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Design Failure Modes and Effects Analysis (DFMEA) of a Human Powered Recumbent Vehicle

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Abstract **- American Society of Mechanical Engineering (ASME) organizes International Human Powered Vehicle Challenge (HPVC) to provide a technical platform to budding technocrats to manifest the application of sound engineering design principles. This competition aims at "development of sustainable and practical transportation alternatives" [6]. In HPVC, students team up to engineer a highly efficient vehicle which can be utilized in our everyday use- from commuting to work, to carrying goods to market. A recumbent vehicle is a two/ three wheeler which places the rider in a laid-back reclining position. These vehicles are abundantly in use in West. They have wide applications-as means of transportation, recreation, exercise and as a freight vehicle. These vehicles are human powered and makes no use of fuel. Thus, they are eco-friendly in nature. In ASME HPVC, recumbents are designed and fabricated indigenously by the students. The recumbents in ASME HPVC are slightly modified to have fairings so as to have an increased speed for racing purpose. Given the non uniform roads that the vehicle will be subjected to especially in India, it is quite important to have a safe and strong design of the vehicle. Thus, the possible critical failure points and its mode of failure needs to be identified in the design stage itself and preventive measures be taken. An effective tool for making a failure analysis is DFMEA (Design Failure Modes and Effects Analysis) which is an augmentation of widely used Failure Modes and Effects Analysis (FMEA) technique. This analysis is done in the design stage. DFMEA has been used to predict and analyze various failure modes of a recumbent vehicle, its cause & effects and to outline preventive measures. Risk Priority Number (RPN) methodology is used to identify the critical parts which are more vulnerable to failure and needs extra attention.**

Keywords: Recumbent Vehicle, ASME HPVC, Human Powered, Design Failure Modes and Effects Analysis (DFMEA), Risk Priority Number (RPN), RPN graph

1. INTRODUCTION

World Human Powered Vehicle Association defines Human Powered Recumbent Vehicle as "a vehicle with a seat position that is inclined backwards and the bottom bracket and the pedals are attached front" [8].These vehicles are driven by muscular strength. The vehicle's application areas are- commuting of passengers, transportation of goods, means of exercise, means of transport in rough terrain, inaccessible areas and to help in relief tasks in emergency situations like drought, floods etc. The Human Powered Vehicle Challenge organized by ASME aims at development of vehicles with such service potentials as well as being eco-friendly. The competition involves design, fabrication and on ground races. The design and the fabrication are entirely done by the students.

Given the rigors of the terrain, human force and freight loading that the vehicle will be subjected to, a safe and an efficient design is of utmost importance for successful operation of the vehicle. This includes identification of potential failure points, modes of failure, cause and effect of the failure and taking required preventive measure at an early design stage.
The Failure Modes and Effects Analysis (FMEA) technique of failure analysis is the apt tool for the above project. As defined by American Society of Quality (ASQ), "Failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service." [3]. For failure analysis in design stage, Design Failure Modes and Effects Analysis (DFMEA) methodology of FMEA is used. Thus, DFMEA is applied on the project and failure analysis is made. Risk Priority Number (RPN) is used to have a numerical analysis of the potential failure modes and based on this number the sensitive parts of the vehicle are identified and preventive measures are taken. The main design aspects of the recumbent vehicle consists of the Frame, Roll over Protection System (RPS), Tie rod, Suspension, Storage frame and Steering column.

2. FAILURE MODES AND EFFECTS ANALYSIS

Otherwise known as Failure Modes, Effects and Criticality Analysis (FMECA), it is a methodic, well ordered and thorough going analysis of various failure modes, their causes and effects. It leads to identification of the critical components of the subject under study to facilitate implementation of preventive measure.

The application of FMEA dates back to 1949 when procedures for conducting FMECA were described in US Armed Forces Military Procedures document MIL-P-1629.

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With the onset of 1970s, FMEA became widely used in automotive sector as well as in space projects. NASA programs using FMEA variants included Apollo, Viking,

Voyager, Magellan, Galileo and Skylab while in automotive sector; it finds its use in Ford Motor Company and Toyota. At present FMEA is popular in other sectors like semiconductor processing, food service, plastics, software, and healthcare.

FMEA can be categorized into 3 types as in System, Design and Process FMEA [4]. Of the three, Design FMEA or DFMEA is used to analyze designs before the design is given to start production.

Risk Priority Number is a numerical based analysis of components based on their sensitivity to failure. This number helps in spotting the more critical components and thus helps in making the design sturdy as the "danger spots" are given extra attention during fabrication.

For having the best design, DFMEA along with RPN methodology has been implemented in the project ASME HPVC.

3. DFMEA AND RPN METHODOLOGY

The various parts of the recumbent trike were outlined. For each part, failure modes and its causes & effects were determined. Next, Severity of the failure, Likelihood of occurrence of failure and Likelihood of detection of the failure were determined for each failure mode. All these parameters were assessed and marked from 1 to 10. Details of these parameter ratings are discussed in the next section. Finally, RPN of each failure mode was calculated.

Table 1: Severity Assessment and Rating Criteria

RPN is the product of numerical markings of Severity of failure, Likelihood of occurrence of failure and Likelihood of detection of failure. Equations (1) and (2) shows the formula for calculating RPN and Total RPN-

RPN= (SEVERITY MARKING)*(LIKELIHOOD OF OCCURRENCE MARKING)*(LIKELIHOOD OF DETECTION MARKING) (1)

TOTAL RPN= SUM OF ALL RPNs (2)

After this, the components/parts were arranged in decreasing order of their RPN. Graph was plotted to get a comparative view of the most critical parts/components. The components/parts with highest RPN is given most importance during fabrication followed by components with next higher RPNs. The main objective is to have a reduced Total RPN [refer (2)] as this would ensure safe design of the recumbent vehicle.

4. SEVERITY, LIKELIHOOD OF OCCURRENCE, LIKELIHOOD OF DETECTION

Severity (S) refers to the degree to which harm will take place if a failure mode occurs. It is marked from 1 to 10. 1 represents "harm with less or zero severity" while 10 represents "harm with maximum severity".
Likelihood of Occurrence (O) refers to the possibility of an occurrence of a failure mode. It is also scored from 1 to 10. 1 suggests "unlikely to occur" while 10 suggests "most likely to occur".
Likelihood of Detection refers to the likeliness of detection of failure if the failure mode occurs. It is too rated from 1 to 10.1 stands for "very likely to be detected" while 10 stands for "very unlikely to be detected". The tables 1, 2 and 3 illustrate the details.

SL. No.	SEVERITY' DENOMINATION	SEVERITY RATING	DESCRIPTION
1.	Hazardous with Maximum Severity and occurs without warning	10	Failure occurs without any prior effects. Vehicle's core design is compromised. Rider's safety is at stake. Vehicle may be inoperable. Vehicle may be dismantled wholly. Occurs due to poor fabrication, non compliance with
2.	Very Hazardous and occurs with warning	9	Failure is life risking. It occurs with a warning. Occurs due to negligence in periodic repair work, poor fabrication, and low quality raw materials. Vehicle needs to be abandoned.
3.	Very High	8	Vehicle is inoperable. Immediate overhauling is the requirement. Occurs due to accidents, usage of non-standardized parts, workforce inefficiency, and non-corporation of vehicle safety standards.
4.	High	7	Vehicle's performance is compromised greatly. Extensive Repair work is necessary.
5.	Moderate	6	Vehicle is operable. Comfort and aesthetics are compromised. Performance loss takes place. Repair can do the job.
6.	Low	5	Vehicle is functional. Audible noises are heard. Minor vibrations are there. Repair work is enough with no replacements necessary.
7.	Very Low	4	Failures due to aligning, fitting, finishing problems. Petty wear and tear occurrence. Can be overcome by re-work of the vehicle.
8.	Minor	3	Ergonomically poor. Repair is needed.
9.	Very Minor	2	Vehicle is functional. Performance slightly below optimum level. Not a concern.
10.	None	1	No striking effect, with the vehicle performance remaining unaffected.

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Table-2: Likelihood of Occurrence Assessment and Rating Criteria

Sl. No.	LIKELIHOOD OF OCCURRENCE' DENOMINATION	RATING	DEFINITION
1.	Extremely High: Failure is unavoidable and perpetual	10	Failure in every fourth component (1:4)
2.	High	9	Failure in every sixth component (1:6)
3.	High: repeated failures	8	Failure in every tenth component (1:10)
4.	High: frequent failures	7	Failure in every 50 component (1:50)
5.	Moderately High: Frequent failures	6	Failure in every 200 component (1:200)
6.	Moderate: Occasional failures	5	Failure in every 600 component (1:600)
7.	Moderately Low: infrequent failures	4	Failure in every 5000 component (1:5000)
8.	Low: Few failures	3	Failure in every 500000 component (1:50000)
9.	Very Low: Isolated failures	2	Failure in every 200000 component (1:200000)
10.	Remote: Failure unlikely	1	Failure in every 3 million component (1:3million)

Table-3: Likelihood of Detection Assessment and Rating Criteria

Sl. No.	DETECTION' DENOMINATION	RATING	DEFINITION
1.	Impossible to detect	10	Almost negligible chances of the failure mode getting detected
2.	Very Remote	9	Very slight chance of detection of failure mode
3.	Remote	8	Far off chance of detection of failure mode
4.	Very Low	7	Minimal chance of failure mode detection
5.	Low	6	Failure mode may be detected
6.	Moderate	5	Moderate chance of detection of failure
7.	Moderately High	4	Fair likelihood of detection of failure mode
8.	High	3	Failure mode detection is high
9.	Very High	2	Higher possibility of failure mode getting detected
10.	Certain	1	Certain detection of failure by controls

5. DFMEA IMPLEMENTATION

The DFMEA was applied on different components of the Human Powered Recumbent Vehicle. Analysis was made on 15 components of the recumbent vehicle namely Frame, Handlebar, Tires, Rims, Cassette, Bottom Bracket, Seat, Storage space, Tie rod, Steering column, Knuckles, Suspension, Fairing, Braking system and Electrical components. The detailed analysis using DFMEA is illustrated in table4.

Table-4: DFMEA WORKTABLE

Sl No.	COMPONENT	FAILURE MODE	FAILURE CAUSE	FAILURE EFFECT	S*	O *	D*	RPN *	PREVENTIVE ACTIONS
1.	Frame	Torsion, Bending, Rolling, Cracks, Broken welds, Structural forces	Axial stress, Impact loading, Fatigue stress, Fabrication Defects	Bending and weakening of frame, Damage to Roll over protection system, All mounting parts gets weakened, Rider's safety is compromised	10	5	8	400	Selection of correct material having high yield stress, Considering high factor of safety in design stage, Careful testing and analysis, efficient welding
2.	Bottom Bracket	Axial loads, Bending, Torsion	Excessive bearing and bending stress	Break in connection of crank with the vehicle, Transmission breakdown	8	3	3	72	Choosing of a material with high factor of safety
3.	Handlebar	Bending failure, Structural failure	Excess of impact loading	Vehicle Imbalance, Rider's Safety is compromised	10	5	5	250	Choose materials with high FOS; Highly efficient design
4.	Cassette & Crank set	Torsion failure, Fatigue failure, Mechanical failure	Excessive wear and tear, accidents	Gear shifting failure, Performance compromised	7	3	7	147	Proper lubrication, Periodical checkups and replacements, use of standard cassette
5.	Storage Space	Impact Failure, Bearing failure	Overloading, Shock loads, Frame faults	Storage space gets damaged	4	6	1	24	The supporting frame should a material of high factor of safety, Loading beyond a permissible range should be prevented
6.	Steering Column	Bending failure, Torsion failure, Buckling	Rough terrain travel, Overloading	Steering Mechanism fails, Rider's safety is compromised	9	4	4	144	Extensive structural testing, proper material selection and design
7.	Tie Rod	Mechanical failure, Cyclic failure	Rough Terrain, excessive loading during steering, loosening of bolts	Steering failure, Severe vibrations, Rider's safety is compromised, Vehicle performance is affected	9	5	3	135	Periodic fitting and repair work, Selection of a material with a high factor of safety
11.	Suspension	Spring failures, Mechanical failures	Inappropriate choice of springs	Rider's comfort as well as vehicle parts are compromised	4	1	2	8	Selection of a standard suspension system
12.	Knuckles	Structural failure, Mechanical failure	Excessive bending, crushing stress	Vehicle performance is compromised, lesser comfort	7	5	8	280	Proper selection of material with high factor of safety
10.	Braking System	Mechanical failure, Heat	Excessive wear and tear, snapping of	Poor braking	10	4	2	80	Periodic checking and replacement
11.	Tires	Sidewall failure, Tread separation, Bead failure	Improper mounting, puncture, Excess inflation	Vehicle becomes inoperable	8	7	3	118	Careful mounting, material testing and analysis, proper inflating process, regular check up
12.	Rim	Brittle or Ductile Fracture, Fretting fatigue, Cyclic torsion	On road damage, large radial and tangential stresses, Faulty mounting	Vehicle becomes inoperable	9	3	6	162	Using standard rims, Proper Suspension system
13.	Rider seat	Frame failure, Misalignment, fitting problem	Excess load causing bearing stress, Stress concentrations, Improper fitting to the frame	Rider's safety & comfort are compromised, Ergonomically poor	9	3	1	27	Selection of proper material with required critical bearing stress, proper fitting and applying cushion
14.	Fairing	Projectile penetration, Tear, Mounting failure	Collision of a foreign object, High velocity wind flow, Head on collision	Aesthetically poor, Reduction in optimal speed, Racing potential hampered	3	5	1	15	Selection of a material with high factor of safety, fairing mountings should be strong
15.	Vehicle Electrical components	Open circuit, Electrical short, connection Stripping	Water entry, Incorrect connection, Electrical Failure	Component becomes non-functional	4	4	1	16	Proper insulation, Correct wiring, Caging the component

6. PRIORITY GRAPH

Priority Graph is a graphical representation of RPNs of the components. After the above analysis, the priority graph was plotted with RPN in y-axis and Components in x-axis. The graph gives a comprehensive view of the components with greater RPNs. Thus, extra care and recommended preventive measures will be taken for such critical components. Fig.1. shows the priority graph.

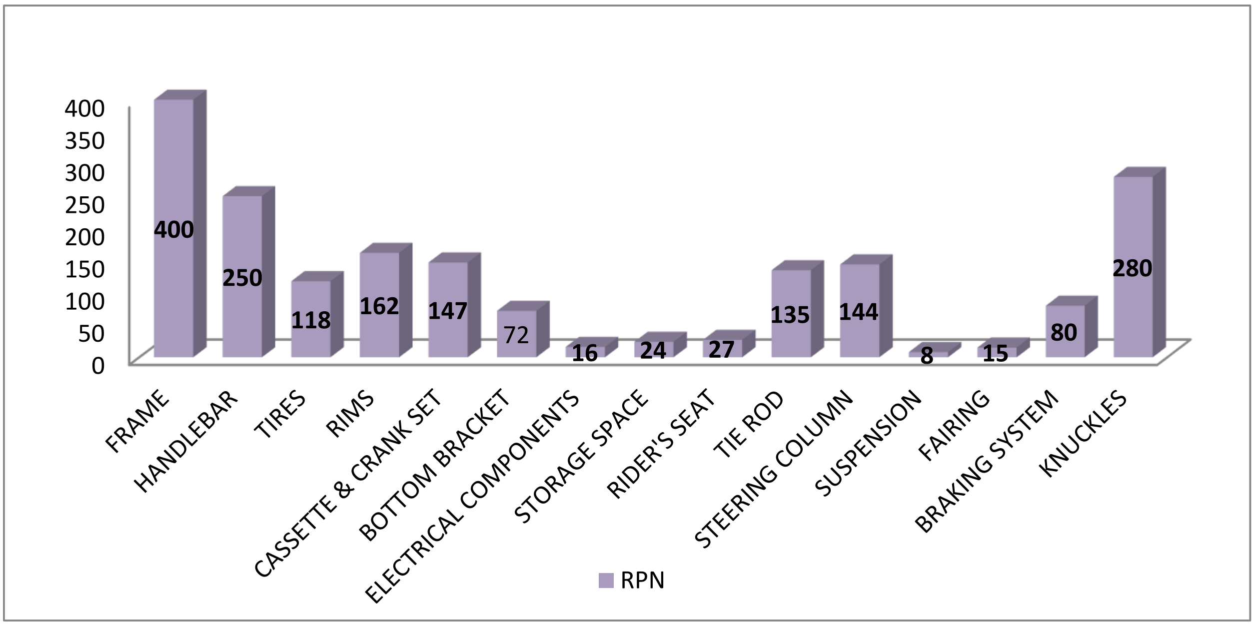

Fig.1. RPN Graph

7. DFMEA ASSESMENT

A full-fledged DFMEA was carried out on the Human Powered Recumbent Vehicle. The analysis brought forth the fact that the Frame, Handlebar, Knuckle, Rim, Cassette & Crank set and Steering Column are the critical components with high RPN which require first hand attention and top notch design and testing.

8. CONCLUSION

The DFMEA was targetfully applied on the components of the Human Powered Recumbent Vehicles. The various analysis aspects as in Severity, Likelihood of Occurrence and Likelihood of Detection were clearly outlined and defined. Based on these aspects, a rating based analysis was done. RPN was calculated for each. The analysis was plotted on a graph to spot the critical components. Required preventive measures were recommended. These findings were incorporated during the design and fabrication of our own Human Powered Recumbent Vehicle. Fig. 2 shows the picture of our recumbent vehicle.

Fig.2.Human Powered Recumbent Vehicle

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BIOGRAPHY

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