AN FTA BASED METHODOLOGY FOR THE DETERMINATION OF FUEL CONSUMPTION VARIATION OF TRACTORS

Juliano Amaral Fernandes, jaf2004@terra.com.br
Maria Lúcia Machado Duarte, mlduarte@dedalus.lcc.ufmg.br
Alexandre Carlos Eduardo, aceduard2003@yahoo.com.br
GRAVI$_{DEMEC/UFMG}$ – Group of Acoustics and Vibration, Mechanical Engineering Department, Federal University of Minas Gerais. Av. Antônio Carlos, 6627. Pampulha. Belo Horizonte/MG Brasil. CEP 31270-901

Abstract. *In the present study, a methodology for determining the factors affecting fuel consumption variation in tractors is proposed using the Fault Tree Analysis (FTA) technique. The mechanical system of a rear traction tractor is modeled and the parameters responsible for the tractor performance are emphasized. From the definition of such parameters (for example: rear weight dynamic, slip, dynamic weight coefficient and power ratio, among others), the equations governing the fuel consumption are described for using in the prediction of tractor's fuel consumption. The use of the FTA for investigating the causes of faults is justified due to the presence of factors that directly or indirectly affect the fuel consumption. Such factors are quantified and utilized in the construction of the fault tree. Through a literature review, the FTA is developed for showing up the events responsible for the fuel consumption variation. The results showed that the FTA methodology presented could be used for determining the influence of each factor in fuel consumption. In fact, the methodology presented gives a step further in what is utilized conventionally, showing that this kind of approach is able to direct more research work.*

Keywords*: tractors, fuel consumption, Fault Tree Analysis*

1. INTRODUCTION

At the actual context of competition and quality in industries, the search for continuous improvement in all production processes has become an important factor to reach profits. Fuel, as an essential item in the production chain, has high costs involved justifying special attention. Fossil fuel, besides being expensive, is normally associated with high CO2 emission, what is being a matter of caution in many countries recently due to the global warming caused by such emissions. Brazil keeps energy programs that encourage the use of alternative energy resources, to decrease the dependence of fossil fuels. The "*Brazilian Program for Alternative Sources of Electric Power*" shelters programs based on biomass, eolic energy and small hydroelectric power plants. However, vehicles still use fossil fuels in large scale, not being benefited by these alternative resources. The Pro-Alcohol, a program created in the 70's, was the world's biggest fossil fuels substitution program by the time for the automotive market. More recently, the PNPB, a "*National Program for Biodiesel Production*" and utilization, is trying to promote self-sustainable projects for biodiesel production using different kinds of vegetal oils produced in different regions of the country. Nonetheless, the great majority of vehicles in Brazil still uses fossil fuels.

According to Krisper and Schimmel (1985), in the agricultural scenario, fuel costs represent about 26% of operational costs, and 60% of this value is spent in heavy soil treatment. The Brazilian's agricultural sector needs to minimize costs of production to hit a high level of quality and price, fundamental to survive in a competitive and global market. This can be reached with TPM (Total Productive Maintenance) and Efficient Equipment Operation techniques applied to production's machines.

Tractors are basic machines for agricultural production in large scale and its efficient operation can be reached through three basic factors: (1) maximizing the fuel efficiency of the engine and mechanical efficiency of the drive train, (2) maximizing tractive advantage of the traction devices, and (3) selecting an optimum travel speed for a given tractor-implement system (Grisso *et al.*, 2004). The two first factors have being searched by equipment manufacturers. This includes the development of engines and transmissions with high-energy efficiency, changes in the configurations of tractive devices (size, format and number of tires, ballasting, amongst others). The optimum travel speed for a given tractor-implement system is better applied by managers and/or operators. The main idea is that with the correct choice of gear and travel speed, the engine of the tractor should work in a region of high-energy efficiency and, therefore, low specific volumetric fuel consumption. Through the application of a higher gear and adjusting the governor throttle position, concept known as GUTD (Gear up, throttle down), a significant fuel economy can be reached, specially at light drawbar loads (less than 65% of full power, when reduced PTO (Power take-off) speed is not a problem (Grisso, 2001).

Several researches have been developed aiming the prediction of the fuel consumption in tractors. Grisso *et al.* (2004) presents some equations for fuel consumption prediction in agricultural tractors. These equations are useful to predict fuel consumption in diesel engines during full and partial loads operations and under conditions when engine speeds are reduced from full throttle. Fuel consumption equations for specific tractor models are presented in Grisso *et al.* (2006). By using the latter equations it is possible to reach a higher level of rightness if compared with the equations described by Grisso *et al.* (2004). Such equations helped finding some responsible factors for the fuel consumption variation object of this work. However, there are other factors not explicit in the equations and the determination of such factors consists in a very complex task.

The Fault Tree Analysis (FTA) is known all over the world as an important tool for evaluating the security and reliability of systems project, development and operation. During more than four decades, the FTA is being used in nuclear, aerospace and transport industries. The FTA translates the fault behavior of a system into a visual flowchart, supplying a visual representation of some combinations of possible occurrences in a system that results in a predefined or undesired event (fault). At the flowchart, the structure of the system and the interactions between the several components can be represented and undesired events can be tracked and eliminated. Complex systems, where faults could cause ambient damages or security problems, use this tool from the project to the life end. The FTA methodology will be used in this work, applied to the event "Fuel Consumption Variation". Factors that influence fuel consumption will be listed. Although there is a great amount of variables involved, the FTA will allow a simple and structuralized visualization of these factors, in order to help understanding how to decrease the fuel consumption levels.

This paper is organized as follows: the next item presents the methodology used for the construction of the fault tree analysis. There it is also presented a simulation for the fuel consumption in order to help understanding the influence of each of the parameters used. After that, the following item presents the FTA itself. The parameters responsible for the fuel consumption variation are presented and discussed. That is followed by the flowchart of the FTA for the event in study. The conclusions are presented after that.

2. METHODOLOGY

In order to analyze the influence of each factor involved on tractors fuel consumption variation, a review on the fundamentals of tractor mechanics, fuel consumption equations and Fault Tree Analysis was made (Fernandes, 2007). The theory involved was then used to describe the top event of the FTA, called "Fuel consumption variation". In order to understand the tractor mechanics, a study of the forces and moments commonly applied in a rear traction tractor was performed according to Zoz (1970) and the factors were related with the fuel consumption. The equations described by Grisso *et al.* (2004) and Grisso *et al.* (2006) provided other sources of variables that influence fuel consumption. In the following items, a brief description about that is presented.

2.1. The Fault Tree Analysis (FTA) application

According to Helman and Andery (1995), the FTA method must be implemented following some guidelines listed below, which are shown and described for the problem of interest in this work:

2.1.1. Definition of the top event (undesired effect)

During fuel consumption monitoring of tractors used at a heavy construction company, great variations on fuel consumption values had been noticed for tractors of the same model. In order to understand this problem and to explain the reasons for this variation, the FTA was used as a tool for determining the causes for the consumption variation. Therefore, the top event of the FTA was defined as "fuel consumption variation". Although variation in the fuel consumption is not necessarily a fault of the equipment, it was attributed as such in order to apply the technique and to detect the causes of this variation. By this way, the events responsible for the fuel variation could be determined.

2.1.2. Definition of the causes affecting the top event

Applying the mathematical modeling equations and foundation, some factors responsible for the variation in the fuel consumption had been related. These and other factors had been found in the literature or were directly related to the fuel system and fuel measurement system.

2.1.3. Grouping the responsible causes for the several events

The causes for the several events were defined, separated and related to the events at higher levels, so to allow the development of the events. The causes had been defined and grouped into main factors such as: slip, operation, fuel, environment, equipment, data acquisition system and security. Secondary events had been related and grouped in branches of the FTA.

2.1.4. Determination of logical relationships between causes

It was noted that any event that occurs separately could have an influence on the fuel consumption variation. So, the logical gate "or" was applied to all logical relationships.

2.1.5. Elimination of the causes to avoid the top event

As the top event is fuel consumption variation, which is not necessarily a fault, some causes cannot be eliminated since they are part of the normal functioning processes of the tractor. So, an adaptation for this FTA was made. By knowledge of the causes that can affect the fuel consumption, preventive or corrective actions should be taken to control these factors and promote a reduction in the values of fuel consumption.

2.2. Fuel consumption simulation

In order to detect the influence of some parameters on fuel consumption, some simulations were made. They helped understanding the importance of each parameters used in the FTA presented later.

According to Grisso *et al.* (2004), the fuel consumption for partial loads and reduced throttle settings can be described by Eq. 1:

$$Q = (0.22X + 0.096)(1 - (-0.0045X \times N_{\mathrm{Re}\,d} + 0.00877 \times N_{\mathrm{Re}\,d})) \times P_{pto} \qquad (1)$$

where:

Q = diesel fuel consumption at partial load and full/reduced throttle, [L/h],
X = the ratio of equivalent PTO power to rated PTO power, [decimal],
N_{Red} = the percentage of reduced engine speed for a partial load from full throttle, [%]
P_{pto} = the rated PTO power, kW [hp]

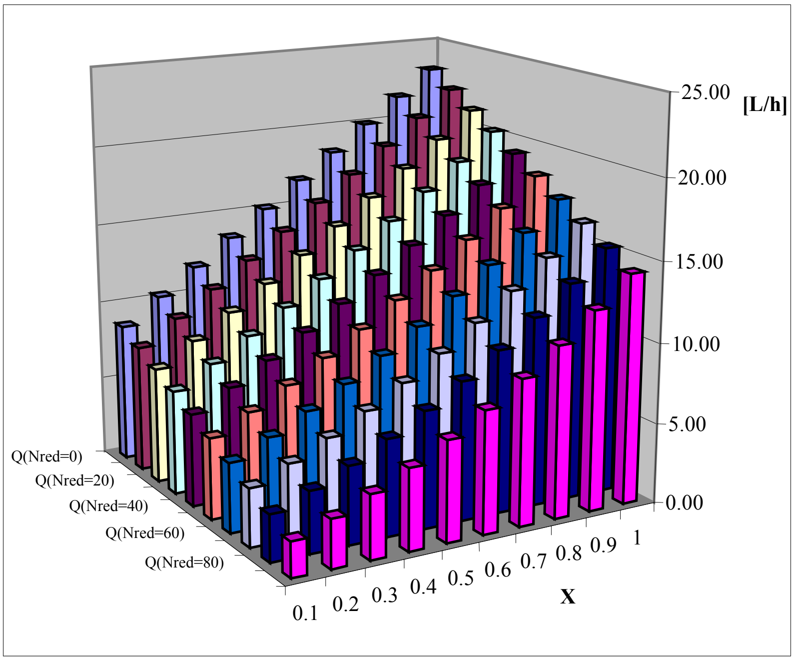

Figure 1 –Fuel Consumption Levels plot for a VALMET 128 4x4 Tractor

Equation 1 was then simulated for a tractor model found in the Brazilian market, in order to verify its consumption fuel level. The VALMET model 128 4x4, with a rated engine power of 89.7 kW was chosen for this simulation. According to Zoz (1987), only 0.82 to 0.84 of the engine power goes to the PTO. So, the rated PTO power was found assuming the smaller of the two efficiencies (i.e., the worse condition). The PTO power of this tractor was then varied in order to get a plot of the fuel consumption as a function of the engine rotation and the percentage of reduced engine speed, Fig. 1.

According to the plot of Fig. 1, the fuel consumption dependence can be visualized and related to the variables power rate and decrease in engine rotation (%). As an example, for a maximum fuel consumption condition, i.e., rated power of one (*X*=1), and maximum rotation (*Q(Nred*=0)), a consumption of 23.24 [L/h] is found. In the condition of minimum consumption, with rated power of 0.1 and rotation reduced in 90%, a fuel consumption of 2.18[L/h] is found, value that represents 9.38% of the maximum value found.

3. FTA CONSTRUCTION

3.1. FTA Parameters

Through the carried out study and methodology presented, the FTA for the top event "Fuel consumption variation" was obtained. The parameters responsible for the fuel consumption variation in tractors are listed below:

3.1.1. Slip

The slippage occurs due the tractive system (tire) deformation, when tire and the surface slips, or when an internal shear in ground structure occurs. Equation 2 gives the variation in fuel consumption caused by slip, according to Giedra e Janulevicius (2005):

$$Q_{TR} = P_e \cdot TR \cdot \eta_{tr} \cdot SVFC \qquad (2)$$

Where:

Q_{TR} = fuel consumption for wheel slippage
P_e = engine power applied [kW]
TR = Slippage coefficient [decimal]
η_{TR} = coefficient of transmission efficiency [decimal]
$SVFC$ = specific volumetric fuel consumption [L/kW.h]

The slip influences the tractive efficiency and fuel consumption. According to Eq. 2, the fuel consumption is a linear function of slippage, that is, the bigger is the slippage, the greater is the fuel consumption. However, the slip is necessary to achieve high tractive force, and the fuel consumption can be minimized by the selection of the correct values of slip. Slip values between 5% and 13% provides maximum tractive efficiency, Zoz et al. (2002). Fernandes et al. (2007) and Fernandes (2007) presented the slippage influence on fuel consumption by using a FTA technique, showing the factors affecting the fuel consumption and related to the slippage analysis.

3.1.2. Operation

The operation factors can be modified by the operator and they can be affected by human faults amongst which can be highlighted the engine rotation and the gear ratio. During the operation of the tractor, the operator can control the engine rotation in order to reduce fuel consumption, forcing the engine to work in a region of maximum fuel efficiency. Applying the "Gear up, throttle down" concept, a reduction in fuel consumption can be obtained.

In accordance with the NTTL - Nebraska Tractor Test Laboratory, at 50% of workload and reduced rotation, in average, an 18% decrease in the fuel consumption was obtained. Therefore, in order to reduce the fuel consumption, it is necessary a good practice of the operator. By detecting a reduction in the power demand, he should adjust the gear so to decrease the fuel consumption.

3.1.3. Fuel

The fuel itself, responsible to supply thermal energy for the engine, is also subject to failure and, therefore, it will influence the fuel consumption. Factors responsible for fuel failures and directly related to fuel consumption are: fuel contamination (caused by water and/or sediments) and fuel out of specification. The type of fuel used (GLP, gas, diesel) has also a direct link to consumption.

3.1.4. Environment

Environment factors are unrelated to the equipment and operator, although influence the tractor efficiency. Therefore, they are also responsible for great variations in consumption. Severe conditions of service will demand high engine power, increasing the fuel consumption. The hardness and type of soil will cause variations in slip and tractive efficiency, having a direct effect on the fuel consumption. The service power is defined as the work carried out during a certain period of time. In tractors, it can be obtained multiplying the drawbar pull to the tractor's displacement speed. The service power is one of the factors that most influence the fuel consumption. It is affected by the ground type, the work speed, the drawbar pull and/or the power requirements of the implement used. The air temperature, humidity and atmospheric pressure influences the air density that enters in the combustion chamber, thus influencing the fuel consumption, the engine's power and emissions. Nevertheless, no work was found quantifying the weighing of these factors on fuel consumption.

3.1.5. Equipment

The age of the equipment will also affect the fuel consumption. According to Siemens and Bowers (1999), depending on the type of fuel and the time of use of a tractor or machine, the costs with lubricant and fuels will represent 16% to 45% of the total costs of the machine. According to Grisso *et al*. (2004), the Nebraska Tractors Test Laboratory (NTTL) findings showed that the average annual specific volumetric fuel consumption fell about 4.8% during the last 20 years. The reason is the evolution of the diesel engines and due to the electronic injection systems. Other equipment devices responsible for fuel consumption variation includes: adjustment and state of injection pumps (injection time), condition of the injection nozzles, fuel filters, air filters, tires, ballasting/weight of tractor, efficiency of the transmission devices, engine power (rated) and fuel leakage on fuel lines.

3.1.6. Data Acquisition System

The system used to collect fuel consumption data also can bring some fonts of errors. If one automatic system is being used, the fails are related with the components of the system. In real cases, the most common procedure to measure fuel consumption in loco is by writing down the amount of fuel used and the hour indicator measure at the moment of refueling. In this system, it is important to guarantee the reliability of the data collected. Generally, failures on this kind of measurements are font of arbitrary errors.

3.1.7. Security

If none of the previous items are affecting the fuel consumption of the machine(s), one needs to be careful, as someone could be taking off the fuel from the tank. It is important to keep the machine in a safe place, avoiding in this way the fuel robbery.

3.2. FTA Representation

Figure 2 shows the FTA obtained for the Fuel Consumption Variation of Tractors according to the parameters mentioned in the previous topic. Only OR gates were used for its construction since for each parameter no sub-parameter depends on the other. For some of the parameters, it was possible to quantify the percentage influence on the fuel consumption variation based on the literature. For the others, more research is necessary. The way the values were quantified was based on the extremes of each situation. For example, slip influence on fuel consumption was obtained based on Eq. (2), assuming no slip and 18% slip as the extremes, resulting in a 25% maximum variation. For operation, the concept of GUTD was used, resulting in a 15% variation. The fuel influence on consumption was based on ASAE data as stated by Grisso (2004) which mentions that diesel tractors consumes 73% less fuel than gasoline tractors, whereas liquefied petroleum LP gas tractors will use approximately 120% more. Using such values produces a variation up to 55%. Finally, environmental influence was obtained by varying the parameter X in Eq. (1) from 0.1 to 1 for a constant $N_{erd.}$, resulting in a work power influence up to 160%.

The FTA representation shown can be used by many sectors. The owners can use it to choose a suitable tractor for his application. The managers can use it for training and maintenance operations. The operators of tractors can use it in order to optimize the operation of the machines. The consequence for all is a gain on fuel consumption reduction.

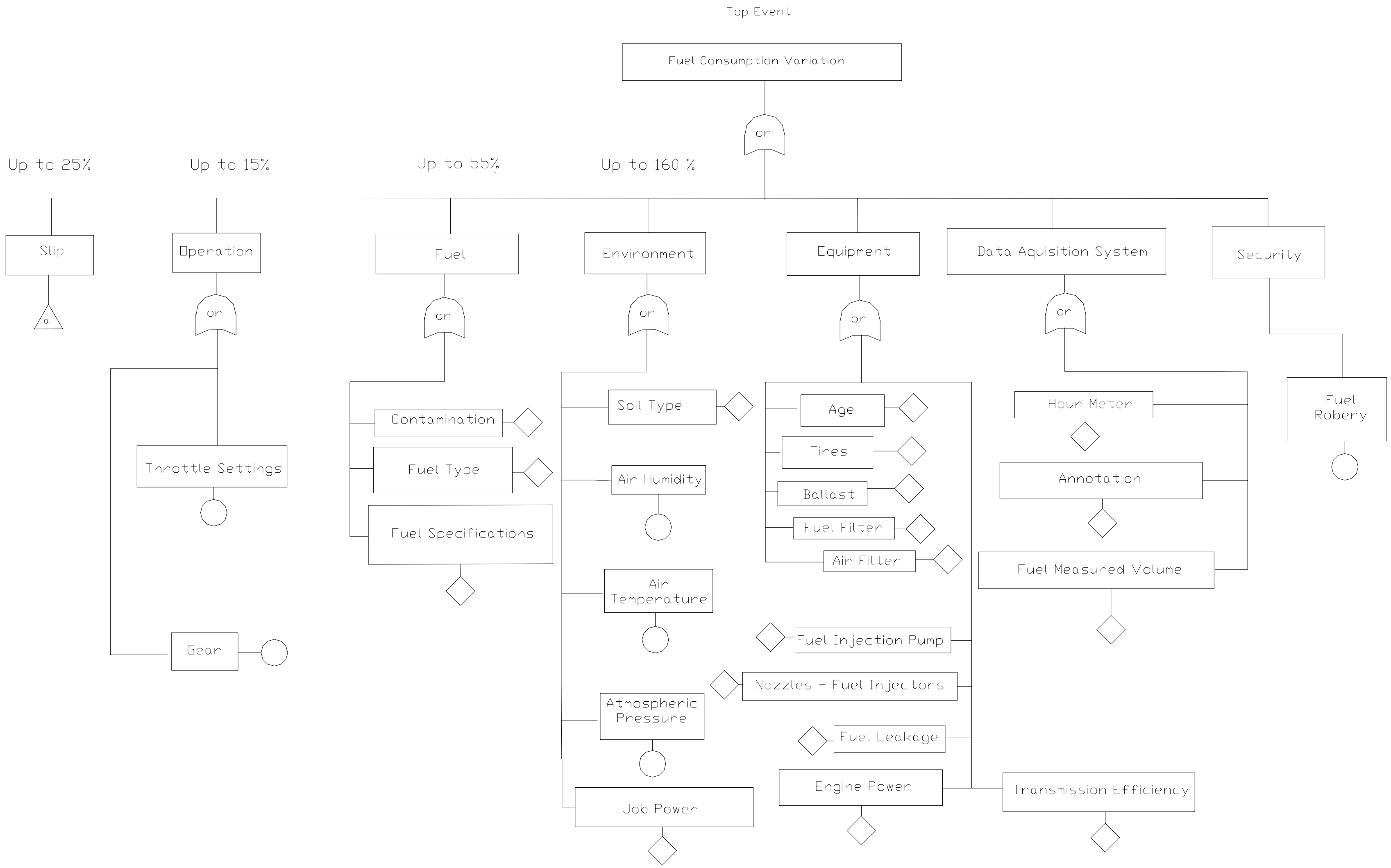

Figure 2 – FTA for the Fuel Consumption Variation in Tractors

4. CONCLUSIONS

The FTA based methodology used for the determination of the fuel consumption in tractors has revealed very useful in identifying the several factors responsible for the variation in the fuel consumption of tractors. However, quantifying the weight of some of the parameters in the fuel consumption could not been entirely determined being a source for more research. The parameters were found in the literature and the weight calculated based on available equations and information.

As presented, the most important parameter for the fuel consumption of tractors is the work power (up to 160%), followed by the type of fuel used (up to 55%), slippage (up to 25% for TR<18%) and efficient operation methods (around 15%).

The methodology presented can be adapted for operators' training programs and should be widely adopted with the objective of searching practical solutions for fuel consumption levels reduction in tractors. The FTA presented can also benefit other sectors such as owners and managers.

5. ACKNOWLEDGMENTS

The authors would like to thanks CAPES for the payment of the scholarship and FAPEMIG for the financial support to attend the conference.

6. REFERENCES

Fernandes, J. A., 2007, "Tractors Fuel Consumption Variation Study by Using the Fault Tree Analysis – FTA" (in Portuguese), M.Sc. dissertation, Mechanical Engineering Department, Federal University of Minas Gerais, Belo Horizonte, MG, Brazil.

Fernandes, J. A., Duarte, M.L.M., Eduardo, A.C., 2007, "Slippage Influence on Fuel Consumption by Using FTA Technique" Proceedings of the COBEM 2007, 19th International Congress of Mechanical Engineering, Vol.1, Brasília, Brazil.

Giedra, K.; Janulevicius, A., 2005, "Tractor Ballasting in Field Transport Work". TRANSPORT, Vol XX, No 4, pp 146–153.

Grisso, R. D. and Pitman, 2001. "Gear up and Throttle down - Saving Fuel". Virginia Cooperative Extension Publication 442-450, Virginia Tech, Blacksburg, VA, <http://www. ext.vt.edu/pubs/bse/442-450/442-450.pdf>

Grisso, R.D.; Korcher, M. F.; and Vaughan, D.H., 2004. "Predicting tractor fuel consumption". Applied Eng. in Agriculture 20(5): 553-561.

Grisso, R. D.; Vaughan, D. H.; Roberson, G. T., 2006. "Method for Fuel Prediction for Specific Tractor Models"; ASABE Meeting Presentation, Paper Number 061089. Portland, Oregon.

Helman H., Andery, P. R. P. 1995, "Análise de Falhas. Aplicação de FMEA e FTA". Belo Horizonte: Editora Fundação Cristiano Ottoni, 156 p., 1995.

Krisper, G.; Schimmel, J.,1985, "Electronic driver information and automatic shifting system for tractors". Paper 85051. Presented: International Symposium on Automotive Technology & Automation, Vienna, Austria, ISATA.

Siemens, J. C. and Bowers, 1999, W. W. Machinery Management: how to select Machinery to fit the real needs of farm managers. Farm Business Management (FMB) series, John Deere Publishing, East Moline, JL.

Zoz, F. M., 1970, "Predicting Tractor Field Performance". ASAE Paper No. 70-118, July 1970.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.