Design, Analysis and Fabrication of a Detachable Human Powered Vehicle (HPV)

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***Abstract*:** *In a world dependent on fossil fuels which are diminishing, utilization of human kinetic energy will help troubleshoot various mechanical challenges and fuel limitations. This paper deals with Design, Analysis and fabrication of a semi-recumbent type Human Powered Vehicle (HPV). The focus on the design is to make the vehicle durable, ergonomically comfortable and could be afforded by masses. The innovative feature like the detachable frame enables it to dismantle and easier to carry along. To avoid the structural failures, computer simulations are also done using the Finite Element Analysis (FEA) and Computational and Fluid Dynamics (CFD) to make the design structure robust and aerodynamic to drive. The physical testing like smoke test and UTM is also done to validate the shape and strength of the vehicle.*

Keywords—*Human Powered Vehicle, Aerodynamic Efficiency, Ergonomics, Computational Fluid Dynamics, Finite Element Analysis.*

I. Introduction

In the recent times the dependence of mankind on fossil fuel has been increasing at a tremendous rate. To make up for this high consumption and to promote energy sustainability we propose the development a lightweight, rider friendly, agile and practical HPV which can be effectively used for everyday transportation. In this paper we present a case study and guide for design, analysis and fabrication of HPV. We named the vehicle as “FATEH” (name is from Urdu meaning Victory). Our HPV “FATEH” has undergone rigorous designing, analysis, computational modelling and physical testing to meet the required standards of ASME. The frame fabricated is detachable and can be packed in an average canvas bag. Moreover, the 6 piece fairing adds to the advantage of practicality. Even with these required standards being met we plans to achieve a set of additional objectives which include exceptional safety, practicality and performance in aluminium frame and carbon fibre fairing. Our vehicle is a semi-recumbent bicycle with aluminium tubing and carbon fibre fairing. By using aluminium we have ensured that the overall weight of the frame and the HPV is kept at a check without compromising the overall strength of the HPV. We also purpose the use of standard bicycle components to ensure that the HPV could be repaired easily. The safety of the rider is of top priority for our team. Physical testing as well as FEA made sure that the frame will provide it with strength to meet the ASME HPV standards with minimum deformations. Also the overall cost of our HPV is kept lower than most of the HPV available in the market to make it a commercially viable option to the standard bicycles.

II. Design

A. Design Objective

The mission of our team is to create and implement ideas to improve the portability, furthering functionality and building a strong segment in global market for HPVs. Focusing safety, comfort, providing various customizations and add on features for its market appeal. Expanding the field of HPVs will provide as a solution to use of non-conventional sources of energy and sound fitness option. Also contributing to reduce the global dependency and imparting social responsibility. Some of the key features besides practicality are:

- Safety
- Innovation
- Ergonomically comfortable
- Durability
- Cost Effective

B. Background

The rising cost of fuel and its impact on environment has forced government and companies to take steps to reduce our dependency on them. Hence, some people are turning towards greener means of transportation such as CNG powered vehicles or bicycles. Though transportation through bicycles might seem to be a good alternative but many shortcomings such as low top speed, no storage space, no safety features has opened a new dimension for a new type of vehicle which merges the simplicity of a bicycle along with the practicality and feature richness of a car.

All these aspects and shortcomings can be fulfilled with a Human Powered Vehicle which is as good as a car with the robustness of a bicycle.

C. Frame

The frame is the most important aspect of the HPV. It has to support the weight of the rider and the fairing, has to be light in weight and at the same time has to be strong enough to bear all the ASME specified load limits. Along with it, the concept of packing the vehicle in an average sized bag is innovative. This involved detaching the frame into 3 pieces and getting assembled by quick release seat clamps, readily available in the market; figure shows the various clamping joints.

Fig. 1. Frame of HPV and clamp design

The layout of the drive-train the crank adjustability, backrest and bum rest adjustability, were the primary focus while designing the frame.

D. Fairing

The fairing is also equally important as the frame. It is not only an outer covering of the HPV but it also acts as an aerodynamic feature too; cutting the air and reducing the air drag that saves the rider from extra efforts and microbiological air agent. Complying with the concept of portability, the fairing is made into 6 pieces and is assembled with the vehicle separately. Each piece of the fairing consists of tubes, embedded into it which slides down inside Rollover Protection System (RPS) tubes and are clamped to the frame members. Thus RPS has multiple roles, one as a safety feature and also acts as a hinge point for the fairing.

Fig. 2. Conceptual model of fairing

Research work for the fairing included not only studying the aerodynamics and the laws associated with it but also the understanding of composites with which it had to be fabricated. The type of shape of the fairing, drag forces, frontal area, skin friction all were studied extensively and their effect in the overall performance of the HPV.

E. Rear Triangle

To aid simplicity and folding mechanics, a cantilever type single sided rear fork was planned to install but due to higher risk of toppling during side load cases, the idea was changed to maintain structural strength along with detachable option as shown in the figure below.

Fig. 3. Rear Triangle Design

F. Drive train

Ultimate preciseness and accuracy is required by the drive train design as the vehicles propulsion for endurance run is greatly based on its refinement.

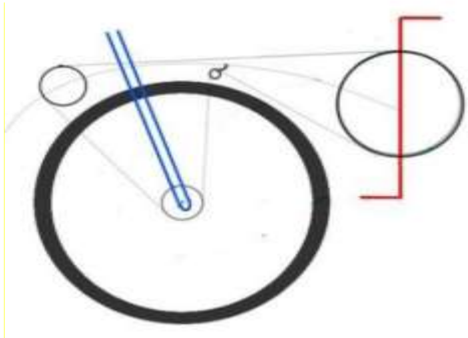


Fig. 4. Drive train arrangement

A front wheel drive is chosen to reduce complexity, reduce drive lag, low weight and rider safety. It was decided to use a tested and profoundly used gear train design as it can steer the vehicle with stationary pedals and improved cornering speed and steering stability while cornering. Also an option for pedal length adjustment is given suiting various driver needs. To counter the change in chain length, tensioners are used.

G. Ergonomics

Ergonomics play a vital role in modern design, if it is not comfortable, it cannot sustain in the market. Special care is taken in the design for the driver comfort; arrangements like the front fork adjustability, bum adjustability, pedal adjustability, steering adjustability and the seat inclination adjustability are provided in the structure using the clamps (as shown in figure 1) and slots as shown below. This will enable the 95% of the Indian riders to drive the vehicle comfortably; it was verified using the mannequin in the CAD software itself.

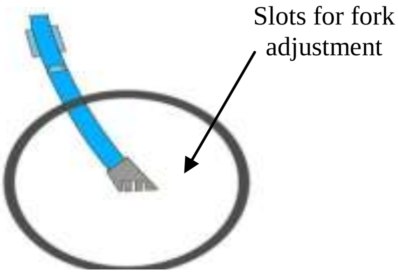


Fig. 5. Front Fork Adjustment

H. Design Specification

After rigorous fact finding and research activity, team finalized the following specifications. These specifications were sorted to accommodate the shortcomings of the commonly used bicycle and added comfort & safety of the car.

TABLE I. DESING SPECIFACTION SHEET

Design Specification	Method	Constraint	Design Goal
Top Speed	Hand calculations	25Km/h	40 Km/h
Turning radius	Hand calculations	8m	6.5 m
Ground clearance	CAD. Fabrication	3 inch	5 inch
Bracking	Hand calculations	6m	4m
RPS top load	FEA	2670 N	--
RPS side load	FEA	1330 N	--
Weight	Hand calculations	35 Kg	30 Kg
Storage space	Hand calculations	2.5 ltr	6 ltr
Angle of visibility	Physical testing	180 Degree	210 Degree

I. Innovation in Design

- Detachable Frame: The frame is fabricated in a way that it can be detached easily so that the whole HPV can be packed into a canvas bag, making it portable. The design of the fairing is a six piece design which provides ease of detachability. The whole detaching process is kept as simple as possible to avoid the complexity, this further provided the compactness. This would result in a situation like a person carrying his clothes in a suitcase and a whole vehicle in the other. By this, the HPV can be taken to next level of commuting.

Fig. 6. Dismantled HPV

- ACT RPS (Axial Compressible tubular Rollover Protection System): It is a new concept for rollover protection system, which is detachable and decreases overall area of frame, and hence, enhancing its packaging. The thing that separates it from the traditional arrangement is that despite being detachable it outstands normal RPS in terms of strength showing test value of 2700N (tested through FEA) which easily covers up the specified norms by ASME i.e. 1330N.

  Various parameters such as safety, weight, complexity etc. were compared between various rollover protection systems. The results thus obtained were summarized with 0-25 scale in chart given below.

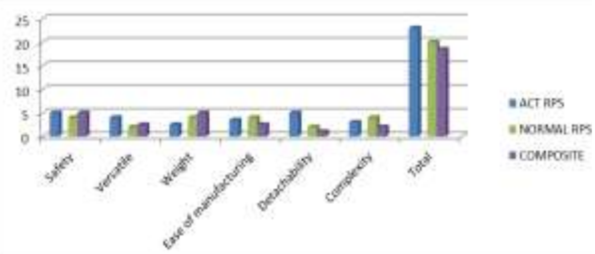


Fig. 7. Comparison between ACT RPS, Normal RPS and Composite RPS

- U-tube Protection: The front end of the vehicle is provided with a U-tube that is capable of taking maximum amount of shocks that may arise due to front collision. The RPS would protect the rider during rolling or sliding of vehicle, an additional protective measure is added on the front to protect the rider from frontal impacts.

- WRSS (Wet Road Stability System): Side flaps are included in the design to minimize the chances of slipping during slippery (wet) road conditions during braking. The concept behind the provision of this is to provide the rider with gradual decrease in speed. It has been incorporated as an alternative that stands close to ABS (Anti Braking System). Calculations are done to find the drag force with and without the side flaps and it was observed that the side flaps increased the drag by 30-35% depending on the vehicle velocity.

Fig. 8. Wet Road Stability System

- Mobile Charging Socket: Provision of mobile holding and charging socket using the flexible dynamo is also there. With this, one can easily attach the dynamo to charge the battery and can log to maps/navigation for directions or attend phone calls. The purpose of doing this is that the rider must focus on road and can use the phone easily without much concern. It would also help the rider to communicate with the team members.

III. Testing & Analysis

A. Structural Analysis

- Rider weight load Case: Analysis of structure for rider loads is examined on various road conditions to validate the functionality of vehicle. For making the vehicle a solution to the mass market its scope of usability is widened. The structure is tested to withstand various road inputs under the weight of the rider. Also it is necessary to split the frame into 3 pieces for HPV folding but it hampers the structural strength. Thus the frame and its two sliding joints became the critical parts to analyze. The weight of the rider is multiplied by 3 times to configure safe static load analysis condition. A load of 2670 N is considered safe also complying with ASME standards and more than 3 times the weight of the rider.

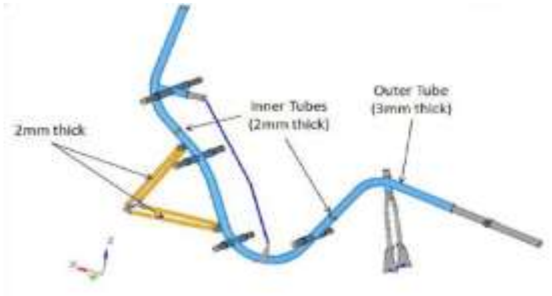


Fig. 9. FEA modelling of the frame

The frame is modelled using the 2D shell elements in hypermesh software (shown in figure 9) and is calculated using the optistruct software. The results are post processed using the hyperview. Only the structure of the HPV is considered for the FEA, the mechanisms are simulated separately. The loads and boundary conditions are shown in figure 10. Using the conservative approach, both the front and rear forks are fixed in all the 3 translational and rotational degree of freedom as the wheels are attached at these points.

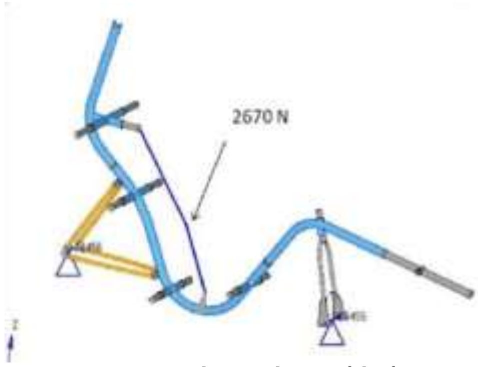


Fig. 10. Boundary conditions of the frame

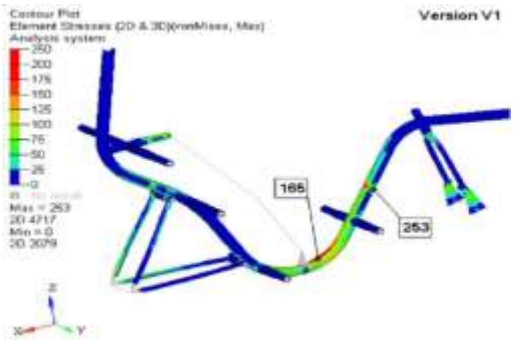


Fig. 11. FEA results: Elemental stress (N/mm^2)

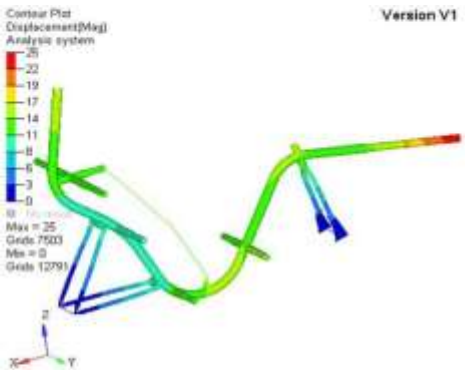


Fig. 12. FEA results: Displacement (mm)

The von-mises stress and displacement results are shown in figures 11 and 12 respectively. The maximum stress of $253N/mm^2$ is observed on the frame near the joint and is lesser than the yield stress limit of the material ($276N/mm^2$), thus, the structure is safe for this load condition.

- Effect of pedalling force on frame: Adjustable and detachable pedal arrangement is designed to suit various rider comfort and aid in packing of HPV in one bag. The pedal arrangement is analyzed to check whether the sliding pair will remain intact in worst force application by the rider. Validation of this improves the compactness of vehicle packaging. Along with 2670N at COG, maximum force of 500 N was applied along the axis of the sliding tube to simulate the physical condition. Rider weight and pedalling force are the input forces acting simultaneously while riding. Outer and inner tubes are both changed to 3mm thickness and are held by clamping screws. The FE model and load application are shown in figure 13. For this pedal slippage calculation, the translation in axial direction on the front fork is constrained but the rear fork is fixed.

Fig. 13. FE model of the frame

The von-mises stress plot (figure 14) shows the maximum stress value of 189N/mm^2 and is lesser than the material stress limit and thus, is safe.

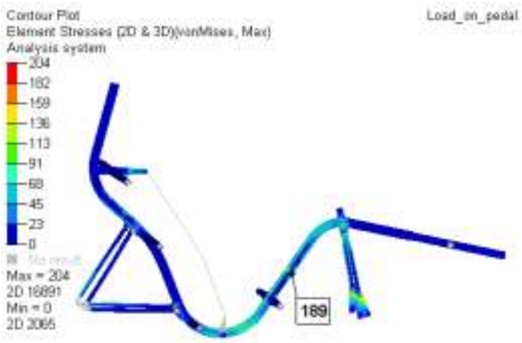


Fig. 14. FEA results: Elemental stress (N/mm^2)

- <u>Side loading analysis:</u> To examine the behaviour of the structure under side load, the worst case is when the whole of the side load (1330N) is applied on the uppermost side member. The force due to the rider is also applied as shown in the figure below. All the dof on the front and the rear fork are fixed for this calculation.

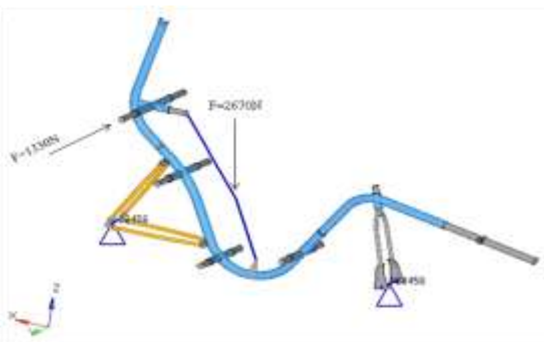


Fig. 15. Loads and boundary conditions for side loads

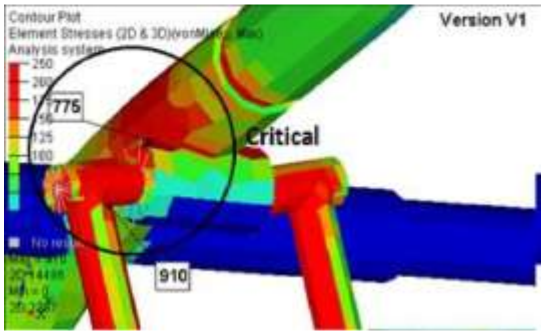


Fig. 16. FEA results: Elemental stress (N/mm^2)

The structure is critical at the above shown location due to the side load on the upper member. The von-mises stress value at the upper connection of the rear fork is very high. Thus, some design changes are made in the structure to improve the strength of the frame under this load condition.

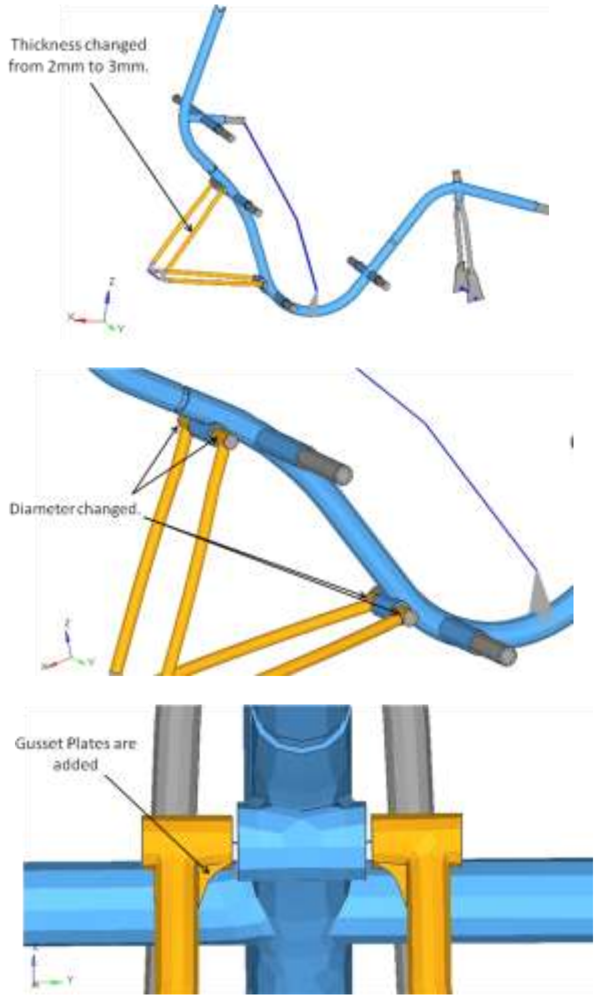


Fig. 17. Geometric changes in the frame

After making the above mentioned changes in the structure, the FE model was calculated again and the stress results are shown in figure 18.

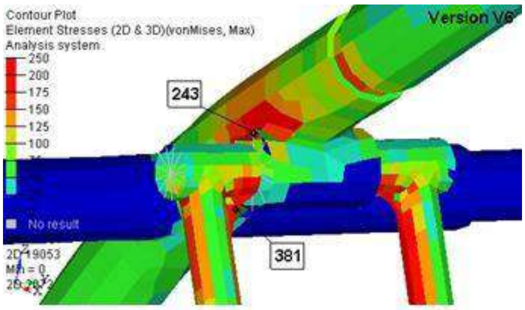


Fig. 18. FEA results: Elemental stress (N/mm^2)

The gusset plate of 3mm provides the bending strength to the fork and the stress level at this location came down to 381N/mm^2 from 910N/mm^2. The stress value at the weld area is also reduced from 775N/mm^2 to 243N/mm^2. Thus, the above mentioned changes were necessary for the structural strength and were incorporated in the structure.

- Landing Gear: It provides the stability to the HPV at slow speed and stand still positions. Landing gear is tested for load of 500N which equals 50% weight of the vehicle. The suitable thickness of the pipe was calculated using the FEA and is shown below.

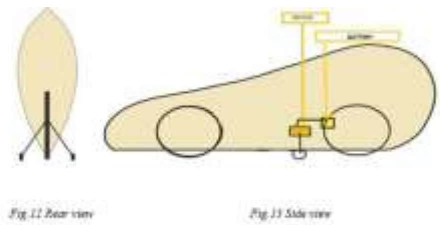


Fig. 19. Landing gear design

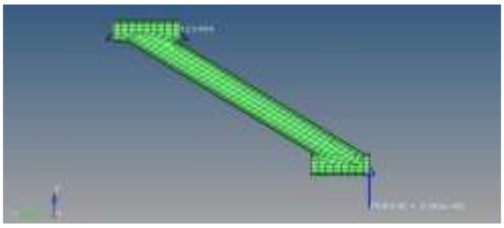


Fig. 20. FE modelling of the landing gear

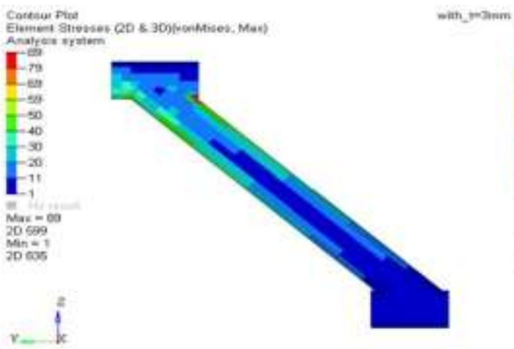


Fig. 21. FEA results: Elemental stress (N/mm^2) with 3mm thickness

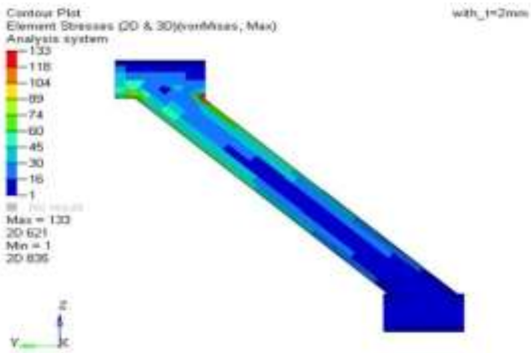
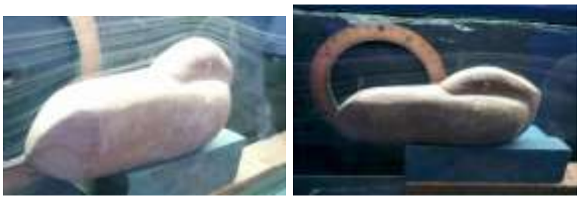


Fig. 22. FEA results: Elemental stress (N/mm^2) with 2mm thickness

As landing gear is subjected to cyclic loading a stress limit of 100 N/mm^2 is kept safe for the fatigue failure. Also, the weight saving is not considerable at this component, so the 3mm thick landing gear structure was finalized to be on the safer side.

B. Aerodynamic analysis

Aerodynamic hand calculations were done for open and closed fairing. Closed fairing increases weight but is more aerodynamically stable, whereas open fairing decreases weight but imposes aero losses and performance reduction. Basic shapes were studied and a blend of best ergonomics and aerodynamic shape was created through clay modelling and tested and after finalization of shape CAD surfacing was done.



a) *Bubble* b) *Duck*

c) *Torpedo* d) *Blend Shape*

Fig. 23. Wind Tunnel Testing

On placing these shapes in a smoke tunnel chamber, it was observed that the blend shape, show little signs of significant vortex formation or distortion in the airflow around it, moreover the streamlines show uniformity. Thus, this shape proves to be aerodynamically stable.

Fig. 24. Conceptual model of full fairing

Computational Fluid Dynamics: The shape of the HPV underwent rigorous amount of testing. Before starting the Computational Fluid Dynamics (CFD) analysis, the prototype model of HPV was tested by the smoke tunnel test rig which helped in validating the basic shape of HPV in terms of air flow, streamline, turbulence and vortex formation (if any). The underlying idea was to compare it with the pre-existing HPV shapes and creating a blend which was more efficient in terms of aerodynamics.

The wind tunnel testing of the model suggested certain changes in the design. In order to understand the physics of the problem with respect to fluid flow CFD analysis was done. The wind tunnel testing was done to compute various drag forces and pressure drops occurring on the body. Various air flow trajectories are shown in the figure 25. It can be observed that the front of the vehicle is subjected to a velocity of 13m/s and exiting the vehicle body on the tail end at a velocity of about 3m/s (approx.).

It is clear from the CFD plot that the flow remains attached to the surface of the fairing from nose to the tail end. Due to the aerodynamic nature of the body a smaller and weaker slipstream is generated and also the flow has a little turbulence after it leaves the body which on a whole is good for the vehicle.

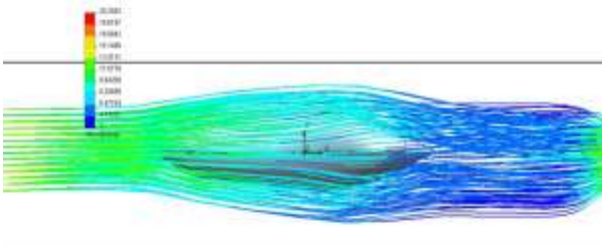


Fig. 25. Air flow lines

As the frontal velocity plot gave a satisfactory result, it so was necessary to test the model for another possible scenario of cross flow trajectory of air. It helped to check the stability of vehicle in case of a cross flow of air and so check the creation of vortex or turbulence (if any). The figure below gives a careful examination of the model subjected to the analysis at a cross flow air velocity of about 14m/s. Another reason for subjecting the model to such high air velocity was to check it for the worst of wind conditions.

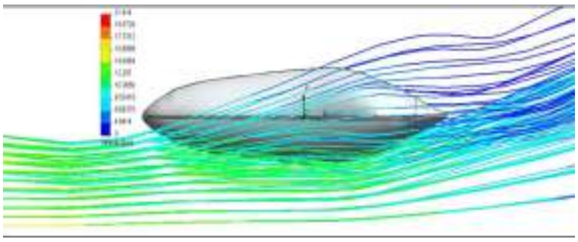


Fig. 26. Air flow lines

C. ACT RPS analysis

The new concept is developed to lock the multiple sections of the detachable mechanism. The calculation is done to find the desired offset distance required in the operating lever of the clamp mechanism to make it elliptical in shape. The lever presses the outer pipe of the frame (that has a vertical slot inside it) which in turn applies pressure on the inner pipe. The two pipes are held only by the friction acting between them (μ=0.1).

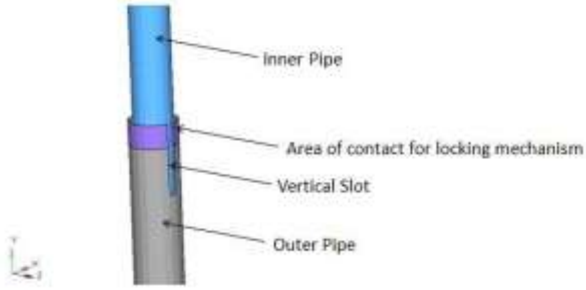


Fig. 27. FEA model of ACT clamp.

The mechanism is to be designed to hold a vertical force of 2700N (FOS=2). The joint will possess same behaviour in compression and tension. The calculation is done using the iterative method in which the gap is variable. The model is simulated in 2 steps:

- The lever is pressed to close the gap in the slot and to apply pressure to the inner pipe.
- The vertical force is applied to verify the amount of force that the assembly can hold due to friction.

Trial 1: The offset distance of 2mm (closing distance) is simulated but only 67% (1809N) of the vertical load was sustained through friction and the inner pipe slipped. This was also tested physically as shown in the figure below to verify the simulation results and it was seen that the pipes slipped at the load of 1800N validating the FEA results.

Fig. 28. Slippage test on UTM

Trial 2: When the offset distance of 3mm is simulated, the friction was able to hold the assembly for 97% (2619N) of the maximum load before slipping. Thus, it was decided that the minimum offset distance to hold the 2700N of vertical load should be more than 3mm.

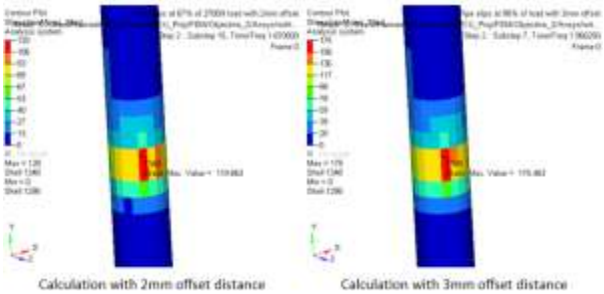


Fig. 29. FEA results for ACT Elemental stress (N/mm^2)

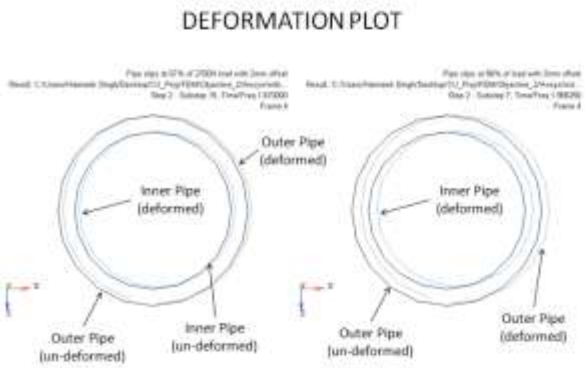


Fig. 30. FEA results for ACT displacement (mm).

IV. SAFETY

A. *Rollover Protection System*

The design of the HPV RPS structure is tested using the FEA simulation as explained above for the side loads and the changes as mentioned above were incorporated in the design.

B. *Inertial Seat Belt*

Inertial seat belts are used in the HPV to insure the safety of the rider from shockwaves due to accident. Factory made seat belt is chosen to be sure on safety while channelizing work according to the schedule. These are pre-tested for much higher load range and momentum changes. The activity of ratchet and pawl system was also studied for similar forces on HPV.

C. *Steering Mechanism*

The main motive behind using a tiller steering mechanism was to provide ease of ingress and egress for the rider. The steering mechanism is derived from BMX fork; hence there was no chance of excessive play or looseness.

D. *Surface Finishing*

Removal of any kind of sharp edges, protrusions as well as pinch point both on the inside (to decrease chances of injuries to the rider) and on the outside (to retain aerodynamic shape, to decrease the hampering in airflow and to attain higher efficiencies) were done soon after the completion of fabrication.

E. *Hazards analysis*

Cushions are provided on both sides of the seat to protect the rider during turning over of the vehicle or any collision. These cushions prevents the shoulders as well as arms of the rider to rub against any part of frame or fairing preventing the chances of minor and severe scratches during any accident. No compromise was made on the basic safety measures and each rider is recommended to wear helmet before riding the HPV.

F. *Additional Safety Measures*

- First Aid Box: A first Aid box is installed in the HPV behind the rider's seat providing an ease of accessibility that will help in case of emergency.
- Hydrator: A water hydrator is installed below the first aid box. The idea is to prevent any chances of dehydration and unconsciousness due to longer periods of cycling.
- Air Ducts: Air ducts are provided on the fairing. These helps to maintain the continuous and gradual airflow within the fairing helping in ease of evaporation of rider's sweat resulting in cooling and preventing unconsciousness because of higher body temperature.
- Rider's field of view: The vehicle is designed to provide the clear view of 210 degree to the rider; rear view mirrors are also installed as an extra safety feature.
- Helmet and safety accessories: Helmet is must when it comes to safety of rider in any two wheelers. Safety accessories such an electric bell is also installed to warn off people of the incoming vehicle, headlight of high intensity and range of 450m for ease of travelling during night and adverse weather conditions

such as fog etc, tail light to warn the followers beforehand while taking a turn, fluorescent tapes for ease of visibility of the vehicle while on road during night and rear view mirrors to help the rider keep an eye on what's happening in the back; provides an ease in changing lanes.

V. MATERIALS USED:

A. Aluminum 6061:

Aluminium is used keeping in mind its reasonable strength with light weight and also as it doesn't form rust on its surface, which further decrease the chances of infections that may arise due to coming in contact. Aluminum is easy to machine and is readily available.

B. Carbon Fibre:

Due to the high strength to weight ratio and capability to get intricate surfaces, carbon fibre is used in the manufacturing of vehicle's fairing.

C. Carbon Aramide:

Kevlar is provided on the inside of the fairing to provide additional safety and protect the rider from carbon fiber splinters etc that may arise due collision of vehicle.

VI. CONCLUSION

The conceptual design of Human Powered Vehicle meets the criteria of ASME (American Society of Mechanical Engineers). It is ergonomically better due to incorporation of various adjustable systems such as sitting system, pedalling system, steering mechanism. It has an estimated low cost (in terms of repair) because of ease of replacement of major parts due to feature of detachability incorporated into the frame making it a good commercially saleable entity. More to it the entire frame weighs below 28kgs making it easier to carry in one's luggage bag thereby taking HPV to a whole new level of mobility. Following is the comparison summary of the objectives achieved.

TABLE II. CONCLUSION

Design Specification	Constraint	Design Goal	Achieve ment
Top Speed	25Km/h	40 Km/h	41 Km/h
Turning radius	8m	6.5 m	6m
Ground clearance	3 inch	5 inch	5 inch
Bracking	6m	4m	4m
RPS top load	2670 N	--	--
RPS side load	1330 N	--	--
Weight	35 Kg	30 Kg	28 Kg
Storage space	2.5 ltr	6 ltr	6 ltr
Angle of visibility	180 Degree	210 Degree	210 Degree

From the above summary it can be seen that, the Human Powered Vehicle "FATEH" is an efficient concept and is capable of changing the local transportation era in the society.

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