Design, Development and Testing of Human Powered Recumbent Tricycle

Ajay Dhanopia, Shyam Khandelwal, Dilip Garg, Trivedi Kaushik, Nishant Kumar, Sunil Manani, Alok Mathur
Department of Mechanical Engineering
Swami Keshvanand Institute of Technology Management & Gramothan, Jaipur
Email- ajay_dhanopia@rediffmail.com

Abstract: **The fuel consumption associated with transportation needs is clearly an issue known throughout the world. The world's dependence on petroleum/diesel based fuels needs to undergo a transformation to alternative fuel sources and a new means of transportation itself. This paper delineates the design, fabrication and testing of an efficient human powered vehicle as a potential answer to this need. The primary purpose of this vehicle is to transport its rider from one location to other in a safe and comfortable manner. A human powered ground vehicle, in its most simple sense, is the traditional bicycle. However, rider comfort, stability, safety, aerodynamic drag and mechanical advantage are some of the issues associated with the traditional upright bicycle. Consideration of these factors led us to design a recumbent tricycle. This Human Powered Vehicle is a partially faired, recumbent type tricycle using the tadpole (two front wheels and one wheel in the back) configuration. Advanced techniques of Finite Element Analysis (FEA) and Computational Fluid Dynamics (CFD) have been used to test the design of this model. A physical prototype was fabricated and tested to ensure the safety of the rider as well as pedestrians around the vehicle.**

Keywords: **Human power, rider comfort, safety, stability, tricycle.**

1. INTRODUCTION

Transportation plays a key role in overall development of the society, both economically and socially, by extending accessibility of resources and markets. Nevertheless, it has many spillover effects such as traffic congestion, safety, global warming and depletion of non-renewable sources of energy. In India, there are presently close to 18 million petrol-powered two wheelers and about 1.5 million petrol and diesel powered three wheelers besides a large number of four wheelers. All these vehicles are consuming natural resources which will be depleted in the coming times. This paper, therefore, discusses the design of a *human powered recumbent tricycle* which does not depend on fossil fuels. It has a simple design delivering high performance, is easy to maintain and is safe. It is therefore capable of replacing fueled vehicles for some applications, contributing towards environmental sustainability. Manufacturing cost of this tricycle has to be reasonable and affordable so that it can replace the present two wheelers and three wheelers running on fossil fuels. In the design, safety and comfort of the rider has also been considered meticulously. Some of the problems faced with the design of a traditional cycle are, *inter-alia*:

- They have an uncomfortable seat and driving posture which causes fatigue to the rider after some time. In an upright position, the body weight rests entirely on a small area causing discomfort after some time.
- The rider is not able to utilize all his physical efforts while driving.
- A traditional rickshaw type configuration (delta configuration) has chances of skidding when negotiating a sharp turn at a higher speed.
- Aerodynamic drag has not been taken into consideration in the traditional design.
- Safety for the rider is not adequate.
- Traditional tricycle design lacks the aesthetic considerations that result into disinterest of the younger generation and de-motivation for their use. So they often use petrol based two or three wheelers even for a short distance.

The proposed design, therefore, aims to rectify or reduce the aforesaid drawbacks and create an eco-friendly, comfortable and aesthetic tricycle.

2. DESIGN OBJECTIVE

The objective of the design is to design a human powered three-wheeled vehicle (trike) with a maximum speed not exceeding 24 km/hr [1], and which is able to

- have a reasonable stability of the vehicle on sudden application of brakes.
- gives a better driving comfort to a rider due to its ergonomic considerations.
- run smoothly on obstacles such as a speed bump, stones, or slopes.
- complete above mentioned tasks while maintaining driver safety and vehicle control at the same time.
- reduce the aerodynamic drag to impart maximum riding efficiency.
- eliminate the requirement of a differential gear box while negotiating a sharp turn to be cost-effective.
- help rider utilize his full effort and thus minimize fatigue

3. DESIGN CONSIDERATIONS

We considered three general tricycle configurations for the rider. In an upright configuration a rider sits in the conventional position whereas in a recumbent configuration, the rider sits reclined with feet extending forward. In another configuration known as prone, rider lies with face down and head pointed in the direction of travel. Designing a vehicle with a low ground clearance minimizes frontal area and, consequently, reduces aerodynamic drag. This design of human powered vehicle (HPV) therefore keeps the frame low to the ground to provide an advantage to the rider. An upright design is less desirable as it requires the rider to remain in a vertical position most of the time with the major part of the body subjected to drag forces. In the prone position, the rider feels discomfort in a long drive. Therefore out of the three positions of the rider, a recumbent design was considered most suitable for the proposed tricycle design.

4. DESIGN OVERVIEW

4.1 Design Overview of Recumbent Trike

The recumbent design, as mentioned in section 3, is aerodynamic and ergonomic. This design enables the driver to have a comfortable ride at all times as the body weight is distributed comfortably over a large area supported by back and buttocks. It can also have an option of adjustable seat to enable adoption of a comfortable position by individual rider. The tricycle roll over protection system (RPS) has been designed in order to enhance the overall safety of the vehicle especially in case of a frontal or side impact [1]. It is also equipped with a rear suspension system which provides a comfortable ride to the driver. A five-gear transmission system provides a good tractive effort with a positive drive. The proposed design is exhibited in Fig. 1.

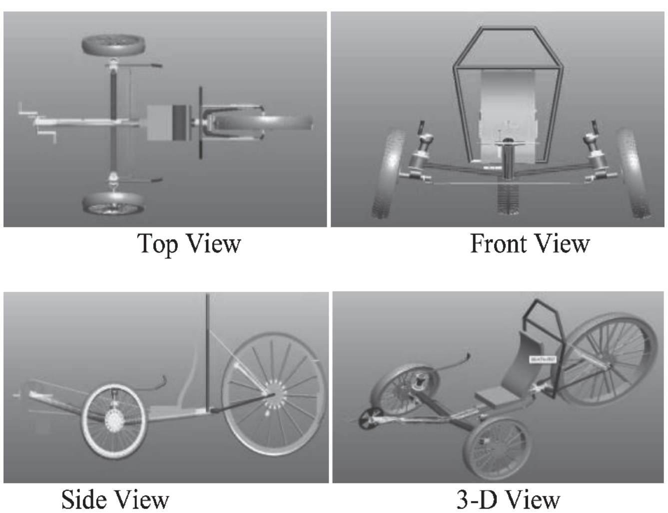

Fig 1: Different views of proposed design

4.2 Special Features

The proposed design differs from conventional ones particularly in terms of aerodynamic considerations and driving chain specifications. To accomplish the first, the fairing material has been replaced from glass fiber sheet to fiber sheet. A card board mould was initially used (Fig. 2) to get physical realization of fairing. We prefer card board because it is cheap, and can be easily shaped. Figure.2 shows the fairing mould configurations.

Fig 2: Card-board mould for fairing

As in section 5.2, we have preferred rear wheel drive which has inherent disadvantage that the transmission path of power is long and requires a long chain to be used. Due to long chain drive, it may impose the tight side on the slack side. The solution made to overcome the above difficulty is the use of two idler sprockets in the drive train. The idlers are small sprockets that are used to provide tension in the chain and to avoid any contact of the chain with the frame and the body of riders. To avoid the problem of chain alignment a derailleur is installed in opposite sense just before the rear derailleur. Figure.3 shows the drive chain idler arrangement in the fabricated tricycle.

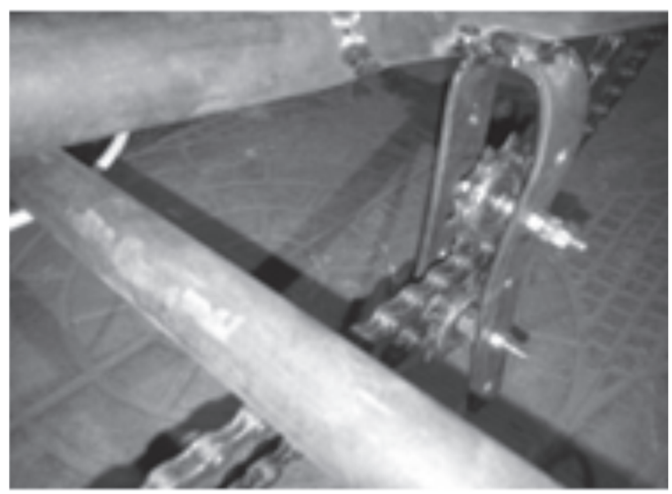

Fig 3: Drive train idler arrangement

5. DESIGN CALCULATION

5.1 Frame design

The frame has been designed aerodynamically in consistence with the overall safety of the rider. It is designed to have minimum frontal area and a fairing shape to suite a good laminar flow. The frame also incorporates various systems, like steering system, braking system, transmission system etc., to work in an effective manner. For the frame, alloy steel AISI 4130 with specifications as mentioned in Table.1 was selected. It contains molybdenum and chromium as strengthening agents and low carbon content (0.30%) with an excellent fusion weld property.

Table I: Physical specification of AISI 4130[2]

S.No.	Physical Properties of AISI 4130	Numeric value
1.	Density (g / cu.cm) at 25°C	7.85
2.	Specific Heat (J/kg-K) at 50-100°C	477
3.	Thermal Conductivity (Watt/mk) at 100° C	42.7
4.	Modulus of Elasticity in Tension (GPa) at 25° C	190-210
5.	Impact Strength –Izod (J) at 25° C	61.7

5.2 Power Transmission System

It is known that a front wheel drive has more traction advantage than the rear wheel drive [3]. Unlike the traditional bicycle having a rear wheel drive, the current design has a front wheel drive to gain the traction advantages. It was also decided to provide a gear-shifting mechanism with different sizes of driven sprockets in the tricycle to achieve different speeds and maximize the torque, whenever required, in sandy and hilly regions. Driving wheel having 26 inches diameter and two front wheels with 20 inches diameter were also selected as an integral part of the transmission system.

5.2.1. Maximum and Minimum Speed of Pedaling for Maximum Speed of Vehicle

We use the relation N=60V/πD with N being RPM of the driving wheel with diameter D to calculate V which is the maximum velocity corresponding to the RPM 'N', neglecting frictional and other losses. For a typical maximum speed of 24 km/hour, the design iterations reveal following data as per Figure 4:

Diameter of driving wheel (sprocket) d_2=10 inch = 0.254m

Diameter of sprocket1 (d_1) = 6 inch = 0.152m

Diameter of sprocket2 (d_2) = 4 inch = 0.1016m

Diameter of the driven (rear) wheel D= 26 inch = 0.660m

R.P.M of driver wheel = N =

(60*24*1000)/(3.14*0.660*3600*)

=193 r.p.m ……………………………...………..(1)

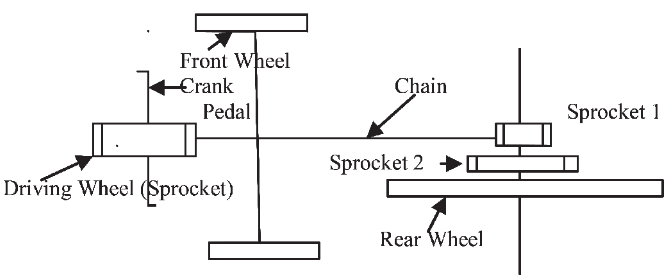

Fig 4: Power Transmission Gear Train

As all sprockets are fixed on the same axle, hence r.p.m of all sprockets will be same.

$N_1 = N_2 = N$

R.P.M of driving sprocket1= N_3 when chain is on 6 inch sprocket.

R.P.M of driving sprocket2= $N_{3'}$ when chain is on 4 inch sprocket.

Now $N_3 = NxD_1/ D_3$= 193*6/10= 115.8 r.p.m

Now $N_{3'} = NxD/D_3$ = 193*4/10 = 77.2 r.p.m

5.2.2 Determining the length of chain

With reference to the specifications of chain as shown in Table.2 we calculate the number of links and the length of chain in alignment with the theory of power transmission through belts, ropes and chain.

Table 2: Physical Specification of Chain [4]

S.No.	Terms Used in Chain	Specification
1.	Pitch of Chain	.012m
2.	Centre Distance (Cassette and Crank Set) (a)	1.78m
3.	No of teeth on larger (front) sprocket z_2	44
4.	No of teeth on smaller (rear sprocket z_1)	29

The length of chain is always expressed in terms of the number of links, or L= L_n x p

Where L= length of the chain (mm)

L_n= number of links in the chain

The number of links in the chain is determined by the following approximate relationship [5]:

L_n=2(a/p) + [(z_1+z_2)/2] + [(z_2-z_1)/2π)^2]*(p/a)…….......……..(2)

Where z_1 ,z_2 are numbers of teeth on the driver and driven sprockets respectively, & a is the centre distance between the two sprockets.

No. of links k = 2(1.78/.012) + (29+44)/2 + [(44-29)/2*3.14)^2 *(.012/1.78) = 334

Length of chain L = 334*.012 = 4m

5.2.3. Determining the corresponding force to be applied at pedal

Considering the first loading condition total tractive effort required on the rear wheel of the tricycle is calculated.

Inputs are

- Gross weight of the tricycle acting on the rear wheels (W)= 1112 N
- Radius of the rear wheel (r_w) = 660mm = .660m
- Desired maximum speed of the tricycle (V_{max})= 24 km/hr = 6.67m/s
- Desired acceleration time (t_a) = 10 sec [1]
- Gradient (α)=0°
- Coefficient of rolling resistance between tire and road

Crr =0.017 (contact surface asphalt) [3]

Total force on pedal

$$F = \frac{F_R r_w}{r_c} x \frac{r_1}{r_2} \quad (3)$$

Where F = total force on pedal in N

F_R= total tractive force in N

r_w = radius of rear wheel in mm = =660 mm

r_c= length of crank arm in mm = 180 mm

Total Tractive Force $F_R = R_R+G_R+F_{AR,}$

Rolling Resistance (R_R) = W x C_{rr} = 1112*0.017 = 18.9N,

Accelerating Resistance (F_{AR}) = Wx(V_{max} –V_{min}) /gt_a

$= [1112*(6.67-0)] / (9.81*10)$

$= 75.6$ N,

So total Tractive Force (F_R) = 94.5 N

$$\text{Radius of sprocket} = \frac{p}{\sin\left(\frac{180}{N}\right)}/2 \qquad (4)$$

r_1 = radius of front sprocket in mm = 10 inch/2 = 127 mm

r_2 = radius of rear sprocket in mm = 6 inch/2 = 76.2 mm

where p is the pitch of chain in mm

Force at pedal

$$F = \frac{94.5*660}{180} * \frac{127}{76.2},$$

F = 577.5 N

5.2.4. Mechanical Advantage

M.A = Output Force/Input Force

F/F_R = 577.5/94.5 = 8.95

5.3. Seat and Seat Adjustability System

Rider support is handled by a foam seat which was manually shaped according to the requirements of the design. Integrated into the seat base is steel plate to the main tube of the frame and a bracket punched with a series of holes to reduce weight. The main concerning factor while deciding the seat is that it should be adjustable according to the varying heights of individuals.

5.4 Design for Safety

Rollover Protection System: All vehicles must include a rollover protection system (RPS) that protects all drivers in the vehicle in the event of an accident [1,6]. Functionally, the RPS must:

- Absorb sufficient energy in a severe accident to minimize risk of injury
- Prevent significant body contact with the ground in the event of a fall (vehicle resting on its side) or rollover (vehicle inverted)
- Provide adequate abrasion resistance to protect against sliding across the ground.

Self locking safety belt has been used to provide maximum safety especially when driver feels any impact during riding, it has been self locked. The design also incorporates a reflector which provides the safe riding in nights as well as a ringing bell system to aware people during the heavy traffic.

6. ANALYSIS

6.1 Frame Analysis

Assuming a worst-case loading scenario with rider weight being 55 kg the loading was applied to the frame on the centre of gravity keeping the part of the frame on which wheels are mounted as fixed.

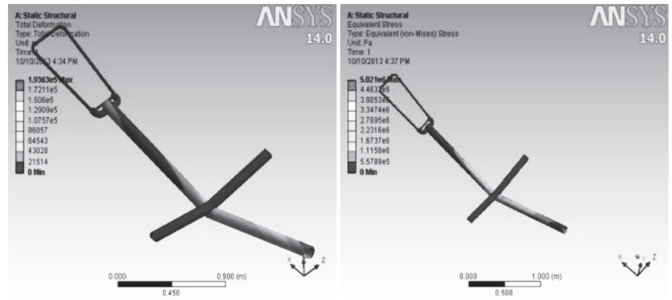

Fig 5: Equivalent deformation & equivalent stress in the frame as per ANSYS

The maximum stress of 3.4 MPa occurs at the welded joint of the tubes. The maximum deflection is slightly less than 1 mm at the front of the frame. The simulation indicates stress concentrations at a few points, mostly pronounced around the intersection of the main beam and axle tube as shown in Figure.5. The stress concentration at the interchange appears to be partly an artifact of the finite element method. Furthermore, it occurs at a location that has a significant weld bead, distributing the load around more metal and reducing the stress as shown in Figure.5. The overall analysis showed that the stress is reasonably below the acceptable level and it paved the way for the analysis of other parts.

6.2 Rollover Protection System Analysis

The roll-bar must be made to withstand the maximum load expected in a crash situation. Based on the seat back angle and height of each rider roll-bar can be designed. The roll-bar must be high enough to provide head protection for the tallest rider while wearing a helmet. In addition to a top impact, the roll bar must also provide side protection to the rider. In addition, its span should accommodate a rider in horizontal position comfortably. The strength of RPS was checked on two cases: a 600 lb (272.15 Kg) top load directed 12º from vertical towards the rear, and a 300 lb (136 kg) side load directly horizontal at shoulder height[1].

6.2 Aerodynamics Analysis

The Computational Fluid Dynamics (CFD) analysis was performed for the fairing using mesh representation as shown in Fig. 6.

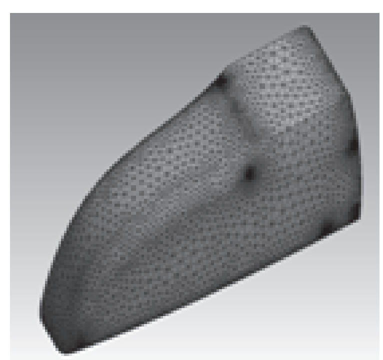

Fig 6: Mesh representations for CFD analysis of the faring

Three different speeds of tricycle 24 km/h was considered for this analysis .The results of CFD analysis proved that the aerodynamic stability of the vehicle as maximum pressure by air for closed body was 20 Pa at maximum velocity of 24 km/hr.

7. FABRICATION

The fabrication process involves the transformation of the initial virtual design into a physically realizable form. It started by making frame of the desired shape to which Rollover Protection System (RPS) was properly welded (Figure.7). Metal Inert Gas (MIG) welding has been used throughout the process.

Fig 7: Fabrication of Frame

8. TESTING

8.1 Rollover Protection System (RPS) Testing

The RPS was tested as stated by prescribed safety rules and regulation hand book [1]. The roll protection system must be able to support a load of 600lbf applied to the top of the roll bar, directed downward at an angle of 12° from the vertical and a side load of 300lbf applied horizontally to the side of the roll bar at shoulder height [1]. The roll bar is acceptable if there is no indication of permanent deformation, fracture, or delaminating on either the roll bar or the vehicle frame, and the maximum elastic deformation is such that it does not come into physical contact with the driver's helmet, head or body.

Table 3: Results of Load Testing for RPS [1]

Content	Maximum Value	Actual Value
Top Loading	750 lbf	600 lbf
Side Loading	750 lbf	300 lbf
Deflection in Top Loading	2 inches	0.75 inches
Deflection in Side Loading	1.5 inches	0.6 inches

Experiments were performed to measure the elastic deformation of the roll bar protection system in the top and side directions as shown in Fig. 8. The results are reported in Table 3.

Fig 8: Testing the top and side of RPS

8.2 Frame Testing-

It is important to determine whether the frame material is correct and in compliance to our design requirement. This can be done by applying three times more load than the weight of an average human being in order to counter the effect of gravitational forces and bumping of vehicle on road.

8.3 Testing of Trike

The fabricated trike was tested for performance in accordance to the guidelines of ASME for their human powered vehicle competition [1]. A test track of approximately 2 km lap length with level & inclined portions was prepared. The trike was driven by a team of 5 riders individually and sequentially. The limitation on each rider was to ride the trike for at least 5 km, or for 30 minutes, whichever was earlier. The results of the performance testing are summarized below:

- No of riders: 5
- No of riders who completed their ride without undue stress: 5
- Maximum speed achieved: 24 km/hr
- Maximum upward incline: 15 degrees
- Maximum distance driven by one rider (without any fatigue): 5.3 km
- Vehicle Weight – 58.35 kg or Less
- Turning Radius – 3.65 meters or Less
- Braking Time – 10 Seconds or Less in 6 meters as the stopping distance.

The fabricated prototype was thus found to be satisfactory in performance.

9. CONCLUSION

The proposed Human Powered Recumbent Tricycle undoubtedly presents an eco-friendly and potential solution to the ever increasing petrol crises both in India and abroad. It can be suitably used for hustle free transportation with maximum speed of 24 km/hr for human beings especially in a moderate traffic scenario. The tricycle can be modified by incorporating solar powered drive to augment the human power. The CFD analysis assumed the strength and safety. The physical trials for a running of more than 10 kms have established maneourability, usability, endurance as well as safety & stability. The Prototype was entered into competition and was:-

- Awarded the National winner in Mechanical Stream by International Society for Science, Research & Development (ISSRD) in the ESIC Engineering Student Innovation-2014 competition at Bangalore, India. Also published the brief about the winning team in Technical Education OUTLOOK 2014 annual publication of ISSRD at International level.
- Secured the 7th position in design category at national level competition "Human Powered Vehicle Challenge" organized by American Society of Mechanical Engineering (ASME) at IIT, Delhi [7].

The design can be further improved by adding solar powered drive, which will increase the range of fatigue-free drive. The cost aspects can be taken into consideration and economies of scale may be employed to reduce the unit cost of the tricycle. There are definite possibilities of launching a commercially viable venture after the improvement & discussed above.

REFERENCES

[1] Rules for the 2013 Human Powered Vehicle Challenge, India. http://www.asme.org/events/competitions/human-powered-vehicle challenge-(hpvc).

[2] Physical Specification of AISI 4130 Alloy Steel, http://www.efunda.com/materials /alloys/alloy_steels/show_alloy.cmf. Accessed on 10 May, 2014).

[3] Chetan A. S, Mahalle A.K, (2012) 'Design Optimization of Speed Ratio for Conventional Chain Drive Used in Tricycle', International Journal of Innovative Technology and Exploring Engineering, Vol. 1, Iss. 1, pp. 40-43.

[4] Gulati V, Mehta S, Kashyap A, Pawar, K, (2012), 'Design and FEA of a Recumbent Trike', International Journal of Applied Engineering Research, Vol.7, Issue-11, pp. 45-51.

[5] Bhandari V.B (2013) 'Design of Machine Elements ', 3rd edition, Tata Mc-Graw Hill Education, New Delhi.

[6] Rollover Protection System for Driver Safety. http://www.asme.org/ events/competitions/human-powered-vehicle-challenge (Accessed on 20 June, 2014).

[7] Human Power Vehicle Challenge India-2014. https://www.asme.org/ wwwasmeorg/media/ResourceFiles/Events/Competitions/2014-ASME-HPVC-India-Results-Overall.pdf

◆ ◆ ◆