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FAULT TREE ANALYSIS FOR NON-STOICHIOMETRIC COMBUSTION OF DIESEL GAS ENGINE

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Abstract. *In order to reduce pollutants emissions from internal combustion engines with compression blend ignition designed to operate as the Diesel cycle, new devices have been developed in recent years to operate as the Diesel cycle with the addition of new fuels, which in addition to reducing pollutant emission could lower the cost of operation due to the possibility of use of some fuels of greater availability. In this case, the diesel oil is used only as the pilot flame, which is responsible for the ignition of the second fuel, the natural gas. Many publications discuss the environmental and economic gains of the use of natural gas as fuel application; however, nothing is said about the change of reliability indexes and the appearance of new failure modes in the engine. In this study, we analyze the non-stoichiometric combustion of this engine through a system reliability analysis tool called Fault Tree Analysis (FTA), a failure mode that is inserted in the internal combustion engine when it starts to operate as dual fuel . For this analysis, it is necessary to split the engine into subsystems showing its functional tree and integrate a diesel gas kit in this system. New failure mode occurs with greater severity than the existing in the traditional diesel engine system, leading to new design and maintenance practices. The end-user, according to this need, will have an extra parameter to choose from whether to adopt a Diesel Gas system.*

Keywords: stoichiometric*, engine, diesel gas, dual fuel, reliability*

1. INTRODUCTION

The diesel engine is present in the movement of cars, trucks, trains, ships and power generators, so it is a great symbol of the technological advancement of the 20th and 21st centuries, but a big inconvenience of this equipment is its emission of pollutants, which causes damages to the environment and human health. Because of this, in recent years, alternatives for the reduction of harmful elements emitted by this engine, such as sulfur dioxide and particulate matter, have been pursued [41].

An alternative found is to replace much of the diesel fuel by natural gas, which has no sulfur in its composition and does not emit particulate matter, in the diesel engine by installing a device called “diesel gas kit”, which introduces the natural gas responsible for replacing much of the diesel fuel into the combustion chamber.

However, the addition of a new device to the engine will cause new failure modes and intensify certain existing failure modes of the Diesel engine, one of cases will occur with non-stoichiometric combustion [4].

Stoichiometry is the correct proportionality of fuel for complete combustion, and when these proportionalities are not respected, engine failures, loss of performance, and discharge of unburned fuel in the environment may occur[55]. Through fault tree analysis, this study will assess the probability of non-stoichiometric combustion in an engine adapted for “diesel gas kit”.

Initially, we will carry out a detailed study on the "diesel gas kit" device, analyzing the functionality of its components and their respective failure modes, and how non-stoichiometric combustion would develop. This way, through published databases, we show the reliability indices of each component directly involved in this failure mode and display the occurrence values of this failure for 4000 hours - which would be the time of the first major revision for small trucks traveling in urban stretches, and for the time evolution of this failure [35], [40].

In this study, we aim to guide the designer in the development of this type of device and to analyze the reduction in the occurrence of this type of failure, and also to provide end-users with a parameter to better evaluate the choice for this type of system.

2. LITERATURE REVIEW

Reliability and Failures

Generally speaking, reliability is associated with the successful operation of equipment, that is, equipment that performs the functions for which it has been designed, preferably in the absence of failures. In engineering analysis, we must define reliability as a probability [52], [46].

However, to define reliability is also necessary to define failure. The term failure is difficult to define because it depends on each particular case. In general, the term is defined as the failure of a component or system in meeting its expected performance. Failure is directly associated with the user's needs and concepts of the item or system, because there can be simple defects that alter a system only visually, or complex, catastrophic failures that could endanger the operators' lives or the environment integrity [7], [16], [46].

To perform analyses of reliability under the parametric approach, using statistical methods based on failure data experimentally collected associated with the phenomenon studied, one can adjust the distribution that best represents the probability density function of failure times, allowing consequently to determine the best statistical representation of the functions of reliability and failure rate [16], [28].

In this article, because of the failure mechanisms of the components presented in the text, exponential models are utilized, which can be used to model the reliability of systems with heterogeneous causes of failures and independent random failure rates [16], [46] - quite common in electronic components, and the Weibull model, which appears to be quite adequate for the analysis of failure in mechanical equipment, which usually occur as a consequence of accumulated damage [18].

Exponential distribution

Exponential distribution is characterized by a function of constant failure rate, and is the only one with this property. It is one of the simplest mathematical terms, and is extensively used as a model for the lifetime of electronic products [46], [56].

It is employed in cases where failures occur randomly with a fixed rate and with no wear mechanism; the probability density function for the failure time t with exponential distribution is given by the equation:

$$f(t) = (1/\alpha)e^{(-t/\alpha)}, \; t \geq 0 \qquad (1)$$

where $\alpha < 0$ is the average life span, noting that the parameter α has the same unit as the failure time t, that is, if t is measured in hours, α will also be measured in hours.

The reliability function R(t), which is the probability of the product to remain operational until time t, is given by the equation[46]:

$$R(t) = e^{(-t/\alpha)} \qquad (2)$$

The failure rate associated with the exponential distribution is constant and equal to 1/α, that is, a sample of the former unit that has not failed; it has the same probability of failure of a new unit in a future interval. This property is called lack of memory of exponential distribution.

System Reliability

A system is a collection of items whose proper coordinated operation leads to system operation according to the specifications of design. In the reliability analysis of systems, one must model the functional relationship between various items (parts, circuits, subsystems) to determine the reliability of the system as a whole [29], [30]. The assessment of system reliability based on the study of the reliability of its basic elements is one of the most important aspects of reliability analysis of systems [46].

Fault Tree Analysis (FTA)

Fault Trees are logical representation models; they represent the qualitative characterization of a system failure, or a combination of initial events (failures of components) that cause the occurrence of the top event. Through methods such as Boolean algebra, it is possible to evaluate fault tree quantitatively by calculating the probability of occurrence of the top event [29], [30].

Quantitative evaluation of Fault Trees involves the determination of the probability of a failure. The OR gate represents the union of two or more events and the output event will be the sum of the probability of occurrence of input events. The AND gate is the intersection of two or more events and the output event is the multiplication of the probability of occurrence of the input events [30].

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3. Diesel Gas Kit

The concept of gas-diesel technology (Dual Fuel) has its basis in the use of the diesel cycle original engine and in the combined combustion of natural gas and diesel. This change is obtained by installing an adaptation of the original engine with no structural modifications, maintaining a more efficient cycle of operation; this adjustment is called Diesel Gas Kit [2], [9].

In this application, diesel fuel consumption is reduced to a pilot injection, responsible for starting the combustion of the gas fuel, which, in turn, enters the engine cylinder together or with a slight delay with respect to the injection of the diesel, depending on the "kit" used [42], [25]. Figure 1 shows the possible arrangements of the injection nozzle in the Dual Fuel engine cylinder.

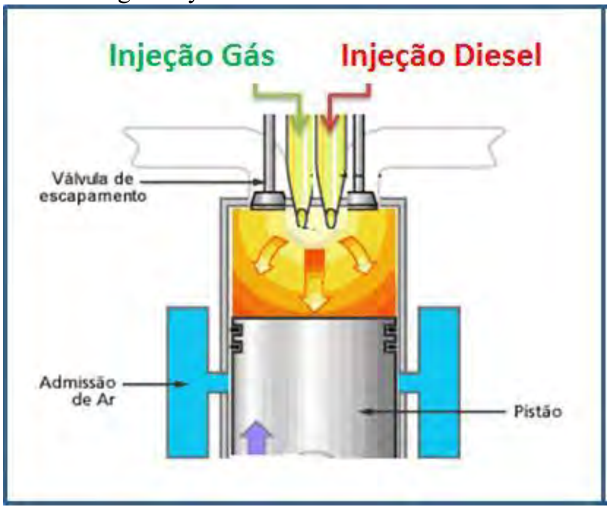

Fig. 1. Arrangement of pilot diesel injection and gas injection in the combustion chamber [4].

Some advantages of the gas-diesel system are the small changes in the engine, the flexibility to use pure diesel or diesel and gas simultaneously, and the possibility of converted engines operating under conditions of torque and power close to those of the original engine using only diesel [2], [21].

The replacement of diesel by natural gas already provides, in a first moment, a significant reduction of particulate matter in exhaust emissions, and also the potential for reducing pollutants NOx (flexibility in operation with lean mixture, delayed diesel injection, ignition of the air/gas mixture), SO_2 and CO_2 (lower carbon/hydrogen ratio of the natural gas) [1], [14], [25].

A. Operation

In third generation diesel gas kits, the solenoid valve of the gas cylinder opens after actuation of the selector switch and the gas flows through the pipe to the pressure regulator, where the pressure is reduced to 1 bar [6], [9], [12].

After this adjustment, the gas reaches the linear actuator, which acts as a butterfly, freeing the passage of a certain amount of gas to the gas injector according to signals sent by the electronic controller, which interprets information derived from the system sensors and calculates the quantity of gas to be injected [6], [9], [12], [55].

The gas injector will provide the gas inside the combustion chamber after the injection of diesel (pilot). At this point, the gas combusts, causing the engine to operate. A lambda probe is placed at the exit of the exhaust gases to verify the amount of oxygen in the output and feedback the electronic controller, so that it is able to correct the gas input [11], [55]. Figure 2 shows the operation of the diesel gas kit.

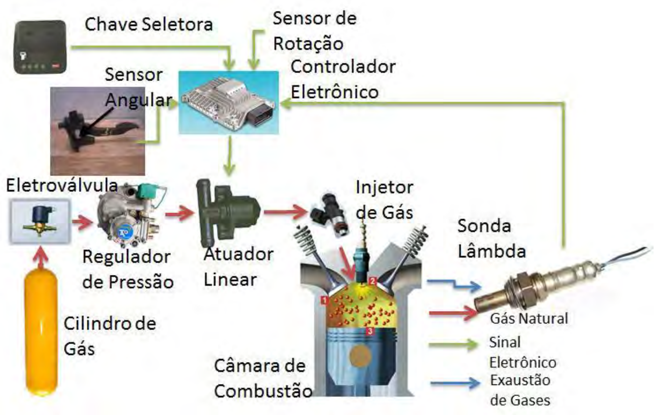

Fig. 2. Third generation Diesel Gas Kit operating diagram[4].

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Diesel Gas Kit subdivision

The gas injection system comprises a gas injector, which is responsible for injecting gas into the combustion chamber after the injection of the pilot fuel (diesel), and the shutoff valve, which regulates the amount of gas. The system of Actuation, Control and Communication consists of the following: pedal sensors, which inform the need of fuel in the combustion chamber to regulate the engine torque; gas quantity sensor, which indicates when there is not enough gas and performs automatic return to diesel-only operation; and temperature sensors. The switch is activated by the user, selecting the diesel-only or Dual Fuel operation modes. The lambda probe (or oxygen probe) verifies the amount of oxygen leaving the engine exhaustion to power the electronic controller, seeking a better adjustment of the stoichiometric fuel mixture. The electronic controller is responsible for interpreting all these signals and controlling the operation of the diesel engine, interacting with the engine electronic controller. The linear actuator makes the mixture richer or leaner according to the signal received from the electronic controller.

The system for Storage and Transport of gas is composed of the gas tank, which should be regulated by INMETRO, or an international organ; the safety valve, which should open in the event of pressure above the safety limit and evacuate the gas system; and the transport system, consisting of the gas pipeline and pressure regulator, which should regulate the gas pressure in the pipeline. The Pilot Flame system comprises the diesel engine injection and control subsystem. Its function is to provide a small amount of diesel fuel to the system in order to start combustion. In this case, the control and activation system of the diesel gas kit must communicate with the diesel central controller. The diesel central controller sends a signal to the diesel injectors, which will reduce the amount of diesel injected into the combustion chamber to until 5% of the initial amount. The small amount of diesel injected is sufficient to initiate combustion in contact with air at high temperature. With the combustion of this small amount of diesel, the gas injected will detonate and perform the power cycle. This subdivision is shown in Figure 3.

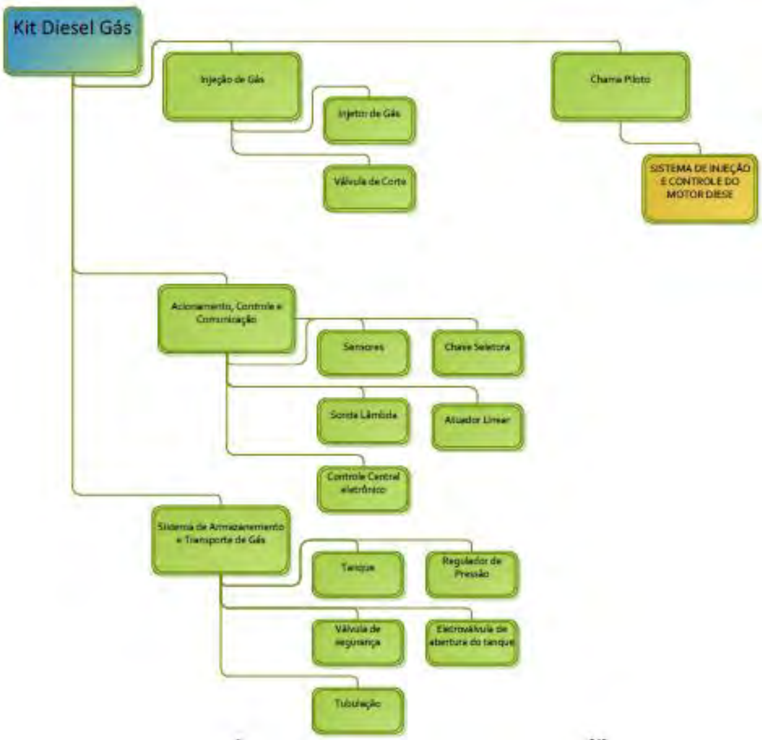

Fig. 3. Diesel Gas Kit functional tree [4].

Stoichiometry of Diesel Gas Combustion

The gas and air mixture should be fairly homogeneous. Its combustion induces peak values and rates of pressure rise lower than those verified for diesel cycle engines, resulting in a more "stable" and silent operation of the engine. The same occurs with respect to alcohol/air and hydrogen/air mixtures [17], [55].

The air/fuel ratio controlled by the electronic controller and gas injectors should be within certain limits, because very lean mixtures can cause engine failures and very rich ones favor the occurrence of detonation [55].

These values are calculated using a parameter called lambda (λ). To calculate this parameter is necessary first to establish the ideal stoichiometric ratio, which is given by [17], [55]:

$$\left(\frac{A}{C}\right)_S = \frac{massa\ de\ ar\ ideal}{massa\ de\ combustível\ ideal} \qquad (5)$$

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Diesel is predominantly a dodecane ($C_{12}H_{26}$) that contains impurities (S, N, etc.), natural gas is a hydrocarbon C_xH_y, and the air mixed with natural gas is rich in N_2 and O_2. The equation of natural gas real combustion is given by [11], [13], [14]:

$$C_{1,089}H_{4,1568} + 2,1285\ O_2 + 8\ N_2 \rightarrow 1,089\ CO_2 + 2,078\ H_2O + 8\ N_2 \quad (6)$$

and diesel combustion is [27], [48]:

$$C_{12}H_{26} + 18,5\ O_2 + 69,56\ N_2 \rightarrow 12\ CO_2 + 13\ H_2O + 69,56\ N_2 \quad (7)$$

The equation for the unbalanced complete combustion of the mixture diesel/gas occurs by [11], [13], [14]:

$$C_xH_y + S + O_2 + 3,76\ N_2 \rightarrow CO_2 + H_2O + SO_2 + N_2 + O_2 + particulas \quad (8)$$

and the equation for the unbalanced incomplete combustion is [11], [13], [14], [33]:

$$C_xH_y + S + O_2 + 3,76\ N_2 \rightarrow CO + CO_2 + H_2O + SO_2 + N_2 + O_2 + NO + NO_2 + particulas \quad (9)$$

Although the combustion of diesel and gas/diesel combination result in the same general equation, diesel/gas combustion, owing to predominance of methane, results in larger portions of $CO_2, H_2O\ e\ O_2$ mass and smaller portions of SO_2 mass [11].

When λ is smaller than zero, combustion presents little excess of oxygen and little fuel, with small probability of occurrence, and it is known as lean combustion. When λ is greater than 1, there is excess fuel, which means that is not completely burnt, and it is called rich combustion. When λ equals 1, combustion is in its optimum ratio, and it is called stoichiometric combustion [17], [37] [55].

4. RESULTS AND DISCUSSION: FAILURE BY INADEQUATE COMBUSTION

Inadequate combustion failure mode

Combustion is considered inadequate when the fuel that reaches the combustion chamber is insufficient for engine operation (lean combustion), and fuel is not burned or partial burned in the engine, causing engine stall; or when there is excess fuel, causing incomplete combustion (rich combustion), and excess fuel is expelled to the environment [9], [21], [55].

Inadequate combustion is a result of non-stoichiometric mixture associated with correction incapability of this event [8], [38], [21].

Non-stoichiometric mixture may occur because of problems with pilot diesel injection and gas injection [4],[38], [21].

Failures in the pilot injection of diesel may be related to low quality fuel; wrong amount of diesel injected, which may originate from the diesel injection pump and the dual fuel kit, and also to failure in the diesel injection nozzle, which is caused by clogging, faulty electrical connection, or component wear [4], [38].

Failures in the gas injection are related to low quality gas and failure in the electronic command, linear actuator and gas mixer [4], [38], [21].

The ability of non-correction of these events is associated with failure in the electrical command, and in the automation and control system, caused by failure in the oxygen probe [4], [55].

Occurrence of inadequate combustion is linked with the events described in the fault tree presented in Figure 4.

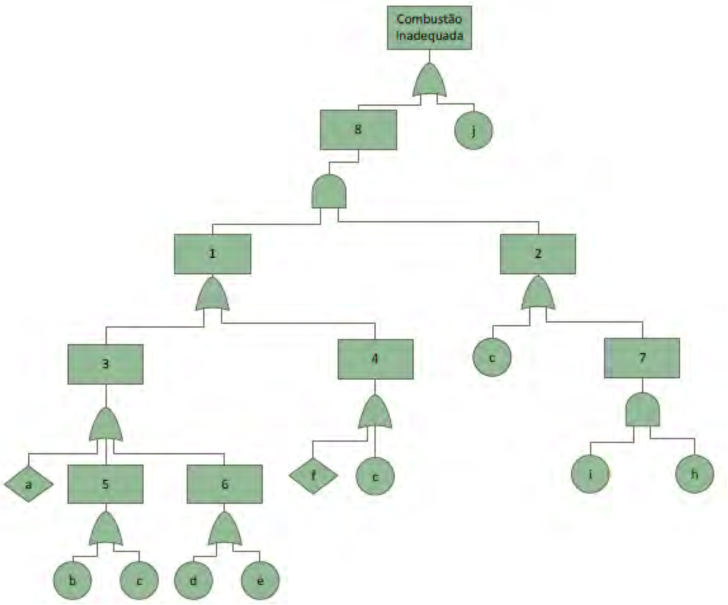

Fig 4. Construction of the Diesel Gas Kit Fault Tree for inadequate combustion [4].

Table 1 shows the numbers and letters used in the fault tree construction shown in Figure 4.

Table 1 – Numbers and Letters for inadequate combustion used in the FTA.

Item	Event	Failure probability
1	Non-stoichiometric mixture	F(1)
2	There is no correction	F(2)
3	Pilot diesel injection	F(3)
4	Gas injection	F(4)
5	Dieselinjection wrong calculation	F(5)
6	Diesel injection nozzle failure	F(6)
7	Automation and control failure	F(7)
8	Mixture failure	F(8)
D	Mechanical Failure	d
E	Clogging	e
F	Low quality gas	f
H	Lambda probe failure	h
I	Failure in the open-loop system (electronic controller operation mode)	i
J	Linear actuator failure	j
A	Low quality fuel	a
B	Problems in the injection pump	b
C	Failure in the electronic controller	c

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The equation of Failure Probability is calculated by Boolean algebra as follows:

$$F(T) = (F(8))\ OU\ j \qquad (10)$$
$$F(8) = (F(1)\ E\ F(2)) \qquad (11)$$
$$F(1) = F(3)\ OU\ F(4) \qquad (12)$$
$$F(3) = a\ OU\ F(5)\ OU\ F(6) \qquad (13)$$
$$F(5) = b\ OU\ c \qquad (14)$$
$$F(6) = e\ OU\ d \qquad (15)$$
$$F(4) = f\ OU\ c \qquad (16)$$
$$F(2) = c\ OU\ F(7) \qquad (17)$$
$$F(7) = i\ E\ h \qquad (18)$$

Rearranging equations 12 and 17 with equations 13, 14, 15, 16 and 18, we will have:

$$F(2) = c\ OU\ [i\ E\ h] \qquad (19)$$
$$F(1) = \{a\ OU\ [b\ OU\ c]\ OU [e\ OU\ d]\}\ OU\ \{f\ OU\ c\} \qquad (20)$$

Substituting OR by + and AND by - in 19 and 20, we will have [29], [30],:

$$F(2) = c + [i \cdot h] \qquad (21)$$
$$F(1) = a + b + c + d + e + f \qquad (22)$$
$$F(T) = (a + b + c + d + e + f).[c + (i \cdot h)] + j \qquad (23)$$
$$F(T) = c + j + [(a + b + d + e + f).(i \cdot h)] \qquad (24)$$

Isolated failures in the electronic controller of the circuit or in the linear actuator generate inadequate combustion [4].

Failure may also occur if there are defects in some components of the diesel fuel injection pump or gas kit (dual fuel), or even problems related to fuel quality, associated with failed lambda probe and open-loop mode, which is the way the electronic controller manages the system without signals of corrections sent by the probe. A failure in the open-loop mode is considered as a general failure of the electric command, so *i* would assume the value of *c*, therefore, formula 21 becomes:

$$F(2) = c + [c \cdot h] \qquad (25)$$
$$F(2) = c \ \cdot [1 + h] \qquad (26)$$
$$F(2) = c \qquad (27)$$

Substituting in (11)

$$F(T) = (a + b + c + d + e + f) \cdot [c] + j \qquad (28)$$
$$F(T) = (a + b + d + e + f + 1) \cdot [c] + j \qquad (29)$$
$$F(T) = c + j \qquad (30)$$

In this case, the values of *c* and *j* assume the values of failure of the electronic controller and linear actuator, respectively.

Modeling of failure of critical components

According to the mode of operation and equipment characteristics, using data obtained from the database in the literature, one can find the reliability of the main components of diesel gas system [5], [53].

For electronic components, we use the Military Standard 217F (United States of America, Defense Department, 1991) norm and, hence, we can calculate the values of reliability using exponential distribution [46].

1) Electronic Controller

Using the calculation proposed by MIL-HDBK-217F [53], page 5-3, and modeling the controller as a microprocessor, we have :

$\lambda = (C_1 \cdot \pi_t + C_2 \cdot \pi_e) \cdot \pi_Q \cdot \pi_L$ Failures per 10^6 hours (31)

Above the 16 bits of memory $C_1 = 0.28$
$C_2 = 0$ for microprocessor
$\pi_Q = 1.0$ for microprocessor
$\pi_L = 5.8$ for linear circuit

$\lambda = 1.624 \cdot 10^{-6}$

As it is electronic equipment, and failure mechanisms are random, one can calculate reliability as exponential distribution, as seen in equation (2).

$$R(t) = e^{(-1{,}624 \cdot 10^{-6} \cdot t)}$$ (32) For 4000 hours

$R(t) = 99.35\%$
$F(t) = 0.65\%$
$MTTF = 615{,}763$ hours

Figure 5 shows the reliability curve for the electronic controller.

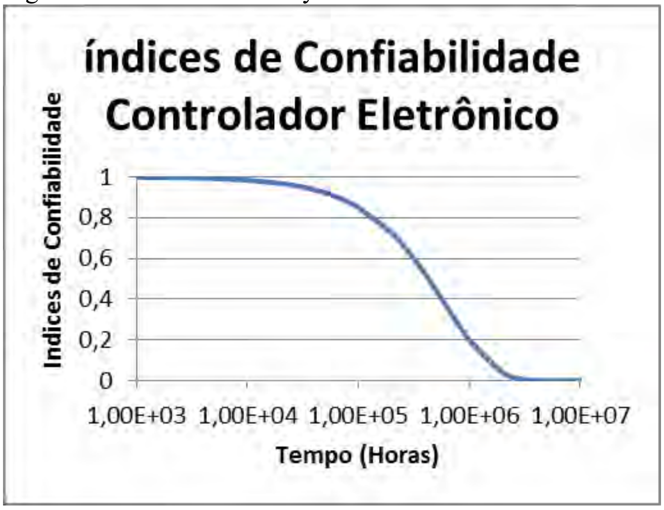

Fig. 5. Graph: Reliability versus Electronic Controller Time [4].

2) Linear Actuator

Using the calculation proposed by MIL-HDBK-217F [53], page 12-3, we have: Considering DC Synchronous Engine type.

$\lambda = \lambda_b \cdot \pi_e \cdot \pi_s \cdot \pi_n$ Failures per 10^6 hours (33)

Environmental factor $\pi_e = 1.0$
Size factor $\pi_s = 2$ – small.
Synchronous Motor and Poles factor $\pi_n = 3{,}2$ – 4 poles
λ_b Basic failure rate for operation at 80 °C = 0.27
$\lambda = 1.728 \cdot 10^{-6}$

As it is electronic equipment, and failure mechanisms are random, one can calculate reliability as exponential distribution, as seen in equation (2). [53].

$$R(t) = e^{(-1{,}728 \cdot 10^{-6} \cdot t)}$$

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(34) For 4000 hours
R(t) = 99.31%
F(t) = 0.69%
MTTF = 578,703 hours

Figure 6 shows the reliability curve for the linear actuator.

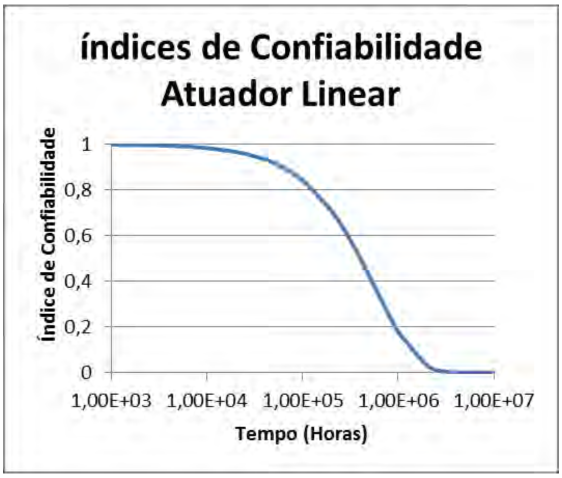

Fig. 6. Graph: Reliability versus Linear Actuator Time [4].

B. Inadequate Combustion failure probability for 4000 hours and time evolution.

Reliability for 120,000 kilometers traveled is also assessed, because this is the time of the first major revision in the engine, when there is significant replacement of parts (replacement of the injection pump is also recommended) and, therefore, it would be the right time for the first major revision of diesel gas kit [35]. Average speed of traffic should be estimated for the evaluation of operation hours. The average speed of traffic in the city of Sao Paulo is 30 km/h, if the 120,000 kilometers were traveled at this speed, the time required would be 4000 hours [40]. It is estimated that the system is installed in a small urban truck working in large cities, where its operation will be performed with varying load and speed, unlike a highway truck that usually operates at constant speed in less severe conditions[4].

Considering equation 30 and the failure probability previously calculated, Table 2 shows the estimated cumulative failure for 4000 hours.

Table 2 – Numbers and Letters for inadequate combustion used in the FTA.

Inadequate Combustion Failure for 4000 hours

	c	j	F(T)
Estimate	0.647%	0.517%	1.182%

Figure 7 shows the cumulative failure probability curve for inadequate combustion failure.

Figure 7. Failure Estimate versus Diesel Gas Kit Time for Inadequate Combustion

5. CONCLUSION

In this study, we aimed to predict the occurrence of non-stoichiometric combustion of a diesel engine adapted for Dual Fuel (diesel/gas), identifying critical items and possible new failure modes. To this end, it was necessary to understand the operation of this system and the components used in this operation. For this, it was necessary to subdivide the diesel gas kit according to its functionality and assess the operation of the system as a whole, the subsystems, and their items, allowing the construction of the Diesel Gas Kit functional tree.

Considering these failures of the engine operating with the diesel gas kit, it was possible to run a Fault Tree Analysis. Through the FTA, it was possible to survey data on the reliability of critical items in this diesel gas kit with the aid of data published in references, resulting in the failure analysis of each item and identifying the impact of non-stoichiometric combustion on the engine operation.

The probability of non-stoichiometric combustion - which causes the engine to operate with underperformance and emit more pollutants to the environment, being in disagreement with environmental legislation - is of 1.182%. Despite the reduction in pollutants emissions and diesel consumption, the addition of these new components reduces the reliability of the engine, increasing the probability of failure considering the inclusion of new failure modes compared with the original diesel engine.

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