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Mathematical models to predict fuel consumption criteria under different operating conditions

[1]Zain AL-Abideen A.sabar , [2]Salim Almaliki

[1,2] Department of Agricultural Machinery and Equipment, College of Agriculture, University of Basrah, Basrah, Iraq.

Email: pgs.zainalabdeen2sabbar@uobasrah.edu.iq
Email: Salim.bander@uobasrah.edu.iq

Abstract

Estimating the fuel consumption of the tractor when performing various agricultural operations helps improve the productivity of agricultural equipment, so the aim of this research is to design an electronic system to measure fuel consumption as well as evaluate energy requirements under different operating conditions. The field work included many experimental factors, represented by the use of two types of tractors, the first with four-wheel drive and the other with two-wheel drive. Different plowing depths (10, 15, 20, 25 cm) and different engine speeds (1200, 1500, 1800 rpm) were used, as this was applied with three forward speeds of the tractor (Gear1, Gear2, Gear3). The results showed that increasing the engine speed from 1200 to 1800 rpm led to an increase in quantitative fuel consumption (QFC) in each gear (G1, G2, G3) by (24%, 27%, 33%), respectively. Increasing the plowing depth from 10 to 30 cm leads to an increase in quantitative fuel consumption by (10%, 16%, 17%) for (G1, G2, G3), respectively. Increasing the engine speed from 1200 to 1800 rpm increased fuel consumption per unit plowed area (FCPA) by 28%, 11%, and 7%, while increasing the plowing depth from 10 to 30 cm increased fuel consumption by 33%, 21%, and 16% for G1, G2, G3 respectively. The results also showed that changing the type of drive from two-wheel drive to four-wheel drive increased QFC and FCPA by 5% and 25%. The validation of the models were satisfactory, and it demonstrated an accuracy of approximately 95% for predicting QFC rates and 97% for predicting FCPA.

Keyword: Quantitative fuel consumption, Fuel consumption per unit plowed area, 2WD, 4WD,

Introduction

Fuel consumption of agricultural vehicles is an essential factor for those working on the agricultural side to seek information about the maintenance and improvement of the use of agricultural vehicles. Fuel is the main energy source for most agricultural vehicles, including tractors, and provides the energy required to perform and propel the tractor to overcome pulling forces (1). Estimating the amount of fuel consumption of the tractor while performing various agricultural operations helps in choosing the best productivity of agricultural equipment. There are several methods and techniques for measuring the fuel consumption of the tractor. All methods have advantages and disadvantages that depend on the tractor, used equipment, and operating conditions (2). Fuel consumption is directly related to the power requirements of agricultural tasks and can be reduced by properly understanding how tractor power is distributed. An improvement in tractor performance will reduce the amount of fuel consumed for a given operation and thus lead to environmental and financial benefits. The ability to predict tractor performance during field operations is of great interest to scientists, manufacturers, and users in order to improve the overall operation of agricultural tractors (3). Predicting a tractor's fuel consumption can lead to more appropriate decisions about maintaining optimal tractor performance. The rate of fuel consumption during soil tillage operations varies greatly due to various factors that affect it, such as soil texture, soil moisture, type of tractor (two- or four-wheel drive), size of the tractor, and the machines used. (4) , (5). Therefore, fuel consumption is not constant and varies depending on operational conditions. Fuel consumption can be reduced through appropriate matching of factors affecting performance. Optimal operation of agricultural vehicles includes: (a) maximizing the fuel efficiency of the engine and the mechanical efficiency of the drive train; (b) Maximize the traction power of traction devices; and (c)

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choosing the optimal travel speed for the tractor and machine system (6). Therefore, performance modeling of tractors and agricultural machinery based on effective parameters is crucial for farmers as well as manufacturers due to increased attention on fuel conservation. Many studies have been developed to predict fuel consumption in various sections of agricultural operations that use power, such as traction, tillage equipment, and tire resistance, and the most important of them can be explained as follows: Researchers (7) designed a device to measure fuel consumption. An electronic circuit was used to process and store the digital pulses coming from the flow meter sensors. One of the sensors was installed where the fuel enters the injector pump, and another flow meter was placed where the fuel returns to the fuel tank. In another study conducted on the effect of various tractor factors on three fuel efficiency criteria (hourly fuel consumption, area-based fuel consumption, and specific volumetric fuel consumption), it was found that engine speed, transmission devices, and work load significantly affected fuel consumption (8). (9) conducted a study to measure fuel consumption and drag force during the plowing process. The collected data was used to create a model of the tractor's fuel consumption using dimensional analysis. The results of the regression analysis showed that the model is able to predict fuel consumption rates with high accuracy. (10) confirmed in a study that increasing the overall energy efficiency of agricultural pullers can have a positive effect in reducing fuel consumption. Engine speed and load are among the factors on which the fuel consumption of the puller greatly depends. (11) explained in a study to predict fuel consumption based on time, fuel consumption per unit area, and fuel consumption based on traction capacity through several inputs. The results showed the effect of the measured parameters on fuel consumption. The efficiency of the model in the study was excellent, and the accuracy in prediction reached about 95%.. (12) Developed a model to predict fuel consumption (TFC, AFC, SFC), where fuel consumption was greatly affected by the factors studied, which included plowing depth, soil moisture percentage, tire pressure, cone index, engine speed, and theoretical speed. (13) designed a device to measure fuel consumption using a secondary tank. The tank was installed and connected to the fuel tank in the tractor through pipes and two valves. (14) A study to predict fuel consumption by using different depths and different forward speeds of the tractor and calculating fuel efficiency and fuel consumption based on time and specific volumetric consumption. (15) also conducted an experiment to study the amount of fuel consumption (liters/ha) and the performance of the tractor under the influence of different depths and speeds. The results of the experiment showed that increasing the plowing depth from 15 to 20 cm led to an increase in energy requirements by 15%.. (16) worked on developing a program using the Visual Basic programming language to predict the performance of a group of agricultural tractors. A traditional farming system was used with a mounted plow and three meters to collect data from a four-wheel drive (4WD) type tractor. A system has been developed to measure, display and store various tractor performance parameters. The developed system consists of several available sensors and transducers. The developed system consists of a microcontroller to process the data received from the sensors. It was tested under various field operations and the results showed the reliability and accuracy of the system. (17). The aim of this research is to develop mathematical models to predict fuel consumption of agricultural tractors in two different modes (two-wheel drive and four-wheel drive) under different operating conditions. As well as designing a high-accuracy, low-cost fuel measuring system.

I. Materials and Methods

Tractors and equipment used in the experiment

Two tractors were used in the experiment, the first tractor (leader) is of type CASE JX75T and the second tractor (follower) is of type MASSEY FERGUSON 440 Xtra. A chisel plow with (7) tines distributed in two rows, four in the front row, and three in the rear row, mounted on the second tractor with a distance of 30 cm between each tine in the same row.

Transducers, sensors and data acquisition system

A load cell device of electronic type (Load Cell) in an S-shaped configuration was used as a pulling force gauge, connected between the leader and follower tractors. This responsive sensor is linked to a data collection system, according to (18). Additionally, the penetration depth of the plow tine was measured

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using ultrasonic wave electronic techniques through an Ultrasonic sensor. The distance is calculated using the time of reflection (round trip time of the wave), and calculated using Equation (1). The distance between the sensor and the soil surface is determined using Equation (2), as mentioned by (19).

(The measured distance (md) = (T * V) / 2 (1)

Where:

T: Time interval between the transmitted and received wave

V: Speed of sound (340 m/s)

To find the tillage depth, the following equation is used:

Tillage depth = DF - DT (2)

Where:

Tillage depth: Depth of tillage (cm)

DF: Distance measured on a level paved ground (cm)

DT: Distance measured in the field during plowing (cm)

The theoretical speed of the tractor was measured using the fifth wheel technique and an Encoder Sensor. The wheel is attached to the first tractor, and the Encoder sensor is connected to the data collection unit. This technique consists of a wheel with a circumference of 1250 mm, freely movable, and two gears, the first containing 21 teeth and the second containing 8 teeth. The Encoder sensor generates 360 pulses per revolution for the sensor axis. The large gear is installed at the center of the wheel axis, while the small gear is installed on the sensor axis. The working principle of the Encoder Sensor is to generate 360 pulses per cycle, so the total pulses will be (2.625 × 360) equals 945 pulses per cycle for the wheel. Dividing the distance covered by the wheel per cycle, which represents the circumference of the wheel (1250 mm), by the number of pulses (945), gives 1.32 mm per pulse (20); (21) ;(22). The practical speed of the tractor was measured using the same fifth wheel technique employed in measuring the theoretical speed, but applied in the field at the moment the experiment begins, with the tractor loaded.

A fuel consumption measuring system was designed and manufactured electronically, consisting of a small tank, a fuel filter for purification, pipes, and two Flow meter sensors with a precision of measuring discharges (0.25 - 0.1) liters/minute. The first sensor is used to calculate the amount of fuel entering from the system tank to the fuel pump belonging to the first tractor (CASE JX75T), and another sensor with the same specifications is connected between the return fuel pipe (fuel returning from the fuel pump and injectors) and the system tank.

The working principle of the sensor is when the fuel passes from the system tank towards the fuel pump through the pipes, it is calculated through pulses processed by the data processor (Arduino) for each pulse. Similarly, the second sensor measures the amount of fuel returning from the fuel pump and injectors towards the system tank. The difference between the incoming and outgoing fuel quantities represents the consumed fuel quantity calculated by the data processor as shown in the diagram in Figure (1).

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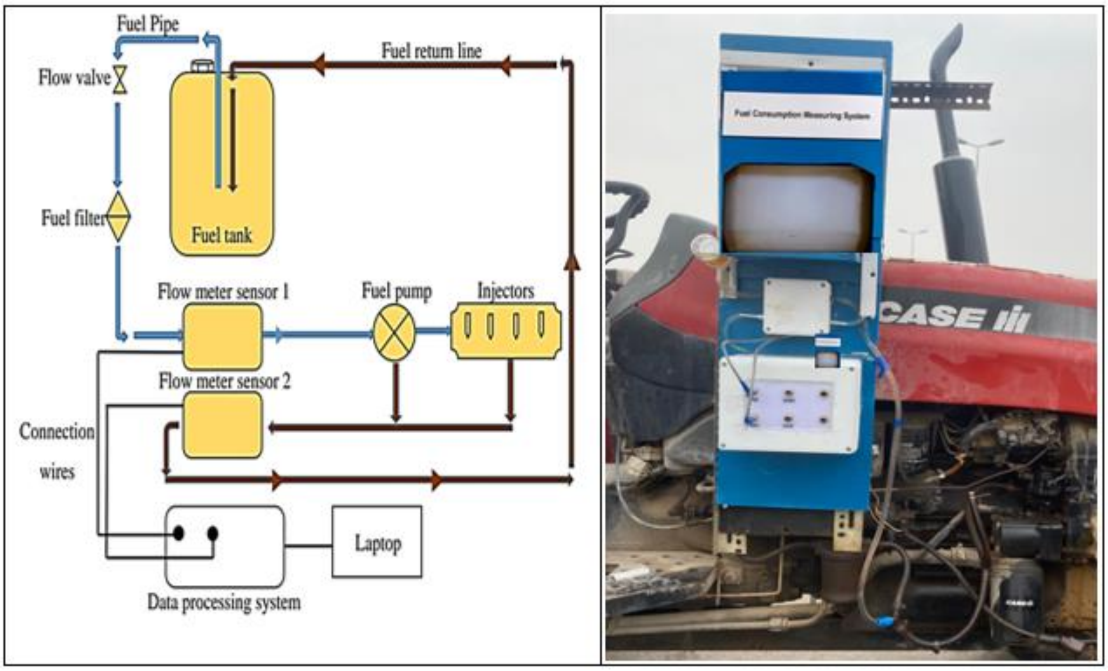

Figure (1) diagram of the fuel consumption measuring system

The fuel consumption for the tractor has been calculated based on two criteria:

1- Quantitative fuel consumption (QFC): This is the amount of fuel consumed during a certain period of time, according to Equation (4).

QFC = FC / T (3)

Where:

FC: Fuel consumed (L)

T: Time taken (hr)

2 . Fuel consumption based on plowed area (FCPA): This is the amount of fuel consumed (in liters) to plow one hectare, calculated using Equation (5.(

FCPA = (10 * QFC) / (Va * w) (4)

Where:

FCPA: Fuel consumption based on plowed area (L/ha)

Va: Actual speed (m/sec)

W: Operating width of plow (m)

Results and Discussion

The Design Expert Software version (8.0.6.1) was utilized, which statistically analyzes the data to determine its significance. Additionally, it provides an ANOVA TABLE, graphs the relationships between research inputs and outputs, and furnishes predictive equations for each research output.

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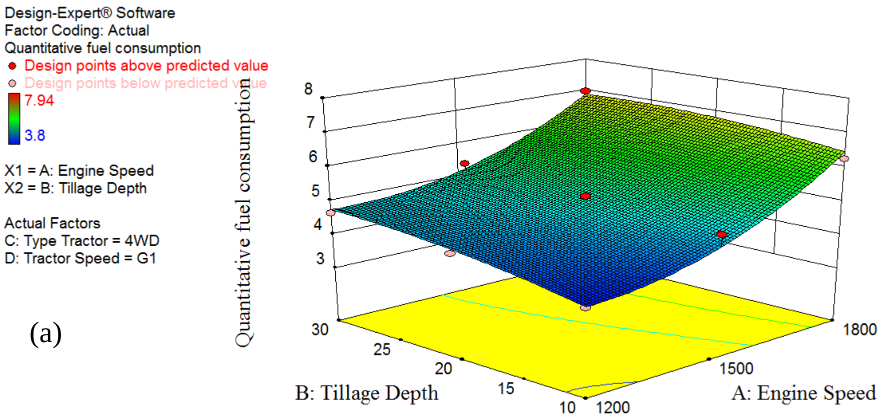
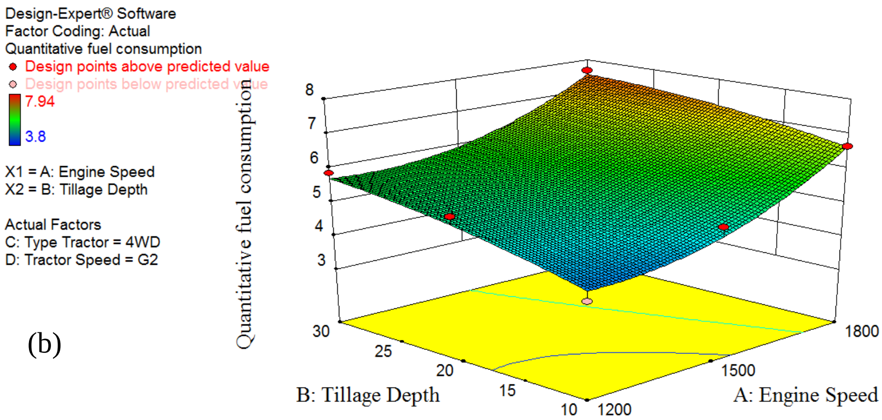
Quantitative fuel consumption (QFC)

Figure (2, A-C) shows the effect of engine speed, plowing depth, and their intersection on quantitative fuel consumption in a four-wheel drive (4WD) tractor for a different forward speed in each gear (G1, G2, G3), respectively. The results showed that increasing engine speed leads to an increase in quantitative fuel consumption. For example, increasing the engine speed from 1200 to 1800 rpm increased the quantitative fuel consumption in each gear (G1, G2, G3) by (24%, 27%, 33%) respectively. This is because the amount of air entering the engine is not sufficient to burn fuel due to the short duration of the intake stroke. Moreover, quantitative fuel consumption increases when the engine is heavily loaded to provide additional power and overcome overload. However, sometimes the engine speed decreases due to this load, which requires increasing the amount of fuel supplied to the engine to keep its speed relatively constant, which is consistent with findings (23).

The results indicate that increasing plowing depth leads to increased fuel consumption. For example, increasing the plowing depth from 10 to 30 cm leads to an increase in quantitative fuel consumption by (10%, 16%, 17%) for (G1, G2, G3), respectively. This is because deep plowing requires a higher traction force, which in turn imposes a load on the engine, causing its speed to decrease. To maintain the engine speed, the amount of fuel supplied to it must be increased to maintain its speed constant. In addition, increasing plowing depth leads to a decrease in the forward speed of the tractor due to increased tire slippage, which in turn increases the time required to cover the distance, resulting in higher fuel consumption. This is consistent with my findings (Sven, 2019). The results also showed that the highest fuel consumption values occur at the intersection between engine speed (1800 rpm) and plowing depth (30 cm), reaching (5.7, 6.5, 5.6) liters per hour in (G1, G2, G3) respectively. The lowest fuel consumption values were obtained at an engine speed of 1200 rpm and a plowing depth of 10 cm.



(a)



(b)

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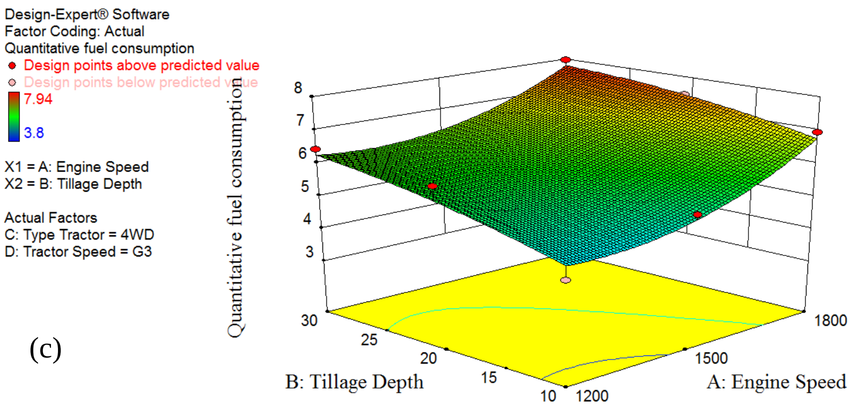

Figure (2 a, b, c) The impact of engine speed, plowing depth, and their intersection on quantitative fuel consumption in a four-wheel drive (4WD) tractor for each gear (G1, G2, and G3).

Figure (3) shows the effect of tractor type and forward speed on quantitative fuel consumption. The results indicate that increasing forward speed leads to increased fuel consumption. For example, when the forward speed was increased from G1 to G3, there was a 16% increase in fuel consumption when the tractor was 2WD, and an 18% increase when it was 4WD. This is because the power requirements of four-wheel drive tractors are higher compared to two-wheel drive, and this is due to the transfer of power to the front and rear wheels in four-wheel drive tractors. Furthermore, changing the drive type from 2WD to 4WD increased fuel consumption, with a 3% increase at G1 and a 5% increase at G3. The increase in fuel consumption is because increasing forward speed requires high power and relatively high engine torque to improve performance.

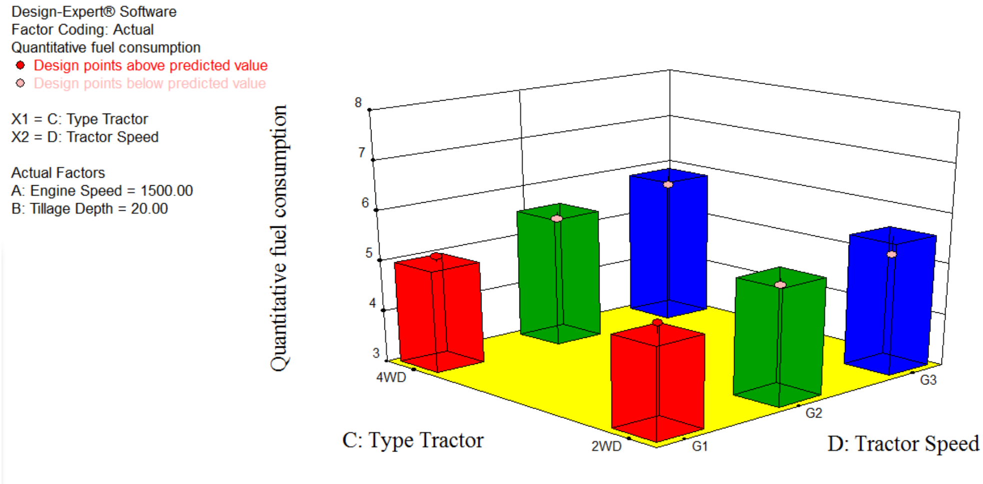

Figure (3) illustrates the impact of tractor type and forward speed on quantitative fuel consumption.

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Figure (4) illustrates the predicted values for quantitative fuel consumption by incorporating all studied factors, including tractor type, engine speed, plowing depth, and forward speed. This relationship was represented by the final equation with the best performance, with a determination coefficient (R^2) of 0.9516, indicating the quality performance of the model.

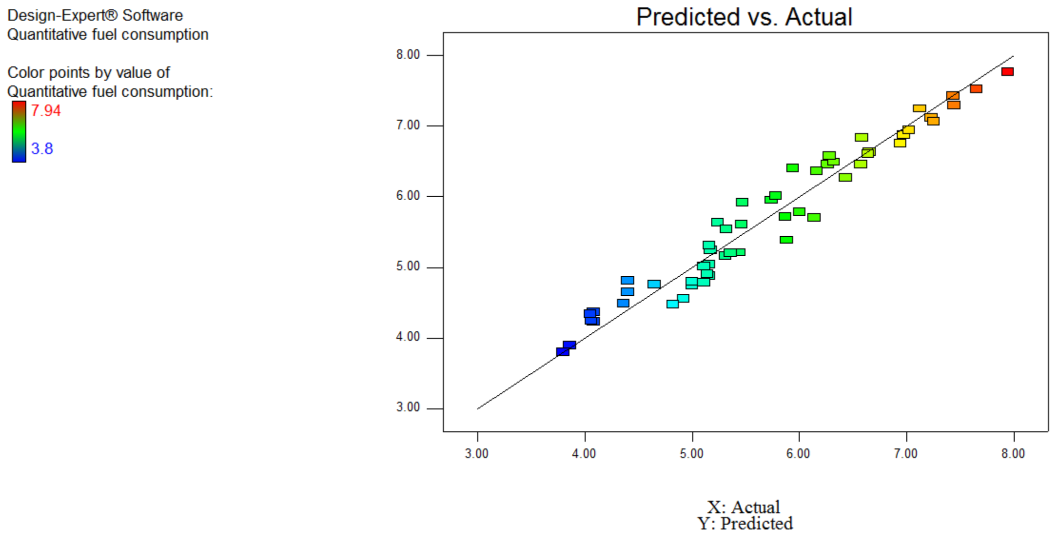

Figure (4) The relationship between real and predicted values of quantitative fuel consumption

Table 1. The final equations in terms of actual factors for predicting quantitative fuel consumption

Tractor speed (Gear)	Two Wheel Drive (2WD)	Four Wheel Drive (4WD)
Gear 1	**QFC =** +12.21117 - (0.015853 * Engine Speed) + (0.13889 * Tillage Depth) - (3.75278E-005 * Engine Speed * Tillage Depth) + (6.83519E-006 * Engine Speed2) – (1.66833E-003 * Tillage Depth2)	**QFC** = +12.14083 - (0.015857 * Engine Speed) + (0.15532 * Tillage Depth) –(3.75278E-005 * Engine Speed * Tillage Depth) +(6.83519E-006* Engine Speed2) -(1.66833E-003* Tillage Depth2)

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Gear 2	**QFC =** +13.00206 - (0.016356 * Engine Speed) + (0.16271 * Tillage Depth) - (3.75278E-005 * Engine Speed * Tillage Depth) + (6.83519E-006 * Engine Speed2) - (1.66833E-003 * Tillage Depth2)	**QFC**=+12.98572 - (0.016360 * Engine Speed) + (0.17914 * Tillage Depth) – (3.75278E-005* Engine Speed * Tillage Depth) + (6.83519E-006* Engine Speed2) - (1.66833E-003* Tillage Depth2)
Gear 3	**QFC** = +13.99200 - (0.016872 * Engine Speed) + (0.16831 * Tillage Depth) - (3.75278E-005 * Engine Speed * Tillage Depth)+ (6.83519E-006 * Engine Speed2) - (1.66833E-003 * Tillage Depth2)	**QFC =** +13.98722 - (0.016876 * Engine Speed) + (0.18474 * Tillage Depth) – (3.75278E-005 * Engine Speed * Tillage Depth) + (6.83519E-006 * Engine Speed2) – (1.66833E-003* Tillage Depth2)

Fuel consumption based on plowed area (FCPA)

Through studying the impact of both engine speed and tillage depth, as well as their interaction, on fuel consumption per unit area in the four-wheel-drive (4WD) tractor mode and tractor speed at each gear (G1, G2, G3) respectively, it observe from Figures (5a-c) that increasing the engine speed leads to increased fuel consumption. For instance, increasing the engine speed from 1200 to 1800 RPM resulted in a fuel consumption increase of 7%, 11%, and 28% in G3, G2, and G1, respectively. This is due to the increase in rotational power requirements with increasing engine speed. The results also indicated that increasing the forward speed led to a decrease in the amount of fuel consumed per hectare within the limits of acceptable slippage (less than 20%). The reason for this is that the plowing process is completed in the shortest time. The results indicated that increasing the tillage depth leads to an increase in fuel consumption. For example, increasing the tillage depth from 10 to 30 cm resulted in a fuel consumption increase of, 33%, and 21% 16% for each of G1, G2, and G3, respectively. This increase is attributed to the increase in pulling force of the machine with depth, leading to increased tire slippage, which in turn reduces the forward speed of the tractor, causing a decrease in the area of tilled soil per unit time, consequently leading to an increase in the consumed fuel quantity. The results indicate that the highest fuel consumption occurs when there is an intersection between the engine speed (1800 RPM) and the plowing depth (30 cm), reaching (44, 31, 21) liters per hectare in G1, G2, and G3 respectively. The lowest fuel consumption was obtained at an engine speed of 1200 RPM and a plowing depth of 10 cm.

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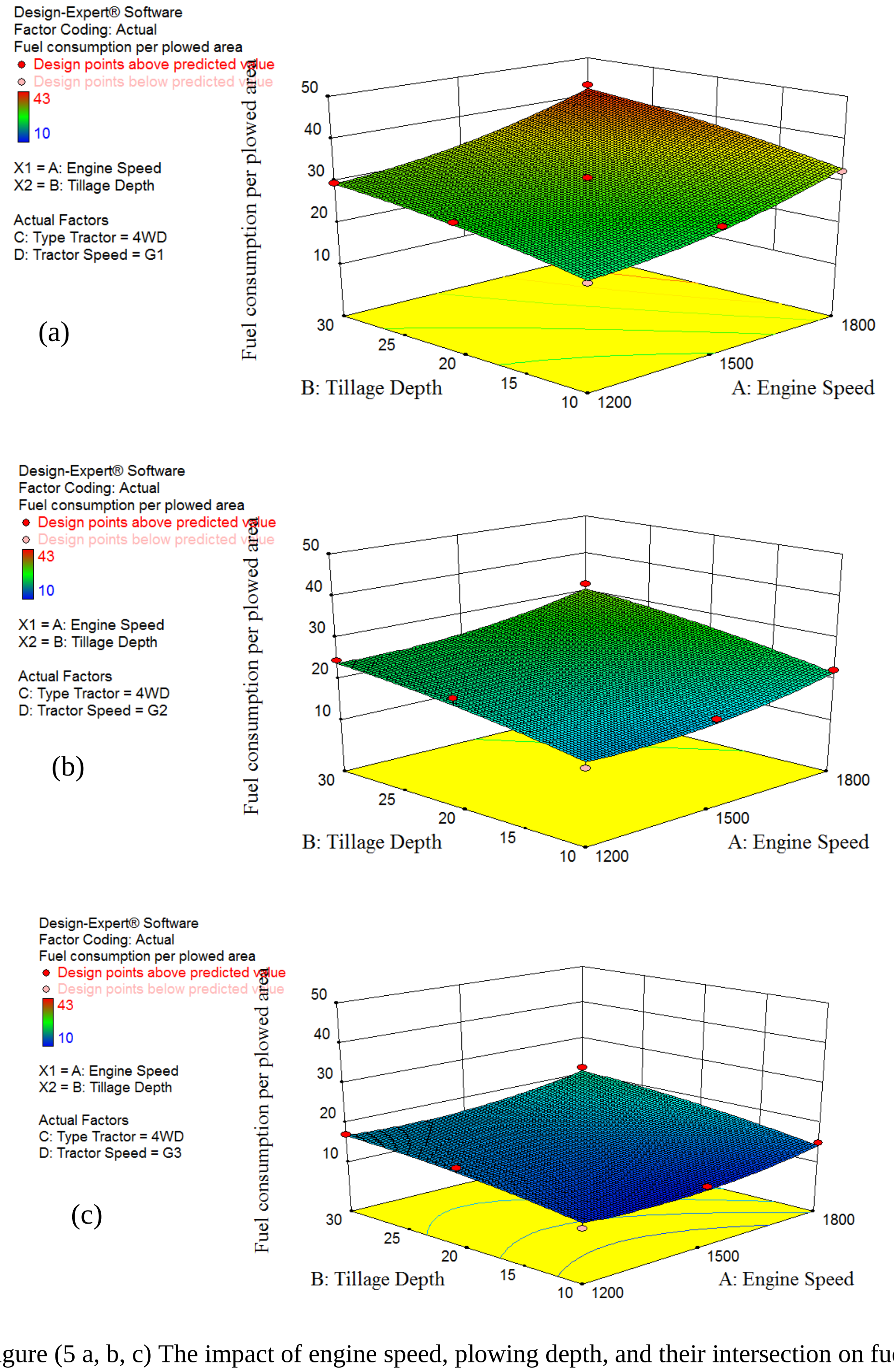

Figure (5 a, b, c) The impact of engine speed, plowing depth, and their intersection on fuel consumption per unit area in a four-wheel drive (4WD) tractor for each gear (G1, G2, and G3).

Figure (6) illustrates the effect of tractor type and forward speed on fuel consumption per unit area. The results indicate that increasing the forward speed leads to a decrease in fuel consumption. When increasing the forward speed from G1 to G3 in a 4WD tractor, fuel consumption decreased by 83%. Similarly, increasing the speed from G1 to G3 in a 2WD tractor resulted in a fuel consumption decrease

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of 86%. This is because the increase in forward speed reduces the time and effort required to perform the work, thus reducing fuel consumption per unit area. The results also show that changing the drive type from 2WD to 4WD increases fuel consumption, with a 2.5% increase at speed G1. Changing the drive type from 2WD to 4WD at speed G3 results in a 25% increase in fuel consumption. The increase in fuel consumption is due to the increased power requirements for operation in 4WD compared to 2WD.

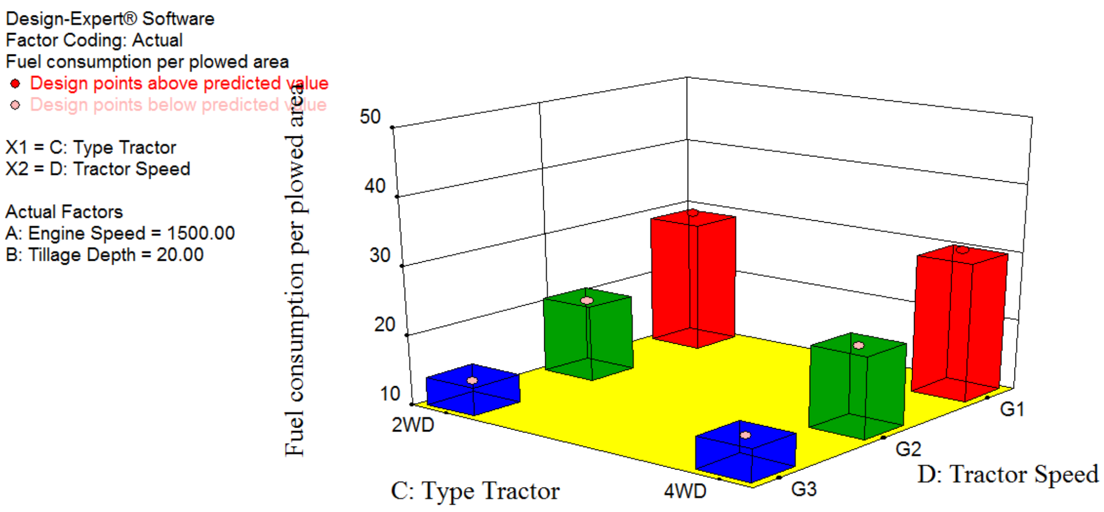

Figure (6) depicts the impact of tractor type and forward speed on fuel consumption per unit area.

Figure (7) illustrates the predicted values for fuel consumption per unit area by incorporating all studied factors, including tractor type, engine speed, plowing depth, and forward speed. It observe from the figure that the predicted values are very close to the actual values along the regression line, with a determination coefficient (R^2) of 0.9712 indicating the quality performance of the model.

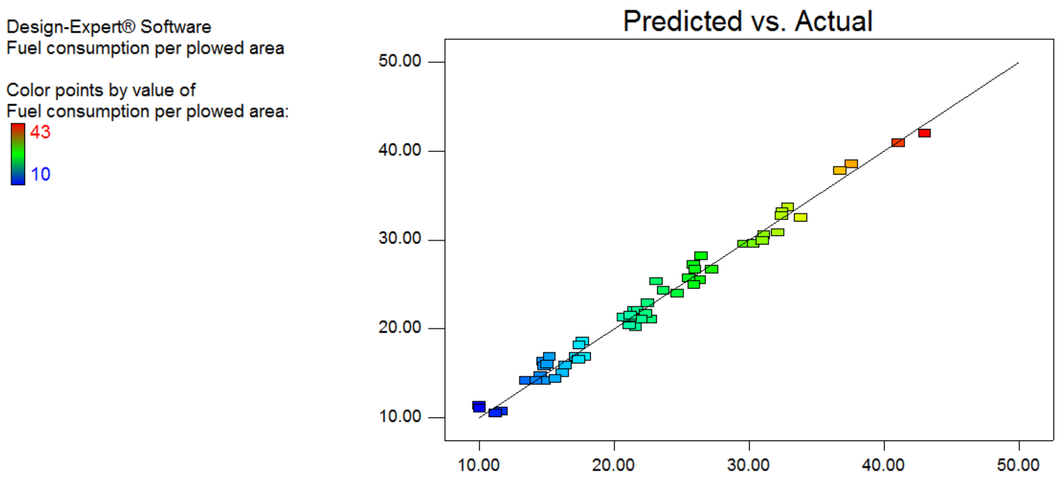

Figure (7) shows the relationship between actual and predicted values for fuel consumption per unit area.

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Table 2. The final equations in terms of actual factors for predicting fuel consumption based on the plowed soil area

Tractor speed (Gear)	Two Wheel Drive (2WD)	Four Wheel Drive (4WD)
Gear 1	**FCPA** =+44.01153-(0.052016* Engine Speed)+ (0.57040* Tillage Depth)+(1.16558E-004 * Engine Speed * Tillage Depth)+ (2.32866E-005* Engine Speed2)-(9.20546E-003 * Tillage Depth2)	**FCPA** =+45.03970-(0.052520* Engine Speed)+ (0.60214* Tillage Depth)+(1.16558E-004* Engine Speed * Tillage Depth)+ (2.32866E-005* Engine Speed2)-(9.20546E-003* Tillage Depth2
Gear 2	**FCPA** =+49.67670 -(0.061505 * Engine Speed)+ (0.58403* Tillage Depth)+(1.16558E-004* Engine Speed * Tillage Depth)+ (2.32866E-005* Engine Speed2)-(9.20546E-003 * Tillage Depth2)	**FCPA** = +50.49583-(0.062010* Engine Speed)+ (0.61577* Tillage Depth)+(1.16558E-004* Engine Speed * Tillage Depth)+ (2.32866E-005 * Engine Speed2)-(9.20546E-003 * Tillage Depth2)
Gear 3	**FCPA** =+51.35741-(0.065855* Engine Speed)+ (0.46900* Tillage Depth)+(1.16558E-004* Engine Speed * Tillage Depth)+ (2.32866E-005* Engine Speed2)-(9.20546E-003* Tillage Depth2)	**FCPA** =+51.99863-(0.066360* Engine Speed)+ (0.50074* Tillage Depth)+(1.16558E-004* Engine Speed * Tillage Depth)+ (2.32866E-005* Engine Speed2)-(9.20546E-003* Tillage Depth2**)**

II. Conclusion

In this research, fuel consumption was evaluated according to different criteria (QFC and FCPA) under different operating conditions, as well as an electronic system was designed to measure fuel consumption. For this purpose, the tractor was used in two modes (two-wheel drive, four-wheel drive). The results showed that increasing engine speed, plowing depth, and forward speed (gear 1, gear 2, and gear 3) led to an increase in quantitative fuel consumption (QFC). The results also indicated that increasing engine speed and tillage depth led to an increase in fuel consumption per unit plowed area (FCPA), while there was an inverse relationship between forward speed and FCPA. The results also showed that changing the type of driving has an effect on QFC and FCPA. Fuel consumption (QFC and FCPA) was lower in two-wheel drive tractors than four-wheel drive tractors. The results indicated that the predicted values for both fuel consumption based on unit area and quantitative fuel consumption, by introducing all the factors under study, the predicted values are very close to the actual values along the regression line, and this indicates the quality of the model's performance. New equations were formulated to predict the relationship between the research variables and outcomes for both types of tractors (2WD and 4WD).

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