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Modeling and Prediction of Power Loss in Agricultural Tractors Using Response Surface Methodology (RSM): A Study on the Effects of Drive Type, Tillage Depth, and Operational Speeds

Baneen Abdulhakeem Mohammed   Salim Almaliki

Department of Agricultural Machinery and Equipment, College of Agriculture, University of Basrah, Basrah, Iraq.

Email: baneen.abd@uobasrah.edu.iq

Email: Salim.bander@uobasrah.edu.iq

I. Abstract

This research aims to develop a predictive model for power loss in agricultural tractors resulting from slippage and rolling resistance, utilizing Response Surface Methodology (RSM). Field experiments were conducted using two tractors with different drive systems (two-wheel drive, 2WD, and four-wheel drive, 4WD), equipped with a three-furrow plough. Tests were performed under varying operational conditions, including tillage depth (10, 15, 20, 25 cm), forward speed (1.90-5.35 km/h), and engine speed (1250, 1500, 1750 rpm). Drawbar pull was measured using an electronic load cell, while theoretical and actual speeds were determined employing a fifth-wheel technique and encoder sensors. The results demonstrated a strong positive correlation between increases in tillage depth, forward speed, and engine speed, and the rise in power loss. Forward speed exhibited the greatest influence (325%), followed by tillage depth (183.3%), and then engine speed (12.1%). The four-wheel drive (4WD) tractor consistently showed higher efficiency and lower power loss compared to the two-wheel drive (2WD) tractor across all tested conditions. A mathematical predictive model was developed using Design-Expert software, achieving a high coefficient of determination (R^2 = 0.9801), which confirms its accuracy in estimating power loss based on the studied operational variables. This model provides a practical tool for engineers and operators to optimize the adjustment of operational parameters, thereby contributing to fuel economy and enhanced energy efficiency in agricultural operations.

Keyword : Operational speed, 2WD, 4WD, Engine speed,

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II. Introduction

Power constitutes the central indicator in evaluating the operational efficiency of agricultural machinery, as it represents the energy variable capable of accomplishing agricultural work within a specific time frame. The power produced by the agricultural tractor engine undergoes gradual loss during its transmission to the point of actual utilization, known as 'power loss,' which is attributed to the interaction of combined mechanical, operational, and environmental factors. The primary function of the tractor is to generate self-propulsion and operate attached implements. During its interaction with the soil, three modes of power loss occur: loss in the transmission system, loss due to motion resistance, and loss caused by wheel slippage. While human influence on the first mode remains limited, control over the other two factors is possible through the adjustment of operational parameters. Previous research indicates that 20-55% of engine power can be lost as a result of the interaction between tires and the soil surface layer, due to the phenomena of slippage and rolling resistance (1, 2, and 3). It is noted that the traction characteristics of agricultural tires are highly sensitive, with drawbar efficiency reaching a theoretical maximum of approximately 75%. This confirms that the minimum power loss is no less than 25%, even under optimal conditions—a percentage that increases in real-world field contexts (4). Power loss has direct economic and environmental consequences, as it is closely linked to fuel consumption and, consequently, greenhouse gas emissions (Herman, 2014). This underscores the need for practical strategies to rationalize energy consumption in agricultural operations. Among the most prominent adjustable parameters affecting the performance of drive wheels are: the vertical load on the wheel, tire inflation pressure, and slippage rate. The optimal adjustment of these inputs plays a crucial role in tillage operations to reduce the energy loss associated with slippage, which positively reflects on fuel consumption and operational time (6, 7). The combined effect of soil physical properties and tire specifications on rolling resistance and energy dissipation has also been demonstrated (8).

Study (3) investigated energy dissipation due to motion resistance as a key performance indicator for towed wheels, and developed a model for predicting energy loss in soil-working implements using datasets obtained from a soil bin facility and single-wheel tester. Energy use efficiency in the soil-wheel interaction was analyzed at a soil bin testing facility. The input parameters included: speed, tire inflation pressure, and wheel load. This was achieved by integrating the capabilities of the non-parametric DEA (Data Envelopment Analysis) technique and a hybrid statistical-mathematical modeling methodology, RSM (Response Surface Methodology) (9). In the context of improving operational efficiency, a study (10) analyzed tractor traction efficiency and evaluated power loss under the influence of two operating strategies (maximum power utilization vs. power optimization via gear change followed by fuel reduction) and different speed levels. The results demonstrated the superiority of the power optimization strategy, which achieved a fuel consumption reduction of 22.43%, highlighting the potential for improvement through operating system management. Another study (11) confirmed a direct proportional relationship between tillage depth (in the 11-23 cm range) and the overall power transmission efficiency (from 66% to 95%), accompanied by a concurrent decrease in power loss through the transmission system, especially in the rear axle.

Recent research is moving towards developing intelligent transmission systems for tractors, such as those supported by speed prediction technologies to improve energy consumption in hybrid vehicles (12), or the use of evolutionary algorithms like ICA, which achieved a 29% energy saving in soil leveling operations compared to traditional methods (13). These developments also contribute to paving the way for designing advanced tractors capable of reducing power loss in variable field environments (14).

This research aims to develop a predictive model for power loss in agricultural tractors using the Response Surface Methodology (RSM), under different operational conditions including drive system (2WD/4WD), tillage depth, engine speed, and forward speed. The goal is to provide a model that contributes to improving the energy efficiency of agricultural operations.

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III.Materials and Methods

Equipment and Tractors Used in the Experiment

Two tractors were utilized in this study:

- Tractor 1 (Lead Tractor): A CASE JX75T model.
- Tractor 2 (Implement Tractor / Control): A MASSEY FERGUSON 440 Xtra model.

A three-furrow reversible moldboard plow was mounted on the second tractor (MASSEY FERGUSON) to carry out plowing operations during the experiment.

Data Acquisition and Processing System

To measure the draft force between the two tractors, an electronic load cell with an S-shaped design was employed. It was installed in the mechanical linkage connecting the lead tractor and the following tractor. The load cell was connected to a data acquisition system to record readings, following the methodology outlined in reference (15).

The distance between the tractor and the soil surface was measured using an ultrasonic sensor operating on the time-of-flight principle. The distance (md) is calculated based on the time (T) taken for the transmitted ultrasonic wave to be reflected and received back, using the relationship:

Md = (T*V)/2 (1)

where (V) represents the speed of sound in air (340 m/s).

To determine the plowing depth, a differential measurement approach was used. This involved first measuring the reference distance (DF) on a paved, level surface, and then measuring the distance (DT) during the actual plowing operation in the field, according to the equation:

Plowing Depth = DF – DT (2)

For measuring the theoretical speed of the tractor, a "fifth-wheel" methodology equipped with an encoder sensor was utilized. A measuring wheel with a circumference of 1250 mm was mounted on the lead tractor and connected to the data acquisition unit. The system consists of two gears: a main gear (21 teeth) fixed at the center of the wheel's axle, and a secondary gear (8 teeth) mounted on the sensor's shaft. The encoder generates 360 pulses per full revolution of its shaft. Through the gear ratio between the two gears, 945 pulses are generated per full revolution of the measuring wheel (2.625 × 360). This allows for calculating linear displacement with an accuracy of 1.32 mm per pulse, by dividing the wheel's circumference (1250 mm) by the total number of pulses (945 pulses/revolution), as detailed in reference (16).

The measurement of the practical (actual) tractor speed was conducted using the same "fifth-wheel" system, but applied under real operational conditions in the field at the start of the experiment, with the tractor under full load during the plowing operation.

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Experimental Procedure

The study was conducted using a Full Factorial Experimental Design to evaluate the effect of four key independent variables on the response variables:

1. **Tractor Drive System:** At two levels: Two-Wheel Drive (2WD) and Four-Wheel Drive (4WD).
2. **Plowing Depth:** At four levels: 10, 15, 20, and 25 cm.
3. **Engine Speed:** At three levels: 1250, 1500, and 1750 revolutions per minute (RPM).
4. **Forward Gear (Ground Speed):** At three levels: First Gear (G1), Second Gear (G2), and Third Gear (G3).

The combination of the four factor levels resulted in 72 main experimental treatments (2 × 4 × 3 × 3). To enhance statistical reliability, each treatment was replicated three times, bringing the total number of experimental runs or plots to 216 (72 treatments × 3 replications).

These 216 experimental units were randomly distributed across three field blocks to minimize the effect of spatial variability. The length of each experimental run (plot) was set at 20 meters, with adequate spacing allocated between replications to ensure the independence of each trial and prevent interference.

Calculation of Power Loss Due to Slippage and Rolling Resistance

The power dissipated (lost) due to wheel slippage and rolling resistance phenomena was estimated using Equation (3):

$$PL = Pd - PF \qquad (3)$$

Where:
PL: Power Loss in kilowatts (kW).

Pd: Power available at the wheels (Wheel Power) in kilowatts (kW).
PF: Useful drawbar power (Drawbar Power) in kilowatts (kW).

The power available at the wheels (Pd) was calculated based on Equation (4):

$$Pd = (F + R) \times Vt \qquad (4)$$

Where:
F: Drawbar Pull in kilo newtons (kN).

R: Rolling Resistance force in kilo newtons (kN).

Vt: Theoretical tractor velocity in meters per second (m/s).

As for the useful drawbar power (PF), it was calculated from the drawbar pull and actual (practical) velocity data recorded by the data acquisition system, using the relationship (5):

$$PF = F \times Va \qquad (5)$$

Where:
Va: Actual tractor velocity in meters per second (m/s).

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Results and Discussion

Figure (1) illustrates the effect of plowing depth on power loss. The results demonstrate a direct proportional relationship between increased plowing depth and higher power loss values. Increasing the depth from 10 cm to 25 cm led to a 183.3% rise in power loss. This is attributed to several factors, including: the increased total soil mass being moved, the higher slip rate, and the consequent increased load on the engine and transmission system. These findings are consistent with the observations reported in study (11).

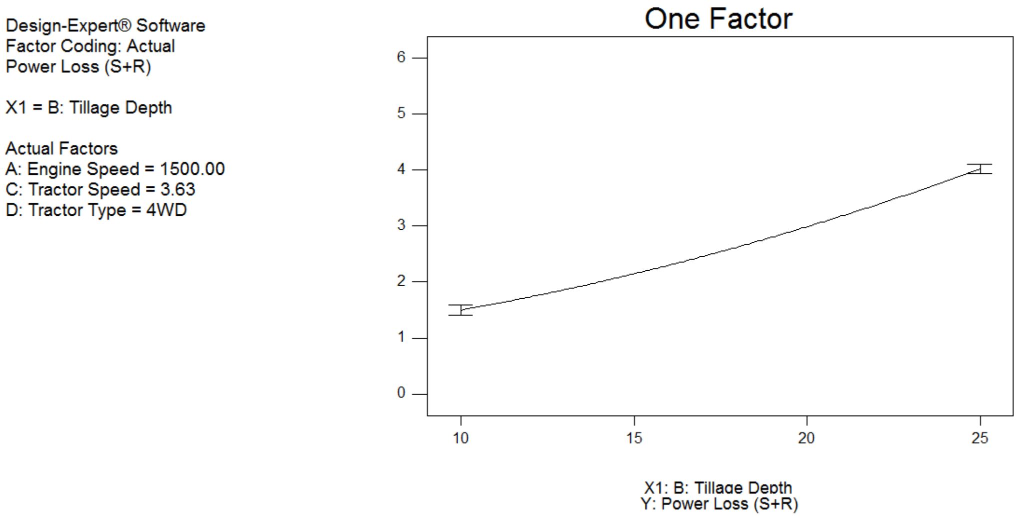

Figure 1. The relationship between plowing depth and power loss.

Figure (2) illustrates the impact of forward speed on power loss. The results reveal a direct proportional relationship between forward speed and power loss, where increasing the speed from 1.90 to 5.35 km/h led to a 325% rise in power loss. This increase is attributed to the fact that higher forward speeds result in greater traction resistance, coupled with a decrease in engine operational efficiency, leading to the dissipation of a larger portion of the generated power. These findings align with those reported in study (10).

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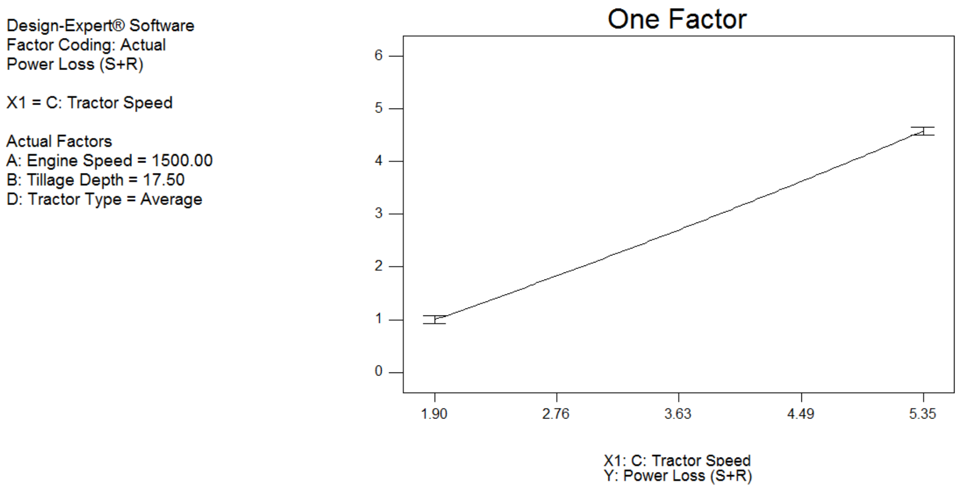

Figure 2. The relationship between forward speed and power loss.

Figure (3) illustrates the effect of engine speed on power loss. The results demonstrate a direct proportional relationship between increased engine speed and power loss, where raising the speed from 1250 to 1750 revolutions per minute (rpm) led to an approximate 12.1% increase in the power loss percentage. This rise is attributed to the fact that higher engine speeds result in increased forward speed, which in turn elevates traction resistance and slippage, negatively impacting the overall engine efficiency. Additionally, this increase amplifies the losses caused by internal friction and motion resistance, thereby raising the magnitude of power loss. These findings are consistent with the observations reported in study (9).

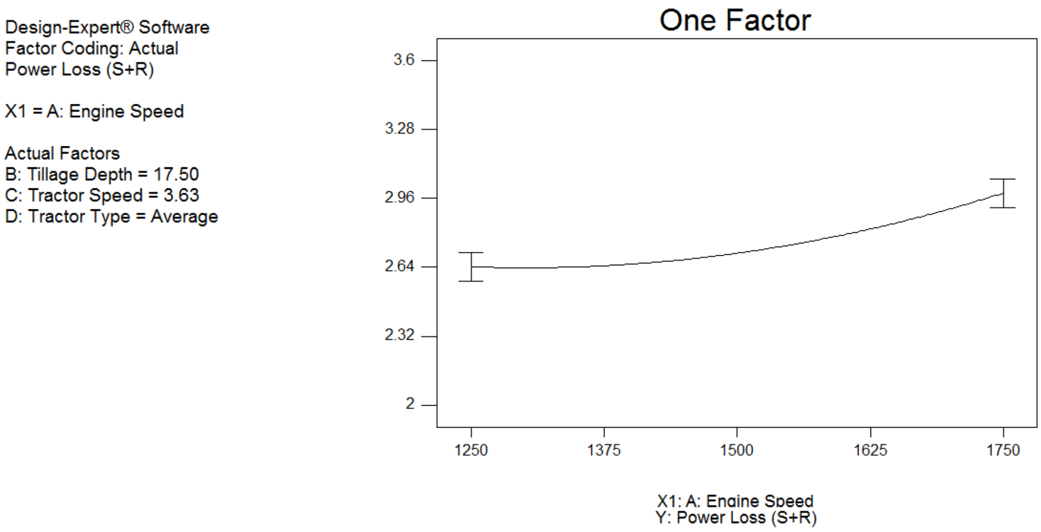

Figure 3. The influence of engine speed on power loss.

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Figure (4) illustrates the influence of tractor type on power loss. The results show that the four-wheel drive (4WD) tractor achieved the lowest power loss, reaching (2.5) kilowatts, while the rear-wheel drive (2WD) tractor recorded the highest loss value, which was (2.8) kilowatts. This is attributed to the reduced slippage in four-wheel drive tractors, as well as their more efficient utilization of the available engine power, which enhances overall efficiency and reduces power loss.

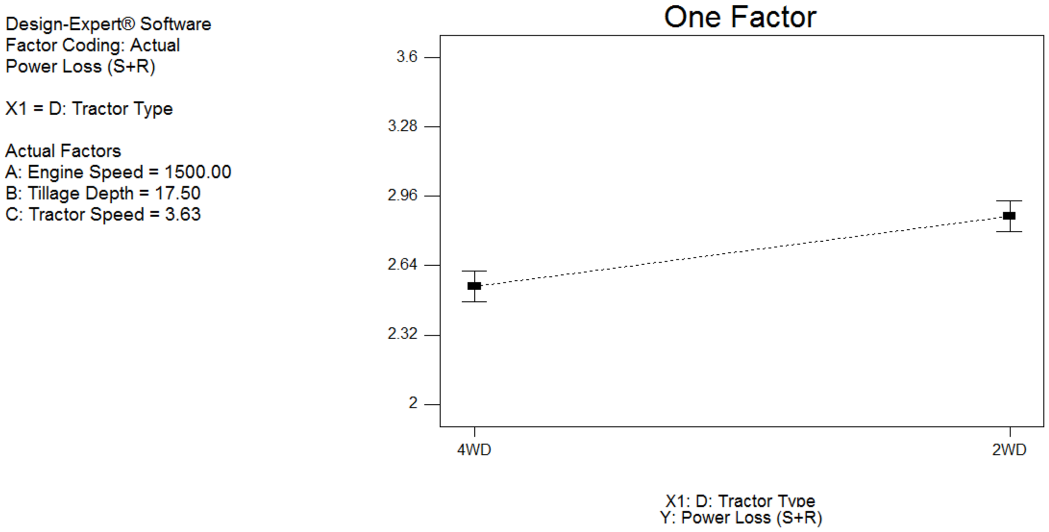

Figure 4. Influence of tractor drive system (2WD vs. 4WD) on power loss.

Figure (5) illustrates the effect of the relationship between engine speed and tillage depth, and their combined impact on power loss. The results showed that the lowest level of power loss was approximately 1 kilowatt, under operating conditions consisting of an engine speed of 1250 RPM and a tillage depth of 10 cm. Conversely, the highest level of power loss was recorded at around 6 kilowatts, at an engine speed of 1750 RPM and a tillage depth of 25 cm.

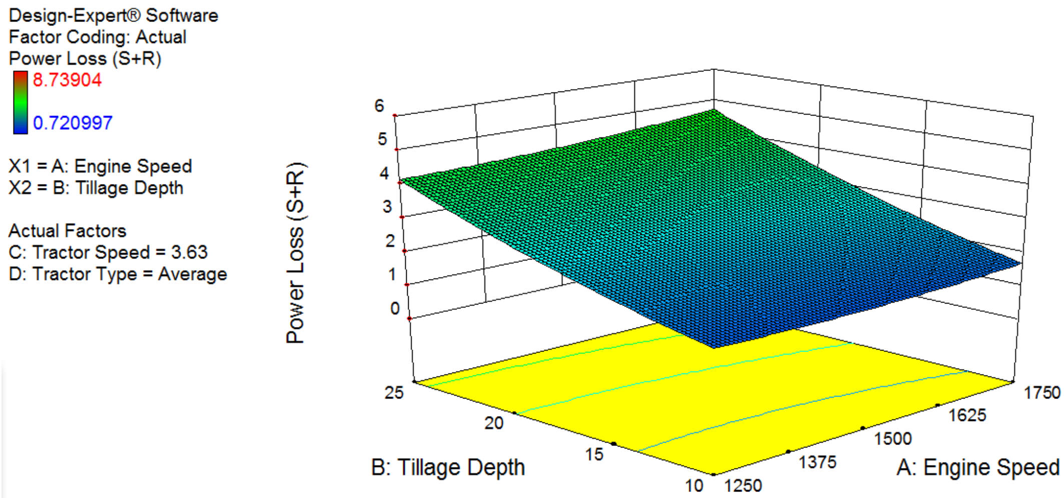

Figure 5. Combined effect of engine speed and tillage depth on power dissipation.

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Figure (6) illustrates the effect of tillage depth and tractor forward speed, as well as their interaction, on power loss. The results showed that the lowest recorded power loss value was 0.73 kilowatts, achieved under operating conditions of a tillage depth of 10 cm and a low forward speed of 1.90 km/h. Conversely, power loss peaked at 8 kilowatts when using a tillage depth of 25 cm with the highest forward speed of 5.35 km/h.

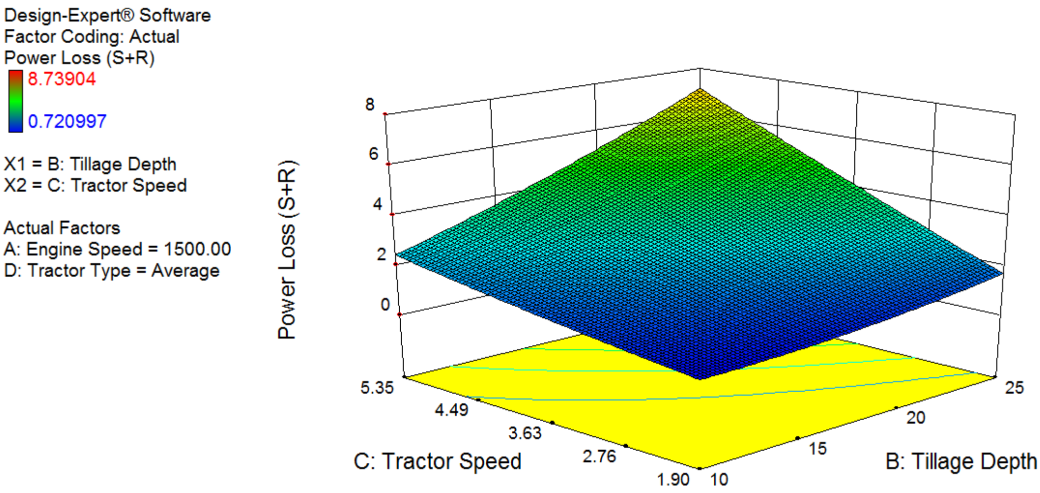

Figure 6. Combined influence of tillage depth and forward speed on power dissipation.

Figure (7) illustrates the effect of the relationship between engine speed and tractor forward speed, and their interaction, on power loss. The results showed that the minimum power loss was 1.90 kilowatts when operating the engine at 1250 RPM with a tractor forward speed of 1.90 km/h. In contrast, the maximum power loss was recorded at 6.00 kilowatts when the engine speed increased to 1750 RPM combined with a high tractor forward speed of 5.35 km/h.

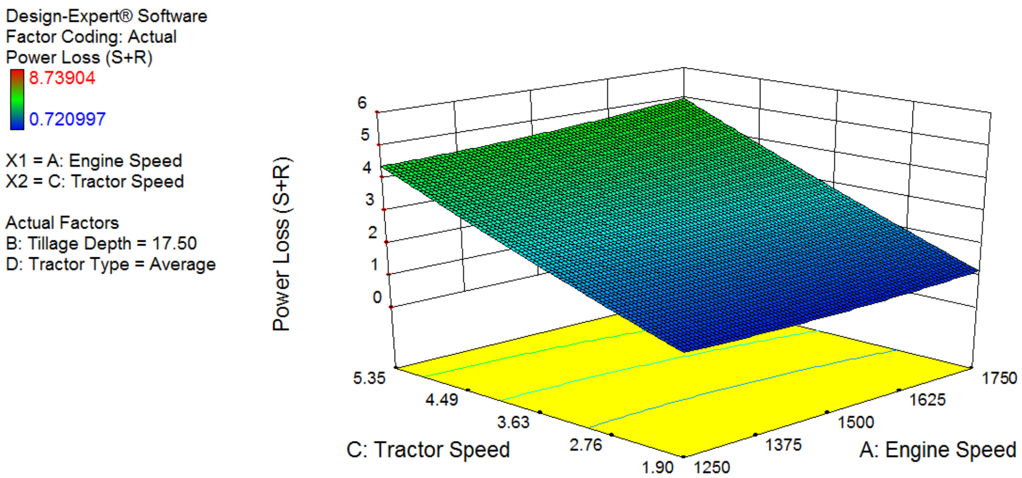

Figure (7) Effect of the interaction between engine speed and forward speed on power loss

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Figure (8) illustrates the effect of the interaction between engine speed and tractor type on power loss. The results showed that the lowest power loss was 0.75 kilowatts when using a four-wheel drive (4WD) tractor at a low engine speed of 1250 RPM. In contrast, the highest power loss was recorded at 3 kilowatts when using a two-wheel drive (2WD) tractor at a higher engine speed of 1750 RPM.

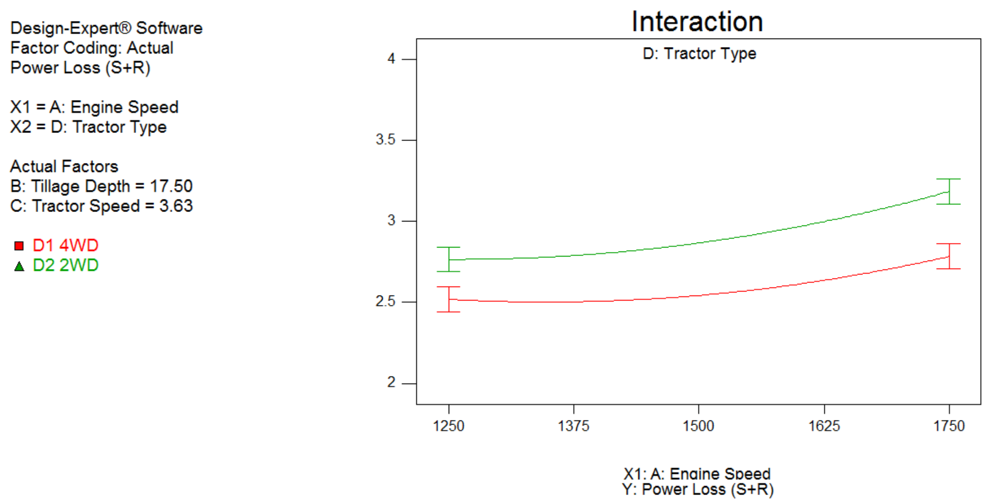

Figure (8) Effect of the interaction between engine speed and tractor type on power loss

Figure (9) illustrates the effect of the interaction between tillage depth and tractor type on power loss. The results showed that the lowest recorded power loss value was 6.5 kilowatts, achieved when using a four-wheel drive (4WD) tractor at a tillage depth of 10 cm. Conversely, the highest power loss value, reaching 9.8 kilowatts, was recorded when using a two-wheel drive (2WD) tractor at a tillage depth of 25 cm.

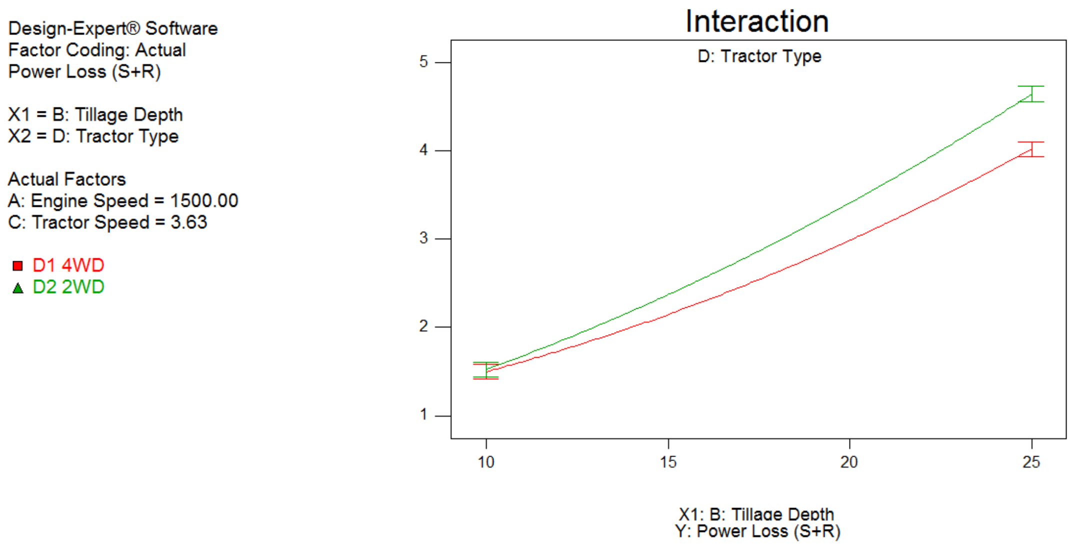

Figure 9. Combined influence of tillage depth and tractor drive system (2WD/4WD) on power dissipation.

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Figure (10) illustrates the effect of the interaction between engine speed, tillage depth, and forward speed on power loss. The results showed that the most influential factor was forward speed, contributing 325%, followed by tillage depth, which contributed 183.3%. In contrast, the least influential factor was engine speed, with a contribution of 12.1%.

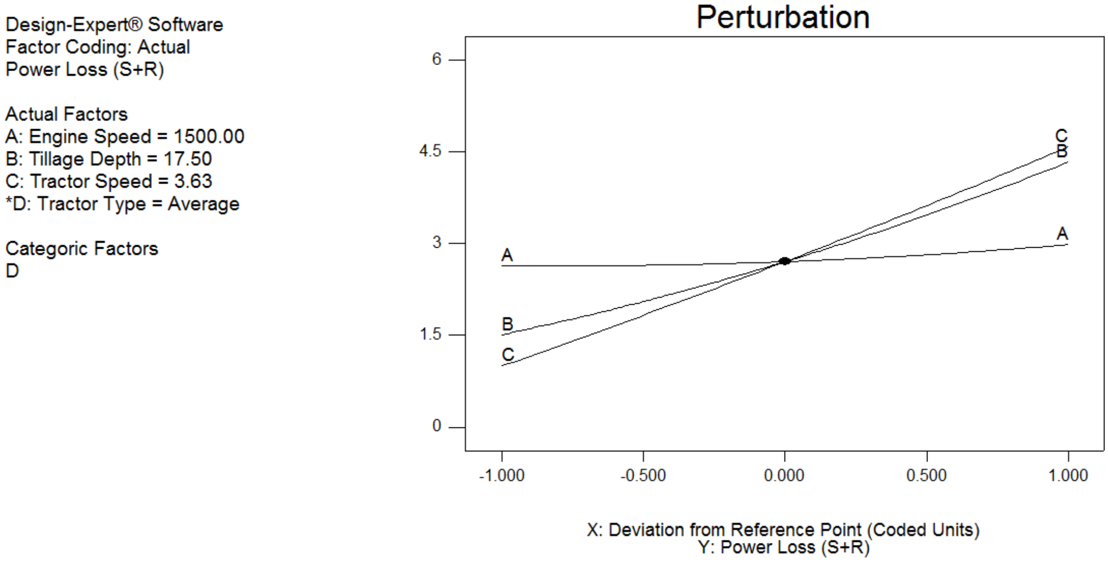

Figure 10. Influence of individual factors (A, B, C) on power loss magnitude.

Design Expert software was used to develop a predictive model for power loss. All independent factors (tillage depth, forward speed, engine speed, and tractor type) along with their interactions were included as inputs in the analysis. The relationship between these variables and the target value was represented by a regression equation, which achieved a coefficient of determination (R^2) of 0.9801. Figure (11) shows the correlation between the predicted power loss values and those calculated using Equation (6).

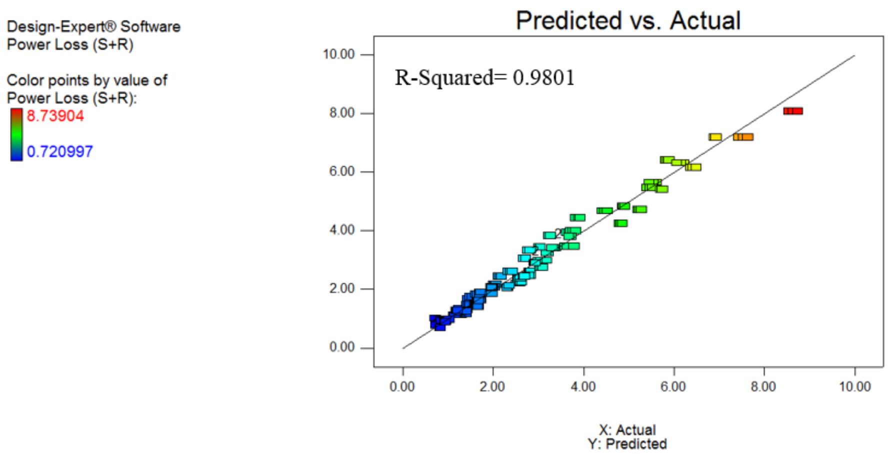

Figure 11. Correlation between predicted and experimentally measured power loss values.

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Tractor Type **4WD**

Power Loss (S+R) =

+8.13680
-6.59047E-003 * Engine Speed
-0.30510* Tillage Depth
-0.89953 * Tractor Speed
+5.20458E-005* Engine Speed * Tillage Depth
+2.80612E-004* Engine Speed * Tractor Speed
+0.071718 * Tillage Depth * Tractor Speed
+1.73048E-006 * Engine Speed^2
+3.86238E-003* Tillage Depth^2
+0.028487 * Tractor Speed^2

Tractor Type **2WD**

Power Loss (S+R) =

+6.91121
-6.28174E-003* Engine Speed
-0.26534* Tillage Depth
-0.79179* Tractor Speed
+5.20458E-005* Engine Speed * Tillage Depth
+2.80612E-004* Engine Speed * Tractor Speed
+0.071718 * Tillage Depth * Tractor Speed
+1.73048E-006* Engine Speed^2
+3.86238E-003* Tillage Depth^2
+0.028487* Tractor Speed^2

(6)

IV. Conclusion

In this research, the power loss due to slippage and rolling resistance was calculated under different operating conditions. The results revealed a clear direct proportional relationship between increasing each of the following factors—tillage depth, forward speed, and engine speed—and the increase in power loss in the agricultural tractor. Forward speed had the greatest impact on the loss percentage. The four-wheel drive (4WD) system demonstrated higher power transmission efficiency and incurred lower losses compared to the two-wheel drive (2WD) system. This is attributed to its reduced slippage rate and more optimal utilization of available power. The study highlights the importance of optimally adjusting operating conditions—particularly forward speed and tillage depth—as an effective strategy for minimizing the energy loss resulting from slippage and rolling resistance. The Response Surface Methodology (RSM) successfully facilitated the development of a highly accurate predictive mathematical model (with a coefficient of determination of 0.9801) for power loss. This model accounts for the main independent variables and their interactive effects. The developed mathematical model provides a practical tool that engineers and farmers can use to predict energy loss and make optimal decisions for adjusting operating parameters (such as selecting appropriate tillage depth and speed based on the tractor type). This ultimately leads to reduced fuel consumption, lower operational costs, and mitigated environmental emissions. The research recommends conducting future studies that encompass a wider variety of soil conditions and testing tractors with advanced transmission technologies to generalize the model and enhance its effectiveness.

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