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# Design and Development of Braking and Transmission Systems of an Electrically Powered All-Terrain Vehicle

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*Abstract : The project aims to design an Electric All-Terrain Vehicle (EATV), namely eBAJA. Our goal is to design, develop and analyze a single seat, all terrain, sporting vehicle whose structure contains the driver. While sizeable research has been conducted in all-terrain vehicles powered by petrol and diesel engines, no major research has been done in the development of ATVs powered by sustainable energy sources. The vehicle is to be a prototype for a reliable, maintainable, ergonomic and economic production vehicle which serves a recreational user market. The vehicle should aspire to market leading performance in terms of speed, handling and ruggedness over rough terrain and off road conditions. The design report focuses towards explaining the procedure, methodology and calculations involved and utilized in designing the off road electrically powered vehicle.*

*Keywords : Electrically powered all-terrain-vehicle, Drive-train, Electric Motor, Battery, Constant Velocity Axles, Braking, Master Cylinder, Stopping Distance, Grade-ability, Acceleration, Weight Distribution.*

## I. INTRODUCTION

While sizeable research has been conducted in all-terrain vehicles powered by Petrol and diesel engines, no major research has been done in the development of ATVs powered by sustainable energy sources.

As gas prices fluctuate and environmental concerns continue to be pushed to the forefront, we hear more and more about electric ATVs. For most people, however, electric off-road vehicles are still part of the great unknown.

Most electric vehicles share a few common features and tendencies. First off, they are almost completely silent. This can be a little strange at first, as all you really hear is the sound of the tires on the trail and a quiet hum from the electric motor, but you do get used to it.

Another common trait is torque. Electric motors have 100% of their torque available immediately, so getting up to speed from idle happens very quickly. Horsepower generally peters out quickly, however.

Maintenance is usually inexpensive; electric motors have fewer moving parts than conventional gas motors, which mean fewer parts to wear out. You also spend less money to run them as a full charge adds pennies to your energy bill, compared to whatever you have to pay to fill up at the pump. Additionally, spark plugs, along with oil, air, and fuel filters are all non-existent, so we never have to replace them. Hence, we plan to design an Electric All-Terrain Vehicle powered by an electric traction motor.

## II. METHODOLOGY

### A. *Literature Review*

**Research paper [1]** involves calculation and verification of braking force in the design process of an automobile. While designing the braking system, the main objective is to generate more braking force than ideally required to account for inefficiencies in mechanical linkages and hydraulic systems. This paper reviews the basic principles and considerations in the braking system design process and further explains the general procedure for the same. The paper also explains a validation method for any designed braking system using a brake performance triangle (BPT).

The paper concludes that braking force on the vehicle depends on coefficient of friction, deceleration rate, specification of rotor, caliper piston, master cylinder and pedal ratio and the applied force should be more than the required braking force.

In **research paper [2]** the design and analysis of plastic and aluminum master cylinder are performed. And it is concluded that, the plastic master cylinder is very advantageous for automobiles.

The following conclusions were made:

1) The weight of Master Cylinder made up of Acetyl Polymer i.e.0.157 Kg is less than Master cylinder made up of Aluminum i.e. 0.355 Kg.

2) The Master Cylinder made up of Acetyl Polymer material can bear more stress i.e.0.826358 N/mm2 than master cylinder made up of aluminum i.e. 0.661251 N/mm2.

3) The Thermal flux in Master cylinder made up of Acetyl polymer i.e. 546.163 K/mm2 is more than Master cylinder made up of aluminum i.e. 367.992 K/mm2. Thereby Heat transfer rate is good for Acetyl polymer than aluminum.

The disc brake is a device for slowing or stopping the rotation of a wheel. Repetitive braking of the vehicle leads to heat generation during each braking event. Transient Thermal and Structural Analysis of the Rotor Disc of Disk Brake is aimed at evaluating the performance of disc brake rotor of a car under severe braking conditions and there by assist in disc rotor design and analysis. Disc brake model and analysis is done using ANSYS workbench 14.5.

**Research paper [3]** analyses the thermo-mechanical behavior of the dry contact of the brake disc during the braking phase. The coupled thermal-structural analysis is used to determine the deformation and the Von Mises stress established in the disc for the both solid and ventilated disc with two different materials to enhance performance of the rotor disc. A comparison between analytical and results obtained from FEM is done and all the values obtained from the analysis are less than their allowable values. Hence best suitable design, material and rotor disc is suggested based on the performance, strength and rigidity criteria.

Adjusting bias with a dual master cylinder setup is typically done with something called a balance bar. The balance bar is built into the pedal itself, and is a totally mechanical way of adjusting bias. The use of balance bar is a new concept and it is not used in most of the conventional vehicles. Incorporating this concept in ATV can be very helpful as brake bias can be adjusted according to the terrain**. Research paper [1]** involves principles to do brake calculations without adjustment of brake bias. We have used those principles to do brake calculations involving a balance bar system to adjust brake bias.

Acetyl Polymer master cylinders are more advantageous than aluminum master cylinders as concluded by **research paper [2]**. Our ATV requires two master cylinders of bore sizes 0.625 inches for front and 0.75 inches for the rear for producing adequate braking force. After conducting market research Vikram Auto master cylinders of above mentioned bore sizes are found to be most suitable for the designed ATV.

Comparing the different results of temperature rise, deflection, and stress field obtained from analysis shows that in the ventilated cast iron disc reduction in temperature, stresses and deformation by 31.47% and 22.5% 8% respectively than the solid disc. It is concluded that ventilated type disk brake is the best for the present application in the ATV. The calculated outer and inner rotor diameters for ATV are 7.84 inches and 6.69 inches respectively. Rotors are designed accordingly on the software CATIA. All the values obtained from the analysis of the designed rotor are less than their allowable values. Hence the brake disk design is safe based on the strength and rigidity criteria.

Preliminary research was conducted in order to get a better idea of alternatives for the design, whether theoretical or commercially available. The research was separated into two phases. The first phases reasonably determined a transmission which would function to change the speed ratios. The second phases determined a secondary method to further reduce the speed and to connect the transmission section to the differential. Notes on each alternative where taken in regard to the maximum rated rpm and torque, weight, inertia, cost, efficiency, or any other product information available.

In selecting transmission system, a choice had to be made between the Single Speed Transmission, Manual transmission and CVT. However the incorporation of CVT was cancelled due to the following problems. While reading **research paper [2]** it was learnt that tuning of CVT requires the person to physically change the available combinations of weights and springs to see which set produces the best performance, which is a tedious job. Also coupling from the Motor to the CVT unit would not be readily available and would have to be fabricated.

*B. Braking System*

- Study of dynamic weight transfer from rear to front when brakes are applied.
- Thermal and finite element analysis of rotors of disc brakes on soft wares like Ansys and CATIA.

*C. Transmission System*

- Selection of motor was made by surveying the market, analyzing various motors in the market for the desired grade-ability, optimum acceleration, studying power to weight ratio along with being economical, it was found the Mahindra Reva electric traction motor, which is used in Mahindra Reva electric car would be a viable alternative to power the eBAJA.
- Selection of the drive was made by studying various alternatives along with their advantages and disadvantages. The rear motor rear wheel drive was selected, ie the motor and the transmission are mounted to the rear of the vehicle, and also the drive is transmitted to the differential of the rear wheels because it promoted better weight distribution of the vehicle and also is more economical to fabricate as the power-train and drive-train assembly can be manufactured as a whole.
- Selection of transmission involved analyzing the motor characteristics and since the electric motor in concern is sort to have high enough torque, higher motor efficiency and a much wider power band, the idea of a multi speed transmission became obsolete since it adds an additional unnecessary complication and hence the selection of single speed transmission was made, which is much more simpler, cost effective as well as less space consuming as compared to multi speed transmissions all together.

- Selection of joints used in transmitting torque from the motor to the axles involved looking at efficiency, inclination range of the join. Constant Velocity axles were selected as these provide greater stability at higher angles, they can be used at as high as 45 degrees without much wear or instability caused and are much smoother and quieter in operation than compared to Universal Joints.

## III. CALCULATIONS

### A. Braking System

Weight of vehicle with driver ($W_c$) = 855 lbs

Max speed of vehicle (S) = 51.33ft/sec

Rolling radius of front tire ($r_{mf}$) = 12 inches

Rolling radius of rear tire ($r_{mr}$) = 12 inches

Friction of Coefficient (μ) of road = 0.8

Wheelbase (L) = 168 cm

Vertical Height of vehicle's C.O.G ($h_{CG}$) = 52.5cm

Front weight = 855*0.4 = 300 lbs

Rear weight = 855*0.6 = 555 lbs

Dynamic weight transfer at 0.7g deceleration

= $W_c * h_{CG} *$ 0.7/L = 257 lbs

Dynamic front weight = Vertical Force on Both front Tires

($F_f$) = 300+257=557 lbs

Dynamic rear weight = Vertical Force on both rear tires

($R_2$) = 555-257=298 lbs

Friction Force on each Front Tire ($F_{FF}$)

$= \mu * \frac{F_f}{2}$ =222.8 lbs

Front Brake Torque ($T_f$) = $F_{FF} * r_{mf}$

= 2699 in-lbs

Friction Force on each Rear Tire ($F_{FR}$) = $\mu * \frac{R_2}{2}$ = 119.2 lbs

Rear Brake Torque ($T_r$)= $F_{FR} * r_{mr}$

= 1435 in-lbs

Kinetic Energy of moving car ($K_T$) = $W_C * \frac{S^2}{29.9}$

= 12920.94 ft lbs

Kinetic Energy to rear brakes ($K_R$) =$K_T * \frac{T_R}{(T_F + T_R)}$

= 4697.46 ft lbs

Kinetic Energy absorbed by each rear brakes ($K_{RE}$) = $\frac{K_R}{2}$

= 2348.73 ft lbs

Effective Rotor Radius($r_{eff}$) = 3.4 inches

Coefficient of friction between pad and rotor ($\mu_{pr}$) = 0.30

Number of calipers in front= 2

Number of calipers in rear= 2

Number of pistons (each caliper) = 2

Piston Diameter ($D_P$) = 1 inches

Piston Area (each caliper $A_o$) = 2 * 0.785 * $D_P$ * $D_P$

= 1.57 $inches^2$

Maximum Hydraulic Pressure in front ($P_{max}$)

$= \frac{T}{(\mu_{pr} * A_p * r_{eff})}$ = 1090psi

Maximum Hydraulic Pressure in rear ($P_{max}$)

$= \frac{T}{(\mu_{pr} * A_p * r_{eff})}$ = 586psi

Pedal Effort = 115lb

Pedal Ratio = 6:1

Front/Rear bias = 40%/60%

Manual Pushrod Force ($F_{MC}$) = Pedal Effort*Pedal Ratio

=690lbs.

The use of balance bar makes 60/40 front/rear bias-

Front force = 690*0.6= 414lbs

Rear force = 690*0.4= 276 lbs

Area of MC piston required front($A_{MC}$) = $\frac{F_{MC}}{P_{max}}$

= 0.3798 sq. inches

MC Bore required ($Ø_D$) = 0.625 inches

Nominal Bore =5/8 inches

Area of MC piston required rear($A_{MC}$) = $\frac{F_{MC}}{P_{max}}$

= 0.4709 sq. inches

MC Bore required ($Ø_D$) = 0.7500 inches

Nominal Bore = 3/4 inches

Stopping distance ($d_S$) from speed of 51.33ft/sec

$$=\frac{S^2}{2 * a_{max}} = 51.33^2/2g = 51.14 \text{ ft}$$

Time to stop $= \frac{S}{a_{max}} =$ 2.23 seconds

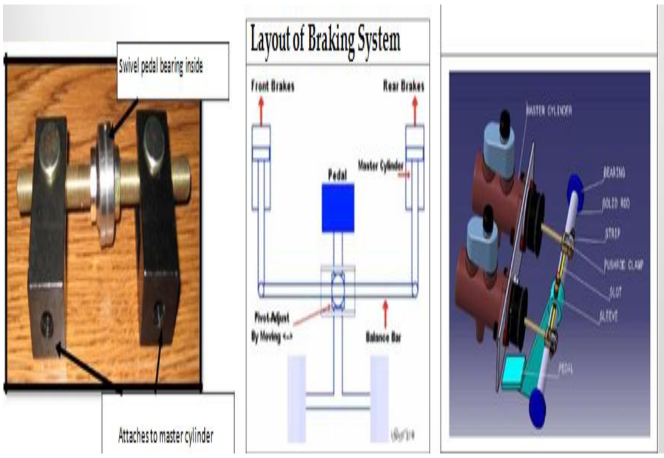


Figure 1: Layout of braking systems

*B. Transmission System*

- The rear motor rear wheel drive was selected, i.e., the motor and the transmission are mounted to the rear of the vehicle, and the drive is also transmitted to the differential of the rear wheels. The power from the differential to the driving wheels is then transferred through constant velocity axles, which enable higher inclination and put lesser load on the suspension system of the ATV.
- Also, because the roll cage of the ATV is such that it has ample space at the rear of the vehicle.
- The main component of the drive train is the Electric Traction motor.
- To obtain the desired gear-ability and on further surveying the market, it was found that the Reva electric traction motor would be ideal to be used for powering the eBAJA.
- The specs of the Reva motor as received from the Mahindra Ltd. Dealer

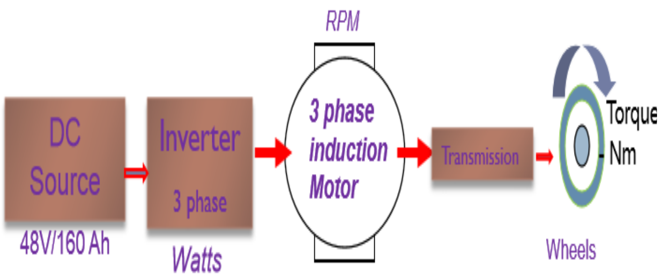


Figure 3: working of wheels

**Mahindra REVA Electric Traction Motor Specifications are:**

MAX Power: 11.5 KW

MAX Torque: 54 Nm

Rated Voltage and Current: 48V, 350 A

MAX Motor rpm: 9000 rotations per minute.

Tire Size: 24 inches Diameter; 6 inches width.

Motor to Gearbox Ratio = 10.83

Transmission Unit is Electrically Controlled.

- For transmitting power to the rear wheels, universal joint would be made between the transmission output and the CV axle which would provide better stability and the CV axle would then give output to the wheel bearing which in turn would be connected to the wheels.
- For transmitting power to the front wheels universal joints would be used.

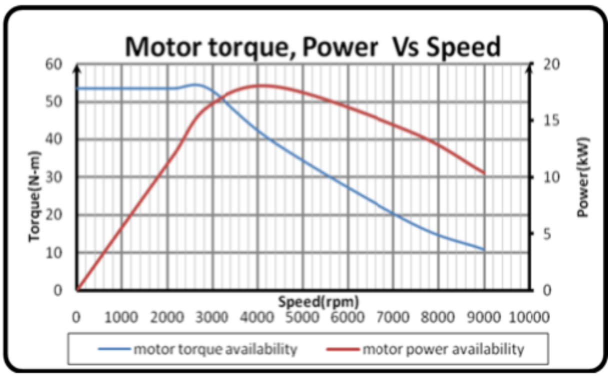


Figure 2: Motor torque , power vs speed

**AXLE CALCULATIONS**

The aim of the axle is to have enough strength to transmit the required torque to the wheels.
Considering a solid shaft,

From the torque equation, $\frac{T}{J} = \frac{\tau}{R} = \frac{G\theta}{l}$

Considering, $\frac{T}{J} = \frac{\tau}{R}$

$\tau$ is the shear stress of the material used, which would be a material constant.

The material used is **steel 1020**.

- The selection of material used, ie steel 1020, is included in the above design report of the ATV. The selection is based on the listed characteristics such as, material strength, durability, and ability to withstand shocks and sudden impact, cost effective and the ease of availability.

For which shear stress = 243 MPa

So, J = $\frac{\pi}{32} \times d^4$

R =d/2, where d would be the safe diameter to transmit the torque.

Simplifying we get, $d = \frac{\sqrt[3]{16T}}{\sqrt[3]{\pi\tau}}$

$$d = \sqrt[3]{1.13} \times \sqrt[3]{10^{-6}}$$

So, $d = 1.04 \times 10^{-2}$m = 1.04 cm.

Taking F.O.S. = 2 (factor of safety),

*d = 2.08 cm.*

**Hence, to transmit 54 Nm of torque with factor of safety 2, the diameter of solid shaft has to be greater than or equal to 2.08 cm.**

Since density of steel 1020 = $7900 \frac{kg}{m^3}$

Assuming length of shaft = 75 cm.

Volume of solid shaft = $\pi r l$ = .0000254 $m^3$

So mass of the solid axle = 0.2 kg

Weight of the required axle = 19.66 N

**TOP SPEED CALCULATIONS**

At top speed, the engine would be running at 5000 RPM.

Reduction Ratio = 10.83

Radius of wheel = 12 inches = 0.3048 m

RPM of Axle = 5000/10.83 = 461.7 rpm

Angular Speed of Shaft = 461.7$\times \frac{2\pi}{60}$ = 48.37 rad/s

Linear Speed of vehicle = 0.3048 * 48.37 = 14.74

Linear Speed = 14.74 $\times \frac{18}{5}$ = 53 KMPH

**ACCELERATION CALCULATIONS**

For the acceleration of the eBAJA, various studies were performed on the Reva to calculate the time taken by the car to accelerate to a speed of 40 KMPH. A normalized plot of the collected data was retrieved which yielded a mean acceleration time of 7 seconds for the car to attain the set speed of 40 KMPH. Now,

Weight of Mahindra Reva with a 70 Kg passenger = 900 Kg

Acceleration = $\frac{Vf}{t} - \frac{Vi}{t} = \frac{40}{t} - \frac{0}{t} = \frac{40}{7} * \frac{5}{18}$

= 1.59 m$/s^2$

So, Tractive force developed = car weight x acceleration value = 900 x 1.59 = 1428.57 N

Weight of our proposed eBAJA = 400 kg (including a 75 kg passenger)

So, Effective acceleration of the eBAJA = $\frac{1428.57}{400}$

= 3.57 m/$s^2$

Predicted time for the eBAJA to reach 40 KMPH = $\frac{40}{7} \times \frac{5}{18}$ = 3.11 seconds.

**GRADEABILITY CALCULATIONS**

For calculation of Grade-Ability percentage,

Tractive Factor = $\frac{ET}{GW} \times \frac{GR}{TR} \times TE$

Where,

ET = Engine Torque

GR= Gear Reduction Ratio

TE = Transmission Efficiency

GW = Gross Weight

TR = Tire Radius

According to our eBAJA design

ET = 54 Nm = 5.4 Kg m

GR = 10.83

TR = 0.85

GW = 320 Kg

TR = 12 inches = 0.3048 m

Putting in equation,

Tractive Factor = $\frac{5.4}{320} \times \frac{10.83}{0.3048} \times 0.85$

Grade - Ability = (TF-0.015) = 0.505

Grade – Ability % = 50.5 %

## IV. Results

### *A. Braking System*

Comparing the different results of temperature rise, deflection, and stress field obtained from analysis it shows that in the ventilated cast iron disc reduction in temperature, stresses and deformation by 31.47% and 22.5% 8% respectively than the solid disc. It is concluded that ventilated type disk brake is the best for the present application. All the values obtained from the analysis are less than their allowable values. Hence the brake disk design is safe based on the strength and rigidity criteria. The specifications of our braking system are as follows:

PERFORMANCE DATA

| | |
|---|---|
| Max. Speed | 53 KMPH |
| Max. Acceleration | 3.11 seconds ( 0 – 40 KMPH) |
| Grade-ability % | 50.47 % |
| Stopping Distance | 996.5 cm (from 45 KMPH) |

### *B. Transmission System*

On the basis of axle calculations diameter of shaft is calculated as 2.08 cm.
Top speed of ATV is calculated to be 55KMPH.
On the basis of Acceleration calculations it takes 3.11 seconds to reach 40 KMPH.
The grade-ability of ATV is 50.5%.
On the basis of these results we can conclude the ATV has enough torque to meet the off road requirements and meets the required criteria of top speed.

## V. Conclusions

From the work done in the field of roll cage, transmission and braking system design, we found the following limitations:

1) Real world testing needs to be done in order to ascertain suitability of components.
2) Impact test safety factors determined virtually may be different in real life.
3) Material availability plays a major role in deciding the final components and procedure used for fabrication.
4) Stopping distance and acceleration values may vary from theoretical value due to wind and other factors.

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