

Modeling and Performance Analysis of an Electric Vehicle with MATLAB/Simulink

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Abstract - Conventional vehicles provide good performance and long range. But due to low fuel economy and exhaust gas emissions causing environmental pollution, interest in electric vehicles is increasing. The range of electric vehicles is short and they cannot reach high speeds. With the development of electric motor and battery technology, longer distance vehicles are being produced. Therefore, performance of these vehicles can be optimized by selecting the motors and batteries depending on the region and the drive cycle. In this study, the dynamic model of an electric vehicle was created with MATLAB/Simulink. The energy consumption values of the electric vehicle and their range were determined for drive cycles such as WLTP, NEDC, and HWFET. The effect of parameters such as battery's voltage and energy capacity, motor's rated torque and power, and gear ratio of the transmission on vehicle performance and energy consumption has been examined.

Key Words : Electric Vehicles; MATLAB/Simulink; Mathematical Modeling; Simulation; Driving Cycles; SOC; Energy efficiency.

1. INTRODUCTION

Thomas Parker developed the first electric car in 1884, 25 years after the invention of lead-acid batteries. After that date, many electric vehicle models appeared. However, the development of internal combustion engine technology and the reduction in mass production costs have left electric vehicles behind.

T. HOFMAN and C.H.DAI studied the effect of different gear-boxes on energy. The powertrain system has been investigated using fixed gear system, manual gearbox and CVT gearbox [1]. E. Schaltz, designed and modeled an electric vehicle. This vehicle consumes 148.3 Wh/km of energy. Also explains that a large part of the energy loss is caused by the auxiliary loads, the lighting system, the security systems, the comfort systems and the battery [2]. X. D. Xue, tried to determine the appropriate electric motor for electric vehicles. Electric motors were compared according to efficiency, cost, safety and weight criteria. The study concludes that the permanent magnet synchronous motor is the best motor type [3]. Mahindra e2o is analytically calculated with the help of its technical specifications [4]. Detailed analytical calculation of EV is demonstrated in literatures [5]. The EV can be designed in

MATLAB®/Simulink® environment based on analytical calculation thereby giving intuitive performance results of the implemented vehicle model [6].

The analytical calculation and simulation model will be developed in this paper. The energy consumption values of the electric vehicle and their range will be determined for drive cycles such as WLTP, NEDC, and HWFET. The effect of parameters such as battery's voltage and energy capacity, motor's rated torque and power, and gear ratio of the transmission on vehicle performance and energy consumption will be examined.

2. MODELING

There are primarily five blocks of models –

- Glider(with vehicle dynamics)
- Driveline/Transmission
- Electric motor
- Battery
- Driver(with PID controller)

Input is the desired drive cycle for the vehicle to follow and is provided to the driver block. This driver block will contain a PID controller to match the current velocity of the vehicle with the desired drive cycle continuously and to minimize the error between desired and actual velocity of the vehicle. Fig 2.1. shows the complete simulink model.

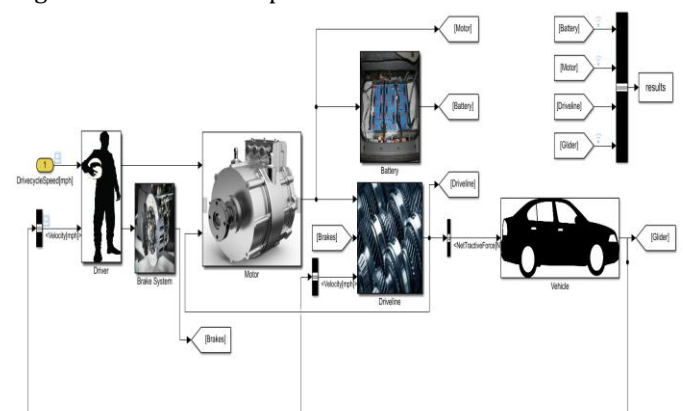


Fig 2.1. Complete simulink model of an Electric Vehicle

2.1 Glider(with Vehicle Dynamics) model

During driving, resistance forces act on the vehicles. Fig 2.2. shows the Vehicle Resistance Forces. These resistance forces are;

- Aerodynamic Resistance
- Tire Rolling Resistance
- Gradient Resistance
- Inertia Resistance

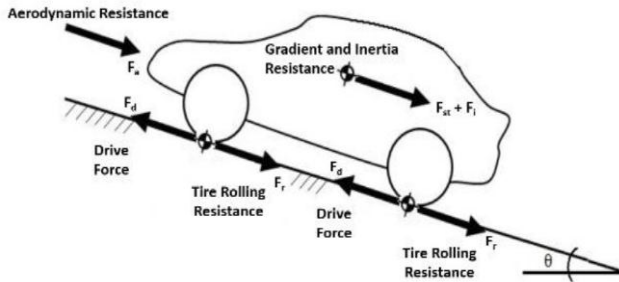


Fig. 2.2. Vehicle Resistance Forces

Table -2.1: General parameters for vehicle dynamics

Parameter [unit]	Symbol
Vehicle mass [Kg]	Mveh
Radius of wheel [m]	Rw
Ratio of gear box	Kg
Frontal are of vehicle [m ²]	Sf
Aerodynamic coefficient	Cd
Rolling resistance coeff.	Vf
Air density [Kg/m ³]	ρ
Grading of the road	α

2.1.1 Aerodynamic Resistance

Opposing force acting on an object moving through a fluid medium. This resistance force is called aerodynamic drag resistance. The aerodynamic drag resistance is calculated as follows;

$$F_{ady} = \frac{1}{2} \rho \cdot C_d \cdot S_f \cdot v_{veh}^2$$

The aerodynamic resistance coefficient is determined experimentally according to vehicle shape and is shown in table 2.2.

Table -2.2: Aerodynamic coefficient for different vehicles

Vehicle Type	Cd
Cabriolet	0.5 - 0.7
Car	0.3 - 0.4
Bus	0.6 - 0.7
Truck	0.8 - 1.5

2.1.2 Tire Rolling Resistance

Due to the elastic structure of the wheel, in front of the wheel contact center, a resistance force against the rotational movement of the tire occurs. The tire rolling resistance is calculated with this equality;

$$F_{roll} = M_{veh} \cdot g \cdot V_f \cdot \cos \alpha$$

Tire rolling resistance coefficient (V_f) varies according to the road surface and is shown in table 2.3.

Table -2.3: Rolling resistance coefficient of surfaces

Road Surface	Vr
Concrete or Asphalt	0.013
Small Gravel Ground	0.02
Macadamized Road	0.025
Soil Road	0.1-0.35

2.1.3 Gradient Resistance

The resistance of the vehicle moving on a sloping road. The gradient resistance appears due to the component of gravity. α expresses the gradient of the path in degrees.

$$F_g = M_{veh} \cdot g \cdot \sin \alpha$$

2.1.4 Inertia Resistance

Newton's II. According to the law of motion, during the acceleration and deceleration of an object, an inertial force is generated in the opposite direction to this motion. This force encountered during positive and negative acceleration of the vehicle is called inertia resistance. This resistance is calculated by this formula;

$$F_{acc} = M_{veh} \frac{dv_{veh}}{dt}$$

Therefore, total tractive force Ft is given by,

$$F_t = F_g + F_{ady} + F_{roll} + F_{acc}$$

$$F_t = M_{veh} \cdot g \cdot \sin \alpha + \frac{1}{2} \rho \cdot C_d \cdot S_f \cdot v_{veh}^2 + M_{veh} \cdot g \cdot V_f \cdot \cos \alpha + M_{veh} \frac{dv_{veh}}{dt}$$

Acceleration of the vehicle is calculated by;

$$A_{veh} = dV_{veh}/dt = [F_t - F_g - F_{ady} - F_{roll}] / M_{veh}$$

Actual velocity of the vehicle is calculated by performing laplace integration of vehicle acceleration which is calculated above.

$$V_{veh} = L^{-1}\{A_{veh}/s\}$$

Fig 2.3. shows the Glider (with vehicle aerodynamics) model.

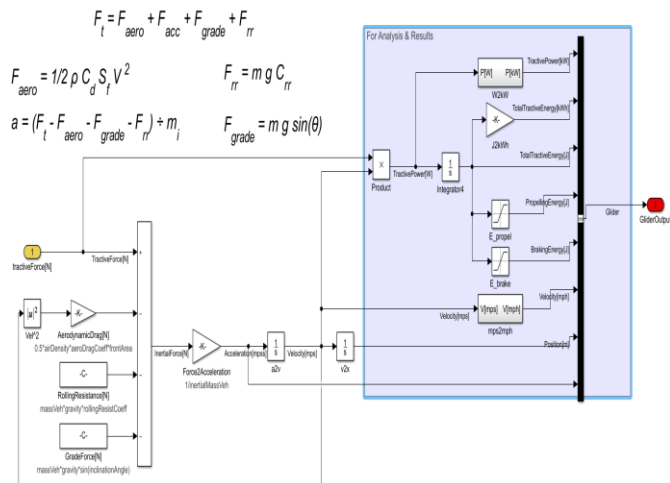


Fig. 2.3. Glider(with vehicle aerodynamics) model

2.2 Driveline/Transmission Model

The total tractive force required at the wheel is provided by the motor through a certain gears. These gears are used to increase/decrease torque and speed produced at the wheel. In this model, gear ratio of 4:1 is used and can be changed by accessing the gear ratio variable in the workspace.

Even spin losses in transmission is considered and modelled, reducing the torque it is transferring from motor to wheel by a certain amount. Another way to model is by considering efficiency of transmission. From the total tractive force required at the wheel, total tractive torque at the wheel is calculated by;

$$T_t = F_t \cdot R_w$$

From vehicle velocity, the angular speed of the wheel or shaft in rpm is calculated by;

$$N_t = 60 \cdot V_{veh} / 2 \cdot \pi \cdot R_w$$

This torque is supposed to be the output of the transmission model having a certain gear ratio K_g . Therefore, torque and produced by the motor which will be input to the transmission model is calculated by;

$$T_m = T_t / K_g \text{ i.e } F_t \cdot R_w / K_g$$

Also angular velocity of the motor in rpm is given by;

$$N_m = N_t \cdot K_g$$

Fig 2.4. shows the Driveline/Transmission model.

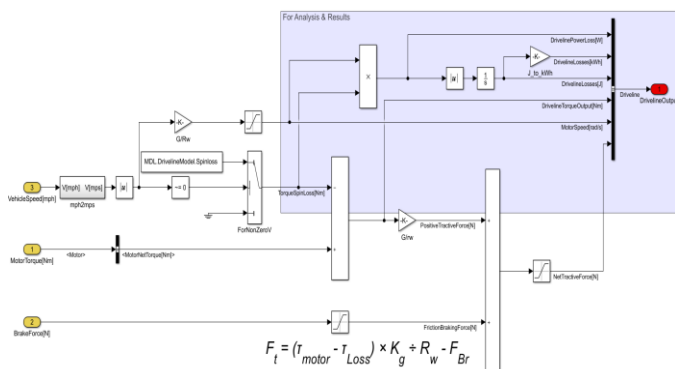


Fig. 4. Driveline/Transmission model

2.3 Electric Motor Model

In electric vehicles, up to now, 4 different electric motors have been used. These electric motors;

- Direct current motor,
- Asynchronous motor,
- Permanent magnet synchronous motor,
- Switched reluctance motor.

As a result of the evaluation, permanent magnet synchronous motor is considered to be suitable for the model. For this reason, technical specifications of the MOTIVE MV255 electric motor of TM4 have been used in our model.

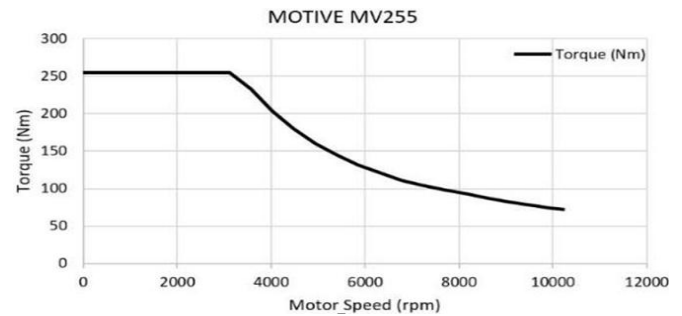


Fig. 2.5. Electric Motor Torque Curve

Using motor output torque T_m and its angular velocity N_m , its output power is calculated by;

$$P_{mo} = 2 \cdot \pi \cdot N_m \cdot T_m / 60$$

The losses in motor can be modelled using a torque-speed-efficiency curve of the motor which will give the efficiency of the motor η_m depending on its torque and speed and the input power can be calculated by;

$$P_{mi} = P_{mo} / \eta_m ; \text{ or losses can be calculated by equation;}$$

$$P_{ML} = k_c \cdot T_m^2 + k_i \cdot \omega + k_\omega \cdot \omega^3 + C$$

Where ω - motor speed in rad/s and K_c, K_i, K_ω, C are constants. And input power to the motor is given by;

$$P_{mi} = P_{mo} + P_{ML}$$

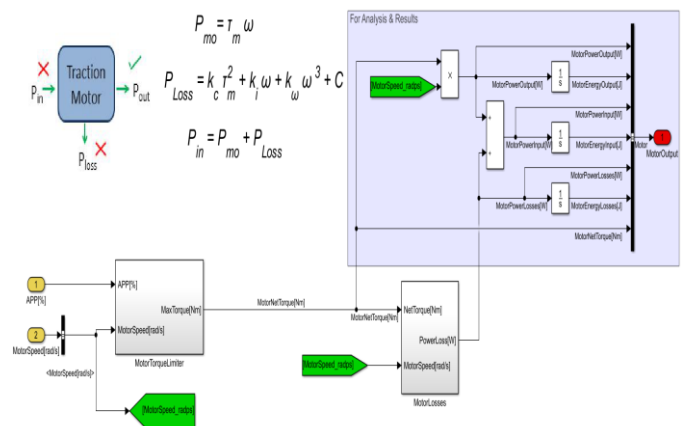


Fig. 2.6. Electric motor model

2.4 Battery Model

Different types of batteries shown in fig 2.7 are analyzed and compared before selecting the preferred one.

Name	Value for Battery Type				Unit
	Li-Ion	Na-NiCl ₂	Ni-MH	Li-S	
Maximum Charge	75	84	85	80	Ah
Nominal Voltage	323	289	288	305	V
Stored Energy	24.2	24.2	24.2	24.2	kWh
Maximum Voltage / Minimum Voltage	339 / 308	275 / 304	274 / 302	290 / 320	V
Initial Charge	100	100	100	100	%
Number of Cells per Cell-Row	12	12	20	26	-
Number of Cell-Row	17	30	20	1	-
Internal Resistance charge/discharge	1/1	1/1	1/1	1/1	Ω
Operating Temperature	33	270	36	30	°C
Specific Heat Transition	0.4	6	0.4	0.08	W/K
Specific Heat Capacity	795	950	677	1650	J/kg*K
Mass of Battery	318	457	534	173	kg
Battery Price	300	500	400	250	€

Fig. 2.7. General parameters of electric battery

Na-NiCl₂ batteries have proved to be the best alternative from the standpoint of energy consumption (12.6 kWh/100 km). Besides that, its low price, improved lifecycle or great functioning under normal conditions in harsh environments are other significant advantages. One downside of these batteries is elevated operating temperature, which allows the electrolyte battery to solidify while the vehicle is not being used. Therefore, an external device that maintains the operating temperature of the battery under functional parameters is required.

According to studies, it has been observed that the highest energy consumption (17.2 kWh/100 km) is accomplished by Li-S batteries. However, due to their low weight, improved capacity for energy storage and low price compared to other battery technologies, they may be one of the best options for systems with high capacity for energy storage.

Ni-MH batteries, despite having a reasonable energy consumption, (15.7 kWh/100 km) they are inefficient, having an increased energy density and power, heavy weight as well as an outdated technology.

Nowadays, Li-Ion batteries have the largest share of electric vehicle equipment market. Moderate energy consumption (14.7 kWh/100 km), continuous decline of the cost price, advanced manufacturing technology, increased cycle life, low weight and high energy storage potential make Li-Ion batteries an optimal choice in this field. Their drawback is reflected by high working temperatures, which can adversely affect their energy efficiency and lifecycle. All these represent risks regarding safe exploitation of the vehicle.

After analyzing and comparing the above types of batteries, we'll be using specifications of Li-ion battery in the study. The battery power output provided to the motor P_{mi}, which is calculated above is added with an assumed constant auxiliary consumption of 600 W which constitutes to the actual battery output power P. The battery open circuit voltage Voc and internal resistance R are assumed to be non-

varying throughout the simulation. The battery current is calculated by using equation;

$$I = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4RP}}{2R}$$

Losses in battery is calculated with the help of the battery current and is given by;

$$P_{bi} = I^2 \cdot R$$

Total internal power output of the battery is given by;

$$P_i = I \cdot V_{oc}$$

By integrating the above internal power output P_i, Energy output is calculated and by subtracting it with stored energy, the current state of charge (SOC) of the battery is calculated. The simulation is made to halt when SOC depletes below 5%. Fig 2.8. shows the Battery model.

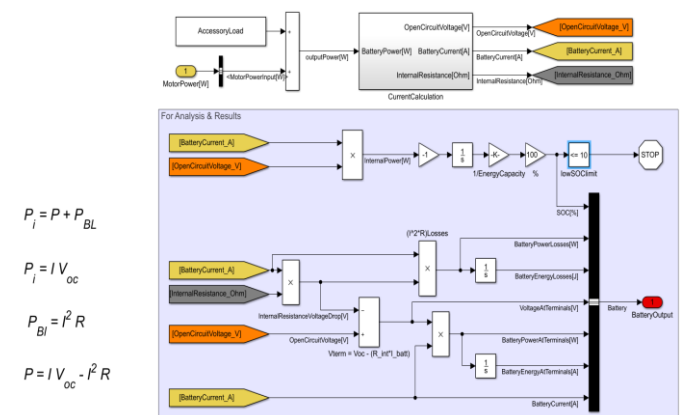


Fig. 2.8. Battery model

2.5 Driver(with PID Controller) Model

The PID controller equals the vehicle speed to the cycle speed. The PID controller outputs between -1 and 1. Positions -1 to 0 indicate braking, 0 to 1 controls the gas pedal. Fig 2.9. shows the Driver(with PID Controller) model.

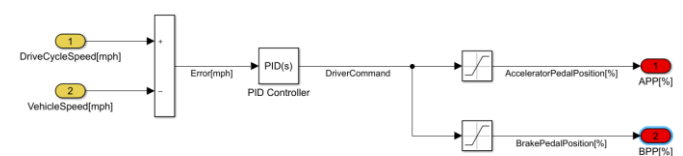


Fig. 2.9. Driver(with PID Controller) Model

3. RESULT

General parameters used in the simulation are shown below;

Battery –

- Voltage : 340V
- Energy capacity : 40KWh
- Initial SOC : 95%
- Min. SOC to stop the vehicle : 5%

Transmission –
Gear ratio 4:1

Motor –

Torque rating : 320Nm

Power rating : 100KW

Drive cycle used to compare effect of parameters : WLTP. And some general parameter values required for calculation of vehicle dynamics.

Performance analysis of the vehicle for different drive cycles are carried out.

WLTP drive cycle

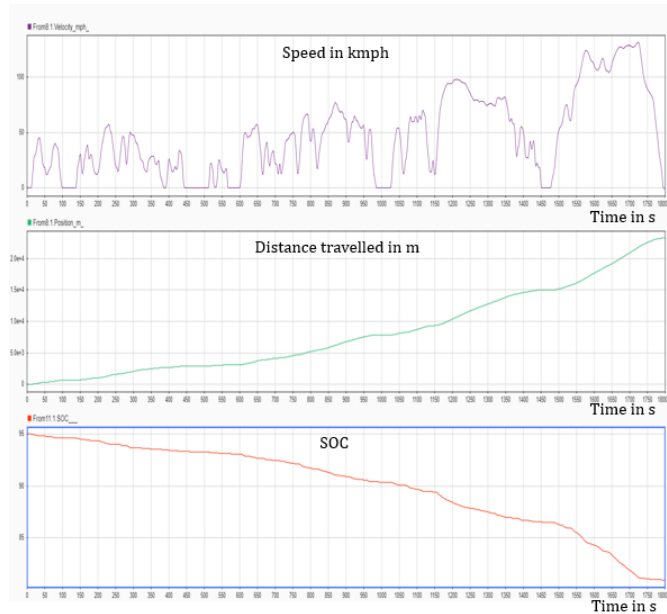


Fig. 3.1. WLTP Results

As shown in fig 3.1, in WLTP Drive cycle, which has a maximum speed of 132km/h, the vehicle travels 23.25km in 30min and SOC of its battery reduces to 81% from the initial 95%(i.e consumption of 14%). So, it can be observed that the vehicle consumes 240Wh/km and has a range of 150km.

NEDC drive cycle

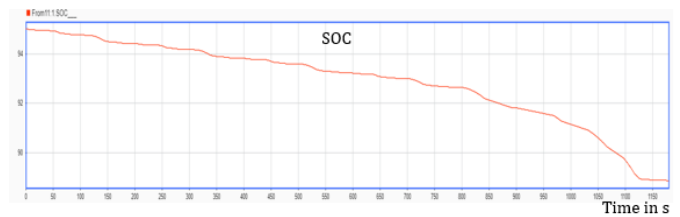
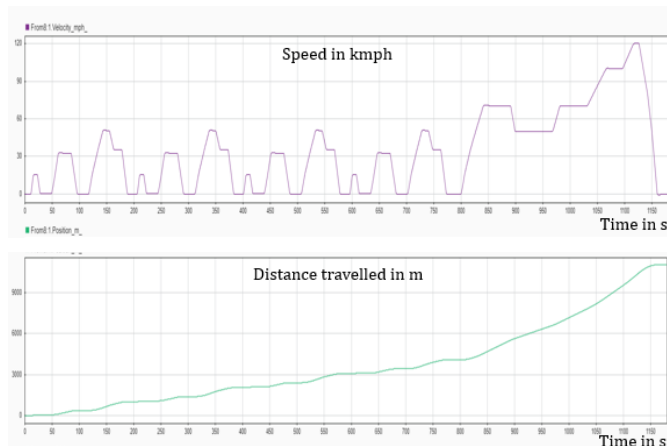


Fig. 3.2. NEDC Results

As shown in fig 3.2, in NEDC Drive cycle, which has a maximum speed of 120km/h, the vehicle travels 11km in 20min and SOC of its battery reduces to 89% from the initial 95%(i.e consumption of 6%). So, it can be observed that the vehicle consumes 218Wh/km and has a range of 165km.

HWFET drive cycle

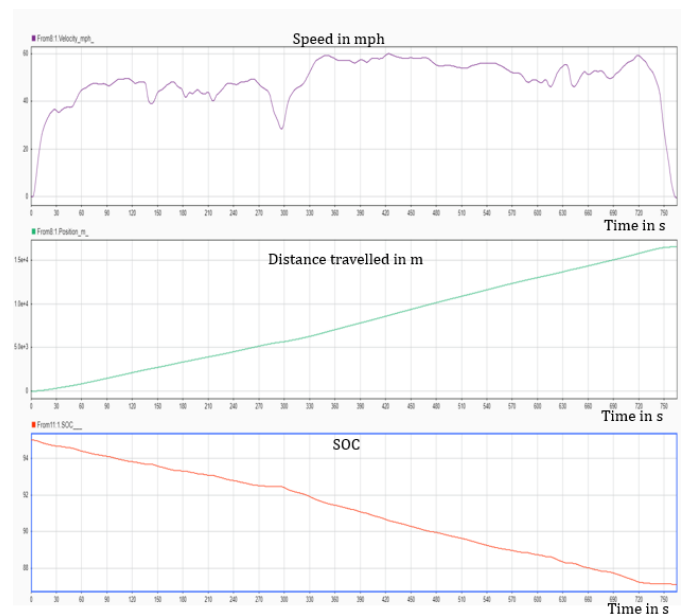


Fig. 3.3. HWFET Results

As shown in fig 3.3, in HWFET Drive cycle, which has a maximum speed of 60mph, the vehicle travels 16.5km in 13min and SOC of its battery reduces to 87% from the initial 95%(i.e consumption of 8%). So, it can be observed that the vehicle consumes 194Wh/km and has a range of 185km.

Effect of certain parameters on performance of the vehicle is analyzed below;

3.1 Driveline/Transmission

Analysis of effect of gear ratio on the performance and status of the vehicle is done.

3.1.1 Gear ratio

■ 4:1 vs 8:1 ■

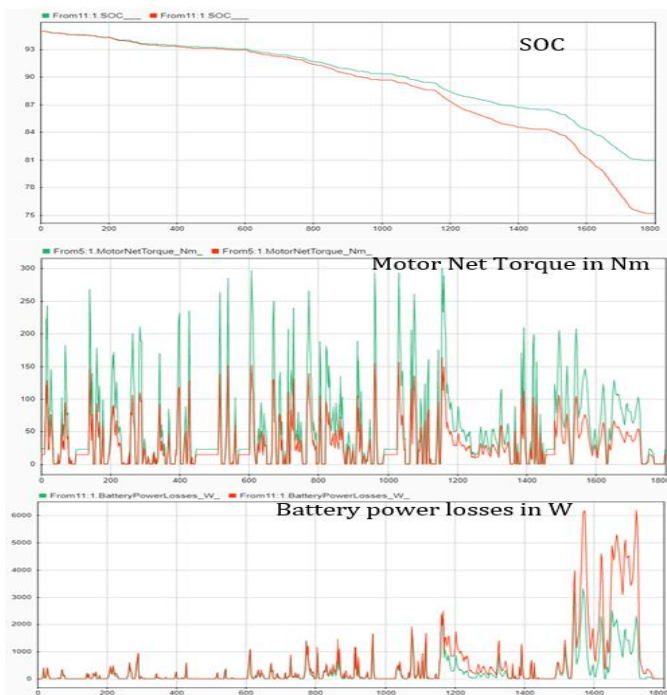


Fig. 3.4. SOC, Motor Net Torque and Battery Power losses

Observation – As shown in fig 3.4 with gear ratio of 8:1, SOC of the battery depletes to 75%, and maximum motor torque required is 160Nm. Whereas with gear ratio of 4:1, SOC of the battery depletes to 81%, and maximum motor torque required is 300Nm. With higher gear ratio in differential, the torque which is required from the motor to follow the given drive cycle reduces, enabling the vehicle to go for higher accelerations. But it increases the battery current and correspondingly losses too. And also SOC of the battery depletes faster. Therefore, with a higher gear ratio electric motor with smaller rated torque can be used which will cut some expense but since the SOC of the battery depletes faster, a battery with higher energy capacity will be required which will increase expenses. Therefore, for short and fast drives, higher gear ratio in transmission is chosen and for long and moderate drives, lower gear ratio in transmission is preferred.

3.2 Electric motor

Analysis of effect of maximum torque of the motor and its power rating on the performance of the vehicle is looked into.

3.2.1 Torque

■ 340Nm vs 100Nm ■

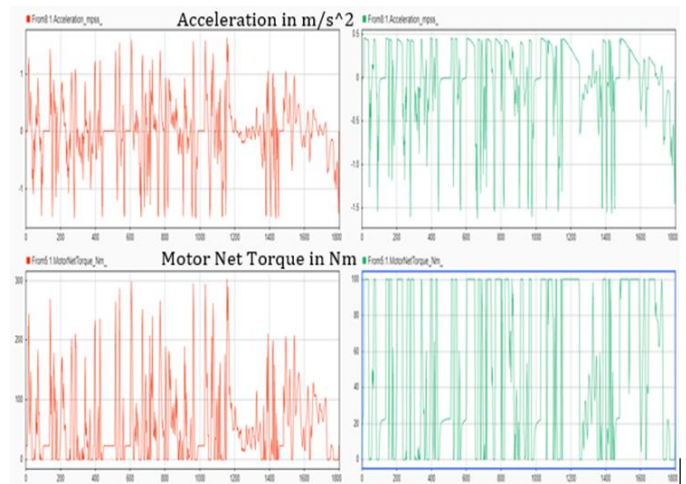
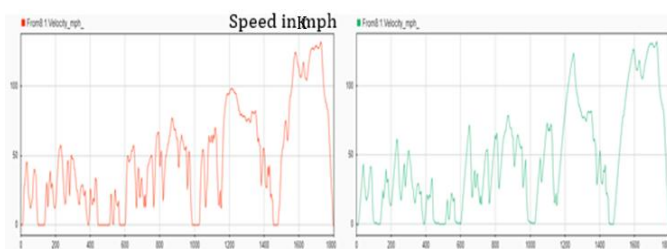


Fig. 3.5. Speed and Acceleration of the vehicle and Motor Net Torque

Observation - As shown in fig 3.5 electric motor with low maximum torque cannot provide high accelerations. Here, it is observed that the motor with max. torque of 100Nm can provide upto only 0.5m/s² as it reaches its max. torque of 100Nm. Whereas, the motor with max. torque of 340Nm is providing the maximum acceleration required in this drive cycle which is 1.5m/s² operating at the torque of 300Nm. Therefore, for good accelerations, motor with high maximum torque is chosen which will certainly increase the expense and for moderate accelerations, motor with low maximum torque is preferred which will lower the expenses.

3.2.2 Maximum Power

■ 100KW vs 30KW ■



Fig. 3.6. Speed of the vehicle and Motor Power Output

Observation – As shown in fig 3.6 electric motors with low power rating is unable to provide good accelerations at high speeds. The power $P = T \cdot W$. So, at higher speeds motor will be rotating at a high rpm. At the point of operation at maximum power, if the vehicle is at high speed, the torque which it can produce will be low. Hence, the result of poor

acceleration at higher speed for the motor with low power rating. Therefore, for good accelerations at high speeds, a motor with high power rating is chosen which will cost more and for vehicles driven in moderate velocity, a motor with low power rating is preferred which will cost less.

3.3 Battery

Analysis of effect of battery voltage and its energy capacity on the performance of the vehicle is understood.

3.3.1 Voltage

340V vs 200V

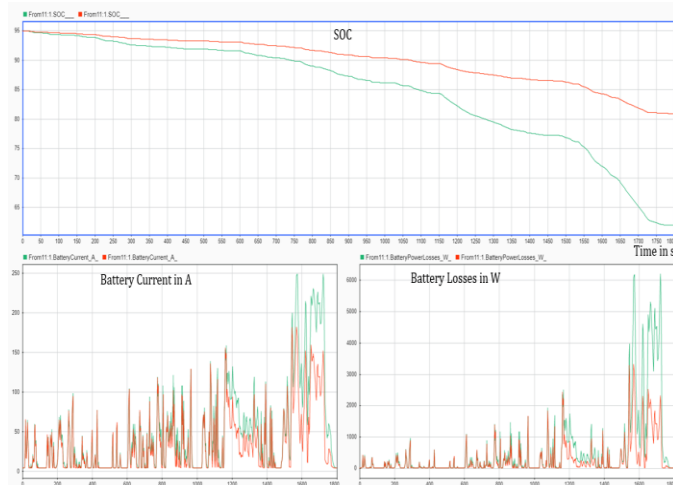


Fig. 3.6. Battery SOC, current and losses

Observation – Considering that both have identical energy capacity, as shown in fig 3.7 it can be observed that the battery with low voltage will provide a higher current discharge which will in turn deplete the SOC of the battery faster and increase the losses. Here battery with open circuit voltage of 200V, depletes SOC of the battery to 62%, whereas battery with open circuit voltage of 340V, depletes SOC of the battery to 81%. Therefore, a battery with higher voltage is preferred to maintain a moderate battery current and reduce losses.

3.3.2 Energy capacity

40KWh vs 24KWh

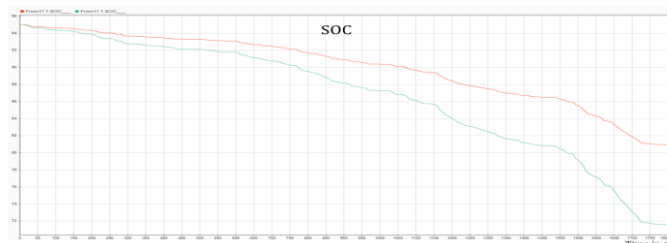


Fig. 3.6. SOC of the battery

Observation – As shown in fig 3.8 battery with higher energy capacity will last for more time as its depletion of SOC is slower. Here the SOC of the battery with energy capacity of 24KWh depletes to 72%, whereas SOC of the battery with energy capacity of 40KWh depletes to 81%. This is purely

because that it is storing more energy and can discharge for a long time and a battery with low energy capacity cannot as it gets depleted faster.

4. CONCLUSIONS

Step-by-step analytical calculation of Electric Vehicle (EV) was presented in this paper. Based on the analytical calculation, EV was modeled in MATLAB®/Simulink® environment. The simulation results are summarized. These observations can be utilized to improve the range of EV. This paper was started with the explanation of vehicle terminology and its analytical calculation. Based on the analytical calculation, step-by-step approach was shown to develop various simulation model blocks such as aerodynamic model, gear box, motor model and battery model. The simulation results in terms of EV range and Battery State of Charge (SOC) were presented for Worldwide Harmonised Light Vehicles Test Procedure cycle (WLTP), New European Driving Cycle (NEDC), and Highway Fuel Economy Test cycle (HWFET) inputs. After that, the effects of various parameters on vehicle performance was analyzed. This paper was intended to be a ready reference for basic calculations and simulation of EV model. The results of analytical calculation and simulation are in close proximity with the data provided by the manufacturer of the vehicle.

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