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Modelling and simulation of Urban electric bus using MATLAB

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Abstract:
Electric vehicles are being acknowledged and gaining popularity throughout the world after seeing the impact of conventional Internal combustion engines on the Climate change.EV usually have poor range and performance, but today many EV's performances are on par with the ICE engine due to the development of technology and optimization processes. This paper presents the modelling and simulation of an electric bus with vehicle parameters of an urban transportation bus. The performance and range of the vehicle model areoptimized for operation in the urban areas where the speed is not much of importance but the capacity and range of the vehicle are crucial. Initially, a battery is modelled and is optimized, then this battery modelis used in the vehicle model which includes the battery and motor. The vehicle model is simulated in asfuds cycle which is the closest to real urban driving patterns. All the modelling and simulation results are validated in the MATLAB environment. The results obtained are useful to predict initial design requirements and employ control strategy to optimise the parameters that reduce the vehicle performance, range and efficiency. This is a system level simulation involving the major component like battery, controls and powertrain. This paper is the basis for a more complex model which includes various sub-system like tires, transmission and auxiliary loads (air-conditioning, electronics, controls) considering the heattransfer and cooling systems.

Keywords: Li-ion, EV, Sustainable energy, Electric bus, MATLAB, Battery Model, Range

1. INTRODUCTION

It is Claimed by NASA that automobiles are the largest contributor to climate change and global warming [1]. India has been ranked third in the list of country thatcontributes to global warming according to [2]. So, it's important to transition from theconventional energy source to sustainable energy. In India majority of the population are poor and their main source of transportation is abus in both rural and urban areas, so electrification of buses should be the first step in thetransition to sustainable energy in India [3]. Although the Electric vehicles are emission free and noiseless it's performance and range are far cry from that of the conventional ICE because of their low energy density. The EV that have good performance and range these days are usually costly because of their light-weight materials and battery.This paper discusses the mathematical modelling of the performance and range of an electric bus with the vehicle parameters of an Indian urban bus. In this model, the Li-ion phosphate battery was selected because of its high-Energy density and specific power [2]. A lot of improvement have been made for the Li-ion battery but the main disadvantage of this battery is weight and cost. The motor is one of the keen components of an EV and for this electric bus,variable frequency synchronous motor is chosen for its high specific power and efficiency at high speed [5]. Simulation is performed in two test cycle one is wide open throttle(WOT) to determine the acceleration and other is Simplified federal urban driving schedule to determine its range, torque map and motor power.

2.MATHEMATICAL MODELLING

2. 1.Battery Modelling: The selection of battery is acritical process and are selected based on the parameters like specific energy, density, power, cost and life cycle etc. Some of these parameters are dynamic in nature like charge capacity, resistance, discharge current which results in a more complex model. In this electric bus model, li-ion phosphate is used because of its high-energy density, life cycle, specific power and also good thermal stability which minimises the requirements for cooling [6] which makes the battery safe. Also, the manufacturers of Li-ion battery are high compared to any other battery as they are being used in various applications like smartphones, laptop and cameras. Once the selection process is completed the battery is modelled to predict its parameters. Initially to simulate the performance of the battery system an equivalent circuit model is created which is made up of elements that are predictable like internal resistance and open circuit voltage. The equivalent circuit is as shown in Figure 1.

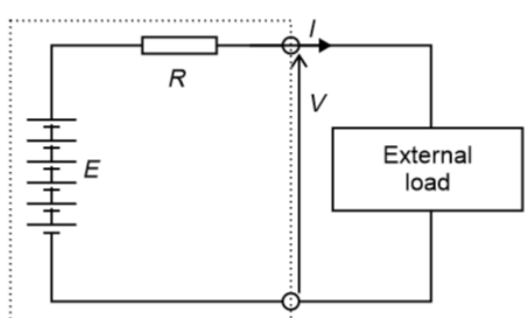

Figure.1. Equivalent Circuit Of Battery

The values of E and R are not exactly constants and they vary based on their state of charge(SOC). Using the graph from datasheet [7], a polynomial open circuit voltage equation is obtained to predict the change in voltage with increasing depth of discharge. Although this equation is not accurate it gives a close approximation of the real battery.

$E = N * (3.05 - 1.2x + 0.5x^2 + 2.3x^3 - 2x^4 + 0.05x^5 - 0.5x^6)$	(1)

Battery parameters that are chosen for the electric bus are shown in Table 1.

Table.1.Battery Parameters

Element	Characteristics
Battery type	Li-ion phosphate
voltage	540V
Nominal voltage	3.2V
capacity	600Ah
Number of cells	170 series,4 parallel
Total capacity	324kwh

2. 1.1. Capacity of a Battery:
The capacity of thebattery is highly dynamic and changes continuously based on the charge removed at a particular time as the vehicle is accelerating and decelerating. It is important to predict the change in capacity of battery because electric bus requires a large amount of current for its operation, so the capacity during the operation in highways and urban areas will be different than predicted. To predict the capacity of a battery initially the peukert capacity of the battery is found, which is equal to normal amphours capacity when discharged at one Ampere [5].

$C_p = I^k T$	(2)

k-Peukert Coefficient (assumed to be 1.125 [11])

To determine the peukert capacity initially,it's assumed that the 600ah battery is discharged at rate of 6 hours,

$$I = \frac{600}{6} = 100A$$

C_p=$100^{1.125} * 6 = 1066ah$
In order to perform the simulation, the battery is simulated at adischarge current of 100A (rated 6h). The charge removed from a battery is determined by the formula,

$CR_{n+1} = CR_n + (\frac{\delta t \times I^k}{3600})\ Ah$	(3)
$CS_{n+1} = CS_n + (\frac{\delta t \times I}{3600})\ Ah$	(4)

Here, CR is the actual charge removed from the battery and CS is charge supplied to the vehicle considering the self-discharge loss within the battery. So, CR is always greater than CS. Then finally Depth of discharge is found using the formula,

$DOD_n = \frac{CR_n}{C_p}$	(5)

Using this equation, a MATLAB program was created and a graph was plotted between Voltage and charge suppliedwhen discharging a constant current of $100A$. If the constant current to discharged is higher, then there will be more voltage drop. The obtained result is shown in the Figure 2.

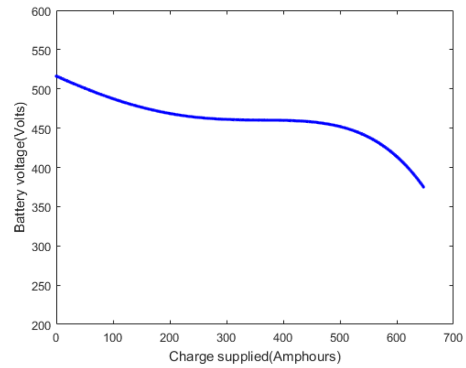

Figure.2. showing the voltage drop as current is discharged from the battery

2. 1.2. Constant power discharge:
In order to run the vehicle at high speed more power is required to be transferred from the tires to the ground, hence it is useful to simulate the battery in terms of discharging constant power from it. So, in this process, the motor is simulated to run at a constant power discharge with constant velocity. In order to simulate this, equation for current is obtained in terms of the set power and is given by as below

$I = \frac{E - \sqrt{E^2 - 4RP}}{2R}$	(6)

For regenerative braking, current is generated and is stored in the battery so the following equation is modified into,

$I = \frac{-E + \sqrt{E^2 + 4RP}}{2R}$	(7)

This equation is used to simulate at a constant power discharge of $100kw$ [5].The resulted graph is as shown in Figure 3.

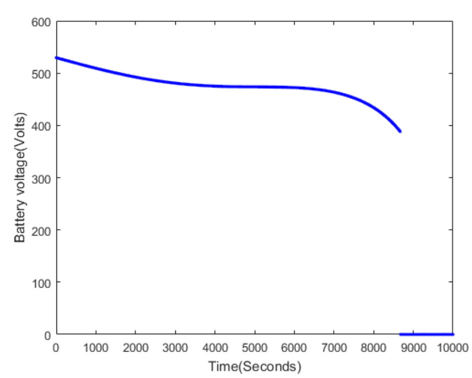

Figure. 3. Shows the battery is discharged at constant 100kw

2. 2.Electric Bus Modelling
Once the battery's dynamic parameters like open-circuit voltage, internal resistance, capacity are found, a complete vehicle system is modelled. In this model, the battery is connected to the motor and the motorsare in turn connected to the wheel. Since it is a rear wheel drive the motor is placed in the rear. The battery is placed in the middle or is spread along the underbody of the bus and is decided based on the location of center of gravity and

vehicle dynamics. This complete system-level model gives an initial prediction about the performance, range and efficiency of the vehicle. This mathematical model of the vehicle is important in the initial design phase as it's quick to change and optimize the variables without building any actual physical prototype. The vehicle specifications are summarised in Table 2

Table 2.Vehicle Parameters

Element	Characteristics
Vehicle Mass	17500 kg
Drag Coefficient	0.7
Frontal Area	$10.2m^2$
Wheelbase	7.264 m
Gear Ratio	7
Efficiency of gear	98%
Rolling Resistance	0.01
Maximum Speed	80 Kmph
Rolling radius	20 in

From [13] the drag coefficient for buses is to be between 0.6-0.7 and coefficient of rolling resistance for Pneumatic truck tires on concrete, for asphalt is between 0.006-0.01.

2. 2. 1.Motor Selection

A variable frequency synchronous motor with liquid cooling was selected for this bus because of its high efficiency, power density and torque. The volume occupied by this motor is significantly less compared to an induction motor [14]. The Remy HVH410 HT was chosen because it meets the specific needs of the vehicle and also for its customization. This is a high-speed motor and generally,high-speed motors are highly efficient, but if the speed of the motor is high then torque decreases. So, in order to bring down the initial speed of the single reduction gear is used [5]. These motor parameters are obtained from the source [9]. The motor specification is Summarised in Table 3.

TABLE 3. Motor parameters

Element	Characteristics
Peak Power Output	275 kW
Peak Output Torque	1273 Nm
Peak Efficiency	95 %
Maximum Operating Speed	6000 RPM
Maximum Input Voltage	740 VDC
Maximum Input Current	320 Amps
Cooling	Oil-Cooling
Maximum Temperature	160℃

2. 2. 2.Modelling of vehicles performance

Acceleration is one of the factors in which electric vehicles has a very poor performance. To determine the acceleration of the vehicle the electric bus is simulated at maximum torque, this type of simulation is similar to that of a full throttle or wide open throttle test of an IC engine. The time taken to reach from $0\ to\ 50\ km/h$ gives the acceleration time of the vehicle as in figure 5. or it is also measured in terms of distance as in figure 6. In order to build the mathematical model, the parameters that are listed Table 2 And Table 3 are used by substituting them in the equation 10.

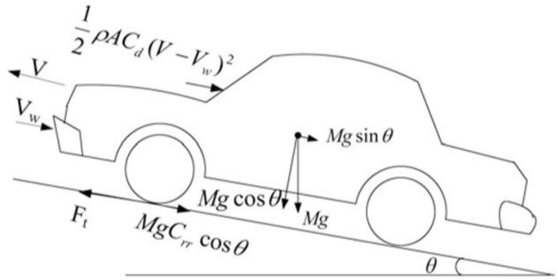

Figure.4. Forces acting on a Vehicle [15]

Initially the tractive force is found which gives the value of the force that is required to propel the vehicle forward against the rolling resistance, aerodynamic drag, linear and angular acceleration and component of force acting downwards if the vehicle is running on a slope. For our calculation we have consideredto run the bus on a flat road. From Figure 4 the equation for tractive force is given as,

$$F_t = F_{rr} + F_{ad} + F_{hc} + F_{la} + F_{\omega a} \quad (8)$$

We assume the wind speed is zero in this simulation.

By substituting the formulas for all the forces in equation (8) we obtain the final equation as follows,

$$F_t = C_{rr}mg + \frac{1}{2}\rho AC_d(V - V_w)^2 + ma + I\frac{G^2}{\eta_g r^2} \quad (9)$$

$$\frac{G}{r}T = C_{rr}mg + \frac{1}{2}\rho AC_d(V - V_w)^2 + ma + I\frac{G^2}{\eta_g r^2} \quad (10)$$

Initially, the torque produced by the motor is maximum (i.e. $T = T_{max}$) and this torque is maintained constantly for some time. After this initial constant torque phase the torque falls non-linearly, in this state the Torque produced is less than the maximum torque (i.e. $T < T_{max}$) [5]. From the graph given in motors datasheet [9], the critical value or speed of the motor is estimated and is found to be $116\ rad/s$at which the maximum torque drops. Considering the gear ratio this angular velocity corresponds to $v = 8.418\ m/sec$ $(30\ km/hr)$. Above this critical velocity, the motor operates at a constant power $250Kw$. So, the torque after the critical velocity is

$$T = \frac{18142}{v} \quad (11)$$

After applying the values for the constants and the known parameters, we obtain a first-order differential equation as 12 and 13

When, $T = T_{max}$	$\frac{dv}{dt} = 0.807 - 0.000253v^2$	(12)
$T < T_{max}$	$\frac{dv}{dt} = \frac{12.85}{v} - 0.146 - 0.000253v^2$	(13)

The above differential equation is used to create the mathematical model in the MATLAB and the simulation is performed varying the value of time from 0 to 60 seconds and estimated value of the velocity is plotted against time and is as shown in figure 5and 6.

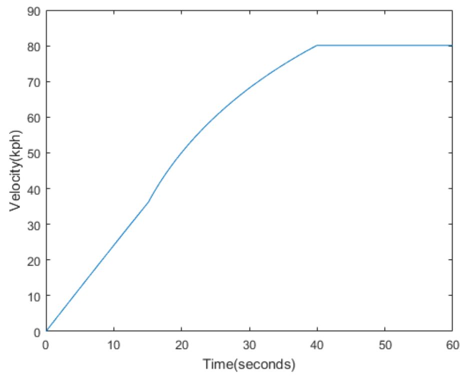

Figure. 5. Full throttle acceleration

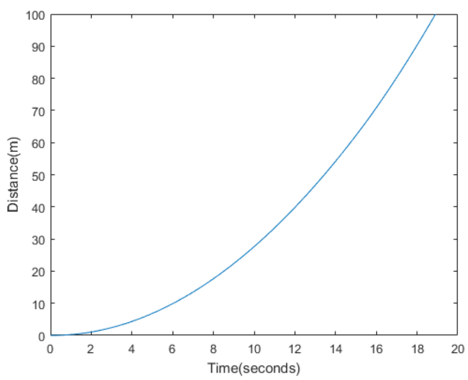

Figure.6. Distance travelled in Full throttle acceleration

From Figure 4 we can see that the bus reaches the speed of $50kph$ at about than $20\,seconds$. Since in Urban areas the average speed of the vehicle is $15-18\,km/h$ according to [3] sothis is sufficient for heavy vehicles like a bus but still the acceleration can be optimized further by cutting down the vehicles weight or by reducing drag. It can also be seen that from Figure 6 the vehicle covers the distance of 10 m in about 6 seconds.

2. 2. 3.Modelling the Range of vehicles

Range is similar to themileage of an IC engine, is the distance travelled by the EV in one full charge. Usually, electric vehicles are known for their low range because various parameters like temperature, speed, State of charge affect the energy stored in the battery and it deteriorates the battery performance and life cycle. So, calculating the range of the vehicle is very crucial in thedevelopment of any Electric or Hybrid vehicles. Range of the electric vehicle also depends on the mass and other vehicle parameters. In order to determine the range, the vehicle is simulated in atest drive cycles which contains varying acceleration, deceleration with respect to time. Each test drive cycle has aprofile ofvarying magnitude of acceleration and deceleration for different time and duration. The most simple but unrealistic test is the constant velocity test where the vehicle is simulated at a constant speed without any deceleration for a certain duration. The simulation is comparatively quicker but it results in less accurate figures. In order to get good accurate figures, the vehicle is driven through a test cycle of changing speed but then again, these types of simulation make the problem more complex and time-consuming. Since the vehicle is designed for urban transportation, the Simplified federal urban driving schedule (sfuds) is used. The file containing the data for sfuds cycle was obtained [10] and it was imported as a MATLAB script file to perform the simulation. The plot between time and velocity of sfuds driving cycle is shown in Figure 7

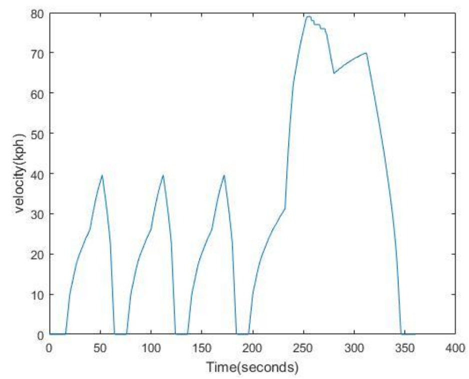

Figure.7. Simplified Urban federal drive cycle

The energy required for the vehicle to move electric bus for one second is given by the equation 14,

$TP = F_t \times v$	(14)

Here the battery needs to provide the energy TP for each second in order to propel the vehicle forward. In order to find the energy supplied by the batter to the wheels we should consider the efficiency of motor and gear systems or any other components between battery and tires. The efficiency of the gear is usually high because only one single reduction gear is used whereas the motor efficiency varies with power, torque and size. The equation of the power transferred at various operating points, are estimated. In order to predict the range of the electric vehicle both the vehicle and battery model are co-simulated in the sfuds drive cycle till the battery is flat or fully discharged. A script file was created for this model and it is then simulated in MATLAB. The Figure 8 is obtained from the result of the simulation.

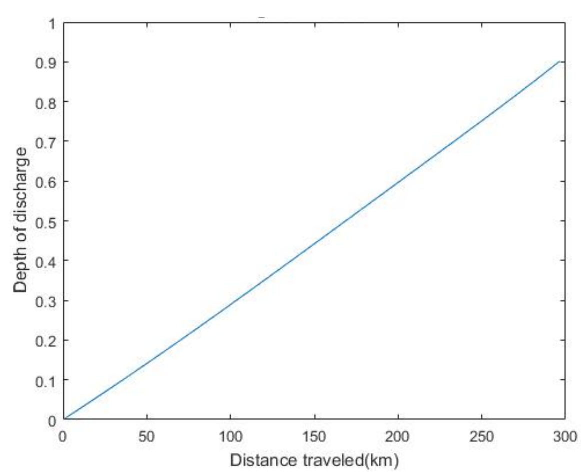

Figure.8. Graph showing the range of the vehicle considering auxiliary load

We can see from the graph that at 90% discharge the electric bus has a range of less than $300km$, but usually the controllers within the battery, stops the battery discharge at 80% in order to prevent the failure of the battery. The range at 80% of discharge would be slightly above $250km$. By reducing the auxillary load or heat generation within the battery and motor, the range can be further increased.

3.RESULT

Apart from Range and acceleration of the vehicle other important parameters are easily obtained from MATLAB, like motor speed against torque, motor Power, efficiency and they are plotted in the following. Figure9 represents the operating points of the motor and it can be clearly seen that at most of the time motor operate at near 450Nm and 1900RPM. By comparing the Figure 9 and Figure 10 we can see that the motor operates closely at about 93% - 94% +. Figure 10 is obtained from the motor's data sheet [9]. In Figure 11 it can be seen that the motor efficiency reaches its peak during its full power and drops during braking or when slowing down, it’s because torque is proportional to the losses in the motor, so during the low-speedoperation, the losses are more and hence less efficient[5].Figure 12 and 13 represents the power of the motor output and the current supplied by the battery during its operation.

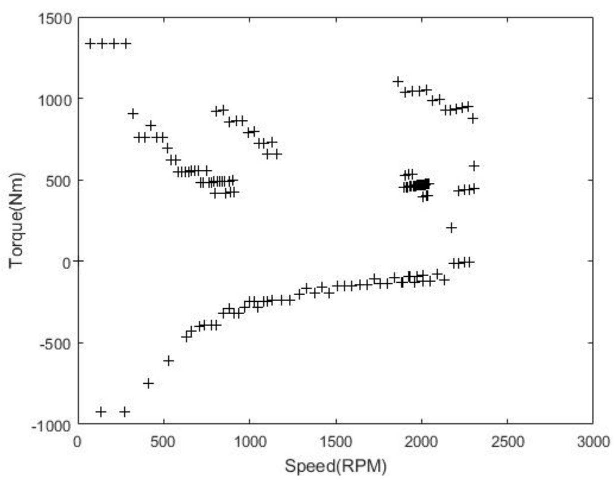

Figure .9. Operating points where the motor is operated

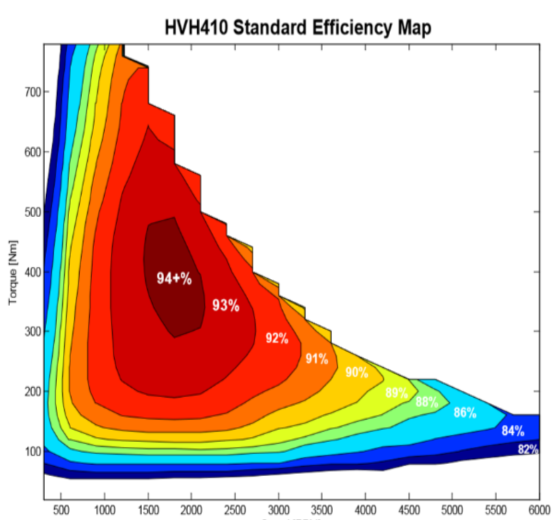

Figure.10. Efficiency map of the selected motor

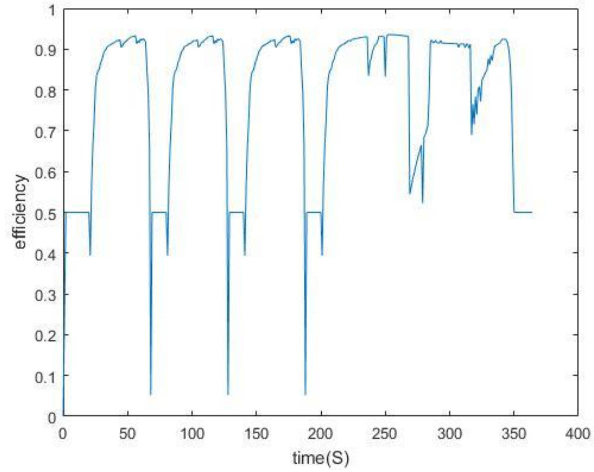

Figure.11. Efficiency of Motor

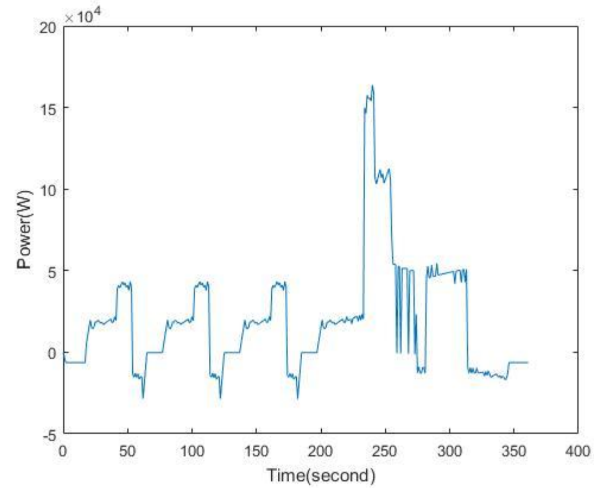

Figure.12. Power of the Motor output

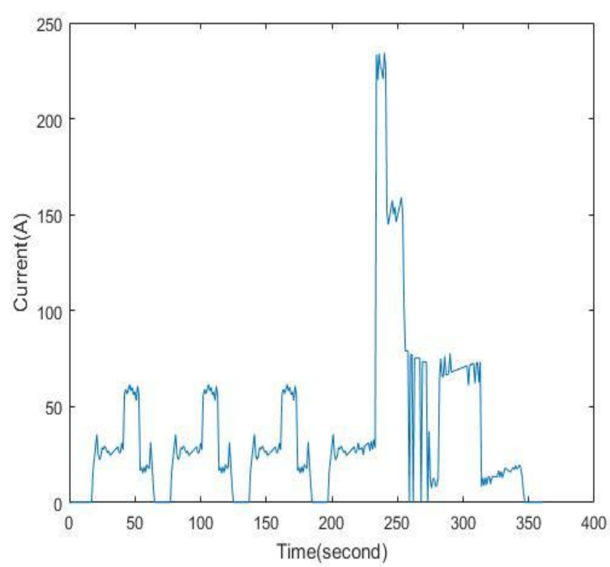

Figure. 13. Current supplied by Battery

In order to minimise the losses within the battery brushless motor without permanent magnet [16] could be adopted and simulated and during regenerative braking the voltage can be kept constant with this motor.

Table.3. Representing the table Nomenclature

NOMENCLATURE			
E	Open Circuit Voltage (V)	F_{rr}	Rolling Resistance Force (N)
N	Number Of Cells	$F_{\omega a}$	Angular acceleration Force (N)
x	Depth Of Discharge	F_{la}	Linear Acceleration Force (N)
C_p	peukert capacity (Ah)	F_{hc}	Force required to climb the slope (N)
T	Time (hours)	n	Number Of Steps
I	Current (amphere)	C_{rr}	Coefficient of Rolling Resistance
R	Internal Resistance		
I	Moment of inertia of the rotor	**Subscripts**	
C_d	Coefficient of discharge	rr	Rolling Resistance
η_g	Efficiency of the Gear	k	Peukert Coefficient
v	Maximum Speed (km/h)	**Greek Symbols**	
F_t	Tractive Force (N)	δt	Time Step (Seconds)
F_{ad}	Aerodynamic Drag Force (N)	ρ	Density (kg/m^3)

4.CONCLUSION

This mathematical model that was built is very useful in the initial design and development process of theelectric vehicle at virtually zero cost. The result shows that this model can perform well on the urban roads with sufficient acceleration and range.Though electric vehicle is completely emission-free its too difficult to adopt in India because of the shortage in energy supply. So alternately Hybrid vehicle with CVT are preferred because of their efficiency[12].So until India has a Stable electricitysupply and battery manufacturers, hybrid vehicle seems to be the best options. MATLAB allows iterating the various parameters until an optimal solution is found and is used to compare between the initial and optimized design. This above simulation gives the basic requirement and performance for designing an electric bus. Further, this mathematical model can be improved by incorporating controllers, considering the heat transfer within the battery and motor, temperature and also estimating the cost.

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