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Development of a General Equation for Estimation of Tractive Efficiency by Dimensional Analysis

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Abstract: Among the three principal ways of transmitting tractor power into useful work; drawbar, power take off and hydraulic, the drawbar power is the least efficient and most used method. Tractive efficiency is a measure of traction performance of the tractor and is widely used for evaluating tractor performance in the field.

This study was conducted to develop a general equation for estimating the tractive efficiency using dimensional analysis technique. Therefore, a single bottom moldboard plow mounted on a U-445, tractor was tested on a loamy-clay soil. Drawbar force, rolling resistant of driving wheel, slippage of driving wheel, cone index of soil, theoretical and actual velocity and dynamic load on driving wheels were either measured or calculated. The experiment was performed at four plowing depths (10, 15, 20 and 25 cm) in three replications. Finally the data was analyzed for developing the general equation of tractive efficiency by forming dimensionless groups.

Finally the general equation for estimating tractive efficiency, was obtained as:

$$T.E. = (10)^{2.830}\,[(\frac{P}{W})^{(0.496)} \times (\frac{C_I.b.d}{W})^{(-0.280)} \times (10)^{(-0.720)(S)}$$

$$\times (10)^{(-4.841)(\frac{r}{d})} \times (10)^{(9.965)(\frac{T.F}{W})}]^{1.0076}$$

This equation can be used to estimate tractive efficiency of various combinations of tractors and moldboard plows provided the dimensionless terms fall within the limits experienced in this research.

Key words: tractor, tractive efficiency, traction, dimensional analysis, moldboard plow

INTRODUCTION and LITERATURE REVIEW

Drawbar power is specified by two parameters of traction and velocity of tractors. As shown by researches, about 20% - 55% of available energy of tractors is lost by tillage devices. This will wear the energy of tires and compress the soil to the extent that there will be harmful damages to agricultural soil. [12]

The comprehensive definition for modern tractor indicates that tractor is an automatic machine having the capacity of producing travtive ,rotary and hydrolic power used for almost all agricultural aspects. Amongst these, travtive power is of great importance and tractor travtive efficiency is crucial in determining and assessing tractor performance. Travtive efficiency is defines as apercentage of power on tractor. Axle transformation to drawbar power which is influencing by tension coefficient, rolling strength and slip percentage of tractor drive wheels.[6]

Also, most simulation and model planning and their analysis are based on dimensional analysis and its expansion. Dimensional analysis is a powerful analytic instrument expressed by dimensions and considerations involved in each phenomenon and its related quantifies. It lets us generalized the laboratory results while time is saved and the results rae more useful and exact to interpret.[8]

Zoz(1979) found a series of equations to estimate the travtive efficiency of two drive wheel tractors based on free diagram of tractor and the analysis of its forces:[11]

(1)

$$DR = \frac{P}{RWS + P\left[\frac{H}{WB} + \left(1 + \frac{B}{WB}\right)\tan\theta\right]}$$

(2)

$$TE = \frac{DBHP}{AHP} = \frac{P \times S_A}{3.6AHP}$$

Where DR is dynamic coefficient, RWS static weight on rear wheels in KN, H is vertical distance of travtive force from earth surface in meters, WB horizontal distance between front and rear wheel centers of tractor in meter, B is the horizontal distance of intersection point of P on tractor to real wheel axels center in meter, θ^{O} is the resultant angle of forces exerted on the vehicle with horizon surface, DBHP is drawbar power in KW, AHP axle power in KW and S_A is the propelling real velocity of tractor in KM per hour.

Gee-clough and et all.(1978) presented the experimental equations of determining the travtive performance of drive wheels, based on researches on 170 different fields. In this experiment, travtive performance of a two wheel tractor while tillage was assessed. This equations are:

(3) $$(c_t)_{\max} = 0.796 - \frac{0.92}{M}$$

(4) $$K(c_t)_{\max} = 4.838 + (0.061 \times M)$$

(5) $$c_{rr} = 0.049 + \frac{0.287}{M}$$

The following relationship is used in fields in different situations

(6) $$c_t = (c_t)_{\max}\left[1 - e^{-ks}\right]$$

Where $(C_t)_{MAX}$ is maximum travtive coefficient, K contant coefficient, (C_t) net travtive coefficient or the ratio of traction to dynamic vertical load on drive axle, (S) is the wheel sliding (Slip) and (C_r) rolling strength coefficient or the ratio of rolling strength force to dynamic load on the wheel. They suggested the amount of 10% wheel sliding to get a maximum efficiency.[5]

"M" is the mobility number of wheel expressed by Freitag (1965) Who, using dimensional analysis, found that different parameters influencing on wheel performance are functions of a dimensionless term which he called Mobility number defined as the following.

(7)

$$M = \frac{CI.b.d}{W}\sqrt{\frac{\delta}{h}}$$

Where M is mobility number, CI cone indexof soil in KPa, b,d width and diameter of wheelin meter, respectively and (W) the weight on drive wheel in KN, δ is deformation of tire (while it is on hard earth) in meter and h is section height of tire in meter.[3]

In a research by Zoz and Brixius(1979), the following relationship was obtained to predict tractive efficiency parameters on hard surface(Concrete)

(8) $$\frac{F}{W} = A \times \left[1 - e^{-k\frac{b.d}{w}s}\right] + 0.02$$

(9) $$c_t = \frac{P}{W} = A \times (1 - e^{-k\frac{b.d}{w}s})$$

(10) $$T.E = \frac{\frac{P}{W}}{\frac{F}{W}}(1 - S)$$

(11) $$T.E = \frac{A\left[1 - e^{(-k\frac{b.d}{w}s)}\right]}{A\left[1 - e^{(-k\frac{b.d}{w}s)}\right] + 0.02}(1 - S)$$

Here A,K are constant coefficient equaling to 1.02 to 400, respectively. It is worth mentioning that rolling strength coefficient is0.02, based on their proposed model. In other words, the rolling strength is 2% of dynamic load exerted on wheels.[11]

According to most researchers, such as Hauck et all(1984) the travtive efficiency is the most important parameter in assessing the performance of tractor. They mentioned the tractor weight, soil condition, the air pressure and wheel size as the factors influencing the travtive efficiency and consumption fuel volume. Based on their findings, the sliding value of wheel varied from 8 to 16% and there was obtained the best travtive efficiency in 10-15% of slip.

Increasing weights on the drive wheels to reduce sliding less than 8% caused the soil to be compressed. On the other hand, over 16% sliding increased the volume of fuel consumption resulting in severe erosion of tractor tires.[6]

In a research by loghavi and molasadeghi (2002), the travtive efficiency of two common types of tractor in Iran (Messi Fergussen 285 and Universal 650) was examined in different surfaces of plowing depth and three situations of tractor. The result obtained were compared with models predicting tractor performance which showed the inefficacy of messi fergussen tractor in soil applications of high depth even in heavy load. Interestingly, the above tractor was only comparable with tractor universal 650 of implementing surface and medium plowing in heavy load case.[1]

Using dimensional analysis method in research.

There have been done some researches to predict and estimate the parameters of travtive performance such as travtive and rolling strength coefficient. In a research by Wismer and luth(1973), they obtained the following experimental equations to predict field performance of wheeled tractors.[10] They used mobility number of Frietaq(1965) modified by turnage(1979) [9].

(12)
$$C_n = \frac{CI.b.d}{W}$$

(13)
$$c_{rr} = \left[\frac{1.2}{c_n} + 0.04\right]$$

(14)
$$c_t = 0.75 \times (1 - e^{-0.3 \times c_n \times s})$$

(15)
$$\mathrm{P_{db} = Pull \times V_{ac}}$$

(16)
$$Pull = C_t \times W_{ac}$$

(17)
$$P_{db} = Pull \times V_{ac}$$

Gee-clough(1978) determined an equation of predicting the travtive strength of plow based on dimensional analysis.

(18)
$$\frac{D}{aw\sigma} = K_1\left(\frac{\gamma.a}{\sigma}\right) + K_2\left(\frac{\gamma.a}{\sigma}\right)\left(\frac{V^2}{g.a}\right)$$

Here, (D) is the travtive Strength of plow, (a) plow depth, (W) section width of plow, (σ) soil stress, K_1, K_2 are coefficients obtained from experiments and dimensional analysis. (γ) is soil special mass, (V) propelling velocity and (g) is the gravity.

They simplified the above equation by field experiments as:

(19)
$$\frac{D}{aw} = 1.33\gamma.a + 3.06\frac{\gamma V^2}{g}$$

It is worth mentioning that the desired sliding value to attain maximum efficiency was 10% in this research.[5]

Having summed up the previos researches, we performed this research to determine a general relationship to estimate tractor travtive efficiency with dimensional analysis in the field conditions:

MATERIAL and METHOD

There were used Ms-Office XP and Ms Excel to analyse data and draw graphs. The assessed factors in field test were drawbar travtive efficiency, rolling strength force of tractor wheels, sliding percentage of tractor drive wheels, tractor travtive efficiency, soil cone index, tractor real velocity on field and its ideal velocity all of which are main indices of travtive performances. Tractor weight, dynamic load on tractor drive wheels, soil physical characteristics and soil humidity were measured to predict and estimate tractors travtive efficiency while performing initial soiling applications with moldboard plow.

Data collecting was done in research field of Shiraz University. Before the application of the test, the land had underground the wheat cultivation and after harvesting hay and plant waste were packed and removed from the field while the other rest of hay was scattered on the field. There were not symptoms other than some patches of 15 cm high used as the experimental plots. Earth slope was 2 in 1000. The area of each plot was 600 m^2 in 100*6.

To provide desired humidity during plowing, there was the field surface irrigated and field applications were started after measuring and attaining the humidity of 16-18% based on dry weight.

The tractor used in this research was Universal U-445 subjected to a traction force by a heavy tractor of Messi Fergussen 399. A single moldboard plow of 33 cm wide attached to the tractor rear was used in this research. Soil application were performed in three levels of 10-15 cm(surface), 15-20 cm(medium) and 20-25 cm(deep) in 3 iterations. While collecting data, plow depth was controlled carefully. It is worth mentioning that there was adjustment on plow and longitudinal and horizontal scales to reduce the un useful forces on soil devices.

Soil cone index was measured by penetrometer model 1600-SP to the depth of 25 cm. In each iteration, two lines in 40 cm distance were considered for each plow depth. Before plowing the first line of desired depth, two points were chosen randomly in the first, third and fifth 20 meters distance from untitled land so that the cone index value was recorded. This line having been plowed, two points in the second and forth 20 meter distance from plowed land were chosen randomly and their cone index values were recorded. Then two points of unplowed soil in the second and forth distance from the second line, the cone index of two points in the unplowed soil was recorded. Later, some points were chosen from the first, third and fifth distance of plowed soil of the same line with the same depth to determine cone index. At the end, the data collected to determine the soil strength and assess the effect of soil compactness on tractive efficiency were processed on computer. The mean value of the data from one site was recorded as cone index. In other words 40 data were recorded in each iteration to determine cone index. Figure(1) shows the manner of land division and desired points to collect the samples.

The conventional way of two tractor test was used to measure the rolling strength and gross traction force. The set of load cell was installed between two tractors by a chain. In this situation, tractor MF-399 did the traction task and the tractor to be appraised was fastened behind. While load cell set recorded the executed forces based delay time, data collecting was done in two situations. In the first situation,tillage device reached the desired depth in the soil. Therefore the force measured by load cell set was gross traction force. This continued to the extent that there was obtained a certain number of data. The data collecting was done after reaching a certain depth (through direct measurement) and suitable velocity (3 km/hr) while there was performed high care to balance the plow in that depth. In the next stage, there was a similar test done after removing tillage device from the soil. The force measured by load cell set was the rolling strength of appraised tractor while the traction force was supplied by the front tractor. (Fig. 9)

To measured slip percentage of drive wheels, RNAM method and reliable relationship of

(20) $$S(\%)=\frac{A-B}{A}\times 100$$

was used in which (S) is the slip percentage of drive wheel, (A) the distance paved in terms of 10 revolutions of drive wheels in unloaded case and (B) the same for loaded case.

To determine A , B a point of outer wall of rear tire was marked with plaster then, the tractor under appraising was placed in unloaded case in suitable gear and engine revolution (heavy gear of three and engine revolution of 2000 rpm) and the distance paved was measured in terms of 10 revolutions of drive wheels. In the second case, to measure B, plow was placed in the desired depth of the soil to measure the distance paved for 10 revolutions of drive wheels, left or right , the average of which was regarded as the paved distance of rear wheels. In the length of each experimental patch and in the 40 meter distance between two poles, the proceeding velocity and slip percentage of drive wheels were measured. About 30 meters before the first pole, the tractor was in the desired gear and velocity. The proceeding velocity was measured by dividing the distance over the time in the distance of 40 meters.

To determine the tractive efficiency, the following relationship was used:

(21) $$\mathrm{T.E.}=\frac{\mathrm{P}}{\mathrm{P+R}}(1-\mathrm{S})$$

Data analysis

According to the great number of treatment, statistical method of factorial isn't suggested. Therefore the following linear relationship was offered to introduce dimensionless groups to determine the main effect of each treatment[7]

(22) $$T.E.=F_1(\frac{P}{W})F_2(\frac{CI.b.d}{W})F_3(S)F_4(\frac{r}{d})F_5(\frac{T.F}{W})$$

The first and second groups of (22) are functions of W. With dynamic load effect being constant, the next factor effects of the group on T.E will be separated, meaning the net traction values are changed in each depth of plowing and if the dynamic load effects on drive wheels are taken constant, it is possible to examine the variation of net traction value on T.E, and then the effects of cone index value of soil (CI) on tractive efficiency.

To determine the dynamic load, there was determined the static load on drive wheels by placing the rear wheels on scale. Then, plow was attached to hydrolic arms to determine static load after raising the arms, to be used as an estimate of dynamic load on drive axle. The normal component of net traction force vector involved in translating tractor weight on rear wheels was determined by drawing the tension line resulting from connecting center points of bottom strength and tractor tension center and finding slope angle of this line with surface level (θ) while added to previous values [4]

$F_1(\frac{P}{W})$ group analysis

Data logarithme related to the wheel number and tractor T.E were plotted on one graph (Fig 2) by their $Log(\frac{P}{W})$ of the points. For the points on the graph with similar $Log(\frac{P}{W})$, their distance from origin was determined geometrically showing an indication of logarithmic variation of $\frac{P}{W}$ against numerical values of $Log(\frac{P}{W})$. Corresponding the length of these distances with related numerical value of $Log(\frac{P}{W})$ there was the graph of each iteration obtained. Drawing the best alignment line, each graph had a specific slope "n" calculated, as the mean, 0.496. Therefore

(23) $LogF_1(\frac{P}{W}) = 0.496\ Log(\frac{P}{W})$

Or

(24) $F_1(\frac{P}{W}) = (\frac{P}{W})^{0.496}$

The result of the first iteration of process, are shown in figure (3).

$F_2(\frac{CI.b.d}{W})$ group analysis

Numerical value of the following relationship was first determined to analysis this group.

(25) $Log(T.E.) - LogF_1(\frac{P}{W}) = LogF_2(\frac{CI.b.d}{W})$

Know as the "first residual". In other words, the effect of $\frac{P}{W}$ variation from tractive efficiency was removed in the aspect of a linear relationship. The numerical values of the above relationship were plotted versus $Log(\frac{CI.b.d}{W})$. Regarding the number of iterations, the slope of "n" was obtained after determining the slope of each graph. Overall, (Fig.4)

(26) $LogF_2(\frac{CI.b.d}{W}) = nLog(\frac{CI.b.d}{W})$

Where

(27) n= -0.280

Giving us

(28) $LogF_2(\frac{CI.b.d}{W}) = -0.280Log(\frac{CI.b.d}{W})$

(29) $F_2(\frac{CI.b.d}{W}) = (\frac{CI.b.d}{W})^{-0.280}$

$F_3(S)$ group analysis

In this stage, there was obtained a linear equation based on numerical values of $LogF_3(S)$ known as " second residual" from (27) and numerical values of (S). The slope of this line is the mean of 3 slopes of graph. The first replication of these graphs are shown in Fig. (5) .

(30) First Residual $-LogF_2(\frac{CI.b.d}{W}) = LogF_3(S)$

(31) $LogF_3(S) = -0.720(S)$

(32) $F\ (S) = (10)^{(-0.720)(S)}$

$F_1(\frac{P}{W})$ group analysis

The "third residual" equation was written as the following:

(33) Second Residual $-LogF_3(S) = LogF_4(\frac{r}{d})$

The values from applying 120 data were determined versus $\frac{r}{d}$ and the best alignment line was determined.

(34) $LogF_4(\frac{r}{d}) = -4.841(\frac{r}{d})$

(35) $F_4(\frac{r}{d}) = (10)^{(-4.841)(\frac{r}{d})}$

Figure (6) shows the first replication of the group analysis.

$F_5(\frac{T.F}{W})$ group analysis

The " fourth residual" was obtained as

(36) Third Residual $-LogF_4(\frac{r}{d}) = LogF_5(\frac{T.F}{W})$

The data related to 120 points from 4 depth of plowing – 10,15,20,25 cm – were classified to provide four points as independent variables and four points as dependent points. The best alignment line relationship was obtained as: (Fig. 7)

(37) $LogF_5(\frac{T.F}{W}) = 9.965\ (\frac{T.F}{W})$

(38) $F_5(\frac{T.F}{W}) = (10)^{(9.965)(\frac{T.F}{W})}$

General equation of tractive efficiency

Using equations (24), (29), (32), (35) and (38) in equation (22), we will have

(39)

$$T.E. = C\,[(\frac{P}{W})^{0.496} \times (\frac{CI.b.d}{W})^{-0.280} \times (10)^{(-0.720)(S)} \times (10)^{(-4.841)(\frac{r}{d})} \times (10)^{(9.965)(\frac{T.F}{W})}]^n$$

Based on (22) we can write

(40) $T.E. = C\ (F_1 \times F_2 \times F_3 \times F_4 \times F_5)^n$

Therefore

(41) $Log\,(T.E.) = Log\,(C) + Log\,(F_1 \times F_2 \times F_3 \times F_4 \times F_5)^n$

The values in the parantheses of (39) are plotted versus T.E. (Fig.8)

As a result, we obtained $Log(C) = 2.830$ and $n = 1.0076$. The general equation of tractive efficiency for tractors was obtained as:

(42) $$T.E. = (10)^{2.830} [(\frac{P}{W})^{(0.496)} \times (\frac{CI.b.d}{W})^{(-0.280)} \times (10)^{(-0.720)(S)} \times (10)^{(-4.841)(\frac{r}{d})} \times (10)^{(9.965)(\frac{T.F}{W})}]^{1.0076}$$

The range of applying general equation of tractive efficiency

The variation range of dimensionless groups in this research are as the following:

Tractor tractive efficiency

$$0.250 \le T.E. \le 0.678$$

The ratio of net traction to dynamic weight

$$0.098 \le (\frac{P}{W}) \le 0.933$$

Wheel number

$$67.628 \le (\frac{CI.b.d}{W}) \le 86.123$$

Amount of slip

$$0.021 \le (S) \le 0.168$$

Rolling radius to drive wheel diameter ratio

$$0.4816 \le (\frac{r}{d}) \le 0.4941$$

Pulling force to dynamic weight ratio

$$0.0539 \le (\frac{T.F}{W}) \le .0577$$

CONCLUSION

The resulted relationship shows that there are some other factors to determine the tractor tractive efficiency such as soil hardness, diameter, rolling radius and dynamic weight exerted over drive wheels. comparing the numerical values of tractive performance from applying available data in equation (21), (42) extracted from table (1) give us a 9.4% increase in tractor tractive performance through equation (42). This can let us review the research results, the data of which are in the range of dimensionless group of equation (42). The result of Maleki's research [2] through this model show a 10% increase in tractor tractive efficiency.

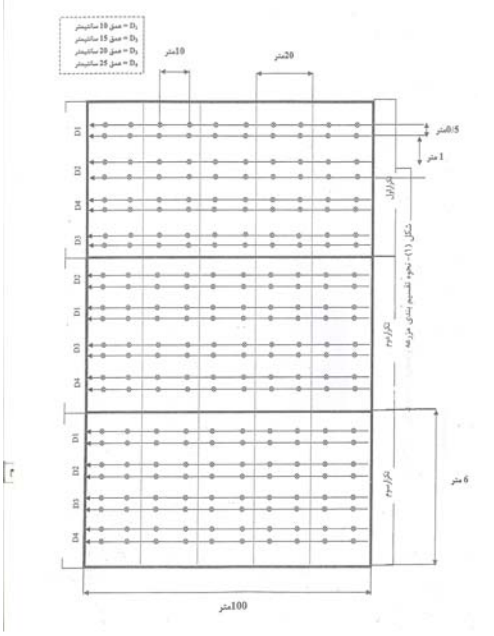

Figure 1. Distribution of points & lines in the field.

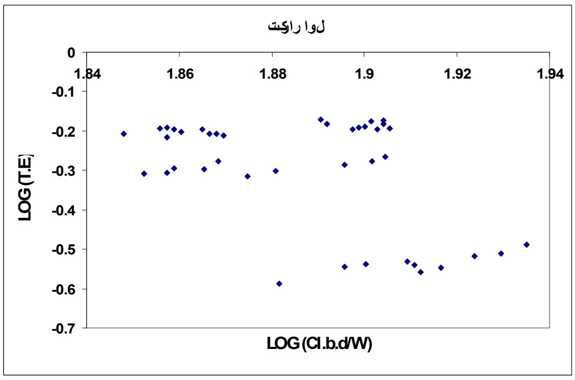

Figure 2. LOG (CI.b.d/W) & LOG (T.E.) (Firsr replication)

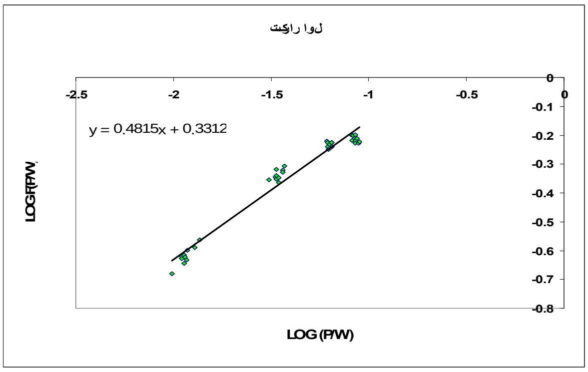

Figure 3. LOG (P/W) & LOG F(P/W) (Firsr replication)

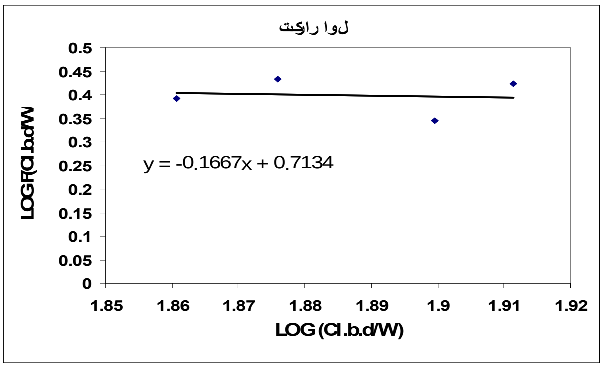

Figure 4. LOG (Cl.b.d/W) & LOG F(Cl.b.d/W) (Firsr replication)

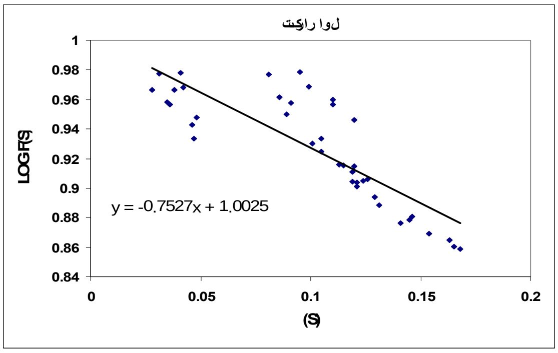

Figure 5. (S) & LOG (S) (Firsr replication)

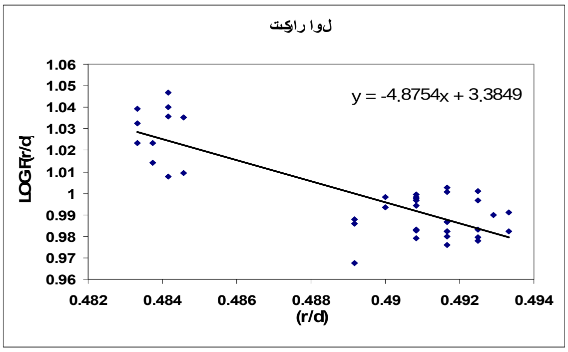

Figure 6. (r/d) & LOG F(r/d) (Firsr replication)

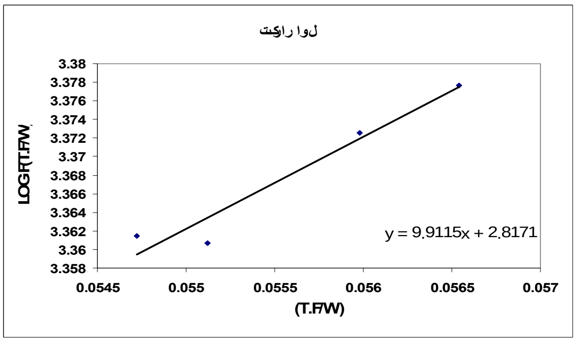

Figure 7. (T.F/W) & LOG F(T.F/W) (Firsr replication)

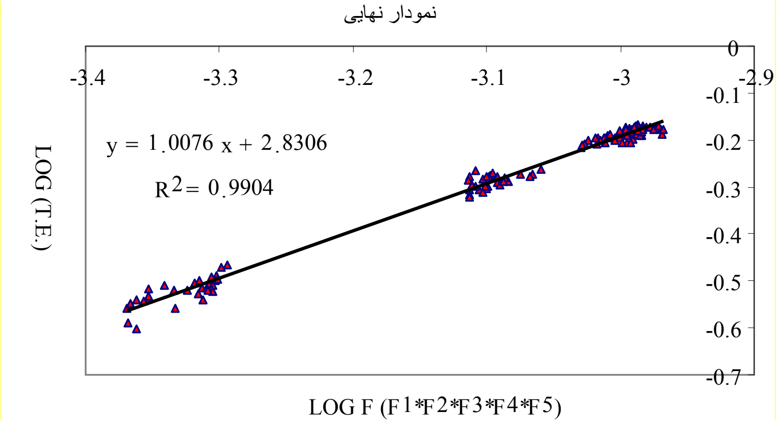

Figure 8. LOG F(F1*F2*F3*F4*F5) & LOG(T.E.) (Final graph)

Figure 9. Two tractor test in the field

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