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Resistive Force Calculation and Battery Pack Configuration using Simulink Model

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Abstract: ***This paper provides a step by step guide for calculation of powertrain unit including the configuration of battery pack of a two-wheeler electric vehicle. Based on the design and desired performance of the vehicle, the total resistance force, torque and power is calculated and designed in MATLAB and Simulink, which is essential for selection of electric motor. Knowing the voltage and capacity of an individual cell the configuration of battery pack is calculated and depicted in SOLIDWORKS Computer Aided Design model. A website is developed which is competent to perform the necessary calculations and display the output of the desired performance parameters.***

Keywords: ***Electric vehicle, MATLAB and Simulink, Torque, Computer Aided Design***

I. INTRODUCTION

With the depletion of fossil fuels and increasing environmental pollution, there is an urgent need to shift from conventional IC engine vehicles towards electric vehicles. They are cheaper to run and maintain and are more efficient than conventional vehicles [1-3]. These electric vehicles can also be made energy independent by coupling them with a renewable source like solar energy [4]. The powertrain system of a two wheeler electric vehicle is depicted in Fig. 1.

All two wheeler electric vehicles like bike, scooter and motorcycle use motors to transfer energy to the wheels. However, these electric motors have variations in terms of their shape, size, torque output and operation processes [5]. Thus, choosing the motor which gives optimal speed and torque output is the most essential step in development of an electric vehicle.

Selection of the drive motor depends upon the maximum power and torque required by the electric vehicle. For the determination of torque, various factors like the aerodynamic resistance, rolling resistance and gradient resistance need to be taken into account [5-8].

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The flow diagram for selecting the motor and battery pack configuration is summarized in Fig. 2.

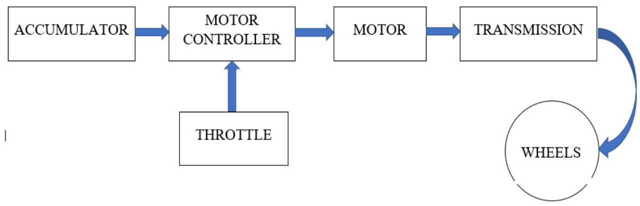

Fig. 1: Powertrain system of a two-wheeler electric vehicle

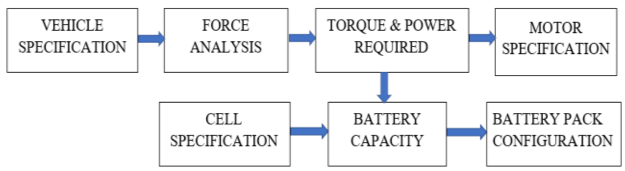

Fig. 2: Flow diagram for selecting motor and battery pack configuration

II. RESISTANCE FORCE ANALYSIS

Force analysis has been carried out to find the configuration of the battery pack. For a conventional two-wheeler electric vehicle, it is done at a constant velocity [8]. Therefore, for this case, the acceleration and hence inertia force is 0.

A. Calculation of Rolling Resistance

The vehicle experiences rolling resistance by virtue of its tires' contact with ground. Its formula is given by:

$$f_r = 0.01(1 + \frac{v}{160})$$

$$F_{roll} = f_r M g \cos(\alpha)$$

Where,
α = slope or gradient
f_r = Coefficient of rolling resistance
M = Total mass (kg)
g = acceleration due to gravity (9.81 m/s^2)
v = velocity (km/hr) [9]

Taking a total mass of 180 kg, 1% slope and 45 km/hr velocity,

$$f_r = 0.01\left(1 + \frac{45}{160}\right) = 0.013$$

$$F_{roll} = 0.013 \times 180 \times 9.81 \times \cos 0.57 = 22.95\ N.$$

B. Calculation of Aerodynamic Resistance

Aerodynamic drag is the resistive force experienced by the vehicle due to viscous air flowing over the vehicle body and rider which opposes the motion of vehicles. It can be calculated using:

$$F_{aero} = \frac{1}{2}\rho A C_d v^2$$

Where,
ρ = Density of air (kg/m^3)
A = Projected frontal area (m^2)
C_d = Drag coefficient and
v = velocity (m/s) [11]

For an electric two-wheeler, the frontal area generally varies between 0.7 to 0.9 m^2 and drag coefficient between 0.5 and 0.7. [11-12]

Taking 1.225 kg/m^3 as density of air, 0.8 m^2 as the frontal area, 0.6 as the drag coefficient,

$$F_{aero} = \frac{1}{2} \times 1.225 \times 0.8 \times 0.6 \times (12.5)^2 = 45.94\ N$$

C. Calculation of Gradient Resistance

Gradient force tends to pull back the vehicle while ascending a slope due to the effect of gravitational force. It is shown in Fig. 3.

$$F_{grad} = Mg\sin(\alpha) \quad [11]$$

Therefore,

$$F_{grad} = 180 \times 9.81 \times \sin 0.57 = 17.57\ N.$$

The total resistive force can be calculated by[11],

$$F_{total} = F_{aero} + F_{grad} + F_{roll}$$

$$F_{total} = 45.94 + 17.57 + 22.95 = 86.46\ N.$$

III. CALCULATION OF POWER AND TORQUE

Optimum power and torque are required in order to obtain the required drive characteristics.

$$P = F_{total} \times v$$

Therefore,

$$P = 86.46 \times 12.5 = 1080.75\ W$$

Torque on wheel is given by

$$\tau_{wheel} = F_{total} \times r$$

Where,
r is the radius of tire in metres.

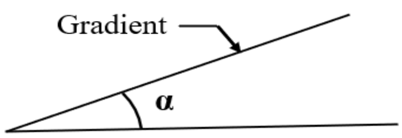

Fig. 3: Gradient angle

Taking the general convention of a two-wheeler tire radius, that is 0.3059 m. Hence,

$$\tau_{wheel} = 86.46 \times 0.3059 = 26.45\ Nm$$

IV. MOTOR SELECTION

Motor specifications have to be established based on the force analysis, for the required maximum speed and the speed required to ascend maximum inclined slope, optimum torque has to be delivered [5]. According to the results obtained, the motor must have the ability to provide the required torque, power and the rotations per minute on the wheel, using suitable gear ratio if required.

V. BATTERY PACK CALCULATION

Battery pack is the most crucial part of an electric vehicle. It provides power to the motor which gives the necessary torque on the wheels to run the vehicle.

A battery pack is made by arranging a number of cells in series and parallel to get the desired power and capacity. Cells in series increase the voltage output whereas cells in parallel connection add up to give the required capacity. For calculating the aforementioned, range of the vehicle i.e. the total distance it travels in a single charge at average speed, is essential.

The energy requirement per km is given by the ratio of power and velocity.

$\frac{P}{v}$, where v is the average velocity in km/hr

$$\frac{P}{v} = \frac{1080.75}{45} = 24.02\ \frac{Wh}{km}$$

Therefore, the capacity required per km is given by the ratio of per km power to the voltage.

$\frac{P}{v}\Big/V$, where V is the voltage in volts.

For optimal speed, higher voltage is preferred. For a 72V battery pack,

$$\frac{P}{v}\Big/V = \frac{24.02}{72} = 0.33\ \frac{Ah}{km}$$

Total capacity of the battery pack is given by,

$$Capacity_{total} = \frac{P}{v}\Big/V \times Range$$

For a range of 150 km,

$$Capacity_{total} = 0.33 \times 150 = 49.50\ Ah$$

It is advisable to keep a factor of safety to account for various losses and degradation in the cells over time. This won't let the cell's state of charge (SoC) to be 0 and will also increase the cell's life cycle.

$$Capacity_{required} = Capacity_{total} \times fos$$

Taking 1.2 as a factor of safety [13],

$$Capacity_{required} = 49.5 \times 1.2 = 59.40\ Ah$$

VI. CELLS

Cells are the building blocks of a battery pack. Every cell has a specified voltage and capacity. Combining them in series and parallel connections gives the desired output.

Using a cell having a nominal voltage of 3.6V and 3Ah capacity, the total number and configuration of battery pack can be found.

A. Cells in Series

The number of cells in series is given by,

$$n_s = \frac{V}{V_{cell}}$$

$$n_s = \frac{72}{3.6} = 20$$

B. Cells in Parallel

The number of cells in parallel is given by,

$$n_p = \frac{Capacity_{required}}{Capacity_{cell}}$$

$$n_p = \frac{59.40}{3} = 19.80 \sim 20$$

For the given specifications, the total number of cells required is 400 and the battery configuration is 20S20P.

VII. RESULTS

The entire calculation, having input parameters i.e. total mass, frontal area, drag coefficient, density of air, gradient angle, radius of tire, velocity, voltage of motor, range, acceleration, voltage and capacity of a cell, is processed in MATLAB and Simulink. Entering the required inputs, the output is displayed on MATLAB.

The equations governing the torque, power and configuration of battery pack as outlined earlier are implemented in MATLAB and Simulink modeling (Fig. 4). The model calculates all the necessary variables namely aerodynamic drag, rolling resistance, gradient force, total force, torque and power. It also displays the cells in series, parallel and the total battery pack configuration. The output tabular column is shown in Table1 and Table2.

The output is displayed in a tabular form along with graphs: 2 sets of 2 graphs each. In the first set, the X-axis represents gradient angle and in the second set it represents speed, while the Y-axis depicts total resistance force and power.

In the first set, the relation between gradient angle (X-axis) and total resistance force and power (Y-axis) was found to be linear (Fig. 5 and Fig. 6). In the second set, the relation between velocity (X-axis) and total resistance force and power (Y-axis) is quadratic (Fig. 7 and Fig. 8).

In Table1, it is observed that the required power increases as the gradient is increased while the speed is kept constant. This is due to the increase in total resistive forces. As depicted in Fig. 9, though rolling resistance decreases a little with increasing slope, the gradient force has a linear increase which results in higher total resistive force and hence the power required and capacity of battery pack.

Also, the required power increases as the velocity increases, keeping gradient constant, as presented in Table2. It is due to the fact that aerodynamic resistance has a direct square relationship with velocity as depicted in Fig. 10. As velocity increases, aerodynamic force increases which leads to increase in total resistance force and hence required power and battery pack capacity.

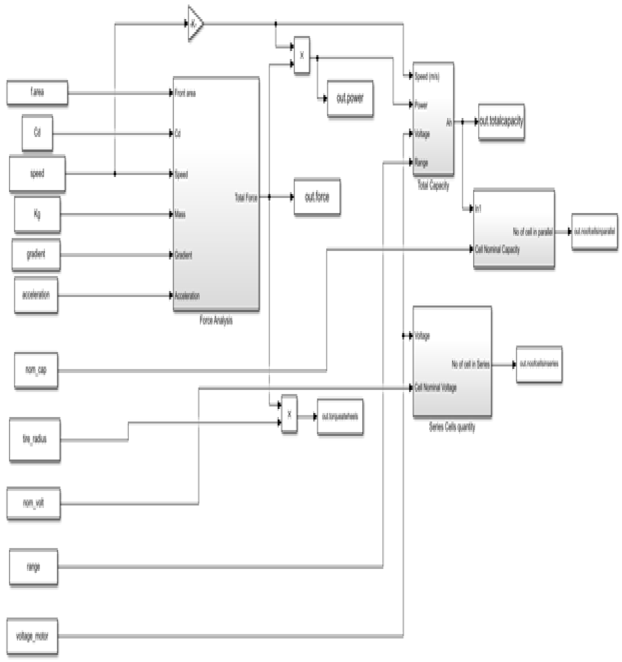

Fig. 4: Simulink model to obtain tabular output

Table1: Simulink output: varying gradient angle, considering the entire range is travelled at that gradient

Total Mass=180kg, Frontal area=0.8m^2, C_d=0.6, Acceleration=0, Tire radius=0.3059m, Motor voltage=72V, Speed=45km/hr, Range=150km, Individual cell voltage=3.6V and capacity=3Ah						
Gradient (Degrees)	Total resistance force(N)	Torque (Nm)	Power(W)	Total capacity (Ah)	Cells(series)	Cells(parallel)
0	68.54	20.97	856.74	47.6	20	16
1	99.35	30.39	1241.92	69	20	23
2	130.15	39.81	1626.89	90.38	20	30
3	160.92	49.23	2011.54	111.75	20	37
4	191.66	58.63	2395.75	133.1	20	44
5	222.35	68.02	2779.41	154.41	20	51
6	252.99	77.39	3162.4	175.69	20	59
7	283.57	86.74	3544.6	196.92	20	66
8	314.07	96.07	3925.89	218.1	20	73
9	344.49	105.38	4306.16	239.23	20	80
10	374.82	114.66	4685.3	260.29	20	87

Table2: Simulink output: varying speed

Total Mass=180kg, Frontal area=0.8m^2, C_d=0.6, Acceleration=0, Tire radius=0.3059m, Motor Voltage=72V, Gradient=1%, Range=150km, Individual cell voltage=3.6V and capacity=3Ah						
Speed(km/hr)	Total resistance force(N)	Power(W)	Torque (Nm)	Total capacity (Ah)	Cells(series)	Cells(parallel)
15	41.96368118	174.85	12.84	29.14	20	10
30	58.93001473	491.08	18.03	40.92	20	14
45	86.10468161	1076.31	26.34	59.79	20	20
60	123.4876818	2058.13	37.77	85.76	20	29
75	171.0790154	3564.15	52.33	118.8	20	40
90	228.8786823	5721.97	70.01	158.94	20	53

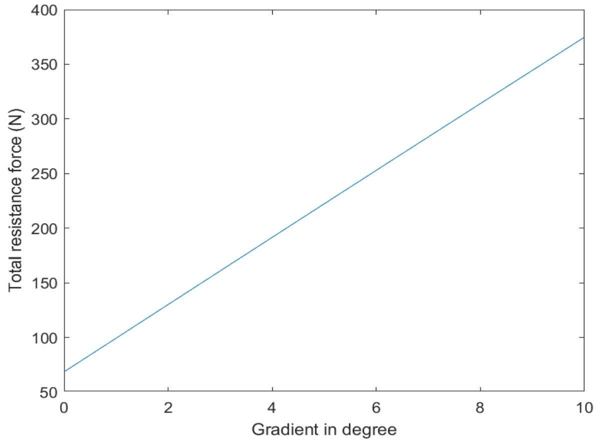

Fig. 5: Total resistance force vs Gradient angle

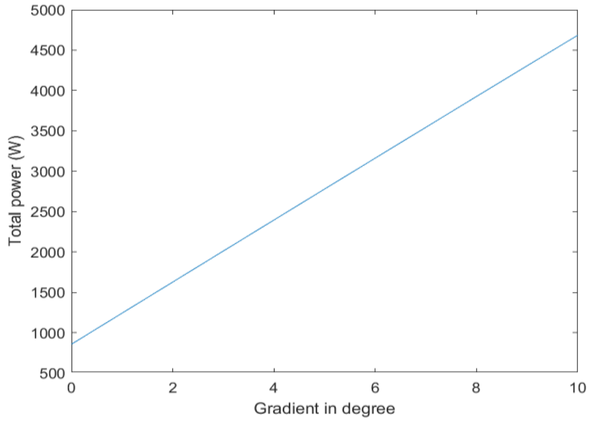

Fig. 6: Total power vs Gradient angle

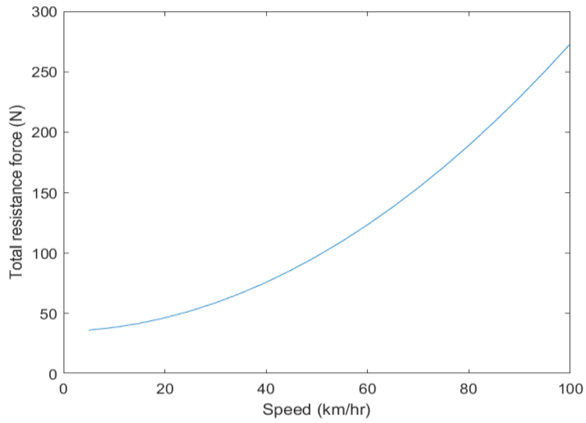

Fig. 7: Total resistance force vs Speed

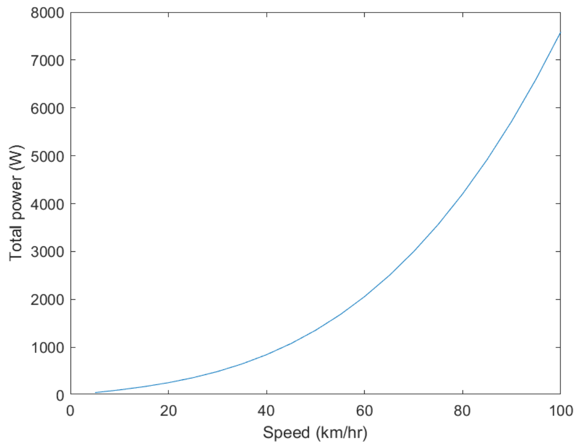

Fig. 8: Total power vs Speed

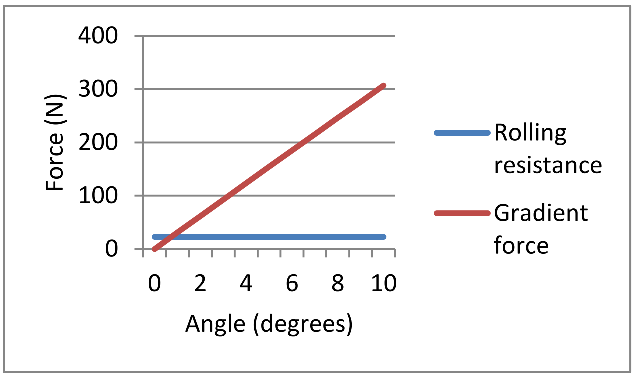

Fig. 9: Rolling and gradient force vs gradient

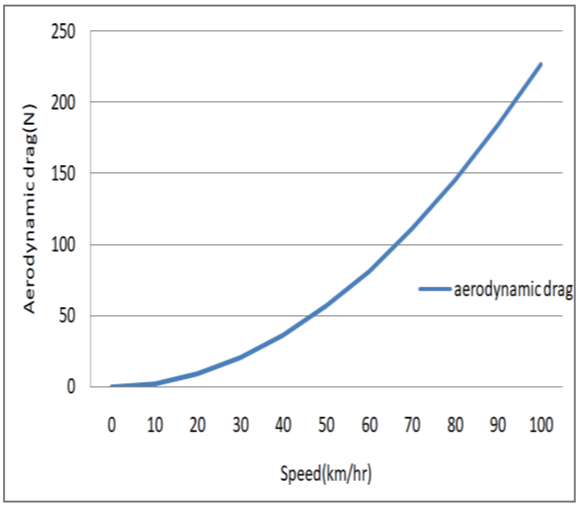

Fig. 10: Aerodynamic drag vs Speed

VIII. WEBSITE

A website has been designed, using HTML CSS JavaScript. It is made using Flask framework, which is a micro web framework supporting python backend and the deployment is done via Heroku which deploys flask based web apps.

Following is the link of the website which can be used freely. By using customized input values (Total mass, frontal area, range, acceleration, tire radius, motor voltage, speed, gradient angle, drag coefficient, density of air and voltage and capacity of a cell), one can get the desired output values (aerodynamic drag, rolling resistance, gradient force, inertia force, total force, torque, power, number of cells in series and parallel and total number of cells required for the battery pack). URL: www.evmotorbike.com

IX. BATTERY PACK COMPUTER AIDED DESIGN

The result obtained from Simulink was applied to design the battery pack configuration in SOLIDWORKS and is illustrated in Fig. 11. For the Computer Aided Design **(**CAD) model, designed for 0 gradient or no slope, 18650 cylindrical cells having individual nominal voltage of 3.6V and 3Ah capacity are used. Cell holders made up of plastic and nickel strips are used to make the series and parallel connections. The battery pack has a configuration of 20S16P and dimensions of 20*15*32 cm.

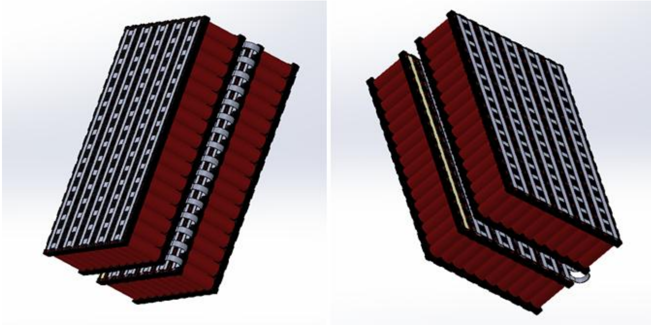

Fig. 11: Battery pack CAD

X. CONCLUSION

The paper provides a step by step guide incorporating detailed information about calculation parameters in the powertrain system of a two-wheeler electric vehicle, required inputs and outputs. Knowing the input variables, the output parameters can be easily calculated using the formulae or the MATLAB and Simulink model which additionally generates the required graphs. All the calculations can also be done in a single click using the calculator available on developed website.

URL: www.evmotorbike.com

Using the cell parameters as input, the required battery pack configuration has also been calculated and the battery pack's computer aided design using SOLIDWORKS is also modeled.

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AUTHORS PROFILE

Nikunj Navinbhai Patel is currently in 3rd year, pursuing Bachelor of Technology in Mechanical Engineering with a minor degree in Automotive Engineering at Vellore Institute of Technology. He is an automotive enthusiast and aims to pursue Masters Degree in Automotive Engineering. He is a member of FSAE formula hybrid Team Uttejit and leads the team currently as the head of Powertrain department. He is a member of SAE International and has attended the Formula Hybrid Competition at New Hampshire, USA held by SAE. He has an experience of more than 2 years of the formula student team and is competent in modeling, designing, manufacturing and analyzing various automotive parts in different softwares. He is a Certified SOLIDWORKS Associate member. He is currently simulating shock wave propagation and its properties using Ansys. Moreover, he is leading the team in the prototype building of Electric Motorcycle.

Ms Ananya Kapoor is a student, currently in third year, pursuing Mechanical Engineering from Vellore Institute of Technology, Vellore. She aims to pursue Masters and PhD in the field of astronomy after engineering. She is a space enthusiast and likes to explore different ideas in various fields. She is the Programmer Representative of Mechanical stream. She is a Certified SOLIDWORKS Associate and was a member of Students for the Exploration and Development of Space in VIT. She is also working on other areas of research like shock waves and shock tube and alternative sources of conventional fuel like biodiesel. She is also associated with Juvenile Care, a NGO based in Vellore.

Om Hemantkumar Purohit is currently pursuing his Bachelor of Technology in Information Technology at Vellore Institute of Technology, Vellore. He is an aspiring data scientist and is also interested in modeling and exploratory data analysis. He is competent in web development as well as game development using C++ as he believes C++ has brilliant libraries that are built on the hardware and work with celerity and efficiency. He also loves coding in python and has made websites using flask framework. He handles all data science related tasks with python and is also experienced in JavaScript. He likes doing exploratory data analysis on various datasets and is active Kaggler.