DESIGN FAILURE MODES AND EFFECTS ANALYSIS (DFMEA) OF AN ALL-TERRAIN VEHICLE

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Abstract

Society of Automotive Engineers (SAE) organizes a student engineering design competition named Baja in which an All-terrain vehicle (ATV) is designed and fabricated by undergraduate engineering students. ATV is a vehicle that can run on a wide variety of terrains and travels on low-pressure tires with a seat straddled by the operator. SAE BAJA involves designing and fabrication of a modified and scaled down smaller version of ATV. Starting from initial design and analysis to actual fabrication of ATV, everything is done by the students. As in any engineering design, there is a constant need to design a safe and sustainable vehicle. This involves predicting and defining all failure modes in the initial design step itself. An effective method of doing this failure analysis is DFMEA (Design Failure Modes and Effects Analysis), which is an extension of popular Failure Modes and Effects Analysis (FMEA) technique and is done in the design stage. In this paper DFMEA technique is used to list out all modes of failure for various components of the ATV, its causes, effects and ways of preventing it. Risk Priority Number methodology of FMEA is used to find out the components which are more susceptible to failure and needs more attention than others.

Keywords: *All Terrain Vehicles (ATV), Baja SAE, Design Failure Modes and Effects Analysis (DFMEA), Risk Priority Number (RPN)*

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1. INTRODUCTION

American National Standards Institute (ANSI) and Special Vehicle Institute of America (SVIA) in ANSI/SVIA 1-2007 [1] define All-Terrain Vehicle is a Motorized, off-highway vehicle designed to travel on four low-pressure tires, with seat designed to be straddled by the operator, and handlebars for steering. Baja competition organised by Society of Automotive Engineers (SAE) involves design, fabrication and racing of an off-road all terrain vehicle powered by a 10 hp Briggs and Stratton engine [2]. This ATV is a modified version of the one defined by ANSI and SVIA. This specially designed ATV consists of a combination of roll cage and frame. The main objective of the competition is to design and fabricate the roll cage and frame from the scratch along with other critical components.

Along with design and development of the frame and roll cage, the a-arms and trailing arms of the suspension systems are also designed. Assembly of other components like power-train, steering system, braking system, wheels etc. are also a part of the competition. On overall, the entire ATV is designed, fabricated and raced by the students.

The design stage is critical for the development of the vehicle. Being an off road and low powered vehicle, a sturdy and safe design is a pre-requisite. Various components of the vehicle can fail in different circumstances leading to compromise in safety and jeopardising the entire project. Hence a comprehensive and systematic analysis of the vehicle in the design stage is off utmost importance.

As advised by Baja in its rulebook [2], this systematic failure analysis can be done by a popular reliability analysis technique called Failure Modes and Effects Analysis (FMEA). As defined by Institute of Heath Care Improvement (IHI), “FMEA is a systematic, proactive method for evaluating a process to identify where and how it might fail and to access the relative impact of different failures, in order to identify parts in the process that are most in need of change” [3]. FMEA evaluates potential failure modes, its causes, effects and ways of prevention. An effective application of FMEA in product design stage is Design Failure Modes and Effects Analysis (DFMEA) which is used in this project. Risk Priority (RPN) methodology of failure prioritisation, a popular sub-method of FMEA is used in this project.

2. FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Failure Modes and Effects Analysis (FMEA) is a systematic step-by-step failure analysis technique. It evaluates processes for possible failure and to prevent them by correcting the process rather than reacting to effects after failure has occurred. FMEA is useful in evaluating new processes prior to implementation. FMEA is an efficient quality and reliability analysis technique. American Society of Quality defines FMEA as “FMEA is a step-by-step approach for identifying all possible failures in a design, a manufacturing or an assembly process or a product or service” [4].

FMEA has wide range of applications in almost every field. FMEA technique was first adopted by National Aeronautics and Space Administration (NASA) for its various space programs like Viking, Voyager, Magellan, and Galileo in 1960s [5]. Later it was adopted by civil aviation and automotive industry, with Society of Automotive Engineers publishing ARP926 [6] [7]. Hoseynabodi et al. (2010) applied FMEA to wind turbine systems [8].It was useful to prevent failures at the design stage of Wind Turbines.

FMEA can be broadly classified into system FMEA, Design FMEA and process FMEA [9]. DFMEA is used to analyze product design before it is released to manufacturing and Process FMEA is used to analyze manufacturing and/or assembly processes.

In SAE Baja project, DFMEA methodology has been used to systematically analyze failure modes of various critical components of the ATV. Since the ATV contains numerous components, it is essential to prioritize different components according to their risk of failure and its effects. In this methodology Risk Priority Number (RPN) method is used to prioritize the failures, its effects, causes and ways to prevent it.

3. DFMEA METHOD AND RISK PRIORITY NUMBER

Design Failure Mode and Effects Analysis (DFMEA) is first done by identifying all the components of the All-Terrain Vehicle. This is followed by identifying failure modes for each component, its causes and its effects on the individual component and the vehicle as a whole. After the above step, severity of the failure, likelihood of occurrence of failure and likelihood of detection the failure is determined for each failure mode. The above parameters are given a numerical rating from 1 to 10. The criteria for the rating are described in later sections of this paper. The above ratings are multiplied to calculate a quantity/index called Risk Priority Number (RPN).

Risk Priority Number (RPN) is the product of the numerical ratings of Severity, likelihood of occurrence and likelihood of detection. RPN is mathematically given in equation 1.

$$\text{RPN} = (\text{Severity Rating}) \times (\text{Likelihood of Occurrence rating}) \times (\text{Likelihood of Detection rating}) \qquad (1)$$

RPN helps to prioritize components to focus on and work in the direction of its improvement. After the RPN is calculated the failure modes of components are prioritized according to the obtained RPN. The failure mode with highest RPN is given the highest importance followed by the next failure mode with next lower RPN and so on. A graph is plotted for different component failures and its RPN.

After the above steps the prevention techniques for each failure mode is listed out and appropriate action is taken according to the priority of the failure modes. The aim of the overall method is to minimize the total RPN (which is the sum total of all individual RPN) of the process. The whole process of DFMEA of the ATV is illustrated in a flowchart in figure 1.

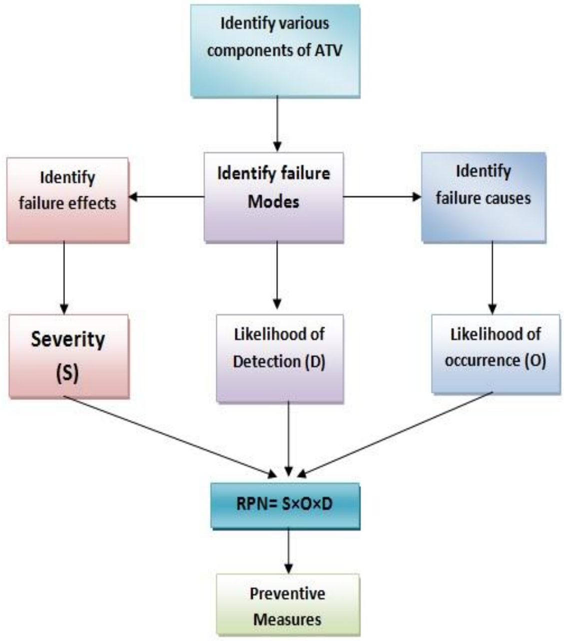

Figure 1

4. SEVERITY, LIKELIHOOD OF OCCURRENCE AND LIKELIHOOD OF DETECTION

Severity (S) is the hazard potential of the particular failure to the individual component and the vehicle as a whole. It is numerically rated from 1 to 10, with 1 meaning no or very minor harm to the system and 10 for extremely dangerous effect on the system. The severity evaluation and rating criteria along with its definition is illustrated in table number 1.

Likelihood of Occurrence (O) gives how likely a failure will occur. Again a rating of 1 to 10 is assigned where 1 meaning “very unlikely to occur” and 10 meaning “failure is inevitable and persistent”. The likelihood of occurrence evaluation and rating criteria along with its definition is illustrated in table number 2.

Likelihood of detection (D) gives how likely the current control will detect the failure mode. Similar to above two parameters, a numerical rating of 1 to 10 is assigned to it, where 1 meaning “the failure will be detected very likely” and 10 meaning “the failure can’t be detected with current controls”. The likelihood of detection, its evaluation and rating criteria along with its definition is illustrated in table number 3.

Table-1: Severity Evaluation and Rating Criteria

SL. No.	SEVERITY CLASSIFICATION	SEVERITY RATING	DEFINITION AND DESCRIPTION
1.	**Extremely Dangerous/Hazardous and occurs without warning**	**10**	Failure occurs unpredictably often without warning. It involves non-compliance with government/safety regulations. Machine operator/driver's safety compromised. Often the machines are beyond repair and vehicle becomes inoperable.
2.	**Very Dangerous/ Hazard occurs with warning**	**9**	Failure is hazardous and very dangerous, but occurs with a warning. It endangers operator/human life and results in damage to vehicle/machine beyond repair. It also involves non-compliance with regulations
3.	**Very High**	**8**	Vehicle/Machine/Item inoperable (primary function loss). It involves major repair and rework. Here safety is not compromised and failure is in compliance with govt. and safety regulations.
4.	**High**	**7**	Vehicle/Machine is operable but at reduced performance. Repair and rework can be done but with difficulty.
5.	**Moderate**	**6**	Primary function of vehicle/machine intact i.e. vehicle is operable but comfort/convenience is compromised. Failure occurs in a part of the overall system but can be repaired.
6.	**Low**	**5**	Vehicle/system is operable but at reduced comfort and with performance is affected. It creates enough performance loss for repair.
7.	**Very Low**	**4**	Small failure which can be overcome by minor modifications. There is no critical loss/effect to the system. Fitting and Finishing failures are involved here.
8.	**Minor**	**3**	It causes little annoyance but no loss of performance. It can be overcome by minor rework.
9.	**Very Minor**	**2**	System/Vehicle is operable with minimum deterrence. Failure is not observed easily. Repair and rework may not be needed.
10.	**None**	**1**	No noticeable effect of the failure and does not affect the operation/performance in any way.

Table-2: Likelihood of Occurrence Evaluation and Rating criteria

Sl. No.	LIKLIHOOD/PROBABILITY OF OCCURRENCE	RATING	DEFINITION
1.	**Very High: Failure is inevitable and persistent**	**10**	Failure in every third component (1:3)
2.	**High: Similar processes have often failed**	**9**	Failure in every sixth component(1:6)
3.	**High: repeated failures**	**8**	Failure in every ninth component (1:9)
4.	**High: frequent failures**	**7**	Failure in every 50 component (1:50)
5.	**Moderately High: Frequent failures**	**6**	Failure in every 150 component (1:150)
6.	**Moderate: Occasional failures**	**5**	Failure in every 800 component (1:800)

7.	**Moderately Low: infrequent failures**	**4**	Failure in every 4500 component (1:4500)
8.	**Low: Few failures**	**3**	Failure in every 30000 component (1:30000)
9.	**Very Low: Isolated failures**	**2**	Failure in every 150000 component (1:150000)
10.	**Remote: Failure unlikely**	**1**	Failure in every 1.5 million component (1:1.5million)

Table-3: Likelihood of Detection

Sl. No.	**DETECTION**	**RATING**	**DEFINITION**
1.	**Absolutely no detection or almost impossible**	**10**	Almost certainty of non-detection. No known controls capable to detect failure mode
2.	**Very Remote**	**9**	Very less chance of detection of failure by controls
3.	**Remote**	**8**	Controls have poor chance of detecting the failure mode
4.	**Very Low**	**7**	Very low chance of detection of failure mode by controls
5.	**Low**	**6**	Controls may detect the failure mode
6.	**Moderate**	**5**	Moderate chance of detection of failure by control
7.	**Moderately High**	**4**	Controls have a good chance to detect the failure mode
8.	**High**	**3**	Controls certainly detect the failures, automatic detection of failure by the process
9.	**Very High**	**2**	Controls almost certain to detect failure mode
10.	**Very High/Almost certain**	**1**	Certain detection of failure and controls

5. DFMEA IMPLEMENTATION

DFMEA is implemented on 20 critical components of the ATV. The analysis is done on the components namely Frame, Bracket, Support, Engine, Transmission, A-arm and trailing arms, Springs, Dampers, Steering column, Steering Wheel, Rack and pinion, Knuckles, Pedal, Braking System, Tires, Rim, Driver seat, Body Panel, transponder and vehicle electrical components. The detailed DFMEA process is illustrated in table 4.

Table-4: DFMEA Chart

Sl. No	**COMPONENT**	**FAILURE MODE**	**FAILURE CAUSE**	**FAILURE EFFECT**	**S***	**O ***	**D***	**RPN ***	**PREVENTIVE ACTIONS**
1.	**Frame**	Structural failure; Bending and breaking of frame	Axial stress exceeds yield stress of material due to excess load and impact loading	Overall Damage to roll cage. Frame breaks or bends. Driver's safety is endangered	10	6	7	420	Choose material with appropriate/high factor of safety(FOS), effective design and analysis; constant testing
2.	**Bracket**	Structural failure, bending and breakage	Bearing and yielding stress caused by excess load and constant vibration	Bracket fracture leading to dislocation of mechanical/structural components which in turn leads to mechanical and structural component damage. Damage to roll cage as a whole	9	5	6	270	Choose materials with high FOS; Effective design and analysis

3.	**Support**	Bending, Breakage and structural failure	Axial stress exceeds yielding stress of material due to excess load and impact loading	Structural damage to Roll cage and driver's safety compromised	10	6	6	360	Choose materials with high FOS; effective design and analysis
4.	**Engine**	Mechanical Failure, Engine component damage	Unavailability clean air and proper fuel	Vehicle become inoperable due to engine failure /damage and risk to driver's life	9	3	4	108	The engine's position should be such that it has free access to clean air and risk to driver is minimum
5.	**Transmission**	Mechanical failure	Fatigue/ cyclic loading	Vehicle becomes inoperable	8	2	4	64	Choose transmission system according to given load, performance and other specification
6.	**A-Arms and Trailing arms**	Bending, Breakage, cracks, structural damage and mechanical failure	Axial stress exceeds yielding stress of material due to excess load and impact loading	Damage to suspension system and rough operation or non-operation of the vehicle	8	7	7	392	Choose material with high FOS and according to vehicle specifications; effective design and analysis
7.	**Springs**	Spring fractures and fails	Due to faulty choice of springs, spring fails due to loads exceeding the yield stress of the material	Damage to suspension system and rough of the vehicle	6	1	3	18	Choose springs according to vehicle loads and other specification.
8.	**Dampers/ Shock Absorbers**	Mechanical failure, Leaking of suspension oil	Cylinder damage due to foreign body/debris	Damage to suspension system and rough of the vehicle	6	2	2	24	Verification of specifications and testing
9.	**Steering Column**	Mechanical failure, excess vibration	Debris leading to steering column failure	Steering failure; Safety of driver and others compromised	9	3	4	108	Verification of desired specification and testing
10.	**Steering Wheel**	Breakage, mechanical failure	Excess load applied by driver	Steering failure; Safety of driver and others compromised	9	2	2	36	Verification of desired specification and testing
11.	**Rack and Pinion**	Mechanical failure, Leaking of fluid, Loosening of Lug nut	Obstruction in movement of pinion over rack, damage to components	Steering failure; Safety of driver and others compromised	9	5	7	315	Verification of desired specification and testing

12.	**Knuckles**	Breakage due to structural failure	Failure due to bending, crushing and tensile stress and double shear	Damage to suspension system and rough operation or non-operation of the vehicle	8	5	8	280	Choose material with high FOS and according to vehicle specifications
13.	**Pedals**	Structural failure die to fatigue, bending and breaking	Excess application of load by driver causes axial load to exceed yield strength of material	Brake failure	9	2	1	18	Choose material with high FOS and careful testing should be done
14.	**Braking System**	Mechanical failure	Not sufficient braking force	Damage to vehicle in undesired circumstances	9	5	3	135	Choose material with high FOS and careful testing
15.	**Tires**	Mechanical failure	Puncture by foreign debris	Inability to operate vehicle	7	8	2	112	Verification of proper specification and testing
16.	**Rim**	Mechanical failure	Damage by debris	Inability to operate vehicle	8	3	7	168	Verification of proper specification and testing
17.	**Driver seat**	Structural failure affecting safety	Excess load leading to bearing stress	Endangers driver's safety	9	2	3	54	Proper fitting and material according to correct specifications of load
18.	**Body Panels**	Structural failure	Colliding of foreign object, Impact loading	Loss in aesthetics	4	4	2	48	Choose material of high FOS
19.	**Transponder**	Electrical failure	Water damage/electrical failure	Endangers driver's safety; disqualification from competition	10	3	5	150	Proper insulation should be provided and wiring should be done properly
20.	**Vehicle Electrical components**	Electrical failure	Water damage/electrical failure	Endangers driver's safety due to contact from electricity	9	5	2	90	Proper insulation should be provided and wiring should be done properly

* S is Severity Rating, O is Likelihood of Occurrence Rating, D is Likelihood of Detection Rating and RPN is Risk Priority Number

6. PRIORITY GRAPH

After DFMEA is done, the failure modes of the components are prioritized according to their RPN in a Risk Priority Graph. Prevention techniques are applied according to the priority of the components from largest RPN to smallest. The RPN graph is illustrated in Chart 1.

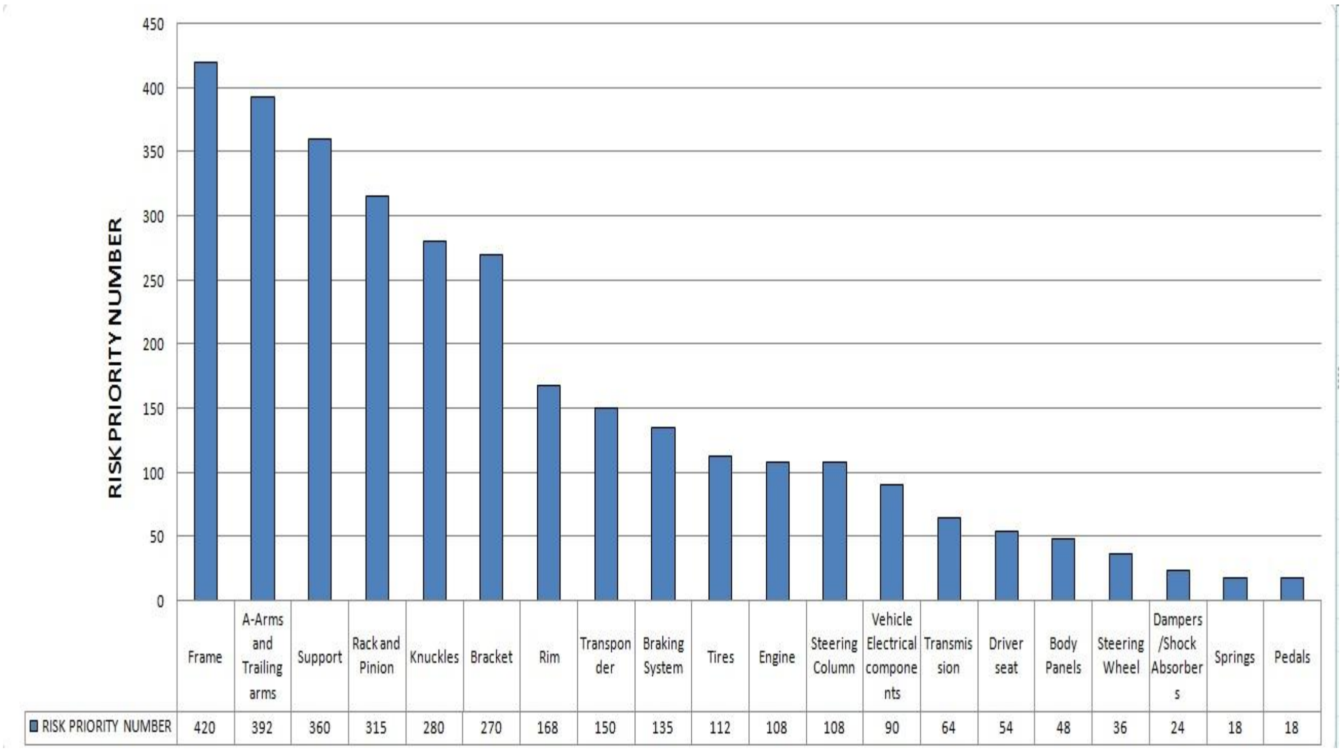

Chart-1: Risk Priority Number Graph

7. DFMEA REPORT ANALYSIS

After prioritising the components according to their RPN, it was found that Frame, A-Arms and Trailing arms, Support, Rack and pinion, Knuckles were in top five according to their failure risk. They also had RPN above 250, which indicate they are very critical to the quality of ATV. Detailed prevention techniques were listed out and proper action taken for these components as well as other components of the ATV.

8. CONCLUSION

DFMEA was carried out listing out all possible failures of the components, its causes and effects. Along with this the severity of the failure modes, its likelihood of occurrence and detection were also singled out. Finally the RPN was calculated for each failure mode, its graph was plotted and the components prioritized according to its failure modes. Preventive measures for each and every component were suggested in this paper to reduce risk of failure of the ATV.

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BIOGRAPHY

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