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Dimensional Analysis based Prediction Model for Fuel Consumption in the Deutz Agrotrac Tractor

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ABSTRACT

Background: Fuel consumption is a critical factor in the performance of an agricultural tractor. And it can be affected by numerous parameters. Farming practices is an essential aspect that affects the cost of operation and the overall efficiency of the tractor. Predictions of fuel consumption rates in tractors and the energy consumption parameters of primary tillage equipment under local conditions are therefore essential selection criteria in purchasing decisions.

Methods: A prediction model for fuel usage during tillage operations was created using dimensional analysis. The model was established by incorporating experimental findings into an equation. The experiment was conducted in the El Ouracia region of Setif, Algeria in 2022/2023 crop season, with fuel usage per time unit determined through topping-up the tank method. The fuel experiment parameters were measured according to their respective standard procedures.

Result: By simulating fuel usage with tillage depth, tillage width, travel speed, soil bulk density and cone index. The constant in the prediction model was obtained. This developed model has the potential to forecast the tractor fuel consumption during tillage operation.

Key words: Cone index, Fuel consumption, Soil bulk density, Tillage depth, Tillage width, Travel speed.

INTRODUCTION

Sustainable agriculture is based on the technology innovated and invented for improving production and productivity (Sharma *et al.,* 2022). Fuel consumption is a critical factor in the performance of an agricultural tractor. And it can be affected by numerous parameters such as tractor's weight, engine power and transmission type (Liu *et al.*, 2019; Singh *et al.*, 2021).

Other parameters might affect the fuel consumption such as soil conditions, weather and farming practices it is an essential aspect that affects the cost of operation and the overall efficiency of the tractor (D'Alessandro *et al.*, 2019). As for tillage operation, it requires the highest amount of energy among all other land preparation operations. Which results high production costs (Tupkanloo and Yazdani, 2017). Jat *et al.* (2020) compared the energy consumption of no-till and conventional tillage methods in wheat production. The researchers found that no-till required 44% less energy compared to conventional tillage. Therefore, there is a need for a reliable and accurate empirical model that can predict the fuel consumption of a mouldboard-tractor under different working conditions such as tillage depth and width, travel speed, plows weight and cone index of the soil. Igoni *et al.* (2020) found in their study the increase in tractor forward speed and ridging height increase in fuel consumption. When compared to circuitous and direct alternation patterns, traditional tillage requires less fuel and time for tillage operation, results in lowering production costs (Sarkar *et al.*, 2016). Moreover, Karadavut *et al.* (2019) worked on the effect of cone index on the fuel consumption and they suggested in their study that reducing soil compaction through practices such as subsoiling could help decrease fuel consumption in tractors. Other researchers consider the soil bulk density as another parameter that can affect the tractor's fuel consumption and Giuggiolini *et al.* (2019) proved that in their study and had a conclusion that the higher bulk density is the higher it demands energy. Using Artificial intelligent in agriculture can help the farmers to manage their production factors in the farm (Bharvey and Sharma, 2023). The present case study focus on Predictions of fuel consumption rates in tractors and the energy consumption parameters (Almaliki *et al.*, 2016; Ranjbarian *et al.*, 2017). This work aims to provide such a model based on dimensional analysis, which can

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help farmers to reduce fuel waste, improve the efficiency of their tractors and ultimately reduce the overall cost of the operation.

Despite previous research on the effect of tillage depth, tillage width, travel speed, cone index and bulk density on fuel consumption, there is still a need to investigate the effect of these factors on the fuel consumption. To address this gap in the literature, we have conducted an experiment including the effect of tillage depth, tillage, width, travel speed, bulk density and cone index on fuel consumption.

MATERIALS AND METHODS

Experimental site description

The experiment was performed at the El Ouracia area in Setif, Algeria. (Latitude of 36°17′17.4″N and longitude of 5°25′52.7″E). (Fig 1), at a private farm on March, 16th 2023 during ploughing operation.

The physical soil characteristics are mentioned in the (Table 1) below:

Agro equipment materials

Tractor specifications

The tractor used to carry out the tillage operation in this study is a Cirta Deutz Agrotrac 150 (Table 2). The tractor even the plow belong to CCLS “Coopérative des céréales et des légumes secs” Sétif.

Implement specifications

The plow used (Table 3) is reversible type and it belongs to CCLS and made by CMA Belaabas. The choice of reversible type is explained by the power request and plowing quality.

Experimental procedures

The plow was attached to the tractor and levelled using the top links of the tractor in order to reduce parasitic forces. The tillage depths were determined by setting the level control of the lifting mechanism (three-point linkage height) to lower the tiller to the desired tillage depth. However, in our experiment we only worked on one single depth, which was 30 cm.

Tractor forward speed was determined by selecting a particular gear that gave the desired speed. In our experiment, it was 3.9 Km/h (Fig 2).

The tillage depth measurement was done by placing the meter rule from furrow bottom to the surface of the tilled land (Fig 3). While the width of cut was measurement by placing a steel tape from one side of the furrow wall to the other end. Time was determined with a stopwatch set at zero before the operation. The cone index was also determined using a cone penetrometer.

The fuel quantity used in the experiment was measured by the topping-up the tank method it is a straightforward way to calculate how much fuel the tractor has consumed over a particular time and it is a process of filling the tank of the tractor fuel tank to its brim before and after each operation test performed. (Fig 4) it works as following:

1. **Fill up the tank:** Fill up the fuel tank of the tractor completely and note the reading on the odometer.
2. **Drive the tractor:** Drive the tractor for a certain period of time, preferably a considerable period and note the reading on the odometer.
3. **Refill the tank:** After driving the tractor for the desired period, refill the fuel tank completely again and note the amount of fuel it takes to fill it up.
4. **Calculate the fuel consumption:** To calculate the fuel consumption of the tractor, divide the amount of fuel used (in liters or gallons) by the period of work (in hours or seconds). The result will give us the fuel consumption of the tractor per unit time.

Model derivation

Independent parameters influencing the fuel consumption

The independent parameters used in the model are the parameters influencing the Fuel Consumption and which are mentioned in (Table 4).

While the dependent variable of the model is Fc_h (Table 5).

The Unit Fc_h used to derive the model is m^3/s however, the Unit we worked with in the field while measuring the fuel consumption is L/h so we need to do a simple conversion using the following conversion formula:

$$1\ m^3/s = 3600.000\ L/h$$

Transformation to dimensionless groups (pi terms)

From Table 1 and 2 we get is a function of (d,b,a,CI,v)
Mathematically:

$$Fc_h = f\,(d,b,a,CI,v) \quad .....(1)$$

The dependent variable = Fc_h.
Total number of variables, n=6.
Total number of fundamental dimensions, m=3.
Therefore, number of dimensionless groups (π-terms).
To be formed = n-m= 6-3= 3.
Equation 1 can be written as:

$$f\,(\pi_1, \pi_2, \pi_3) \quad .....(2)$$

The matrix is presented in (Table 6).

The Null space of the mathematical matrix is 3-dimensional and the karnel is spanned by the following vectors:

$$v_1 = (-2,0,-1,1,0,0)$$
$$v_2 = (-1,0,0,0,1,0)$$
$$v_3 = (0\text{-}1,-2,0,0,1)$$

Each vector represents a dimensionless group:

$$\pi_1 = \frac{Fc}{a^2.v}\ \pi_2 = \frac{b}{a}\ \pi_2 = \frac{CI}{v^2.d}$$

Substituting the values of terms in the following equation:

$f\,(\pi_1, \pi_2, \pi_3) = 0$ Which is:

$$f\,(\frac{Fc}{a^2.v}, \frac{b}{a}, \frac{CI}{v^2.d}) = 0$$

While f is a functional notation for fuel consumption.

Formulation of the fuel consumption model

The method of product and quotient component functions were adopted for development of the fuel consumption model. This prognostic model was developed by simple multiplication and division of the component equations. The validity of combining the equation components by multiplication and division were tested by assuming that the general prediction model is obtained by simple multiplication and division of the terms.

$$\pi_1^1 = \frac{\pi_2}{\pi_3} \quad \pi_1^1 = \frac{\frac{b}{a}}{\frac{CI}{v^2.d}}$$

The relationship becomes: $\pi_1 = kf\,(\pi_1^1)$:

$$\frac{\pi_1}{\pi_1^1} = K$$

Substituting the values of π_1 and π_1^1 into equation:

Therefore, it gives $= \dfrac{Fch}{a^2.v} = K.\dfrac{\frac{b}{a}}{\frac{CI}{v^2.d}}$

Which results that $Fc_h = K.\dfrac{b.d.a.v}{CI}$

The value K is calculated by measuring the fuel consumption in field with the experiment environment conditions known.

Model validation

We rely on the field experiment to validate the model equation. The field experiment was done in EL Ouracia-Setif province on March 16th 2023. The tractor we worked with is CIRTA Agrotrac 150 hp equipped with a four-mounted reversible plow CMA.

We measured the tillage depth, width, the soil bulk density, the travel speed and the cone index. The values we got are explained in (Table 7).

The bulk density was measured by using the clod method were a clod of soil is excavated from the field and weighed. The clod is then dried in an oven at 105°C for 24 h and weighed again. The difference in weight between the wet and dry clod is used to determine the moisture content of the soil. The bulk density is then calculated by dividing the weight of the dry clod by its volume.

$$d = \frac{\text{Weight of dry clod}}{\text{Cylindre volume}}$$

With cylinder volume = $\pi.\, r^2.\, h$ avec (r: Radius of the cylinder, h= height of the cylinder).

The cone index was measured by the penetrometer and the values we got are explained in (Table 8).

Tillage operation, soil's clod was used for obtaining the soil sample from the depth of 0 to 10 cm, 10 to 20 cm and 20 to 30 cm respectively at random in the field to determined textural classification of the soil and the bulk density. The collected soil samples were taken to the laboratory for analysis. The bulk density was determined using clod method.

RESULTS AND DISCUSSION

Establishment of the fuel consumption constant

Based on the equation that we derived in the previous chapter $Fc_h = K.\dfrac{b.d.a.v^3}{CI}$ K was a constant for fuel consumption per working time (m^3/s) model using the topping-up the tank method. In our study, we conducted the experiment in the optimal conditions of work and that is due to our main objective of the study which is to not only establish a predictive model of fuel consumption but also to reduce the amount of fuel consumed while working in the optimum working conditions. We will calculate the constants K by simulating measured field test results cone index CI, bulk density and measured fuel consumption per unit time Fc_h (Table 9).

The Fc_h measured on field was in L/h we need to do a simple conversion as follows:

$$16\text{L/h} = 16*0.001\ m^3/3600\ s = 4.44*10^{-6}\ m^3/s$$

From this equation $Fc_h = K.\dfrac{b.d.a.v^3}{CI}$ we get $K = \dfrac{Fc_h}{\frac{b.d.a.v^3}{CI}}$

By placing parameters with their numerical values, we get: $\dfrac{b.d.a.v^3}{CI} = \dfrac{2.8*1.04*0.383.9^3}{360}$ $*0.0277 = 0.003987344088\ m^3/s$.

The 0.027 is to convert from the unit of $\dfrac{b(m).d(\frac{g}{cm^3}).a(m).v^3(\frac{Km}{h})}{CI\ (N/m^2)}$ to the unit of Fc_h which is: m^3/s.

By doing so K becomes as follows:

$$K = \frac{4.44*10^{-6}\ m^3/s}{0.003987344088\ m^3/s} = 0.001113523163 = 1.1135*10^{-3}.$$

Moreover, this will give us the final model that we will be using to predict the fuel consumption during plowing operation, which is $Fc_p(\frac{m^3}{s}) = 1.1135*\ 10^{-3}*\ \dfrac{b.d.a.v^3}{CI}$.

After building the fuel consumption model using the dimensional analysis method and introducing the tillage working conditions parameters into the mathematical equation. We will now verify the model's prediction results and its accuracy.

1. Tillage width and fuel consumption

We reduce the four-mounted reversible plow into two-mounted reversible plow with a width of 140 cm and keep other parameters in the same values. The fuel consumption will reduce to 8 L/h.

$$Fc_h = \frac{1.4*0.3*1.04*3.9^3}{360} * 0.0277 * 1.1135 * 10^{-3} * 3600000 = 8\ \text{L/h}.$$

Table 1: Physical soil characteristics of the experimental site.

Clay (%)	51.4
Loam (%)	42.98
Sandy (%)	5.58
pH	7.8
EC ($dS.m^{-1}$)	0.194

Table 2: Tractor's technical characteristics.

Engine power	114.47 kW
Brand	Deutz
Type	BF 6 M 1013 E
Cylinder number	6
Engine displacement	7146 cm3
Rated speed	2300 Rpm
Maximal torque	589 N.m
Maximum engine speed	1380 à 1725 Rpm
Transmission	24/12
Rear power take-off speed	540/ 1000 Rpm
Front power take-off speed	1000 Rpm (option)
Advertised lifting capacity	9240 kg
Fuel tank capacity	250 L
Engine oil capacity	18 L
Cooling system capacity	21 L
front wheel dimensions	14.9 R30
rear wheel dimensions	18.4 R38
Total weight	5390 kg

Table 3: Plow specifications.

Number of ploughshares	4 (type reversible)
Power hp	120-160
weight (kg)	1270
Reversibility	Hydraulic
Type of ploughshare	Mixt

Travel speed and fuel consumption

We raised the travel speed of the tractor up to 5 km/h as a result we have got a high jump in fuel consumption up to 33.68 L/h.

$$Fc_h = \frac{2.8*0.3*1.04*5^3}{360} * 0.0277 * 1.1135 * 10^{-3} * 3600000 = 33.68 \text{ L/h}.$$

Cone index and fuel consumption

To see the effect of cone index on fuel consumption the depth of work was changed and that is how we changed the cone index as well and we decreased it to 250 N/m². As a result, the tractor consumes 19.62 L/h.

$$Fc_h = \frac{2.8*0.2*1.33*3.9^3}{250} * 0.0277 * 1.1135 * 10^{-3} * 3600000 = 19.62 \text{ L/h}.$$

Results showed that tillage depth, tillage width, soil bulk density and travel speed have the same effect on the fuel consumption. When these parameters go up the fuel consumption increases as well. And when they go down the fuel consumption decreases. These findings confirm previous studies about the effect of tillage width and travel speed on tractor fuel consumption (Gatea, 2013). Indeed, higher travel speeds tend to result in higher fuel consumption.

To explain why tractor consumes more fuel when working with higher speeds is because it requires more power to move through the soil. This means that the engine has to work harder and as a result, more fuel is burned to provide the necessary power. In addition to that, when tractor travel at higher speeds during tillage, it covers more ground in a shorter amount of time. This means that the tillage equipment has less time to work on each section of soil and may not be able to break up the soil as thoroughly as it

Table 4: Dimensions of the independent variables influencing the Fuel.

Independent Variables	Symbol	Unit	Dimensions
Tillage depth	a	m	L
Tillage width	b	m	L
Travel speed	v	Km/h	$L.T^{-1}$
Cone index	CI	N/cm^2	$M.L^{-1}.T^{-2}$
Bulk density	d	g/cm^2	$M.L^{-3}$

Table 5: Dimensions of the dependent parameters of the model.

Dependent variables	Symbol	Unit	Dimensions
Fuel consumption	Fc_h	m^3/s	$L^3.T^{-1}$

Table 6: Mathematical matrix of the model.

Symbols	Variables of the model					
	a	d	v	Fc_h	b	CI
Dimensions	0	1	0	0	0	1
	1	-3	1	3	1	-1
	0	0	-1	-1	0	-2

Table 7: Bulk density values of different depths.

Depth (cm)	Density (g/cm³)
10	1.31
20	1.33
30	1.04

Table 8: Cone index values of different depths.

Depth (cm)	CI (N/cm²)
15	230
20	250
30	360
40	370

would at a slower speed. As a result, the tractor may need to make additional passes over the field to achieve the desired level of tillage, which requires more fuel. s also why does the travel speed of the tractor affect the fuel consumption mother than any other parameter does?

The fuel consumption also increases when working in higher depths and that is because tillage equipment has to work harder to break up the soil, which increases the resistance that the tractor has to overcome. This results in the engine having to work harder to maintain the same speed, which leads to more fuel being consumed. Moreover, when working depth is increased, it takes longer to till the same area of land. This means that the tractor has to operate for a longer period. Consequently, it requires more fuel to burn.

Table 9: Fuel consumption per unit time and working conditions for plowing operation.

Treatment	Parameters					
	b (m)	a (m)	v (km/h)	CI (N/m²)	d (g/cm³)	Fc_h (m³/S)
1	2.8	0.3	3.9	360	1.04	4.44*

Fig 1: Experimental site (Google Earth, 2023).

Fig 2: Lifting and forward speed control (Setif, Algeria, 2023).

Fig 3: Tillage depth measurement (Setif, Algeria. 2023).

Fig 4: Topping up the tank method (Setif, Algeria. 2023).

Regarding the tillage width and how the fuel consumption increases when tillage width is larger. That is due to the weight of implements that requires more force to move it through the soil when it increases. In this case, the tractor's engine has to work harder to overcome the additional weight, leading to an increase in fuel consumption. Also the weight of the tillage implement creates more friction between the equipment and the soil. This leads to increased frictional losses, which require more power to overcome. Thus fuel consumption rate will rise.

For the soil bulk density and its effect on the fuel consumption it is the same as the three previous parameters and that when soil bulk density increases the fuel consumption increases as well and that could be explained as higher soil bulk density means that more soil is packed into a given area, which increases the weight of the soil being moved. Also, it may be necessary to till the soil at a deeper depth to achieve the desired level of soil destruction. Working with a deeper tillage depth requires more power from the tractor's engine. Also when working with a higher soil bulk density, the soil particles are more tightly packed together, resulting in increased soil compaction. This makes it more difficult to break up the soil, which requires more power and fuel from the tractor's engine to achieve the desired level of soil distraction.

However, the cone index does not affect the fuel consumption the same way as the four previous parameters. We explain the decrease in fuel consumption rates when working in soils with higher cone index by: when working in soils with higher cone index rates, the tillage equipment can achieve the desired soil conditions with fewer passes. This leads to a more efficient tillage process. In addition to that, soil compaction can increase the fuel compaction rate during tillage. However, soils with higher cone index rates are less prone to compaction, leading to less fuel consumption.

CONCLUSION

As a conclusion tractor fuel consumption is highly influenced by the travel speed and they have a positive correlation. The Fuel consumption has a positive correlation also with tillage depth, tillage width and the soil bulk density. However, the fuel consumption has a negative correlation with the cone index. The purpose of this study was to find a model to predict the tractor fuel consumption and the findings helped to achieve the goal of the study. This model may also help farmers to reduce the amount of fuel consumed while still working in the optimal working condition. The model can also get some changes and other studies to make it adaptable for all kind of tractors. As future works, we may involve expanding the scope of the experiment to include a broader range of variables or conditions to help strengthen the findings of the current model.

We may also test the model on other different tractors and see if it works on them as well. In the next studies, we will work on the effect of forward speed especially and its effect on the fuel consumption and find an answer for the question above which is why the travel speed parameter in the fuel consumption equation has the greatest effect on the tractor fuel consumption.

Conflict of interest

The authors are declaring that there is no conflict of interest in the publication of the paper.

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