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ANALYSIS OF THE EFFECTS OF PERIODIC MAINTENANCE OF AGRICULTURAL TRACTORS THROUGH THE METHOD OF EXPERIMENTAL PLANNING

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Abstract. *This study aims to quantify the effects of periodic maintenance of agricultural tractors' engines on the power measured at its power takeoff (PTO), and its fuel consumption. To do this, we use the design of experiments method, 2^5 full factorial without replication, totaling 32 independent assays. For the experiment, we use an agricultural wheel tractor, with six cylinder engine, 6.8 liters, rotary fuel pump and direct injection fuel system, turbocharged with intercooler. The control parameters are chosen based on the authors' experience and their levels are defined experimentally. They are: a) external condition of radiator, b) fuel filter condition, c) air filter condition, d) fuel quality and e) engine oil condition. It can be seen that the parameters with the greatest influence on power are the air filter condition, engine oil condition and a second-order interaction between fuel quality and engine oil. They are responsible for variations in power, respectively of, 2.7%, 2.4% and 1.7%, results based on ideal condition. Fuel consumption presents no significant variation in relation to any of the factors studied, which leads to the conclusion that there is no relation between it and the periodic maintenance of the tractor the way it is proposed by this work. Finally, it is shown that with the correct maintenance, since the extreme condition to the ideal condition, increases up to 7% the power provided by the equipment to work in the field.*

Keywords: power takeoff, design of experiments, periodic maintenance, tractor

1. INTRODUCTION

Agribusiness represented in 2012 a share of 22.15% of Brazilian Gross Domestic Product (GDP), representing 37% of formal jobs and 39% of national exports. According to Garib *et al*. (2015), since the late 1990s, few countries in the world have grown as much in the international agribusiness scenario as Brazil. In the last 20 years, there was a strong increase in agricultural productivity. Grain planted area grew 37%, but production increased by 176% (EcoAgro, 2015). Increased efficiency in fields are due to several factors, especially the development of new planting techniques, better quality seeds, renewal and increase of mechanized fleet and also the use of precision agriculture.

This new structure of agribusiness has brought a need for professionalization with greater control over expenses related to farm inputs, equipment maintenance and inventory, generating new challenges for the machinery industry as a whole, which is being demanded to produce equipment's with higher operation speed, lower fuel consumption and lower maintenance time and cost. Nowadays, the increase of productivity with reduction of expenses is the focus of agribusiness

In this context, farmers and industry are betting on increasing the embedded technology and performing correct periodic maintenance of equipment to assure the right performance and avoid premature component failures (Ferrari, 2015). As a way to determine the benefits generated by correct maintenance, this study aims to quantify the effects on fuel consumption and power in agricultural tractors when used under appropriate periodic maintenance conditions.

Since this industry is essentially technological, all data about products is considered strategical and the relevant literature is restricted and confidential. Therefore, the control parameters were chosen based on the authors' experience and their levels were defined experimentally. The parameters identified as relevant to tractors' performance over power and fuel consumption are: external condition of radiator, fuel filter condition, air filter condition, fuel quality and engine

oil condition. Because of the reasons already explained, in the specific literature only articles related to air filter and engine oil were found.

According to Lacey *et al*. (2003), it is expected that long intervals between engine oil changes results in measurable increases in vehicle fuel consumption and CO_2 emissions. This condition is accentuated when mineral-based engine oils are used, and attenuated with use of synthetic based engine oils.

This phenomenon is due to natural wear caused by relative movement of components inside the engine under normal temperature and pressure operation conditions, generating oxidation and consequent degradation of lubricating oil. An oxidation may cause several potential effects at system, such as formation of deposits, increase oil viscosity, additives efficiency loss and increase of its acidity. The result of this combination of factors ranges from premature component wear to increased CO_2 emissions, increased fuel consumption and corrosion of bearings.

Singh (2011) reports that fuel economy depends on fuel quality and lubricant oil. The friction is influenced by engine speed, load, surface topography of the components, oil viscosity, oil temperature and friction modifier additive used. He conducted an experimental design using the methodology of Design of Experiments, selecting as controlled parameters: speed, load and viscosity of oil. Each being varied in two levels. From the analysis, the author observes that the engine speed and the second-order interaction between speed and load are the factors that influence more significantly the friction loss inside the engine.

Considering that speed and load are inherent to engine to its application and therefore difficult to be modified by the operator, there remains the selection of most suitable lubricant in terms of viscosity for greater fuel economy, less friction loss and consequently higher power.

Taylor *et al*. (2014) conducted experimental tests on diesel engines, concluding that the use of lower viscosity oils presents lower fuel consumption. It was highlighted that this property may be influenced by parameters like temperature, shear rate, pressure, elastohydrodynamic characteristics and surface additives added to oil.

Burnete et al. (2013) corroborate the information, from test of an internal combustion engine with a single cylinder, he verified influence of lubricating oil temperature on power, torque and fuel consumption, the results indicates that an increase of oil temperature provides a significant increase of power and reduction of fuel consumption.

According to Jääskeläinen and Khair (2011), air supply is a critical aspect in diesel engines. The design must ensure that air volume meets the following minimum requirements under all operating conditions,: (1) provide sufficient amount of oxygen to ensure complete combustion, (2) if the engine is equipped with an Engine Gas Recirculation (EGR) system, it must be able to control combustion temperature by reinserting an adequate amount of exhaust gas to combustion chamber, (3) air temperature and pressure must be monitored and (4), the air filter must ensure that the size and concentration of impurities allowed to enter the combustion chambers are acceptable. In addition to these conditions, the airflow must ensure the content renovation of combustion chambers with fresh air and dissipate remaining heat by expulsion of the flue gases.

 Thomas *et al*. (2013) studied the air filter condition effects on vehicles with diesel engines in terms of fuel consumption and vehicle performance. According to his results, the substitution of obstructed air filters decreases fuel consumption in carbureted engines used in vehicles produced in the 70's. Based on that, they tested diesel engines of vehicles manufactured between 2007 and 2009 to determine the condition of maximum obstruction of air filters. Using wet towels to simulate a distributed load loss along admission area, the results indicated a modest decrease of vehicles performance and a small effect on fuel economy.

2. DESIGN OF EXPERIMENTS

Fisher first developed the method of Design of Experiments (DoE) in 1935. It consists in a statistical approach to the optimize design, execution and analysis of experiments. According to Caten (1995), a well-designed DoE reduces the experimental effort and allows reliable conclusions to be obtained; also, it provides access to an important amount of information regarding the studied input parameters and associated experimental error. In relation to the analysis, its tools enables the user to carry out a survey regarding the significance of each parameter over the response variable.

Werkema and Aguiar (1996) defines an experiment as a procedure in which intentional changes are made in the parameters of a system or process, in order to evaluate the possible changes experienced by the response variable, and estimate their causes. A model of the process flow can be seen in Fig. 1. In the case of the agricultural tractors studied in the present work, the parameters are controlled quantities and the variables are those that cannot be controlled. The output data are experimental quantities, which are also called response of the system. It may be directly used or be the input of other assessments of the problem.

When the experiment involves two or more factors as the object of study, according to Montgomery (2005), the experimental design is indicated since it allows all the considered factors to vary, generating all possible combinations of factors and levels. It is the only way to detect interactions between factors. Statistical design of experiments refers to the process of planning the experiment, collect appropriate data and analyze using statistical methods. Resulting in valid and objective conclusions. The DoE methodology also allow us to implement a model of regression to fit the experimental data considering the effects of interactions over the parameters.
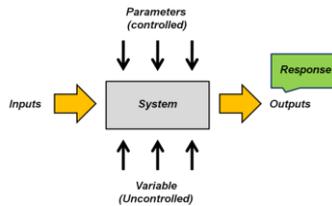
Figure 1. General model of a process or system (adapted from Montgomery, 2005)

The three basic principles of DoE are replication, randomization and blocking (Werkema and Aguiar, 1996; Montgomery, 2005). Randomization refers to the order of the experiments or tests to be determined randomly. Blocking is a design technique used to increase the accuracy of comparisons between factors of interest. It is used to reduce or eliminate the variance transmitted by uncontrollable factors or noises. Finally, replication has two important properties: get an estimate of experimental error and provide a more accurate estimation of the factor effect in the experiment.

Statistical analysis was based on the methodology of ANOVA, which can be seen in detail in Montgomery (2005), Werkema and Aguiar (1996) or Box *et al*. (2005).

3. EXPERIMENTAL SETUP

The laboratory was specifically designed to perform power and fuel consumption measurements on agricultural machines such as tractors and harvesters. In this experimental study, an agricultural wheel tractor, with six-cylinder engine, 6.8 liters, rotary fuel pump and direct injection fuel system, turbocharged with intercooler, was evaluated.

A schematic drawing of the laboratory is shown in Fig. 2 and consists of: (A) external air inlet, (B) evaporative cooler, (C) air blower, (D) agricultural machine (tractor under test), (E) shaft assembly, (F) Foucault current dynamometer, (G) air exhaust inlet (H) air and heated gases exhaust outlet, (I) flue gas extractor, (J) mass fuel consumption measurement system and (L) entrance and exit door.

A supervisory system controls all logic in order to collect and store information provided by the various sensors distributed throughout laboratory and, from these data, control the experimental influence factors.
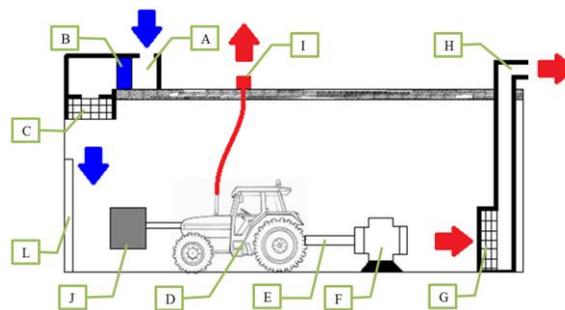

Figure 2. Schematic drawing of dynamometer test room

External air was aspirated from (A), with atmospheric temperature and relative humidity, by a centrifugal fan and insufflated through (C) in front of the agricultural machine in order to obtain a uniform and constant airflow over the area. The evaporative cooler (B) was used to decrease internal air temperature in order to achieve the temperature target.

The dynamometer (F) was connected to the tractor through the shaft assembly, which was divided in three parts: a cardan axis with telescopic extension coupled at power takeoff (PTO) of the tractor, a rigid axis supported on bearings to absorb vibrations and a small axis used to transmit load to the dynamometer.

Air from (C), already warmed by the heat generated in the machine under heavy load operation of (D), was exhausted through (G) and (H) by an axial fan assembled at the discharge line. Flue gases were exhausted to the external environment by an independent exhaust line (I) with use of a centrifugal fan, directly connected to the machine exhaust pipe.

The fuel consumption measurement was performed by a scale system and a set of sensors managed by the supervisory system (J), which was capable to monitor the fuel mass consumption rate of the engine.

For both response variables, fuel consumption and power, the experimental measurement uncertainty was calculated, obtaining, respectively, +/- 0.03% and +/- 0.2% on measured values.

3.1 Analyzed parameters

The determination of parameters and its levels were based at the information provided in the operator's manual of the tractor. The chosen factors were defined in order to obtain a balance between basic periodic and very frequent

maintenances, and others less frequent and more complex and expensive interventions. Then, the levels were defined empirically and labeled as ideal and extreme condition.

3.1.1 External condition of radiator

During harvesting of many agricultural crops such as soybean, debris may accumulate over the engine coolant radiator external surface, which causes fast engine overheating. Thus, the ideal condition was defined as a completely clean radiator, free of obstructions, and its extreme condition was determined empirically through the simulation of a total obstruction. For extreme level determination, a controlled restriction was mounted in front of the radiator and the area covered was gradually increased until engine overheating indicator lighted up in the panel.

3.1.2 Fuel filter condition

Clogged fuel filters are among one of the most common maintenance faults in the field. The ideal condition was defined as clean filters and its extreme level was determined empirically, based on the restriction measured in the fuel line of a set of filters with 300 hours of use, previously removed from a tractor used in soybean crop. For this, a gate valve (manual with fine pitch) was installed at the outlet of final filter, in parallel with a pressure sensor to measure post-filter pressure, placed at the filter distributor head.

The tractor was then started in Full Load Rated Speed (FLRS) condition, which consists in engine full throttle until it reaches its maximum speed, and then gradually apply load to the PTO through the dynamometer, decreasing engine speed until its nominal value. Then, output pressure drop was measured (keeping the diesel temperature constant) in two situations, with new filters and used filters. The obtained values were labeled as ideal and extreme condition. These values were artificially reproduced during experiments.

3.1.3 Air filter condition

Air filter is an essential component. It ensures engine proper operation as it prevents solid particles from entering the combustion chamber and causing premature wear on moving parts such as pistons and rings. This parameter was selected because the operator can easily replace it at the field, but if not substituted it may affect performance and life of equipment.

Ideal condition was defined as clean filters and its extreme level was determined empirically, simulating an obstruction over entire engine intake. To do so, a fabric was used to cover the air admission area until filter change indicator lighted up in panel under FLRS and constant air temperature condition.

3.1.4 Fuel quality

Farmers often reports the occurrence of water contamination in diesel oil stored in tanks of farms, making this an important parameter to be analyzed.

Two levels were analyzed, the first, considered ideal condition, was the commercial S500 B7 diesel (7% biodiesel blended with mineral diesel). As extreme condition, water was mixed until its saturation point according to Brazilian legislation, through Resolution ANP No. 69, 12/23/2014, allows up to 500 ppm of water mixed with diesel oil.

3.1.5 Engine oil condition

As an ideal condition, engine oil indicated by the manufacturer and new oil filters were used, and as an extreme condition, engine oil removed from a tractor used at soybean crop after 300 hours of use.

3.2 Experimental matrix

The experimental matrix was generated in order to obtain the largest possible number of interactions among the selected parameters; it is summarized in Tab.1 below. A complete factorial 2^5, with 32 experiments, was used, as shown in Tab. 2. It is important to emphasize that since the test had only two levels for each parameter, the response will be approximately linear between the level limits. Therefore, it is not possible to identify any non-linearity in the results.

Following the prescription of the DoE method, the experiments were conducted in a random way, with the exception of engine oil parameter. It was decided to not randomize it due to the nature of this operation, since it was not possible to guarantee that all oil has been drained from the internal chambers of the engine at each oil change, which could cause contamination of new oil with used oil.

STATSOFT STATISTICA® 12, R® 3.1.2 and MICROSOFT EXCEL® 2010 were the software used to perform the statistical analysis of experiments.

Table 1. Summary of conditions used to determine ideal and extreme levels of each parameter

Condition	Radiator (1)	Fuel filter (2)	Air filter (3)	Fuel quality (4)	Engine oil (5)
Ideal (+)	Clean and unobstructed	Clean and unobstructed	Clean and unobstructed	Clean	New
Extreme (-)	Obstructed in order to heat coolant until engine indicated overheating.	Restriction applied in fuel line to generate equivalent pressure difference of 300 hours of use	Restriction applied over air intake to generate restriction until engine indicated excessive restriction.	Contaminated with water until saturation	Oil and its filter with 300 hours of use

4. RESULTS AND DISCUSSION

Experimental results of fuel consumption and power, in percent form, are presented in Table 2 below. As reference of ideal condition, the experiment number 31, since it has all parameters at ideal condition. As a highlight, it is possible to verify that experiment number 9 was the one who presented worst performance in both response variables when compared with the standard ideal condition.

Table 2. Percentage results obtained of experimental measures of power and fuel consumption

Execution Order	Parameters and levels					Power [1] (%)	Fuel Consumption (%)
	1	2	3	4	5		
1	-	-	-	-	-	93.3	99.1
2	+	-	-	+	-	91.7	97.6
3	+	-	+	+	-	94.3	97.7
4	-	+	+	+	-	94.8	96.4
5	+	-	+	-	-	96.0	100.0
6	+	+	+	-	-	96.4	98.9
7	-	-	+	-	-	96.2	97.9
8	-	+	-	-	-	93.5	97.0
9	+	+	-	+	-	91.3	96.1
10	+	+	+	+	-	94.8	97.6
11	-	-	+	+	-	96.6	97.9
12	-	-	-	+	-	93.8	97.4
13	+	+	-	-	-	94.5	98.7
14	-	+	-	+	-	91.5	97.0
15	-	+	+	-	-	95.1	97.9
16	+	-	-	-	-	93.6	98.4
17	+	+	-	+	+	93.7	98.2
18	+	-	-	+	+	94.6	99.0
19	-	+	-	-	+	94.6	97.6
20	-	+	+	-	+	96.9	96.9
21	+	-	+	-	+	95.7	97.4
22	+	+	-	-	+	93.7	97.5
23	-	-	+	-	+	96.0	96.7
24	+	+	+	-	+	96.5	97.6
25	-	-	-	-	+	97.4	99.5
26	+	-	+	+	+	98.9	98.6
27	-	+	-	+	+	97.1	98.2
28	-	-	+	+	+	99.7	99.1
29	-	-	-	+	+	97.3	99.2
30	-	+	+	+	+	100.1	99.4
31[2]	+	+	+	+	+	100.0	100.0
32	+	-	-	-	+	93.1	98.1

[1] measured on PTO

[2] standard ideal condition

4.1 Influence of parameters on power

The variance analysis over power is shown below in Tab.3. There, is possible to verify the main effects of each parameter over the mean response, with significance level of 5%. A p-value less than 0.05 indicates that, probabilistically, the factor has a strong influence in the response.

Table 3. Results of variance analysis over power in a complete factorial 2^5, with significance level of 5%

Parameters	Degrees of Freedom	Sum of Squares	Mean of the Sum of Squares	F-Statistic	p-Value
Radiator	1	8.925	8.925	9.78	0.007
Fuel filter	1	0.633	0.633	0.69	0.417
Air filter	1	74.725	74.725	81.86	0.000
Fuel quality	1	2.365	2.365	2.59	0.127
Engine oil	1	56.978	56.978	62.42	0.000
Radiator – Fuel filter	1	3.850	3.850	4.22	0.057
Radiator – Air filter	1	3.713	3.713	4.07	0.061
Radiator – Fuel quality	1	2.475	2.475	2.71	0.119
Radiator – Engine oil	1	4.575	4.575	5.01	0.040
Fuel filter – Air filter	1	1.488	1.488	1.63	0.220
Fuel filter –Fuel Quality	1	0.525	0.525	0.58	0.459
Fuel filter – Engine oil	1	0.475	0.475	0.52	0.481
Air filter – Fuel quality	1	6.938	6.938	7.60	0.014
Air filter – Engine oil	1	0.090	0.090	0.10	0.757
Fuel quality – Engine oil	1	29.453	29.453	32.27	0.000
...	...	...	...	...	...
Residual Error	16	14.605	0.913	-	-
Total	31	211.815	-	-	-

As shown in Tab. 3, the parameters with greater influence on power are, respectively, air filter, engine oil and radiator, while the other parameters presented a poor significance. Likewise, the same table presented the second-order interactions effects, and was possible to identify an important influence of interactions between fuel quality/engine oil and air filter/fuel quality, while the other interactions were poor in significance. These results are displayed in Figs. 3 and 4. According to Montgomery (2005), the third order and higher interactions are negligible in most of the cases and can be used to compute error.

From all parameters with significant influence on power, the air filter, with 2.7% of response variation and engine oil with 2.4% are the most important. Below, the Pareto graph in Fig. 5a, represents its influence variation over the ideal and extreme conditions. Results were referenced as percentage of ideal condition (experiment 31, as explained in Chapter 4).
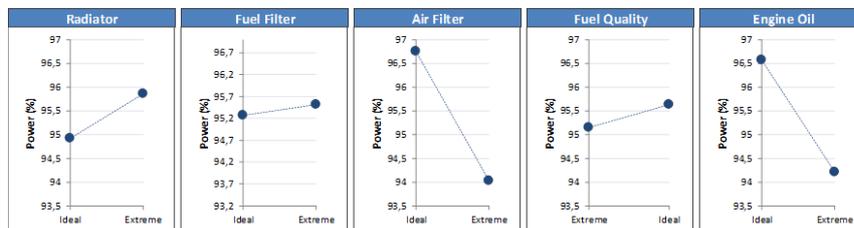

Figure 3. Graph of main effects of each parameter over the mean response on power

Another important finding is that three parameters showed behavior within expected, the ideal conditions analyzed presented better performance than its extreme condition (obstructed, contaminated or with excessive hours of use), which corroborates the need for periodic maintenance on agricultural machines.

Fig. 4 presents all second-order interactions, and the Pareto Chart of Fig. 5a, shows that the interaction between fuel quality and engine oil was significant, with a variation in the response of 1.7%. Due to its high value, it cannot be ignored under the argument of measurement uncertainty.

The fuel filter parameter showed a worsening in order of 0.2% when in the ideal condition. Due to small magnitude of this variation, it is assumed that it is result of measurement uncertainties. In addition, the radiator parameter, which when obstructed increased the power by 0.9%, needs to be better explored in future studies.

Since the extreme condition chosen for the fuel filter in this work reproduces the equivalent maximum number of hours indicated by manufacturer, the fact that it is not affecting power shows that filter had good design margin in relation to its useful life.
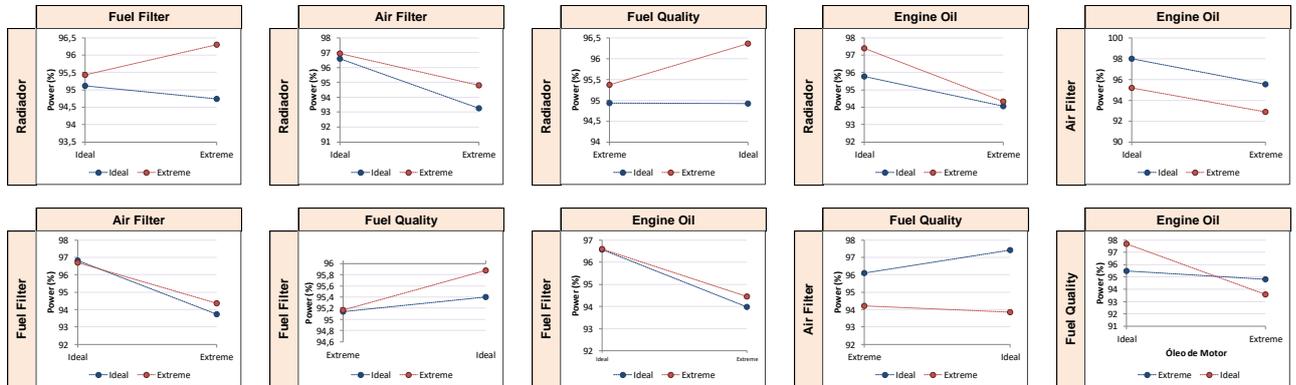

Figure 4. Graph of interactions effects of each pair of parameter over power mean response.

Although acceptable, the condition of no interaction between experiments was not clearly demonstrated in Fig. 5b, this phenomenon was already expected for the reasons cited in Subtitle 3.2, and was demonstrated by an inclination of the mean residual value line.
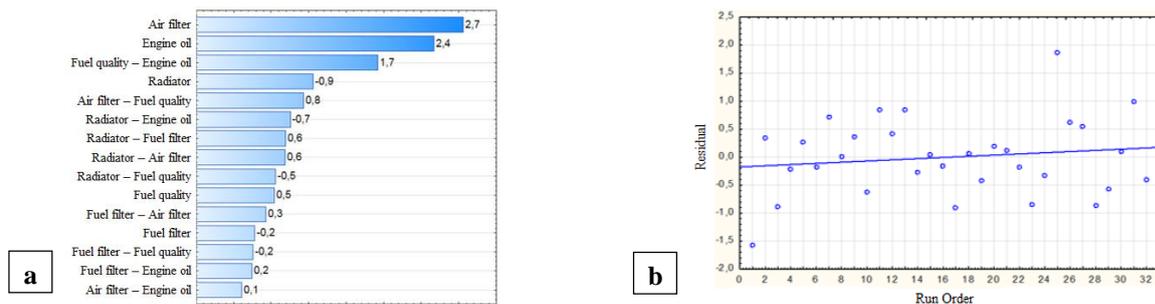
Figure 5. (a) Pareto chart (representing the percentage in relation to response of ideal condition) with parameters effects and they second-order interactions and (b) residual versus observation order to response variable power

To ensure the adequacy of the statistical model, the condition of distribution of the error with zero mean and constant deviation was analyzed. This is presented in Fig. 6a where it is shown the normal probability plot of residuals and Fig. 6b, residual histogram with a normal distribution form. Both figures do not have indications of any discordance with conditions above.
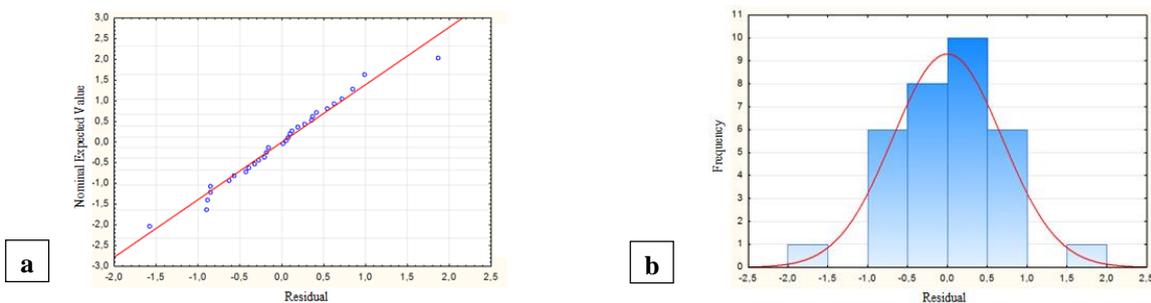

Figure 6. (a) Normal probability plot of residual and (b) residual histogram to response variable

4.2 Influence of parameters on fuel consumption

An equal analysis was carried out to analyze fuel consumption measurements. From the analysis of experimental data set, we obtained the results shown in Tab. 4. It should be emphasized that experiments for both response variables were performed simultaneously.

Table 4. Results of variance analysis to fuel consumption in a complete factorial 2^5 with significance level of 5%

Parameters	Degrees of Freedom	Sum of Squares	Mean of the Sum of Squares	F-Statistic	p-Value
Radiator	1	8.925	8.925	9.78	0.007
Fuel filter	1	0.633	0.633	0.69	0.417
Air filter	1	74.725	74.725	81.86	0.000
Fuel quality	1	2.365	2.365	2.59	0.127
Engine oil	1	56.978	56.978	62.42	0.000
Radiator – Fuel filter	1	3.850	3.850	4.22	0.057
Radiator – Air filter	1	3.713	3.713	4.07	0.061
Radiator – Fuel quality	1	2.475	2.475	2.71	0.119
Radiator – Engine oil	1	4.575	4.575	5.01	0.040
Fuel filter – Air filter	1	1.488	1.488	1.63	0.220
Fuel filter – Engine oil	1	0.525	0.525	0.58	0.459
Fuel filter – Engine oil	1	0.475	0.475	0.52	0.481
Air filter – Fuel quality	1	6.938	6.938	7.60	0.014
Air filter – Engine oil	1	0.090	0.090	0.10	0.757
Fuel quality – Engine oil	1	29.453	29.453	32.27	0.000
...	...	...	...	...	...
Residual Error	16	0.039	0.002	-	-
Total	31	0.203	-	-	-

Considering a significance level of 5%, the most important main effects, according to graph shown at Fig. 7 and 8, were fuel filter and engine oil, while the other three factors (radiator, air filter and fuel quality) showed lower influence in fuel consumption. However, both parameters presented variations of less than 0.6%, according to Pareto graph of Fig. 9a, and it is possible to attribute these variations to measurement uncertainties.
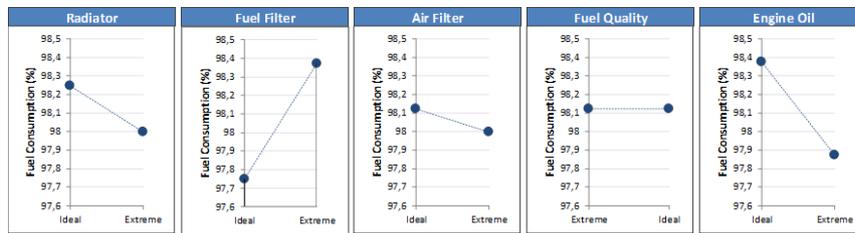

Figure 7. Graph of main effects of each parameter over the mean response of the fuel consumption

For the second-order interactions, the interaction between fuel quality and engine oil were the most important, with variation of almost 2%, greater than the other main effects. As suggestion, this interaction could be an object of study in a future works.
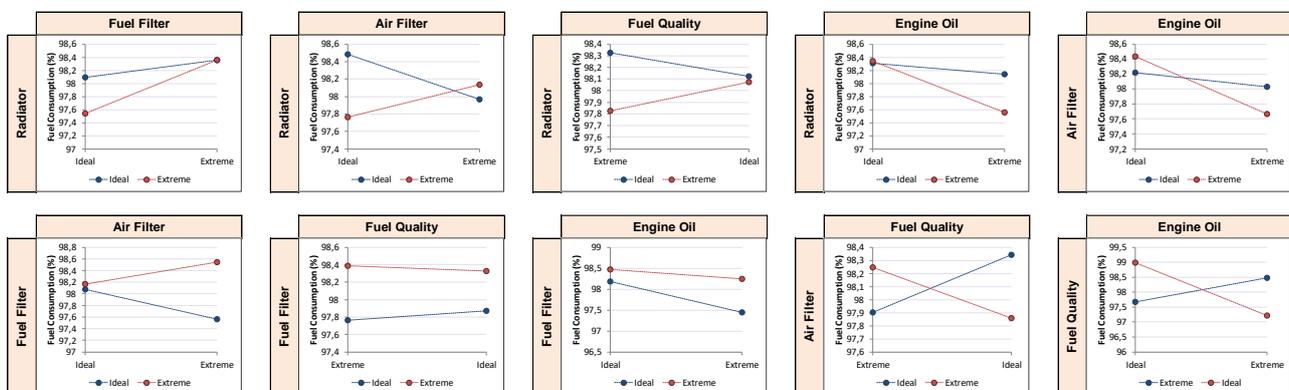

Figure 8. Graph of interactions effects of each pair of parameter over of the fuel consumption

Again, to ensure adequacy of the statistical model, it was verified the distribution of the error with zero mean and constant deviation. The normal probability plot of residuals can be seen in Fig. 10a, and do not present any indication of discordance with conditions above, but residual histogram of Fig. 10b, showed a non-uniform distribution at the right portion of the graph. This can be explained by the chosen method of fuel mass measurement, which consists in a scale system that does not have an adequate resolution compared to the magnitude order of measured fuel variations, which were very small compared to the absolute value. In addition, as expected, the condition of no interaction between experiments is not clearly demonstrated in graph of Fig. 9b for the reasons cited in Subtitle 3.2.
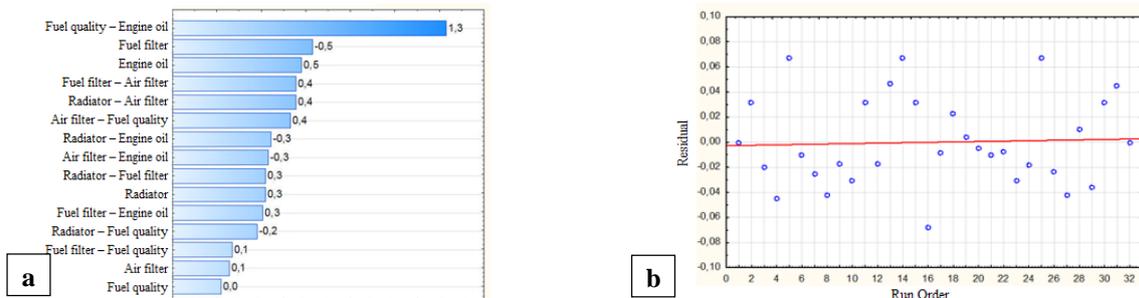

Figure 9. (a) Pareto chart (representing the percentage in relation to response of ideal condition) with parameters effects and they second-order interactions and (b) residual versus observation order to response variable fuel consumption
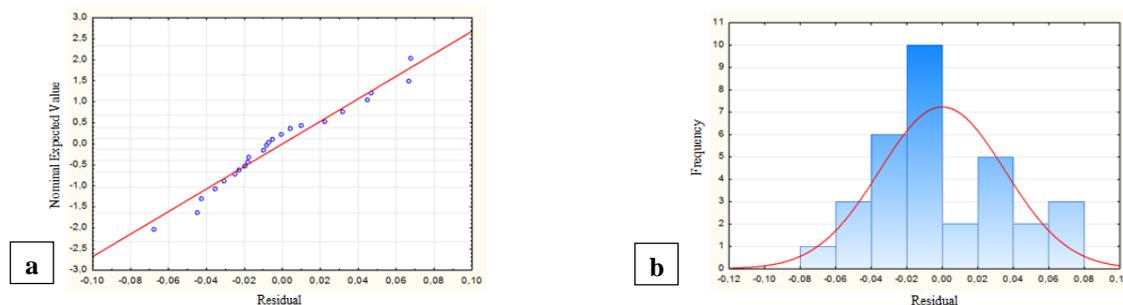

Figure 10. (a) Normal probability plot of residual and (b) residual histogram to response variable fuel consumption

5. CONCLUSIONS

The statistical techniques set used in DoE and its correct execution allow us to establish a complete relationship between relevant factors involved in a process or system. In this context, fuel consumption and power were object of this study.

In power analysis it was verified that among the controlled parameters, the ones that had influence in the result were air filter condition, usage hours of engine oil and a second-order interaction between fuel quality and engine oil condition.

Considering only air filter effects, through restriction of air volume inserted in engine, power varied by approximately 2.7%, while engine oil was responsible for 2.4%. The interaction between oil quality and engine oil effect was responsible for another 1.7% of variation over the final power, but this interaction needs to be further clarified in future studies. The residue analysis performed showed reliable and sufficient results for statistical validation of the experiment.

Fuel consumption analysis showed a small variation in measured values, with highlight to second-order interaction between used fuel quality and engine oil, which still had a very low influence in final fuel consumption. Despite the compromised variability of experiment due to operational limitations, the relative magnitude order of effects and the statistical analysis allow us to conclude there are no differences in fuel consumption related to the parameters used in this study.

Finally, this work showed that the correct maintenance of agricultural tractor, from its extreme condition (which takes into account all factors in its extreme level) to its ideal condition (with all factors in ideal condition) increases by up to 7% the useful power provided by the equipment to work at the field.

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