SLIPPAGE INFLUENCE ON FUEL CONSUMPTION BY USING FTA TECHNIQUE

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Abstract. *In the modern world, there is a strong dependence of non-renewable energy resources, such as fossil fuels, which have high costs associated with its use. Diesel tractors used in agriculture are an example of this situation. So, it is important to understand and quantify the parameters that influence the fuel consumption of such tractors. After a literature review, it was found that one of the most important factors related to the fuel consumption variation is the slippage. By dealing with an event that by itself has many parameters to be raised, the FTA methodology is used in this paper to develop the top event "slippage" in tractors. The FTA is able to show the actual and theoretical speed's influence in this event. Factors like tires, ground and dynamic weight affects the real speed, while engine frequency, gear ratio and tire diameter are responsible for the theoretical speed. By knowing the critical parameters responsible for the slip, a reduction on fuel consumption can be achieved by the manufacturers, operators and maintenance workers.*

Keywords*: tractors, slippage, Fault Tree Analysis*

1. INTRODUCTION

During field operation of tractors, some objectives are sought: the service should be performed in a satisfactory way, both the time spent in the process, as well as the costs associated with fuel consumption, should be decreased, resulting in a production increase. After a literature review, it was found that an important factor related to both time spent and the fuel consumption variation, therefore, affecting the other factors, is the slippage. Slip, also called travel reduction, is a percentage of speed reduction, caused by wheel slip, tire deformations and/or shear on soil structure. Excessive slip can cause a considerable increase in fuel consumption.

So, the objective of this study is to understand the slippage process through Fault Tree Analysis (FTA) technique, applying the results in the investigation of the causes that directly or indirectly affects the fuel consumption levels in tractors.

This paper is organized as follows: section 2, presents a literature review about the slippage process. Section 3 presents the basic tractor relationships, considering the slippage as the ratio of speeds. There, it is also shown the relation between drawbar pull, rear weight static and dynamic weight coefficient. Section 4 presents a basic overview of the fault tree analysis technique and includes fundamental step-by-step instructions for using this methodology. Section 5 presents the factors that will be relevant to the construction of the FTA related to slippage. Section 5.3 presents the FTA developed for the factors obtained. Section 6 presents an analysis of the slippage's influence in fuel consumption model to verify the influence of the slip in fuel consumption variation. Finally, section 7 shows the conclusions of the current study.

2. LITERATURE REVIEW ABOUT SLIPPAGE

According to Zoz and Wiley (1995), the optimum slip, that is the slip required for optimum Tractive Efficiency (TE), varies significantly with soil and tractive device and it can only be used as a rough guideline for proper ballasting. Wheel slip depends upon the soil surface, travel speed and power input to the wheel or tractive device, as well as upon weight (both static and that transferred dynamically from implements and by the tractor itself). Brixius and Zoz (1987) show a plot of tractive efficiency as a function of slip for several ballasting conditions, where the maximum tractive value is obtained when the wheel operates between 5% to 20% slip. Burt *et al.* (1982) achieved similar results. They showed that depending on the soil surface, minimum specific fuel consumption is obtained for these same values of slip. For slip of less than 5%, a large portion of the input power is required to overcome tire motion resistance. Above 20% slip, a high portion of the input power is lost in slip. The determination of an optimum slip coefficient is a very hard task and different values from different authors were found. Corrêa *et al.* (1998) use the value of 10% slip as reference for maximum tractive efficiency in some agricultural soil conditions. Other authors like Wulfsohn *et al.* (1998); Dwyer and Febo (1987); Gee-Clough *et al.* (1977) use a value of 20%, expressing the tractive liquid coefficient.

Barbosa *et al.* (2005) consider that 30% slip represents an extreme loss of energy on traction devices situation, not impossible to be found in agricultural operations. According to Brixius and Zoz (1987), the pull ratio and drawbar pull increases with slippage, while tractive efficiency decreases with high slip levels. Therefore, a compromise in vehicle operation must be reached between obtaining maximum tractive efficiency and high drawbar pull.

3. FUNDAMENTAL CONCEPTS RELATED WITH SLIPPAGE IN TRACTORS

In order to understand the above studies and the physics involved in the process of slippage, some well-known relationships are presented, and the theoretical information used for the FTA development.

3.1. The Slip Relationship (*TR*)

According to Zoz (1970), slippage (Travel Reduction) is obtained through the ratio of speeds as shown in Eq. (1):

$$TR(\%) = 100 \cdot \left(1 - \frac{SA}{SO}\right) \quad (1)$$

Where:

SA = Actual tractor travel speed (Tractor Real Speed), MPH
SO = “No-Load” or theoretical travel speed (Wheel Peripheral Speed at loaded radius), MPH

The actual speed is the real speed of the tractor, based on the displacement of the tractor in relation to the ground. The actual speed can be measured with radar, for example. The “no-load” travel speed, also called “Wheel Peripheral Speed”, is imposed by the engine rotation, the gear ratio (transmission) and the wheel diameter. When the actual speed is different from the theoretical speed, slippage occurs.

The ASAE Standards (2001) defines zero slip (or zero travel reduction) by four different methods, some of them based on zero net traction and some based on zero gross traction.

Zoz and Grisso (2003) mentions that the word “slip” or “% slip” to refer to travel reduction is technically incorrect. Slip occurs between surfaces. Travel reduction is a reduction in the distance traveled and/or the speed that occurs because of: a) Flexing of the tractive device; b) Slip between the surfaces (rubber and concrete, for example); and c) Shear within the soil surfaces. From the point of view of power efficiency, travel reduction is a power loss caused by a loss in travel speed or distance traveled. Slip (travel reduction) occurs any time a wheel or traction device develops pull (net traction) (Brixius and Wismer, 1978).

3.2. Theoretical Speed (*SO*)

According to Zoz (1970), the theoretical speed of the tractor can be obtained by Eq. (2):

$$SO = \frac{(Eng.RPM) \cdot (LR)}{(GR) \cdot (168{,}1)} \quad (2)$$

Where:

Eng. RPM = Engine Rotation, rpm.
LR = Wheel Effective Radius, Inches.
GR = Gear Ratio

Therefore, in order to change the theoretical speed, the operator can change the gear used, as well as the rotation of the engine. The wheel effective radius is related to the tire type and conditions and the weight carried.

3.3. Dynamic Ratio (*DR*)

The dynamic ratio is defined as the ratio between the drawbar pull and the dynamic weight on the wheels. It can be calculated by Eq. (3):

$$DR = \frac{P}{RWS + P(DWC)} \quad (3)$$

Where:

DR = Dynamic Ratio

P = Drawbar Pull, lbs
RWS = Rear Weight Static, lbs
DWC = Dynamic Weight Transfer Coefficient

Therefore, the tires, the soil and the coefficient of traction, also called Dynamic Ratio (*DR*), will influence the actual speed.

3.4. Dynamic Weight Transfer Coefficient (*DWC*)

The Dynamic Weight Transfer Coefficient represents the percentage of weight transferred from the front axle and implement to the rear axle. It is defined as follows:

$$DWC = \left[\frac{H}{WB} + \left(1 + \frac{B}{WB} \right) \tan\theta \right] \quad (4)$$

Where:

H = Vertical coordinate of the implement application point, inches
B = Horizontal coordinate of the implement application point, inches
WB = Wheelbase, inches
θ = Angle of the total resultant force in relation to the horizontal line.

This coefficient is related to the dynamic ratio of the tractor, as shown in the previous item, and it will be, therefore, linked to the actual speed of the tractor. So, by changing this coefficient, it is possible to change the actual speed considered.

4. FUNDAMENTALS OF FAULT TREE ANALYSIS (FTA)

Fault tree analysis is a systematic way to investigate causes for an undesired event in a system (Stamatelatos and Vesely, 2002; Vesely et al., 1981). The logical relationships between the undesired event and the basic events leading to the undesired event are presented in a structured way called fault tree.

4.1. Basic Definitions:

The basic definitions and conventions used at fault trees are:

a) **Top event and intermediate events:** A rectangle is used to represent the top event and any intermediate fault events in a fault tree. The top event is what is being analyzed. Intermediate events are occurrences that contribute to the top event.
b) **Basic events:** A circle is used to represent basic events in a fault tree. It is the lowest level of resolution in the fault tree.
c) **Not developed events:** A diamond is used to represent human errors and events that are not further developed in the fault tree.
d) **Gates:** The gates are logical relationships like “or”, “and”, “not or” and “not and” that connect the several events at a tree. For example, for the “and” gate, the output event associated with this gate exists only if all of the input events exist simultaneously.

4.2. The Fault Tree Development Steps:

According to Helman and Andery (1995), the FTA method must be implemented following some guidelines, as follows:

a) **Definition of the top event (undesired event):** The event to be developed needs to be defined first. It may be a fault, an undesirable event or an event that needs to be controlled;
b) **Definition of the causes affecting the top event:** Any event that will contribute to the top event needs to be determined at this step;
c) **Grouping the responsible causes of the several events:** After defining the causes for the several events, they need to be grouped and related to the events at higher levels, so to allow the development of the events.
d) **Determination of logical relationships between causes:** By observing how the events are correlated to each other, it is possible to determine the type of gate to be used to connect the causes affecting the top event.
e) **Elimination of the causes to avoid the top event:** In this step it is necessary to examine how it is possible to eliminate the events causing the top event.

Each step must be carefully investigated in order to have the fault tree as close as possible to reality. In the following section, the FTA is developed and explained for the object of interest of this study.

5. APPLICATION OF THE FAULT TREE ANALYSIS (FTA) FOR THE SLIPPAGE PROCESS

5.1. FTA Definitions

The FTA was developed for the problem of interest of this study following the steps proposed by Helman and Andery (1995) and presented in the previous section.

Before the construction of the FTA for the slippage, a review of the fundamentals and researches involving the top event slip was necessary in order to understand the system dynamics and the variables that affect the slip process in tractors as showed in sections 2 and 3.

The top event for the present fault tree was defined as slippage, since it is the event that needs to be controlled and understood. That fault tree came as a part of a bigger FTA, the FTA for the fuel consumption variation, described by Fernandes (2007) and Fernandes *et al.* (2007). The reason for that derivation is related to the fact that it has several factors associated to it that could be developed by its own.

Then the causes affecting the top event were obtained after modeling the tractor mechanics (Fernandes, 2007). These were found either in the literature or directly related to the tractive system, equipment and operational conditions. Such causes were grouped into two main parameters connected to the top event: actual and theoretical speeds, as it will be better explained in section 5.2. It was also possible to group in a following level some causes linked to this first level.

Since any event of this process occurring separately could have an influence on the slippage variation, the logical gate “or” was applied to all logical relationships.

The top event of the current fault tree is not properly a fault. It comes as part of a normal functioning process of the tractor device. So, it is not possible to eliminate its cause and an adaptation for this FTA was made in that respect.

By knowledge of the causes that can affect the slippage, preventive or corrective actions should be taken to control these factors, consequently promoting a reduction in fuel consumption, since slippage and fuel consumption are related.

Next, the parameters (causes) responsible for the slippage process will be presented in a more detailed way, in order to allow the construction of the FTA.

5.2. FTA Parameters

After the methodology presented in the previous section, the FTA for the top event “Slippage Variation” was obtained using to the following parameters:

5.2.1. Theoretical Speed

As mentioned in section 3, the theoretical speed is the speed that will occur if the slippage is zero. However, in field operations the theoretical speed is always different from the actual or real speed, so, slippage always occurs. By means of Eq. (2) it is possible to define the theoretical speed as a function of the engine speed, the gear selection and the tires size. During field operations, the engine speed is also a function of the load applied on it, related with its power capacity. The power rate is the ratio of the power required for the service and the rated power of the tractor. It will determine, together with the throttle settings imposed by the operator, the engine speed.

The operator can control the engine rotation, since it is associated with the gear selection, the throttle settings and the power rate and it is a relevant way to decrease the fuel consumption levels. In some situations, especially at light load applications, the operator can reduce the engine speed by selecting a higher gear, maintaining the travel speed. This concept is known as GUTD (Gear Up, Throttle Down). In a tractor with CVT (Continually Variable Transmission), the operator does not select the best gear for the service, since the transmission will select that automatically. Variable transmissions also allow travel at the fastest speed possible without also running the engine at top rpm. This adds further fuel savings during light-duty operation and transport. Therefore, an expressive economy in fuel consumption can be reached (Smith, 2005).

5.2.2. Actual Speed

The actual speed is the real speed of the tractor. It can be measured with radar, GPS (Global Positioning Systems), or manually by dividing the distance traveled by the time. The ratio between its value and the theoretical speed provides the slippage values. The Actual speed is a function of: tires, soil, and the weight of the tractor.

The slippage caused by the tire is a function of its size, type (radial, bias-ply), number (single, duals), dimensions, wear level, tread depth and pressure.

The soil physical properties are governed by its compaction, texture (levels of sand, silt and clay), and structure (granular, platy, blocky or prismatic).

The dynamic weight determines the amount of weight that will be transferred from the front axle and implement to the rear axle of the tractor, during the application and it is based on the rear static weight, the drawbar pull and the hitching system.

5.3. FTA Structure

The parameters shown in the section 5.2 were used in the construction of the FTA for slippage variation in tractor as shown in Fig. (1).

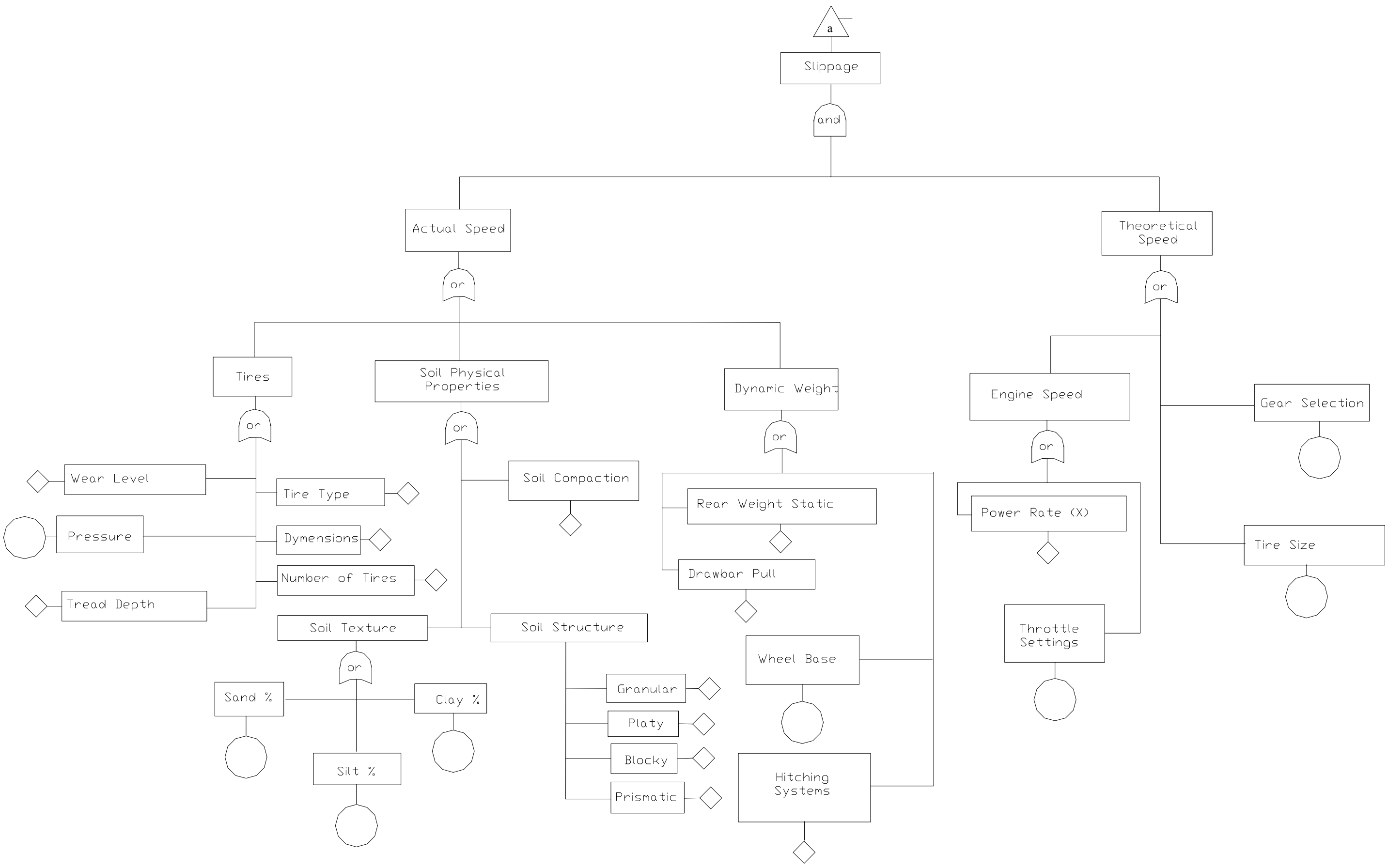

Figure 1 – FTA for Slippage Variation

6. SLIPPAGE INFLUENCE IN FUEL CONSUMPTION

After showing the parameters responsible for the slippage variation in tractors by using the FTA, it is important to associate that with the fuel consumption.

Giedra and Janulevicius (2005) present an analysis of ballast weight and wheel slippage's influence on fuel consumption, under various field and road conditions. Equation (5) gives the variation in fuel consumption caused by slip:

$$Q_{TR} = P_e \cdot TR \cdot \eta_{tr} \cdot SVFC \tag{5}$$

Where:

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

Equation (5) was then used to model the slippage influence in fuel consumption of tractors. Values of 0.9 and 0.3 (L/kW.h) were taken for the transmission efficiency coefficient and specific volumetric fuel consumption, respectively and the engine power applied chosen as 50, 80, 110, 160, 220, 260, 310 kW. Values for slippage were varied from 0% (no slippage) to 18% (extreme situation where the soil deteriorates and the utilization of tire tractors are not recommended, Grašis and Janulevičius (1999), Upadhyaya *et al.* (1997) e Jun *et al.* (1998)).

Figure 2 shows a plot of fuel consumption as a function of slippage, for several levels of engine power.

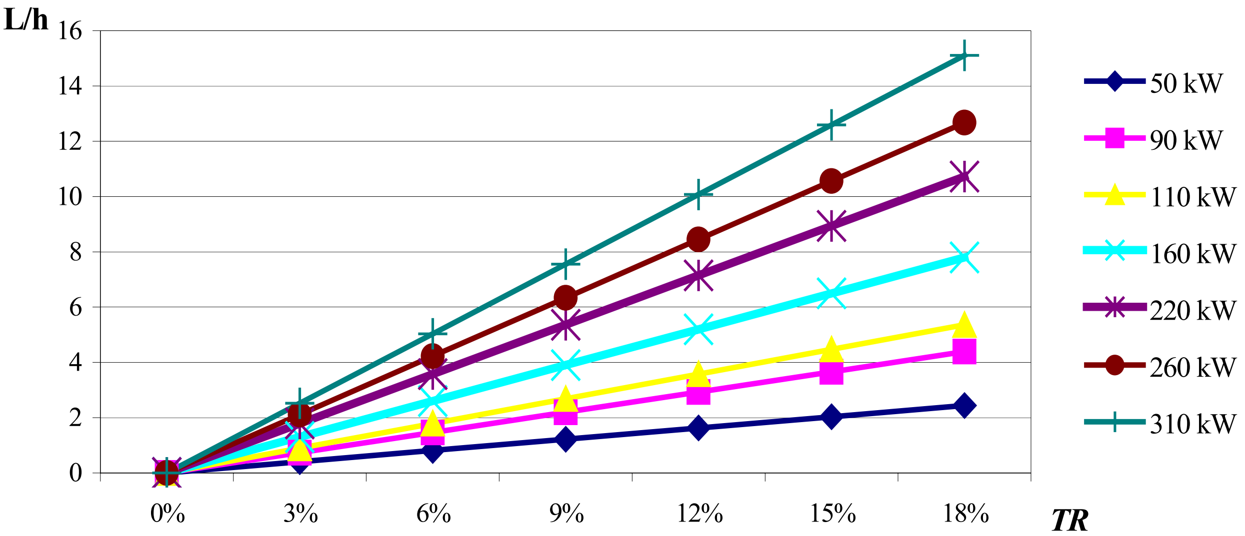

Figure 2 –Slip vs. Fuel Consumption at η_{tr} = 0,9 and SVFC = 0.3 (L/kW.h).

According to Eq. (5), and it can be seem in Fig. (2), the fuel consumption is a linear function of slippage, that is, the bigger is the slippage, the greater is the fuel consumption. However, slip is necessary in order to achieve high tractive force, being the two parameters related. There is an optimum value of slip so to get maximum tractive efficiency. So, there should exist a compromise between maximum tractive efficiency (low fuel consumption) and high wheel pull (high fuel consumption), which are function of the slippage process. So, fuel consumption, slippage and tractive efficiency are related and should be optimized, in order to operate in a more efficient and economical way.

In order to investigate the influence of the slippage in fuel consumption, a tractor commonly founded at Brazilian fields, with 90 kW of engine power was chosen, and its average annual fuel consumption, estimated. Eq. 6 describes the fuel consumption of tractors at full throttle and it was used to estimate the fuel consumption level of this tractor (ASAE Standards, 2002).

$$Q_{AVG} = 0.233 \times 0.9 \times P_{Engine} \tag{6}$$

Where:

Q_{AVG} =Average Annual Fuel Consumption (L/h)
P_{Engine} =Engine rated Power (kW)

The coefficient of 0.9 was applied to Eq. 6 to represent looses between the engine and the power take off (Zoz, 1970). The value of 18.87 [L/h] was obtained for the annual average fuel consumption. This value includes effects of slippage between other field related effects. According to Fig. 2, for a tractor with a rated power of 89.7 kW, the variation in fuel consumption caused by an 18% slip is about 5.36 [L/h], which represents around 23% of the annual average fuel consumption value. Therefore, it can be said that for slippages up to 18%, the fuel consumption variation is about 23%.

7. CONCLUSIONS

By means of the slippage related equations, the FTA methodology was applied and the slippage responsible factors had been detected. The FTA methodology allows a structuralized view of the most important variables that affects the slippage. However, it is necessary more research to investigate each factor alone and its influence for the top event "slip".

Slippage has an expressive influence in the fuel consumption of tractors, so it is desirable to minimize its value. However, slippage is required in order to increase the tractive efficiency and drawbar pull, besides being an event that will always happen. So, a compromise should be achieved between slippage, fuel consumption and tractive efficiency. Although some studies concluded that 7% slippage maximizes the tractive efficiency, therefore, fuel efficiency, since many of the factors responsible for the slippage process are not constant (like the soil properties), a value between 5% to 13% should be used in order to decrease the SVFC (Specific Volumetric Fuel Coefficient).

The FTA for the slippage process shows that many factors are responsible for its variation. The main factors are the theoretical and actual speeds. The actual speed is a function of the soil properties, tires geometry and construction, amount of ballasting, weight distribution of the tractor (Dynamic Coefficient), among others. The theoretical speed is a function of the engine speed, gear ratio and tire diameter.

Some actions can be taken to reduce slippage, like the choice of radial tires instead of bias-ply, tire wear level monitoring, pressure calibration, increasing in the number of tires (dual tires). The addition of weight to the tractor (ballasting) can be taken, but excessive ballast can compact excessively the ground, increasing the power necessary for the service, therefore, the fuel consumption. For the maximum operational efficiency, the operator should select the correct gear and engine speed, applying the GUTD (Gear up, throttle down) concept.

The main conclusion of this work is that slippage values up to 18% influences the fuel consumption in about 23%. For situations where slippage is greater than this value, the losses in fuel efficiency increases so much, not allowing the economical application of tire tractors. In this case, the actions showed above must be implemented in order to decrease the slippage process.

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