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FAILURE ANALYSIS OF AN OFF-ROAD VEHICLE IN SAE BRASIL UNIVERSITY COMPETITIONS: A STUDY OF THE SUSPENSION SYSTEM USING FAILURE MODE AND EFFECT ANALYSIS AND FAULT TREE TECHNIQUES

Ricardo França Santos
r_frana@yahoo.com.br
Rio de Janeiro Federal University - UFRJ, Macaé, RJ, Brazil.

Isabella Arlochi de Oliveira
isabellaarlochi@gmail.com
Rio de Janeiro Federal University - UFRJ, Macaé, RJ, Brazil.

Luciane Caroline de Souza Ferreira
carolsf.96@gmail.com
Rio de Janeiro Federal University - UFRJ, Macaé, RJ, Brazil.

Erick Perassoli da Silva
erickperassoli@gmail.com
Rio de Janeiro Federal University - UFRJ, Macaé, RJ, Brazil.

Felipe Amorim Soares Macedo
felipesamac@gmail.com
Rio de Janeiro Federal University - UFRJ, Macaé, RJ, Brazil.

ABSTRACT

Highlights: FTA is a reliability technique aimed at identifying all the combinations of causes that can give rise to an undesired event, studying the probability of these causes occurring, and prioritizing actions to prevent these causes from happening and resulting in the undesired event. The method allows the analysis of system reliability and the construction of the cause-and-effect relationship of its events, creating an interface with the FMEA tool. FMEA is a reliability tool used to find possible failures in a system and assess their possible consequences. These methods and techniques seek to improve the reliability of products or processes, i.e., increase the likelihood of an item performing its function flawlessly. **Aim**: This paper will analyze failures in the suspension system of an SAE competition off-road vehicle using fault mode and effect analysis (FMEA) and fault tree analysis (FTA) techniques with a view to improving the performance of these vehicles in future competitions. **Design/Methodology/Approach**: The researchers began by defining the suspension system as the object of study with the racing team, followed by collecting information and failure data on this system. The FMEA and FTA tools were then used alongside interviews with the racing team. **Results**: The analysis of the results showed that the two highest probabilities of failure are related to the suspension and the axle sleeve, with values of 38.8% and 20.5%, respectively, and that the rotary terminal is the most critical element. **Research limitations**: The limitations of this research include the subjectivity of assigning FMEA scores due to the team's lack of experience and the limited history of documenting data on vehicle failures related to the dynamics of SAE competitions. **Practical implications**: The practical implications of this study include the possibility of professional improvement for the engineering students belonging to the competition team. **Originality/value**: The literature search revealed that the research topic is original and challenging at the same time. Its results will allow us to re-evaluate the construction project for the Baja competition vehicle.

Keywords: FMEA; FTA, Baja SAE Brazil Program; Suspension System

INTRODUCTION

The contribution of applied research to maintenance projects has been discussed for a long time. However, much of this research does not prove the application of the knowledge acquired by engineering students to their curricular trajectories.

Through the Baja SAE BRASIL Program, engineering students have the opportunity to apply the knowledge they have acquired at school to enhance their curricula and prepare them for the job market. In this program, students are involved in Baja vehicles' development for off-road competition, participating in their entire cycle, i.e., conception, design, construction, and testing. Through teamwork, students participate in regional competitions to benchmark their projects (SAE Brasil, 2020).

In SAE formula competitions, the vehicle's suspension design is fundamental to its high performance, aiming at ensuring its stability, absorbing the irregularities of the terrain, and compensating for the loads on the system (Cabral et al., 2019). However, in SAE competitions with off-road vehicles, the suspension system is even more important to the driver during the competition.

The constant evolution in the quality and reliability of products and high competitiveness of the automotive industries have fostered various methods and techniques for minimizing and eliminating faults. These methods and techniques aim to improve the reliability of products or processes, i.e., to increase the likelihood of an item performing its function without failure (Almeida and Fagundes, 2005).

One of these tools is Failure Mode Effect and Analysis (FMEA), and its main advantage is its ability to predict and prevent problems. This method has advantages such as reducing costs, increasing product reliability, implementing improvements based on data, cataloging information on failures, documenting their causes, and obtaining a risk priority number for each failure (IQA, 2008).

Another widely used tool is Fault Tree Analysis (FTA), which works from a fault to find the possible causes of a problem. According to Lima et al. (2006), this technique makes it possible to detail each fault and its origins, making the FMEA more assertive.

Thus, these tools can be used in large projects in industry and in smaller-scale contexts, such as university competitions created by the Society of Automotive Engineers (SAE), such as Baja and the SAE formula.

Currently, the competition's evaluation criteria comprise various tests, such as safety inspection, project evaluation, dynamic tests, and the endurance test. These tests evaluate the entire project development process and expose the prototype developed under extreme working conditions.

Thus, considering the more assertive results obtained with the integrated use of the aforementioned tools, this study aims to analyze the failures of the suspension system of a university competition off-road vehicle using FMEA and FTA. As a more specific objective, it is expected to identify the main failures of the system's components and their effects and find the possible causes of the failures, with a view to improving the performance of these vehicles in future competitions.

THEORETICAL FRAMEWORK

Failure mode and effects analysis (FMEA)

FMEA is a reliability tool used to find possible failures in a system and assess their possible consequences (Hawkins and Woollons, 1998).

According to Liu et al. (2013), this technique was first used in the aerospace industry in the 1960s to reduce or eliminate risks in a system, process, or project. It proved to be useful in assessing probable failures and preventing their occurrence, and its use was extended to other industries, such as nuclear, automotive, electronics, and chemicals.

The main objectives of the FMEA are to identify and analyze possible failures in a given product or process, point out actions that will allow these failures to be eliminated or at least mitigated, and then document the procedures to facilitate revisions and improvements (Fogliatto and Ribeiro, 2009).

In order to carry out the analysis, it is necessary to form a group of people capable of identifying the functions of the product or process, the possible types of failure, the effects, and the possible causes of this failure. Therefore, the risks of each cause of failure are measured using indices, and based on this assessment, the necessary actions are planned to minimize them with a view to increasing the reliability of the product or process (Rozenfeld et al., 2006).

Fogliatto and Ribeiro (2009) suggest a form to accompany the FMEA with the following fields:

a) Header: generally contains the information needed to identify the form, for example, the FMEA number, the process identification, the department responsible, the study coordinator's details, the participants' details, and the document date;

b) Item/Function: contains a brief description of the operation being analyzed and its purpose or requirement to be met. This stage describes the items under analysis and their functions;

c) Potential failure modes: It describes the possible non-conformities associated with the object under study. It is important to list all the potential failure modes relevant to each operation;

d) Potential failure effects: It defines the defects that have occurred due to the failure modes;

e) Severity (S): A qualitative assessment is made of the severity of the effect listed above in terms of the impact that the potential mode effect has on the system. Severity is measured on a scale of 1 to 10, where 1 is a not very severe effect, and 10 means a very severe effect;

f) Classification: This non-mandatory field is used to classify any characteristics of the operation that need special control;

g) Potential failure causes or mechanisms: A deficiency in the process that generates the failure mode is defined. It is important to list the causes or mechanisms clearly and completely to facilitate efforts to correct or improve the process;

h) Occurrence (O): This relates to the probability that a cause or mechanism already listed will occur. If failure rate data or statistically captured capability indices for similar items or processes are not available, a more subjective analysis must be made, classifying the probability of occurrence in a range from 1 to 10, where the closer to 10, the higher the occurrence of that cause;

i) Prevention and detection control: The controls incorporated into the process that can prevent or detect the cause of the failures mentioned should be listed;

j) Detection (D): It is assumed that the failure mode has occurred, and then the ability of current controls to perform detection is checked. This detection is rated on a scale of 1 to 10, with 1 being a very high probability of the failure being detected and 10 being very low;

k) Risk (R): The risk is calculated to prioritize actions to correct and improve the process, considering the product of severity, occurrence, and detection;

l) Recommended actions: After prioritizing the failure modes by calculating the risk, improvement actions are proposed for the items with the highest risk.

The FMEA form is a living document. This means that even after it has been finalized, it needs to be revised whenever there are changes to this product or process. In line with Fault Tree Analysis, this is the only reliability technique cited in the ISO 9000 standards and, particularly, ISO 9004 (Lima *et al.*, 2006).

Jawagar Shrehari and Raagul Srinivasan (2016) proposed a study with FMEA as an opportunity for students to evaluate in SAE competitions a form of process improvement for reliability in the automotive industry. Due to its ability to examine systems at the component level, this technique points out potential failures that can be quickly identified and evaluated using a systematic process with associated risks. The prioritization of faults according to the defects caused is evaluated within a risk prioritization process calculated according to severity, occurrence, and detection.

Using an FMEA design (DFMEA) to assess the risks of a competition kart (go-kart), these authors found inappropriate suspension selection as a potential failure mode for the suspension system. As a potential failure effect, this could lead to total collapse and vibration in the vehicle, which could probably be caused by improper assembly. As a means of detection, there could be a control process by analyzing load distribution in the suspension system (Shrehari and Srinivasan, 2016).

Fault tree analysis (FTA)

H.A. Watson developed the concept around 1960 to assess safety in aerospace engineering. Sometime later, it began to be used in other sectors of industry to reduce failures and problems that appeared in some equipment and processes (Helman and Andery, 1995).

FTA is a reliability technique that aims at identifying all the combinations of causes that can give rise to an undesired event at the top of the fault tree; studying the probability of these causes occurring, thus studying the probability of the top event; and prioritizing actions aimed at preventing these causes from occurring and resulting in the undesired event (Fogliatto and Ribeiro, 2009).

In this respect, it is considered a top-down failure analysis method, in which the analysis takes an undesired event as its starting point, either a failure or a malfunction, appropriately called the top event. In this event, all the means for its occurrence are defined. Thus, it can be said that from a top event, the lower-level events are established, which are, alone or in combination, the generators of the undesired effect (Rozenfeld *et al.*, 2006).

Using the method makes it possible to analyze the system reliability and construct the cause-and-effect relationship of their events, creating an interface with the FMEA tool (Sakurada, 2001).

Specific symbology is used when structuring the fault tree specific symbology, as shown in **Figure 1**.

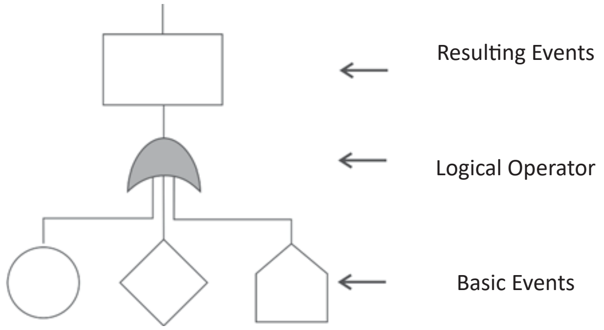
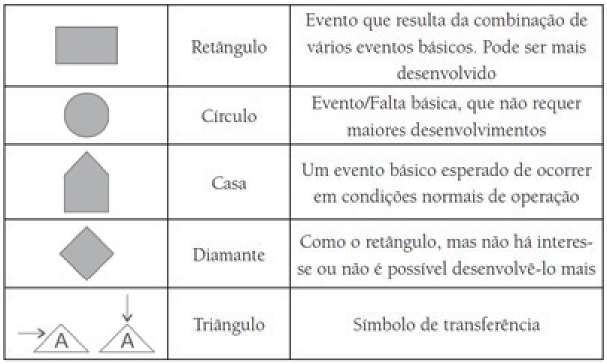


Figure 1. Fault tree symbology
Source: Elaborated from Fogliatto and Ribeiro (2009)

Figure 2 shows the events in the fault tree that can be of five types, and **Figure 3** shows the logical operators for structuring the tree.

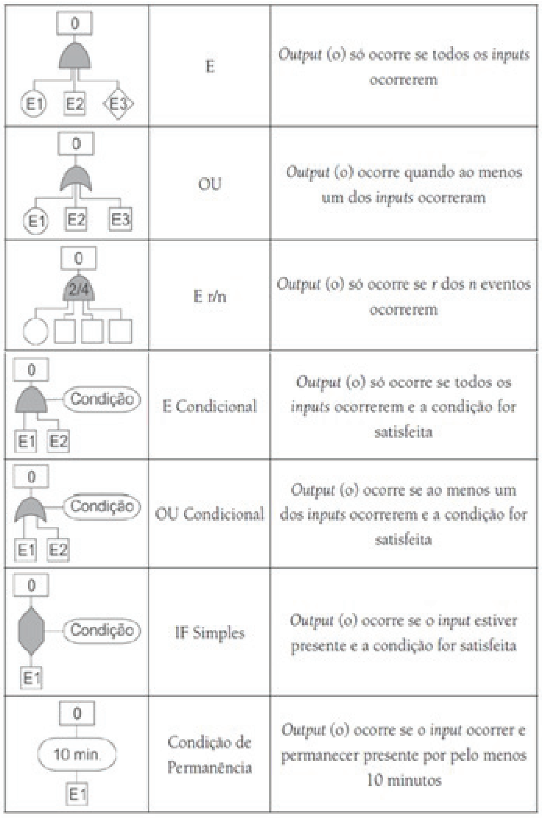
Rectangle	An event that results from the combination of several basic events; it can be further developed
Circle	A basic event or fault that does not require further development
House	A basic event expected to occur under normal operating conditions.
Diamond	Like the rectangle, but of no interest or cannot be developed further.
Triangle	Transfer symbol



	Retângulo	Evento que resulta da combinação de vários eventos básicos. Pode ser mais desenvolvido
	Círculo	Evento/Falta básica, que não requer maiores desenvolvimentos
	Casa	Um evento básico esperado de ocorrer em condições normais de operação
	Diamante	Como o retângulo, mas não há interesse ou não é possível desenvolvê-lo mais
A A	Triângulo	Símbolo de transferência

Figure 2. Events in the fault tree
Source: Elaborated from Fogliatto and Ribeiro (2009)

AND	Output (o) only occurs if all inputs occur
OR	Output (o) occurs when at least one input has occurred
AND r/n	Output (o) only occurs if r of the n events occur
Conditional AND	Output (o) only occurs if all inputs occur and the condition is met
Conditional OR	Output (o) occurs if at least one of the inputs occurs and the condition is satisfied
Simple IF	Output (o) occurs if the input is present and the condition is met
Permanence Condition	Output (o) occurs if the input occurs and remains present for at least 10 minutes



0 E1 E2 E3	E	*Output* (o) só ocorre se todos os *inputs* ocorrerem
0 E1 E2 E3	OU	*Output* (o) ocorre quando ao menos um dos *inputs* ocorreram
0 2/4	E r/n	*Output* (o) só ocorre se *r* dos *n* eventos ocorrerem
0 Condição E1 E2	E Condicional	*Output* (o) só ocorre se todos os *inputs* ocorrerem e a condição for satisfeita
0 Condição E1 E2	OU Condicional	*Output* (o) ocorre se ao menos um dos *inputs* ocorrerem e a condição for satisfeita
0 Condição E1	IF Simples	*Output* (o) ocorre se o *input* estiver presente e a condição for satisfeita
0 10 min E1	Condição de Permanência	*Output* (o) ocorre se o *input* ocorrer e permanecer presente por pelo menos 10 minutos

Figure 3. Main logical operators and their meanings
Source: Prepared from Fogliatto and Ribeiro (2009)

After structuring the FTA, the basic fault data is grouped with each basic event. The probability of occurrence of each of the resulting events, (), must then be calculated, with the most common cases corresponding to logic gates AND and OR. According to Fogliato and Duarte (2011), the probabilities of each event occurring are calculated differently, considering the type of Boolean connector represented:

AND: $$P(0) = \prod_{t=1}^{n} P(E_i)$$

OR: $$P(0) = 1 - \prod_{t=1}^{n} \left(1 - P(E_i)\right)$$

Where,

P(0) the probability of occurrence of the resulting event (output)

$P(E_i)$ the probability of occurrence of the causes that result in the event in the hierarchy of the tree

From the probability of occurrence of all the events in the tree, we can find the criticality of the root causes, which can be calculated by the product of the probability of occurrence of the root cause by the conditional probability of occurrence of the top event, given that that root cause has occurred (Fogliatto and Ribeiro, 2009), as shown by the product:

$$\text{Criticality} = P(Ei).P(H/Ei)$$

Where,

$P(E_i)$ is the probability that the event will occur

$P(H/E_i)$ is the conditional probability that the top event occurs, given that has occurred.

In this way, it is possible to identify the most critical components and thus think of actions that could lead to correction or improvement.

In the literature, some studies have been found on the application of FMEA and FTA in the powertrain systems of autonomous and electric vehicles; however, they have not been found specifically in manned competition vehicles without a military application (Haq *et al.*, 2015; Sedano *et al.*, 2013; Ferencey, 2011).

Ali Babaja UFRJ Macaé

Founded in 2014 by engineering students from the Federal University of Rio de Janeiro (Macaé campus), the Ali Babaja Team aims to design and build a high-performance off-road vehicle for competition under the Baja Program run by the Society of Automotive Engineers (SAE). In this event, engineering students are challenged to develop a prototype, including conception, detailed design, construction, and testing. The competitions take place annually through national and regional stages, promoting a comparative assessment of each team's projects.

Throughout its history, the team has built two vehicles, known as Camel I and Camel II. The first was built in 2014, and, at the 22nd BAJA SAE Brazil Competition in 2015, the team was awarded the title of Fair Play Team. The following year, still with the same vehicle, they won first place in the traction test, also at the national stage.

The Camel II season began in 2017, with construction taking place at the headquarters of partner companies and at the competition venues, which compromised the technical quality and, consequently, the team's results. Nevertheless, the Camel II took part in two national stages and one regional stage. **Figure 4** shows the Camel II vehicle. In 2019, the team dedicated itself to developing the Camel III.

Figure 4. Camel II during competition
Source: The Authors (2021)

Baja SAE Brasil Administrative and Technical Regulations

According to the administrative and technical regulations of the Baja SAE Brasil program, these regulations are divided into administrative, technical, and competition regulations. Item C4.8.2.3 of this document encourages the use of failure modes and effects analysis (FMEA) to evaluate the project, and based on the results of the analysis and tests, a reassessment must be carried out to develop project alternatives.

Item C4.8.4.2 directs the team to quantify the suspension's performance and overall impact on the project, and item 5.7 of the regulations, which deals with suspension, mentions that the vehicle's maneuverability and traction will be tested during a winding course with obstacles in the race. The functionalities of powertrain and suspension systems of an SAE vehicle will be presented below.

Suspension system

The suspension system of an SAE vehicle is responsible for isolating vibrations from the chassis, enabling stability

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and comfort for the driver in competition. It consists of a system of springs, shock absorbers, and joints that allow relative movement between the vehicle and the wheel (Cabral *et al.*, 2019).

Powertrain system

As a way of detailing other components that interact with the suspension system, some definitions will be presented:

a) Engine: This is the component of the vehicle's powertrain responsible for generating the power that will be transmitted to the wheels through the transmission system;

b) Continuously Variable Transmission (CVT): This transmission system has infinite steps within its operating range. It consists of a drive pulley linked to the power source and a driven pulley that is the power output for the next reduction stage. These two pulleys are connected to a V-belt specially developed for this application (Caser; Seraphim, 2014);

c) Reduction gearbox: Its main purpose is to increase torque on the car drive shaft (Vidal *et al.*, 2017);

Tires: These are the components responsible for generating grip to control the car and, in conjunction with the wheels, provide movement to the car, reducing slippage (Cordeiro, 2014).

Damping system

The damping system is primarily responsible for vehicle stability. Its aim is to absorb all the irregularities in the ground through its components, dissipating mechanical energy in the form of heat, noise, and viscous friction. It is also responsible for keeping all four wheels on the ground and improving the car's performance. Damping ensures the integrity of the car's structure.

Suspension System Components

The main components of the suspension system include the wheel hub, the shaft sleeve, the tray, and the damping system. The following definitions clarify the functions of each of these components:

a) Wheel Hub: Component responsible for attaching to the wheel and supporting the brake disk

b) Shaft Sleeve: Component responsible for attaching all the suspension components, such as the wheel hubs, suspension arms, and steering bar

c) Tray: This is the first to receive the shock of an impact suffered by the suspension, as it makes the wheel/chassis connection. This component performs several functions directly related to the vehicle's safety and stability. As a result, a problem with this component can lead to losing control of the vehicle.

d) Damping system: Its core function is to dissipate mechanical energy to improve handling and reduce the vehicle's contact with the ground, increasing the driver's safety and comfort.

Figure 5 shows a layout of the suspension and steering system of the Camel II vehicle.

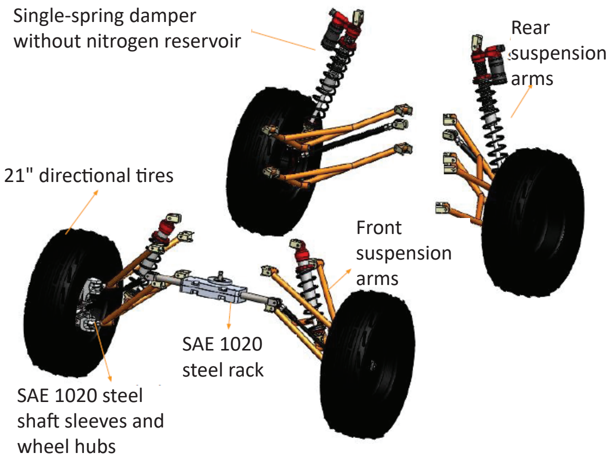

Figure 5. Camel II Suspension and Steering Layout

Source: The Authors (2021)

METHODOLOGY

This work uses a descriptive and quantitative approach, and a case study on the off-road vehicle designed and built by the Ali Babaja UFRJ Macaé team will complement it.

The following stages were considered for its implementation:

Definition of the system to be analyzed: The system chosen as the study object was the suspension system, whose components were mentioned above;

Collecting information about the system and failure data: Through interviews with members of the Ali Babaja UFRJ

Macaé team, the information needed to implement the reliability and maintenance tools was collected;

Implementation of the tools: We chose the FMEA and FTA tools to analyze the information collected. Therefore, the system was thoroughly analyzed to understand its characteristics and interrelationships. The initial versions were then drafted;

Review of the tools: After drafting the form and the fault tree, revisions were made during another interview with the team to ratify what had been done, and only then were the respective calculations performed;

Analysis of the results: The results were analyzed, and opportunities for improvement were found for the team.

RESULTS

After the meetings with the team, the failure data for each system component was collected, and the failure rates were calculated:

- Stud bolts: 2 failures in 64 hours;
- Tray: 2 failures in 64 hours;
- Anchor bolt: 6 failures in 64 hours;
- Labeling terminal: 7 failures in 64 hours;
- Shaft: 1 failure in 64 hours;
- Damping fluid seal: 2 failures in 64 hours.

FTA

A fault tree was assembled for the suspension system, as seen in **Figure 6**.

Using the failure rates and the help of FTA, the probability of the suspension system failing and the car ceasing to function was calculated.

Wheel hub failure: the four stud bolts must fail:

$$P(0) = \left(\frac{2}{64}\right)^4 = 9{,}536.10^{-7}$$

Suspension tray system failure: occurs if the tray or anchor bolt fails:

$$P(0) = 1 - \left[\left(1 - \frac{2}{64}\right)\left(1 - \frac{6}{64}\right)\right] = 0{,}1221$$

Shaft sleeve failure: occurs if the shaft or anchor bolt or rotary terminal fails:

$$P(0) = 1 - \left[\left(1 - \frac{7}{64}\right)\left(1 - \frac{1}{64}\right)\left(1 - \frac{6}{64}\right)\right] = 0{,}2055$$

Damping failure: occurs when the fluid seal fails or when the anchor bolt fails:

$$P(0) = 1 - \left[\left(1 - \frac{2}{64}\right)\left(1 - \frac{6}{64}\right)\right] = 0{,}1221$$

Suspension system failure: occurs if one of the previous failures occurs:

$$P(0) = 1 - [(1 - 9{,}536.10^{-7})(1 - 0{,}1221)(1 - 0{,}2055)(1 - 0{,}1221)] = 0{,}3876$$

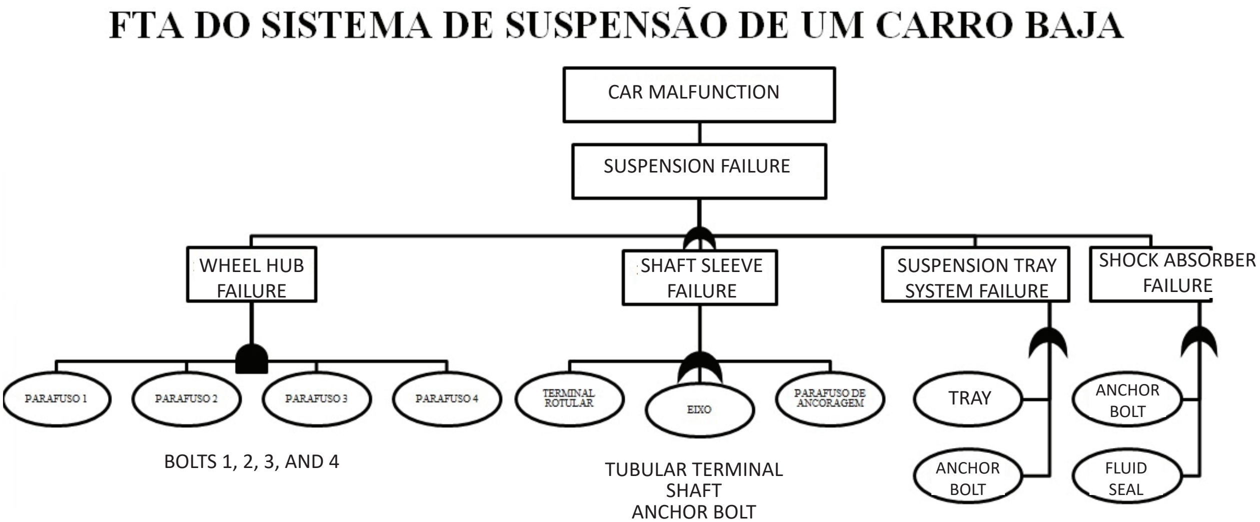

Figure 6. FTA of Ali Babaja's suspension system

Source: The Authors (2021)

After calculating the probability of system failure, the criticality of each component can be assessed:

For the stud bolts:

$$P = 3{,}0517.10^{-5}$$

$$\mathrm{Crt} = 0{,}03125 \text{ x } 3{,}0515.10^{-5} = 9{,}5359.10^{-}$$

For the tray:

$$\mathrm{P} = 1$$

$$\mathrm{Crt} = 0{,}03125 \text{ x } 1 = 0{,}03125$$

Anchor bolt (all in the system are equivalent):

$$\mathrm{P} = 1$$

$$\mathrm{Crt} = 0{,}09375 \text{ x } 1 = 0{,}09375$$

Labeling terminal:

$$\mathrm{P} = 1$$

$$\mathrm{Crt} = 0{,}109375 \text{ x } 1 = 0{,}109375$$

Shaft:

$$\mathrm{P} = 1$$

$$\mathrm{Crt} = 0{,}015625 \text{ x } 1 = 0{,}015625$$

Fluid sealing:

$$\mathrm{P} = 1$$

$$\mathrm{Crt} = 0{,}03125 \text{ x } 1 = 0{,}03125$$

Thus, using the FTA and the above results, it can be concluded that the most critical and, therefore, most important component is the label terminal, followed by the anchor bolt, fluid tray and seal (with the same criticality value), shaft, and finally the stud bolts.

Furthermore, the criticality of the rotary terminal is 1.16 times greater than that of the anchor bolt, 3.5 times greater than that of the fluid tray and seal, 7 times greater than that of the shaft, and 114,420 times greater than that of the stud bolts. This survey shows that greater care should be taken with the rotary terminal and the anchor bolt.

FMEA

A meeting was held to discuss and draw up a report with the failure modes, causes, and effects, thus obtaining the severities, occurrences, and detections from the Baja team. The severity of each failure was calculated. In this respect, in consensus with the team, 50 was the value set as the minimum necessary to prioritize the failure modes requiring intervention. An action plan was then devised, as shown in **Figure 7**.

Based on the results of the FMEA, each scenario and the reasons why each failure occurs should be analyzed, and an action should be evaluated given the corresponding intrinsic risk. For high-risk values, predictive maintenance is suggested, as constant monitoring is required. For risks closer to the minimum risk, the team suggests periodic maintenance and observation of suggestions for reducing the probability of failure.

During the preparation of the FMEA, the competition team met the research team to make a qualitative assessment of severity, an evaluation of occurrence, and an estimation of the ability of the maintenance team's current controls to detect it. **Chart 1** shows the scale used to assess the severity of the process.

The scale in **Chart 2** was used to assess the occurrence of the cause of failure in the process.

When assessing detection by current controls, the maintenance team used the scale shown in **Chart 3**.

Figure 8 shows the risk of failure for each component. The cutoff line was set at values with risks higher than 50. According to this cutoff line, only the risks related to the stud bolt and the shock absorber would be outside the scope of the risk plan at this point in the project until the following evaluation.

It can be seen that the risks related to the shaft and the anchor bolt have their overall value calculated identically; however, the risk related to the shaft has been evaluated from the point of view of occurrence at more than twice the risk related to the anchor bolt; therefore, the former is a priority.

Componente	Modo potencial de falha	Efeito	S	Causa	O	Controle de prevenção	Controle de detecção	D	R	Ação recomendada
Parafuso prisioneiro	Espanagem da rosca	Cubo não prende a roda	9	Operador usando ferramenta errada	1	Treinamento do operador	Verificação com o pente de rosca	3	27	
Bandeja	Flambagem	Carro inoperante	7	Carga excessiva	2	Revisão dos dimensionamentos antes da utilização		7	98	Fazer uso de um *software* de simulações de esforços para ter uma garantia maior que os cálculos estão certos
	Fixação ineficiente	Carro inoperante	4	Rompimento do parafuso	2		Inspeção visual	8	64	Peça sobressalente
Terminal rotular	Flexionar	Mal funcionamento	5	Dimensionamento errado	5		Revisão dos cálculos	8	200	Fazer uso de um *software* de simulações de esforços para ter uma garantia maior que os cálculos estão certos
				Carro sobrecarregado durante o percurso	7	Treinamento do piloto	Inspeção visual	8	280	Esclarecer para o piloto quais são os limites do carro e tentar colocar uma barreira para esse limite não ser ultrapassado
Eixo	Espanagem da rosca	Travamento da roda	9	Uso errado da ferramenta pelo operador	7	Treinamento do operador	Supervisionar a operação	3	189	Durante o processo ter uma pessoa que conheça a operação para supervisionar
Parafuso de ancoragem	Rompimento	Falha de suspensão	9	Erro de dimensionamento	3	Revisão dos cálculos	Inspecionar o projeto	7	189	Fazer uso de um *software* de simulações de esforços para ter uma garantia maior que os cálculos estão certos
				Sobrecarregado durante o percurso	4	Treinamento do piloto	Inspeção visual	3	108	Esclarecer para o piloto quais são os limites do carro e tentar colocar uma barreira para esse limite não ser ultrapassado
Amortecedor	Vedação	Mal funcionamento do sistema de suspensão	6	Falta de manutenção	3	Manutenção periódica	Inspeção visual	1	18	

Figure 7. FMEA for Ali Babaja's suspension system
Source: The Authors (2021)

Effect Severity	Effect	Scale
Very High	Compromises the safety of the operation or involves infringement of government regulations	10
		9
High	Causes high customer dissatisfaction	8
		7
Moderate	Causes some dissatisfaction due to a drop in performance or malfunction of parts of the system	6
		5
Low	Causes slight dissatisfaction, and the customer only notices a slight deterioration or drop in performance	4
		3
Lowest	The failure minimally affects the performance of the system without most customers noticing it	2
		1

Chart 1. Severity Assessment in the Process
Source: Prepared from Fogliatto and Ribeiro (2009)

Occurrence	Failure Rate	Evaluation Scale	
Very High	Failures almost inevitable	10	100/1000
		9	50/1000
High	Failures occur frequently	8	20/1000
		7	10/1000
Moderate	Occasional failures	6	5/1000
		5	2/1000
		4	1/1000
Low	Failures rarely occur	3	0.5/1000
		2	0.1/1000
Lowest	Failures very unlikely	1	0.01/1000

Chart 2. Scale for assessing the occurrence of the cause of failure

Source: Elaborated from Fogliatto and Ribeiro source (2009)

Likelihood of Detection	Status	Scale
Very Remote	The Project Validation Procedure (PVP) will not detect this failure mode, or there is no PVP	10
Remote	The PVP will probably not detect this failure mode	9
		8
Low	There is a low probability that the PVP will detect the failure mode	7
		6
Moderate	PVP can detect the failure mode	5
		4
High	There is a high probability that PVP will detect the failure mode	3
		2
Very High	PVP will almost certainly detect this failure mode	1

Chart 3. Scale for detection by the maintenance team's current controls

Source: Prepared from Fogliatto and Ribeiro source (2009)

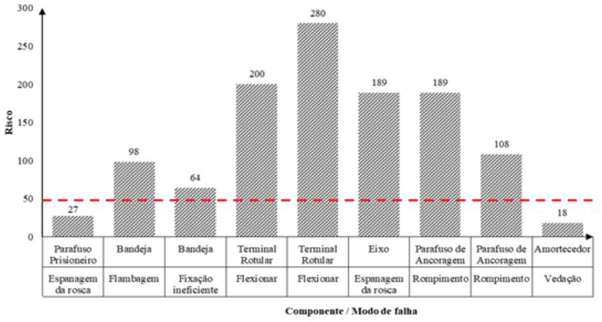

Figure 9. Risk of failure of each component

Source: The Authors (2021)

Considering the subjectivity of the process compared to the rigor of assessing severity, occurrence, and detection, a Pareto analysis was devised, as shown in **Table 1**.

The Pareto analysis shows that the risks to the labeling terminal, the anchor bolt, and the shaft take priority over the other components. As anchor bolt 2 has a cumulative relative frequency close to 80%, it can be included in the list of components that should be prioritized when applying the recommended actions.

Nonetheless, it should be noted that both in the risk analysis process using the risk calculated in the FMEA and in the process carried out using the Pareto analysis, there was disagreement only on the tray component. In this case, we opted to include the tray in the components sensitive to the risk assessment process.

CONCLUSION

FTA allowed us to identify the combination of component failures that lead to system failure and to calculate the probability of failure in the following subsystems: wheel hub, suspension tray, shaft sleeve, damping, and suspension. The two highest probabilities of failure are related to the suspension and the shaft sleeve, with values of 38.8% and 20.5%,

Table 1. Pareto analysis

Component	Frequency	Cumulative Frequency	Cumulative Relative Frequency
Labeling Terminal	280	280	23.87
Labeling Terminal	200	480	40.92
Anchor bolt	189	669	57.03
Shaft	189	858	73.15
Anchor bolt 2	108	966	82.35
Tray	98	1064	90.71
Spare tray	64	1128	96.16
Stud bolt	27	1155	98.47
Damper	18	1173	100

Source: The Authors (2021)

respectively. Based on this data, the criticality of each basic component was calculated, resulting in the rotary terminal being the most critical element, followed by the anchor bolt.

The FMEA analysis provided an overview of the causes of failure in the Baja vehicle's suspension system. It was observed that the element that poses the highest risk to the system is the rotary terminal failure due to the car overloading during the journey, when the driver demands more from the vehicle than it can offer. Although this fault is not severe, its occurrence and difficulty detecting it increase the risk. As a recommendation, it is suggested that the driver undergo training to learn about the car's limits and that a way be found to ensure that this milestone is not exceeded.

The second highest risk is also linked to the labeling terminal; however, in this case, the failure is due to a sizing error. It is followed by the anchor bolt also failing due to a design error and the shaft, which present the same risk. As a recommendation, it was suggested that stress simulations be carried out using software to ensure the results found were relevant.

Next, the components that present the highest risks are, in this order: anchor bolt failure linked to vehicle overload; tray failure due to buckling; inefficient tray, stud bolt, and Damper fixing. Therefore, this is the order in which corrective actions should be prioritized with a view to improving the project.

When monitoring maintenance efforts during the assembly of car components, it is essential that the more experienced team members supervise and guide the others to avoid errors due to inappropriate tool use.

As already mentioned in the SAE Brasil administrative and technical regulations, after evaluating the FMEA, its results should serve as support for an alternative design. The quantification of the suspension's performance and overall impact on the project were assessed along with the fault tree application, and it will be studied in a new Camel III project.

Limitations of this study include the subjectivity of assigning FMEA scores due to the team's lack of experience and the limited history of documenting data on car failures related to the dynamics of SAE competitions, which require frequent changes to the car. Another limitation is the case study, since it is specific to the conditions in which it was carried out, and its conclusions cannot be generalized.

Future work could include a study using stress simulation software to validate the calculations and thus reduce the impact of design errors.

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