International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 07 Issue: 04 | Apr 2020 www.irjet.net p-ISSN: 2395-0072

Design of Steering and Suspension System for Hybrid Tadpole Trike

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Abstract - *In small towns, townships, we need a light weight vehicle to travel from one place to other. Every time if we use a vehicle powered by an IC Engine, that causes problems related to pollution. Moreover, we should find a different solution which can be more sustainable with respect to the environment. Simultaneously, as usage of this vehicle is in the city area or townships, it should be light weight which will benefit in terms of performance and fuel consumption. We have designed a hybrid eco-friendly trike, powered by human power by pedaling and/or by electric motor with a view to provide a green and clean energy vehicle. This vehicle has a capacity of two commuters having seating arrangement adjacent to each other. Though chassis can be the primary weight reduction area, we have focused on other subsystems also to reduce overall weight. This document focuses on the steering and suspension system of the trike. The focus has been put on the simplicity in design, easy maintenance, light weight vehicle and safety of the driver. Most of the components have been chosen keeping in mind their easy availability. Steering is a simple linkage mechanism with push-pull type of steering control. Trike has single pivot rear wheel suspension, and for the front suspension we have implemented pneumatic forks.*

Key Words: Steering, weight transfer, cornering speed, push-pull type of steering control, suspension, forks, single pivot suspension

1. INTRODUCTION

Vehicle weight reduction is a known strategy to address growing concerns about greenhouse gas emissions and fuel use by passenger vehicles.

In the small towns, townships, we need a light weight vehicle to travel from one place to other. Every time if we use a vehicle powered by an IC Engine, that causes problems related to pollution. Moreover, we should find a different solution which can be more sustainable with respect to the environment. Simultaneously, as usage of this vehicle is in the city area or townships, there can be weight reduction chances.

The main objective of designing hybrid trike is to have a light weight and cost effective vehicle which can be used in the small townships. Keeping this in mind, we have designed various subsystems and tried to reduce weight and cost wherever possible. The most important factor considered during the design phase, for enhancing the overall performance, is the weight of the vehicle. Though roll cage can be primary weight reduction areas, we have focused on other subsystems also to reduce overall weight. This document will mainly talk about major weight reduction subsystems of a trike. They are steering, and suspension.

Before going into the details, we need to know overall details of this trike. The trike is a hybrid vehicle which can be driven manually by pedals and/or by electric motor. The trike has a tadpole configuration with maximum width as 60" and maximum length as 82". It has front wheels having diameter of 20" and rear wheel with 28" diameter. It has a capacity of two passengers inclusive of driver. Both passengers can pedal the vehicle. Seating arrangement of passengers is adjacent to each other. Vehicle chassis is designed considering aerodynamic effect, and the overall safety of the passengers. For front of the vehicle, lightweight transparent PolyChloride is used as it provides shield and adequate visibility.

2. STEERING SYSTEM

A steering system begins with the steering wheel or steering handle. The driver's steering input is transmitted by a shaft through a gear reduction system, usually rack-and-pinion or recirculating ball bearings. The steering gear output goes to steerable wheels to generate motion through a steering mechanism. The direction of each wheel is controlled by one steering arm. The steering arm is attached to the steerable wheel hub by a keyway, locking taper, and a hub. In some vehicles, it is an integral part of a one-piece hub and steering knuckle. To achieve good maneuverability, a minimum steering angle of approximately 35 ° must be provided at the front wheels of passenger cars. [1]

Steering is required to guide a vehicle in a desired direction. When a vehicle turns, the wheels closer to the center of rotation are called the inner wheels, and the wheels further from the center of rotation are called the outer wheels. [2]

When we think of a steering subsystem, the things that come to our mind are rack-and-pinion mechanisms. For steering control, we majorly use universal joint and steering wheel. As per our objective to reduce weight and to have cost effective solution, we have designed a simple 4 bar mechanism with simple hand lever to steer this hybrid vehicle.

2.1 Steering System Requirements

- Vehicle should take the desired turn with the movement of steering control.

- Mechanism should be simple, easy to manufacture, lightweight and easy for maintenance.
- There should be a clearance of any component at least 3 inches at any condition with the driver. [3]
- Steering control should not hinder line of sight of the driver.
- Steering mechanism should not restrict pedaling motion of the driver.
- With the maximum angle of turn, there should be clearance of at least 3 inches between the wheels and driver's leg. [3]

2.2 Steering CATIA Geometry

As shown in the below figure, from left, wheel axle A is connected to the steering arm BC. Steering arm BC is then connected to mid-plate DEG through the link CD. The other end of the mid-plate is connected to the right side wheel through the steering arm IH and a link GH. Mid-plate DEG is pivoted as shown in Fig-1 which can rotate about point E when we move link FK in the forward or rearward position.

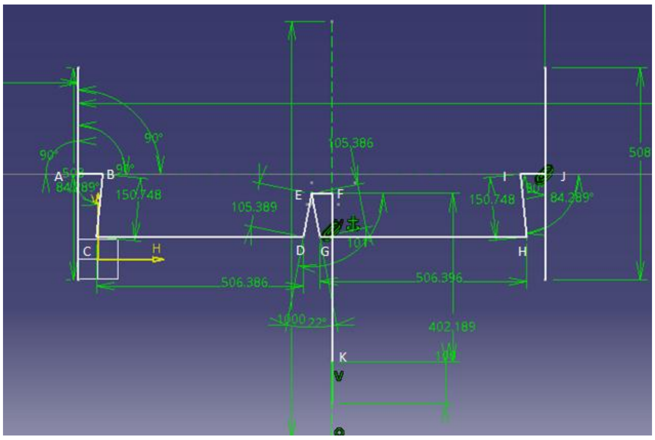

Fig-1: CATIA – Steering Mechanism

We made different geometries in the CATIA similar to above and came up with the following optimized geometry by certain iterations as shown in the table 2.

2.2 Steering Geometry Iterations

As we studied the market data, the turning circle radius for auto rickshaws in Indian market is ~3m.[4] Hence, optimizations were done for achieving turning circle radius (TCR) ~3m for this trike. For this, we selected control factors as θ – angle between ED and EG, steering arm length BC & IH and mid-plate length ED & EG. These iterations are as shown in the below table 2 and Fig-2. We followed an approach of one factor at a time to arrive at the desired TCR. For the same table 1 shows the vehicle parameters which will act as input for steering.

Table - 1: Input Parameters

Input Parameters	Values
Wheel Track	1181 MM
Wheel Base	1250 MM
Wheel Size (Front)	508 MM

Table - 2: Iterations to achieve desired TCR

Input Parameters	Values	Inner wheel angle (°)	Outer wheel angle (°)	Turning circle radius (m)
Theta Value	30	24.52	18.74	4.375
	25	33.1	22	3.286
	23	33.24	22.55	3.258
	22	36.186	23.805	3.096
Steering arm (BC,IH)	120	25.78	18.5	3.934
	130	28.675	19.875	3.72
	140	32.13	22.71	3.41
	150	37	24	3.078
Pivot length (DE, GE)	100	34.74	220.3	3.128
	105	36.89	24.05	3.058

From the above table, final dimensions for the above parameters are as follows:

1. Theta = 22°
2. Steering arm length = 150 mm
3. Pivot Length = 105 mm

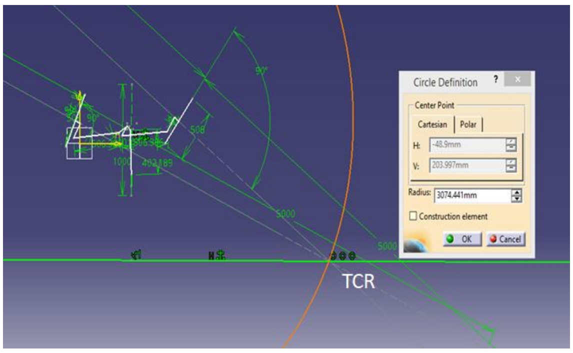

Fig-2: Steering Geometry having TCR ~ 3m

Now we have finalized the mechanism to achieve TCR of ~3m. It is necessary to calculate the steering effort, critical cornering speed in the design of steering.

2.3 Weight Transfer at Critical Cornering Speed

For calculating steering effort, we need some input parameters from the vehicle such as CG, weight distribution, etc. For this, the input data is as shown in table 3:

Table - 3: Input Parameters

Input Parameters	Values
GCW of trike	225kg
Weight distribution Front : Rear	45:55
Height of CG	22" (0.5588m)
Wheel Track	1.181 m
Cornering Speed Max	18kmph (5m/s)
Turning Circle Radius	3 m
Pneumatic Trail	15 mm (Bicycle Tires)

Considering, GCW of trike as 225 kg, weight distribution of 45% on front wheels, and assuming weight is equally distributed between two front wheels in static condition, weight acting on left wheel is,

$W_{FL} = W_{FR} = 22.5 * 225 * 9.81 / 100 = 496.6$ N

Weight on the rear wheel in static condition as per above weight distribution,

$W_R = 225*9.81 - 496.6*2 = 1213.98$ N

Weight distribution is how much weight, or load, each tire has on it at rest. However, when the car goes around a turn, weight will be transferred from the inside tires to the outside tires, which is known as lateral weight transfer. The more weight on a tire, the less traction it will have. With this knowledge, you can control the amount of weight transfer so your outside tires will have the maximum traction available. [5]

To calculate, we started with maximum cornering speed the trike can experience with the turning circle radius having a minimum value of 3m. Lateral weight transfer is given by following formula:

Lateral Weight Transfer = (Weight * Cornering force (g) * Height of CG) / (Track) [5]

g-value during cornering = Lateral acceleration / Gravity

$= (v^2/r)/g = (5*5/3)/9.81 = 0.85g$

Hence, lateral weight transfer = ((225 * 9.81) * 0.85 * 0.5588) / 1.181 = 887.7 N

This will be divided in front and rear wheels = 887.7/2 = 443.85 N

Table - 4: Weight Transfer

Tire Location	Static weight on tire	Lateral Weight Transfer	Weight on Tire during Cornering (Normal Load on each wheel)
Left Front	496.6 N	+ 443.85 N	940.45 N
Right Front	496.6 N	- 443.85 N	52.75 N
Rear Wheel	1213.98 N	-	1213.98 N
Total	2207.2 N		2207.2 N

Thus weight transfer at each wheel is calculated as shown in table 4. All these values are considering that the vehicle is taking a turn towards the right with a cornering speed of 18kmph.

2.4 Self-Aligning Torque

Self-aligning torque (SAT) at each wheel,

SAT = (trail + pneumatic trail) · cos(caster angle) · Fy.

$SAT_L = 0.015 * \cos 0 * 940.45 = 14.11$Nm

$SAT_R = 0.015 * \cos 0 * 52.75 = 0.79$Nm

Hence, SAT = 14.11 + 0.79 = 14.9Nm

2.5 Steering Control Design

Now to calculate steering effort, this SAT can be used and through the linkage, we can reach till the link FK to calculate force. Now to calculate the hand force required, we need to consider leverage.

As our primary goal was to reduce weight, we decided to use a simple push-pull type handle where we can take advantage of leverage. As shown in the below figure, we created geometry of the handle in CATIA to find out required handle length. Also there were constraints that it should not hinder any other subsystems and it should have clearance of 3" from the driver at any condition. As this trike is a hybrid vehicle, the driver may have to pedal to drive it. Considering that situation, it is vital to design steering control such that it would not restrict movement of legs while pedaling. Moreover, the driver should have a clear line of sight. Hence we decided to move away from the conventional steering wheel which comes in front of the driver. We tried to locate the steering control so that it would come in the driver's hands from both sides of the seat. We had two options to make steering control in a way that it can be rotated in the horizontal plane to steer the wheels or can be designed such that push-pull activity of steering handle will cause the trike to take a turn. However, when we tried to design the rotating handle, it was giving restriction to the handle movement. Because it was hitting driver legs to take full steer. Therefore, we selected the push-pull type of handle as a best working option for the trike.

The below Fig-3 is a side view of handle geometry, with the KF link coming from the steering mechanism discussed earlier. To operate the steering mechanism, link KF has to move in forward or rearward direction as per the required turn. L is the hinge which can give advantage of leverage to the driver. All the linkages are connected with the help of rod-ends which allow linkages to move when we push or pull the handle.

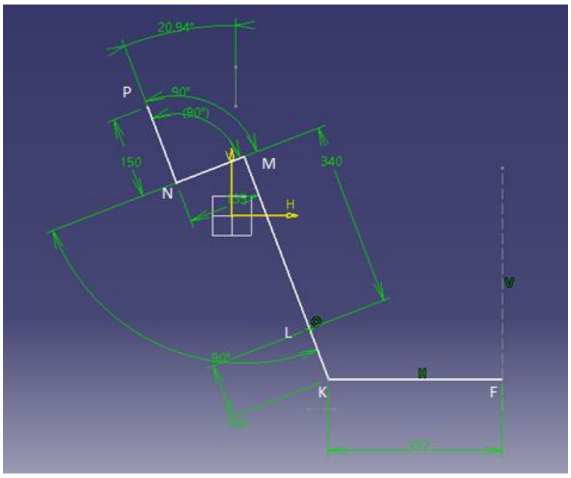

Fig-3: CATIA – Steering Handle Geometry Side View

For steering effort calculation, we first calculated force required to move link KF linearly considering SAT at the wheels to steer.

F_{KF} = 207.2N

Considering hinge at point L,

Force by hand = 0.1*207.2/0.49 = 42.25N =4.31 kg (by both hands)

With the length of linkages and length of steering handle from the steering geometry in CATIA, we made CAD assembly. The diameter of links was decided by tensile stress theory. Bolts were designed considering shear failure and rod ends were selected considering a factor of safety of 3. Fig-4 shows final rendered CAD geometry of the steering system.

Fig-4: Steering System - Overall Geometry

Following table 5 shows final dimensions of steering system linkages.

Table - 5: Summary Table

Description	Value
Steering link 1 length (CD, GH)	20 inch
Steering link 2 length (EF)	2 inch
Steering arm length (BC, IH)	5.9 inch
Mid-plate (ED, EG, theta)	4.1 inch, 22 °
Max wheel angle after steering (inner/outer)	37/24 °
Total handle length	22 inch
Turning circle radius	3 m
Steering Effort	4.31 kg

2.6 Prototype

With these final values, we prepared a prototype to ensure working of the mechanism. This prototype was manufactured on a 3D printing machine. The material used for this was ABS. Fig-5 shows the prototype of steering linkages. With this prototype, we verified the linear displacement of link CD and link GH when we pull link FH to rotate mid-plate DEG.

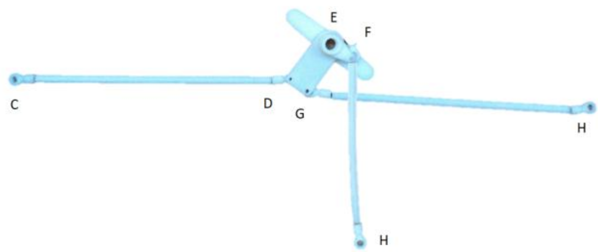

Fig-5: Steering System - Prototype

Finally, we manufactured the steering system as per the design and implemented it in the trike. All the angles were measured and validated with the design data.

3. SUSPENSION SYSTEM

There are two general types of suspensions: dependent, in which the left and right wheels on an axle are rigidly connected, and independent, in which the left and right wheels are disconnected. Solid axle is the most common dependent suspension, while McPherson and double A-arm are the most common independent suspensions. [6]

Springs and shocks are an integral part of any suspension system. But the total suspension system must be considered as a coordinated package, so just changing springs and/or shocks will not always give the desired results. What works on one car might not work on another car because of differences in their system design. [7] As we were designing suspension for the trike, it was necessary to follow a different approach from the four wheeler vehicles.

The purpose of shock absorbers is to control the velocity of the suspension. If the shocks don't have enough resistance, the spring will move the suspension ·too fast and it will have an under-dampened motion. If the shocks are too firm, the motion will be over-dampened. It is important to have just the right amount of dampening to control the spring action of the suspension. [8]

As discussed earlier in this paper, we were having a goal of a cost effective solution for every subsystem. For the trike with tadpole configuration, we have implemented single pivot type suspension for rear wheel and shock-ups for the front wheels.

3.1 Suspension Requirements

- There should not be transfer of shocks to the vehicle and driver.
- Mechanism should be simple, easy to manufacture, lightweight and easy for maintenance.
- There should be a clearance of any component at least 3 inches at any condition with the driver.
- Suspension spring should not hinder with the chain drive to the rear wheel.

3.2 Rear Wheel Suspension

Considering the city application, we assumed the total wheel travel to be 100mm with 40% suspension height. The suspension geometry is prepared in CATIA and analyzed for motion transfer. As shown in the Fig-6, which is a side view of the rear wheel, A is the axle of the rear wheel. We have formed a triangular frame, AB-BC-AC. To the point D, spring DE is connected which is in the horizontal position. Point E is connected to the chassis. Thus we have made geometry of a single pivot point suspension system suitable for the trike.

The geometry is in the static condition. Following values consider dynamic conditions.

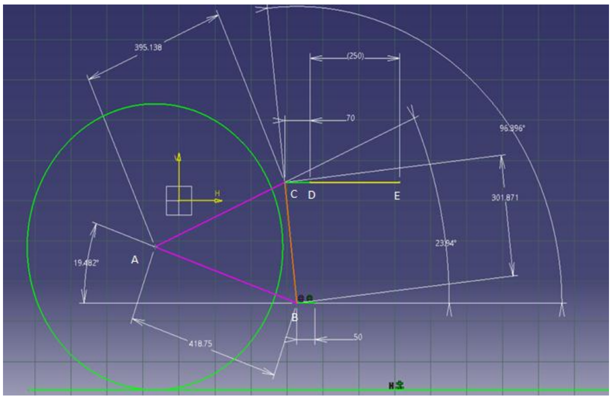

Fig-6: CATIA- Rear Suspension System

In rebound condition (40 mm), the values become

P= 418.75 mm	T= 13.773°
Q= 395.138 mm	U= 29.648°
R= 301.871 mm	V= 102.105°
S= 280 mm	W= 0.436°

In this condition, spring is in its free state and the length of shock absorber is 280 mm.

In jounce condition (60 mm), the values become

P= 418.75 mm	T= 28.482°
Q= 395.138 mm	U=14.939°
R= 301.871 mm	V= 87.396°
S= 203.762 mm	W= 2.638°

In this condition, spring is in its maximum compressed state and the length of the shock absorber is 250 mm.

Table-6 shows with a particular travel of the wheel, how much amount of travel occurs in the spring. Considering both values, leverage ratio is calculated. To calculate the exact leverage ratio, finally, we have plotted a graph of spring travel vs. wheel travel, by taking reference of above CATIA geometry.

Table - 6: CATIA Analysis

Wheel Travel	Spring Travel	Leverage Ratio
5	3.805	1.314
10	7.620	1.312
15	11.450	1.310
20	15.279	1.309
25	19.123	1.307
30	22.975	1.306
35	26.856	1.304
40	30.705	1.303
45	34.58	1.301
50	38.461	1.300

International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 07 Issue: 04 | Apr 2020 www.irjet.net p-ISSN: 2395-0072

Wheel Travel	Spring Travel	Leverage Ratio
55	42.348	1.299
60	46.238	1.298

Chart-1 is graph between the wheel travel and corresponding spring travel. The slope gives leverage ratio.

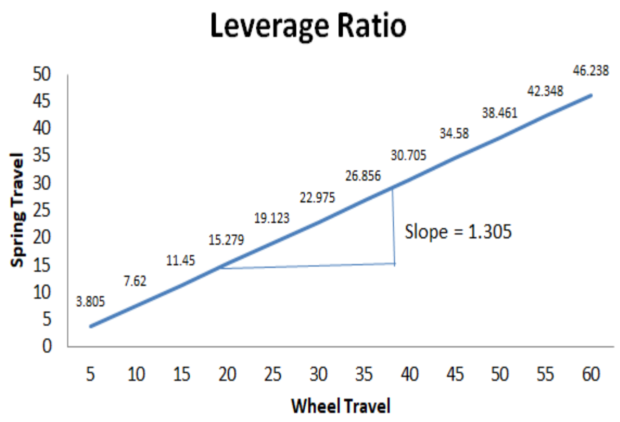

Chart-1: Leverage Ratio - Rear Suspension System

Leverage ratio = Slope of line = 1.305

To calculate maximum force acting on rear wheel,

GCW of trike = 225kg

Weight bias on rear wheel = 55%

Total wt. on rear wheel= 0.55*225

= 123.75 kg.

Hence, force acting on rear wheel = 123.75 * 9.81

= 1213.98 N

Therefore, Wheel rate= Sprung wt. / (Suspension ht. * Wheel travel)= 1213.98 / (0.4 * 100)= 30.35 N/mm

Hence, Spring rate= Wheel rate * (Leverage ratio)^2

= 30.35 * (1.305)^2

= 51.686 N/mm

Available spring rate =61.294 N/mm (i.e. 350 lbs/in)

Wheel rate = Spring rate / (Leverage ratio)^2 = 61.294/ (1.305)^2 = 36N/mm

Fig-7 shows a rendered image of a single pivot point rear wheel suspension.

Table-7 shows final specifications of the rear suspension system.

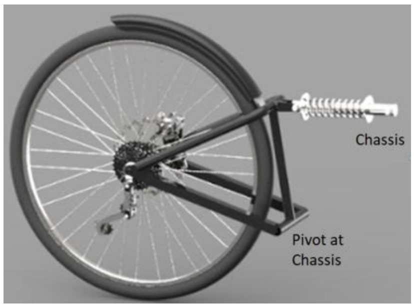

Fig-7: Single Pivot Point Rear Suspension – CAD

Table - 7: Summary Table – Rear Suspension

Description	Values
Leverage Ratio	1.305
Wheel Rate	36 N/mm
Available Spring Rate	61.94 N/mm
Mean diameter of spring	31mm
Spring wire diameter	6mm
Number of turns of spring	12

Fig-8 shows actual manufactured parts and assembly of single pivot point rear wheel suspension.

Fig-8: Single Pivot Point Rear Suspension - Manufactured

3.3 Front Wheel Suspension

As the trike has tadpole configuration, it has two front wheels and one rear wheel. We decided to implement an independent suspension system for both front wheels as we wanted to restrict the effect of one wheel to another and give an experience of minimal shocks to the trike.

As the 55% weight of the vehicle is on the rear and the design is tadpole, the force acting on the front wheels is low.

Hence, sprung weight = 496.6 N

The wheel travel is taken as 100 mm. For such low force conditions, we decided to use suspension forks at front.

Other advantages of using suspension forks are:-

1. Light weight
2. Desired outputs with accuracy
3. Lockout adjustment for gradient
4. Ease in assembly
5. Eliminating use of knuckles

The fork is mounted directly on the wheel axle. Hence, its motion ratio is 1:1. As the total weight acting on the fork with riders is 44kg (approx. 100lbs) and wheel travel is 100mm (approx. 4"), we selected 100psi fork suspension with 4" travel. With this fork, the amount of sag obtained is 40% (which results in a softer ride).

Fig-9 shows the front wheel shock absorber fork which would be mounted to the chassis. Mounting it on the wheels will be similar to a bicycle.

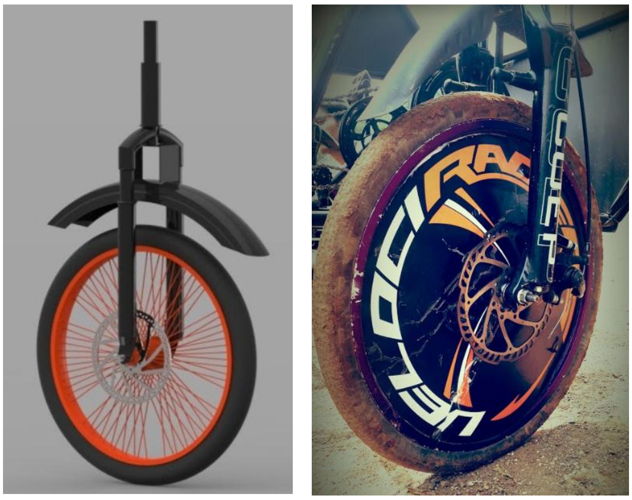

Fig-9: Front Wheel Suspension – CAD & Manufactured

Following figure shows shock absorber assembled with the wheel of trike. Shock absorber is pivoted in the chassis with the help of mounts given in the chassis frame.

4. Testing

We have tested the steering system by driving the trike in the figure of 8 having TCR of 3m. Also, the trike is tested for its maneuverability by designing test tracks which has sharp turns.

For the testing of the suspension system, the same track of maneuverability was used with some sand bags and small stones placed in the track. It was observed that the trike can take sharp turns with minimal steering effort when in motion. Moreover, the rear suspension was giving minimal shocks to the drivers when the trike passed over small stones placed in the track.

5. Conclusions

As stated earlier that main goal was to design a trike which can be useful in the small township, with the implementation of simple steering discussed in the paper, it can be lightweight, easy to assemble anywhere and easy for maintenance. This trike can steer with a maximum inner wheel angle of 37° and TCR of ~3m. Maximum cornering speed which can be achieved safely to take a turn having TCR ~3m is 18 KMPH.

Trike has single pivot point rear wheel suspension which if compared with other vehicles is lightweight and compact. As spring is placed horizontally, it is far away from the chain of the rear wheel. For the front suspension, we have used an independent type of suspension having a shock absorber fork mounted on each wheel.

In overall, the components used in the design of the trike are easy to manufacture, assemble and service. The subsystems explained in the paper have been manufactured and tested on the trike.

ACKNOWLEDGEMENT

The authors are thankful to Team Velociracers for the continuous support and provision of the resources required for this study.

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