In addition, the parts of the tractor, especially tires, will suffer less damage and increase their lifetime.

In the trials carried out with the automatic control system, the fuel consumption decreased, but the average tillage depth values almost did not change. When all these are evaluated, it can be said that automatic control system performed more efficiently according to the warning system and the operator's own control.

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