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Research Article

Mathematical Modelling and Simulation of Battery Electric Vehicle Based on Backward-Facing Approach Technique

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Abstract: Proper and valid simulation of the Battery Electric Vehicle (BEV) is a preliminary step before proceeding to any extensive research for enhancing the BEV performance. Therefore, this study proposed with explanation the simulation of the main components of the BEV along with different validation tests. The proposed model is designed based on the actual components' parameters using MATLAB-Simulink and ADVISOR tool. The vehicle is configured according to backward facing model and the design incorporates the technical specifications of a Malaysia local car, PROTON IRIZ (BEV). It is important to measure the model performance of BEV along with the main measure, which is the State of Charge (SoC), battery voltage, and driving cycles. For benchmarking the results are compared with different design proposed in the literature based on studies that uses New European Driving Cycle (NEDC), Urban Dynamometer Driving Schedule (UDDS) and Japanese 10-15 Mode Driving Cycle (Japan 10-15).The result from the simulated design in MATLAB shows a valid result compared to the declared specifications of the PROTON IRIZ BEV vehicle. For instance, the results NEDC test revealed that the driving range has SoC 31884 seconds (298 Km), which is comparable to the PROTON IRIZ full range of 300 Km. This study presents a foundation support for further study in BEV.

Keywords: Battery Electric Vehicle, backward facing model,driving cycles; state of charge; battery voltages

1. Introduction

Electric Vehicles (EVs) are one of many results of the technological development that is trying to make the life easier and safer. EVs do not only consume energy, but they also produce, store, and transport electricity. For this reason, they look like a great alternative of the fuel vehicles. Furthermore, they are eco-friendly as they don't need neither gasoline nor diesel fuel as they have a reversible energy storage device (Cheng et al., 2016) In order to reduce emissions, powertrain size optimisation based on profile of usage and the kind of the vehicle is considered to be useful. For this objective, backward facing powertrain models that consist of scalable powertrain components, have been used (Ikram et al., 2015).The driver model is not needed for the backward-facing model and from a given drive cycle the vehicle speed could be traced. Upon the vehicle model, the speed trace is enjoined with a view to calculate the angular velocity and torque at the wheels. Therefore, the angular velocity and torque at the Electric Motor are specified as "backwards" using maps or efficiency models through each component of the drivetrain(Zhou, 2008). According to a previous study, the researchers are aiming to optimize the basic design parameters of hybrid electric vehicle drivetrain components, a backward-facing approach has been used. That is a way to minimize fuel consumption and emission objectives, alongside with performance requirements' constraints (Özden, 2013).In this research, the components of the Battery Electric Vehicle (BEV) system were simulated mathematically based on Backward-Facing Approach Technique by using the MATLAB software. In Addition, the successful integration between the components is simulated in the SIMULINK environment of the MATLAB. Moreover, it has been used the technical specifications of the Proton IRIZ BEV (Mohd et al, 2017). For testing and validating the model, four driving cycles were used to measure State of Charge (SoC), Battery Voltage, and Driving Cycles. Modelling and simulating the BEV is an essential and preliminary step for any optimization. Therefore, this study proposed a model of the BEV car with a commonly used configuration and tests the model in different driving cycles. The proposed model will be used in further research to examine different techniques for optimizing the energy use and can be used in many different optimizing approaches.

2.Backward-facing Approach Technique

In order to model aBEV, two ways are established to do the simulation named backward-facing model and forward-facingmodel (Lomonova et al., 2015). As shown in Figure 1, the backward facing model with limited forward-facing capabilities were used.According to Mohan et al. (2013), the backward-facing approach assumes that required criteria are met by the vehicle and so calculates the need of each component to reach the wanted performance. Backward-facing models that contain scalable powertrain mechanisms are usually used for reducing emissions. Another characteristic of the Backward-facing model is that it does not require a driver model, and the speed trace of the vehicle is attained from a specified drive cycle (Williamson, 2013).Compared to forward-facing models, these models additionally keep up a reasonably larger time step, leading to a faster simulation time. A purely backward-facing simulation propagates a high-level requirement. An observation of the simulation time of backward-facing models was done to be an order of magnitude faster than forward-facing models. One of the key advantages of using a “backward model’ is receiving a quicker response when using a simpler model (Gupta, 2017; Jungers, 2009). The backward-facing approach is convenient because of the following factors:

- The testing and assessment of the components of automotive drivetrain usually take place in a lab setting, for example, table of performance or development of result speed vs loss. This indicates that an estimate can easily identify an element's effectiveness as well as make it possible for the computation to advance.
- The attribute of the efficiency/loss estimation makes the use of a simple routine possible along with a larger time step on the order. Hence, the execution of simulation via the "backward-facing" approach can be faster.

In addition, in the calculations of backward-facing, there is no need for driver behavior. The consumer has to input the steering design and a rate account, recognized as the speed track. The power needed to accelerate the vehicle is actually worked out and translated into torque (Yuan et al., 2020). This operation is actually redone at each phase from the vehicle or roadway user interface with the transmission, drivetrain, and so on, up until the electricity make use of is determined. Backward-facing models can pass torque, speed, and power requirements of the drivetrain, as seen in Figure 1 (Mohan et al., 2013).

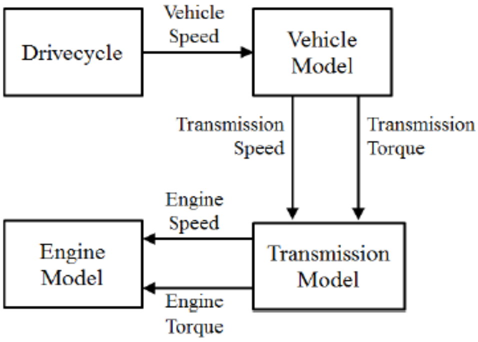


Figure. 1 Backward-facing model(Mohan et al., 2013)

3.Mathematical Modelling of BEV

In this study, the simulation model involved five components, namely, the driving cycle, the electric motor model, the transmission model, the battery charge controller model with DC-DC converter, and the longitudinal vehicle dynamics model, as shown in Figure 2.

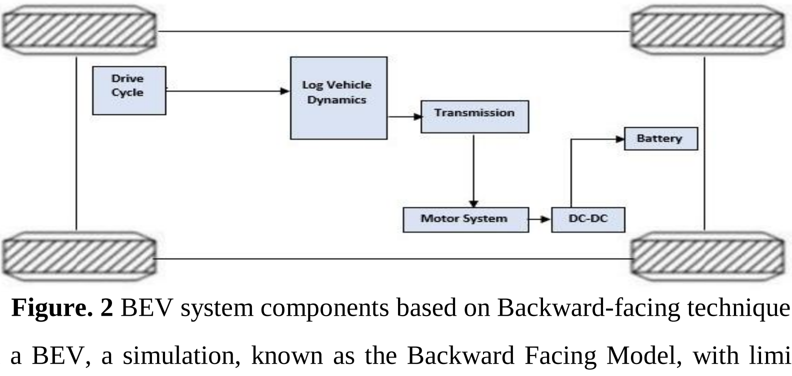


Figure. 2 BEV system components based on Backward-facing technique

In order to model a BEV, a simulation, known as the Backward Facing Model, with limited forward-facing capabilities, was used. This model does not require driver behavior in its backward-facing calculations. The user only has to input the driving pattern, and a velocity profile called the speed trace.

3.1Transmission Model System

The transmission model is the simulation of the gearbox model, and the final drive model. The transmission system contains a transmission and differential of the vehicle, which are connected in between the wheels and propulsion system (Markel et al., 2002). In the identical configuration, the fuel intake value,optimum speed, and velocity scores are extremely influenced by the equipment and final drive ratios.In this model, three results of the transmission system on the torque and speed of the vehicle were consisted of torque multiplication and speed reduction according to the current equipment ratio, torque loss as a result of the velocity of rotational inertia and torque loss because of rubbing. The proportions, loss tables, and various other criteria, such as inertia, were provided as information documents. The torque formula of the transmission system is as shown by the following equation:

$$T_{r,in} = \left(\frac{T_{r,out}}{i_{gear}}\right) + T_{inertia} + T_{gb,loss} \qquad (1)$$

where$T_{inertia}$ = $I_{gb,Inertia}$ (dw_{gb}/dt);$T_{r,in}$=torque required at the input side of the gearbox;$T_{r,out}$=gearbox output torque required;i_{gear}=gearbox current ratio;$T_{gb,loss}$=($T_{r,out}$, $w_{gb,out}$, i_{gear}) = gearbox torque loss;w_{gb}= gearbox speed; and$I_{gb,Inertia}$=gearbox inertia.

The final drive ratio will directly relate to the transmission ratio, therefore, the differential proportion is directly taken as "1". However, differential losses and inertial effects were not included in this model.The 1-Speed transmission ratio will certainly be straight-identified according to vehicle specs. Given that it was designed for the series drivetrain, the proportion can be calculated from the optimum speed offered by the electric motor, as revealed in the following equation.

$$Y_{ear} = \left(\frac{W_{em,max} \times Wheel \times 1.1}{190 \times 0.278}\right) \qquad (2)$$

where$W_{em,max}$=maximum electric motor speed (rad/s); andY_{ear}=desired gearbox ratio.The 190 indicates the maximum speed of 190 kph, and 1.1 is used to include a 10% tire slip condition.

The final drive block can send torque and speed demands from the wheel and axle to the transmission or whatever literally inputs torque to the final drive. It can also transmit actual torque and speed from the gearbox back to the wheel and axle'The last drive model has actually included the effects of losses, inertia, and gear proportion in both the 'request' and 'actual' data circulation courses, while torque loss was assumed to be constant. The gear ratio can decrease the speed input by the gearbox or whatever various other input raises the torque and exists. Inertia was measured, and losses were used at the input side of the gear decrease (Rill & Castro, 2020)**.**

3.2 Electric Motor

The electric motor model will certainly compute the torque and speed capacity at the operating factor by utilizing lookup tables, which are indexed by electric motor speed. The calculation will additionally include the loss as a lookup table, wherein the speed, torque, and inertia can affect the index. The electric motor's optimum torque is established making use of a lookup table indexed by current speed. The electric motor control blocks at the exterior of the block will check for the maximum current and make certain that it is not surpassed (Varatharajan et al., 2020). The output power calculation can be simply shown as the following equations

$$P_{m,req} = P_{m,out} + P_{m,loss}\left(P_{m,out}\, , W_m\right) \qquad (3)$$

$$P_{m,req} = \left(T_{m,out}\, , T_{m,intertia}\right) \times W_m \qquad (4)$$

$$T_{m,intertia} = I_{m,intertia} \times \left(\frac{dW_m}{d_t}\right) \qquad (5)$$

Where$P_{m,req}$=motor power required at electrical side; $P_{m,out}$=motor power output, $P_{m,loss}$=motor power loss (function of motor torque and speed);$T_{m,out}$=motor torque output;$T_{m,req}$=motor torque required; $T_{m,intertia}$= motor torque needed due to inertial effect; and $I_{m,intertia}$=motor inertia.

3.3Energy Storage System (Battery System) includes a DC-DC Converter

The Energy Storage System (ESS) block embodies the battery pack that outlets electricity onboard the modeled vehicle (Wipke et al., 2000). This block takes a power request, usually from the power bus, and comes back the available/actual power result from the battery, the battery voltage and current, and the battery SoC. By convention, good power will definitely be actually discharged.The energy storage system includes the two sub-models, the battery model and D.C. to D.C. converter. The optimal power that the battery could provide is actually calculated due to the battery's operating voltage, which is actually compared to its own minimum voltage, the electric motor's minimum voltage, or even $V_{oc}/2$ value. When the operating voltage declines, either one of these circumstances confines the optimal power provided to the device.The maximum power limit can be actually worked out by making use of the following equation:

(6)

(7)

$$P = V_{bus} \times \frac{(V_{oc} - V_{bus})}{R} \qquad (6)$$

where V_{bus} is either $V_{oc}/2$, the minimum motor controller voltage, or the minimum battery voltage, whichever is larger.

The efficient SoC of the battery can easily be determined using the calculated current. While carrying out the calculation, the model uses Columbia performances and optimal capability values, which are functions of temperature, to calculate the recurring battery ability in systems of ampere-hours (Ah). SoC estimation is actually helped make depending on the following equation.

$$SoC = \frac{\left(Ah_{mx\ capacity} - Ah_{used\ capacity}\right)}{Ah_{mx\ capacity}} \qquad (7)$$

According to Raghunathan et al. (2005), a DC-to-DC converter is actually an electronic circuit or even electromechanical unit that transforms a resource of straight current (D.C.) coming from one voltage level to one more. It is actually a form of an electric power converter and one of the bulks of Electric Vehicles (EVs).When the outcome voltage is lower than the input voltage, the DC-to-DC converters offer a technique to improve the voltage coming from a partially lowered battery voltage, consequently saving room rather than utilizing multiple electric batteries to complete the same thing. The majority of DC-to-DC converter circuits likewise moderate the output voltage.Through adjusting the volume of power saved in the inductor to the quantity of power dissipated in the weight, it is actually possible to determine the resulting voltage of the boost converter.

3.4Longitudinal Vehicle Dynamic Model

The longitudinal vehicle dynamic model is essential because it simulates the dynamic behavior of the car and includes a model for the vehicle, driveline converter, and wheel/axle (Rill & Castro, 2020).According to Markel et al. (2002),calculations in the 'vehicle' block are an agent of the force equilibrium at the tire patch. Offered a speed needed at the end of the moment step, the tractive force and the required speed balanced over the time action are requested of the wheel. Furthermore, offered an offered tractive force and speed limitation, the actual/achieved speed is calculated.This model can calculate the required velocity pressures, including the forces to get rid of resistances (quality, rolling, and air) and inertial impacts at the desired speed, as defined in the drive cycle data. It uses basic vehicle longitudinal characteristics equations. The ordinary speed is computed over both successive time actions, which is taken as the average speed at the beginning of the time action to compute the pressures and the speed needed at the end of the moment step.

The basic dynamical equation consists of quality, air, and rolling resistance. The inertial results and the resultant pressures on the vehicle are received in Figure 3. As shown in the figure, rolling resistances are calculated for each and every axle, which is comparable to grip pressures in simulations. Air resistance and velocity results on lots circulation are additionally included. On the various other hands, the initial power sizing process uses a simpler vehicle model, which thinks all pressures are used at the vehicle's facility of gravity, while the lots circulation effects are ruled out.

$$M_v \frac{dv}{dt} = \frac{\left(F_{tf} - F_{tr}\right)}{F_t} - \left(\frac{F_{vf} + F_{rr}}{F_t} + F_a + F_g\right) / F_{res} \qquad (8)$$

whereF_t=traction forces, F_{res}=resistive forces, F_{tf}=front axle traction forces, F_{tr}=rear axle traction forces, F_{rf}=front axle rolling resistance forces, F_{rr}=rear axle rolling resistance forces, F_a =air resistance forces, $F_a = 0.5\ \rho\ \text{air}\ C_d\ A_f\ V^2$, F_g=grade resistance forces;$F_g = M_v\ g\ \sin(a)$, F_r =rolling resistance forces; $F_r = (a + bV)/F_r M_v g$.

Markel et al. (2002)reported that the wheel and axle model is similar to various other blocks, where it functions with two input and output ports. It transmits the torque and speed asked for from the vehicle block and the offered torque and speed from the final drive and feeds them back to the tire as a propulsion torque at the current speed. The wheel and axle model consists of the losses in the axle bearings, specifically, the wheel and axle inertia, and the tire slip by making use of lookup tables indexed by speed and torque request. The action of braking as a circulation of front and back brakes, and the regenerative (driveline) and rubbing stopping are additionally established. The grip control block manages the limitations of the torque transferred to wheels during braking and grip.The formulas for the stopping method might be methodically composed as adheres to the following equations.

$$BF_{ffb} = \frac{BF_{fb} \times F_{ffb}}{1 - F_d} \qquad (9)$$

$$BF_{rfb} = \frac{BF_{fb} - BF_{ffb}}{1 - F_d} \qquad (10)$$

Where BF_{ffb}isbraking force required at tire patch from front friction brakes, $BF_{rfb}$is braking force required at tire patch from rear friction brakes, BF_{fb}isbraking force required from all friction brakes, BF_{ffb}isfraction of braking supposed to be done by front friction brakes, $F_d$isfraction of braking supposed to be done by driveline, unlessF_d = 1; whenever BF_{ffb} =0.6

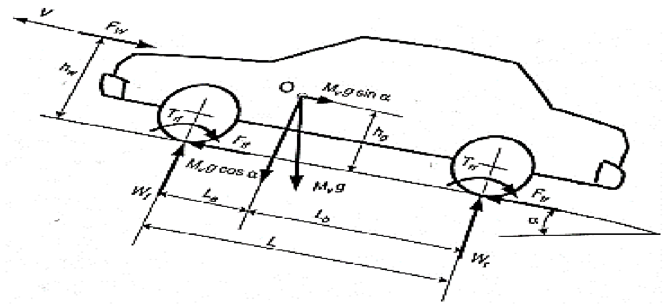
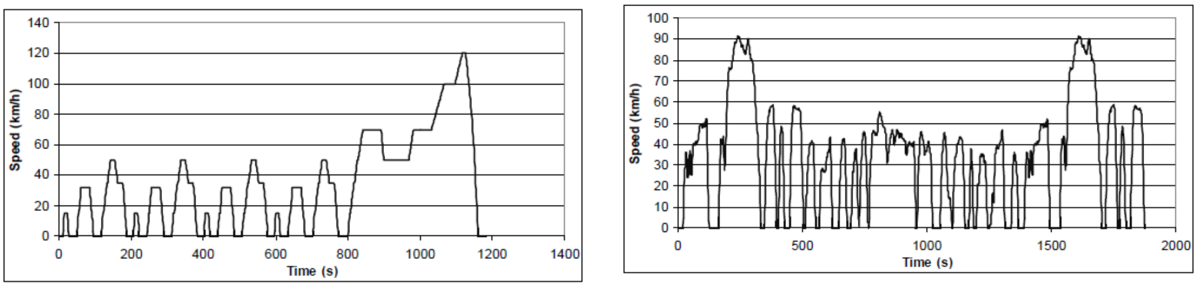


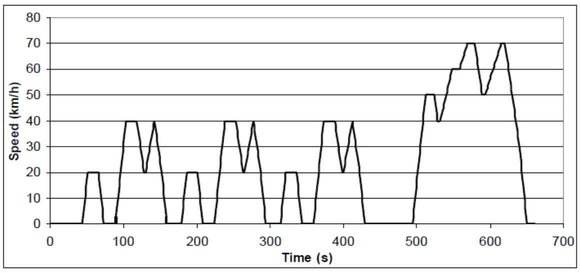
Figure.3 Forces acting on a vehicle acceleration up a slope

4. Driving Cycle

The driving cycle is a series of information points standing for the speed of a vehicle versus time. Various nations and organizations generate driving cycles to evaluate the efficiency of cars in numerous ways, for an example, gas usage and contaminating discharges, as displayed in Figure 4. The driving cycles are for all automobile kinds inside cities or outdoors cities (highways). The driving cycle is composed of standard data easily available in ADVISOR and is dealt with as a 2-D lookup table indexed by speed and time (Kumar & Thakura, 2020).



NEDC UDDS



JP10-15

Figure 4. Driving cycles

The layout restrictions established on the drivetrain, such as the initial velocity-time, the value of traveling at ranked vehicle speed, and the worth of traveling at optimum vehicle speed, can influence the specs of the induction motor. The tractive pressure required to push the vehicle right into the selected drive cycle provides the needed electric motor specifications used in the drivetrain (Sun *et al.*, 2020). Table 1 shows a comparison between the different driving cycles in terms of distance, duration, average speed, and maximum speed. The proceeding subsections contain comprehensive data for the four driving cycles.

Table.1. Summary of drive cycles

No	Cycle Name	Uses	Distance (km)	Duration (s)	Average Speed (km/h)	Max Speed (km/h)
1	NEDC	Small Car	10.9314	1180	33.35	120
2	UDDS	Small Car	17.77	1877	34.12	91.25
3	JP-10-15	Small Car	4.16	660	22.7	70.09

5. Battery Electric Vehicle’s Technical Specifications

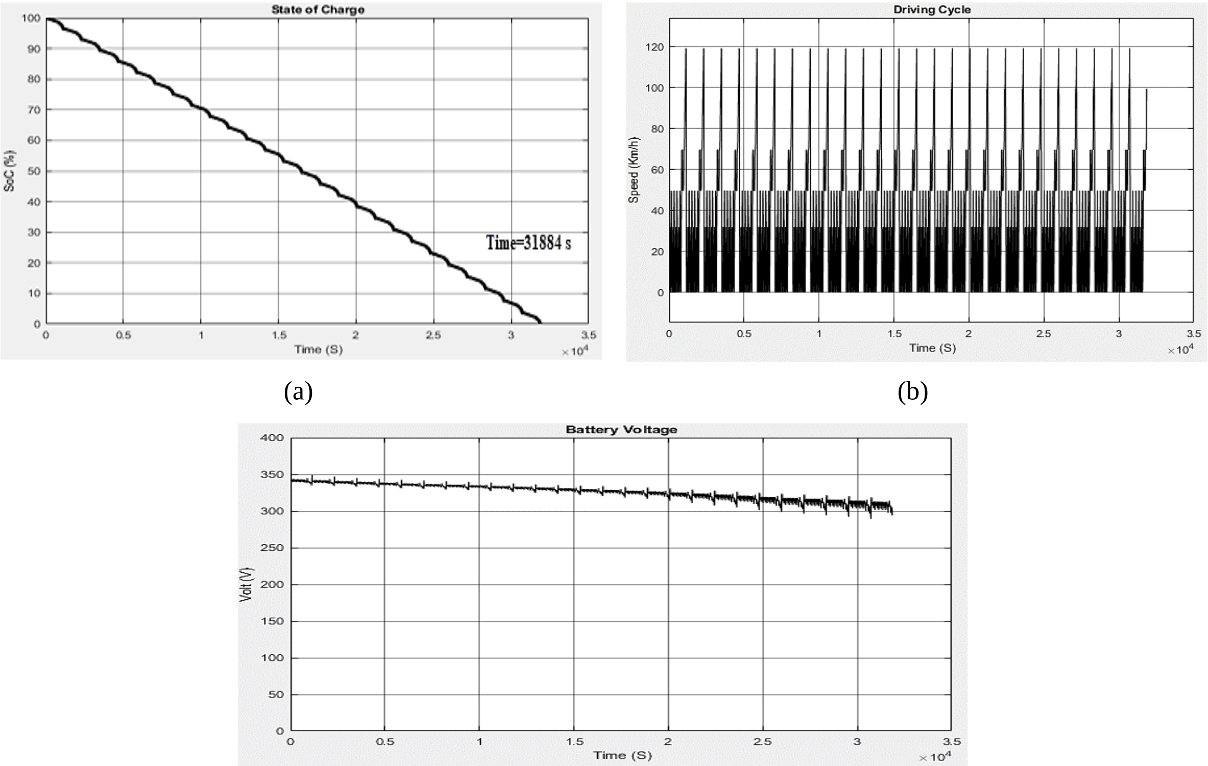
For this particular study, the simulation will be based on the Proton-LG IRIS Vehicle specification. The following will discuss the specification of this model from the electrical and mechanical point of view, the Simulink model diagram for the whole vehicle without auxiliary load and the whole vehicle with the auxiliary load.Each kind of vehicle possesses its detailed power criteria. Some call for a rapid charging treatment, while others can easily go long proximities in between charges, yet a usual attribute is actually the lengthiest battery life span. The battery is affected by various factors, like temperature, depth of ejection, and the operating current. This study has actually included battery criteria that need to be actually considered throughout the style of the battery for a particular use. This is especially essential because the batteries are certainly not correctly matched and can easily be put on too soon, causing added expenses. The procedure of picking the right cell kind needs to think about the previously discussed components and operating features of the vehicle. Choosing proper battery operating specifications is essential as a result of their influence on the financial outcomes of financial investments in electric lorries.Different terms have actually been actually specified for batteries to characterize their functionality. While many fantastic end results have appeared on the performance of surfacing battery modern technologies, most of them originated from research laboratory documents based upon small-scale test runs (Cano *et al.*, 2018). In order to use and optimize the batteries in the right way, all related technical specifications should be known. In order to choose the best battery for the modeled EV, two different technical specifications were used, as shown below. Table 2 shows the technical specification used for the simulation.

Table.01. LG-Proton IRIZ BEV technical specifications

Drivetrain Parameters			
Drive System	Front-wheel drive	Max Output	116 kW
Curb Weight	918 Kg	Max Torque	360 Nm
Adds weight (Cargo)	56 Kg	Transmission	Single Speed 3.37:1
Gross Weight	1516 kg	Normal Voltage	56V *6 Module=330V
Wheel/Axle	Front Wheel Drive 195/55R15	Total Cells	60 * 6 Module=360 Cells
Accessories	Variable ACC_Small_Car	Total Weight	360 * 1.5 Kg=540 Kg
Powertrain	EV – Manual – PTC_EV		
Rated Voltage	330 V		
Rated Capacity	39.6 Kwh, 120 Ah		
Rated Lifetime	10 years \ 160,000 km		
Motor Type	PMAC (YASA-400)		

6. Simulation Results and Discussions

From the simulation results, the basic model using the NEDC has the state of charge scored 31884 seconds, which is equals 298 Km for the full trip. By comparing the full trip score of the proposed models which is reaching 298 Km with the full trip of the original model of LG Proton-IRIZ which is reaching 300 Km, we conclude that both models are nearly the same as shown in Figure 5(a).The driving cycles were selected in order to test fuel economy and vehicle performance for small cars inside cities and highways. The NEDC Mode is a mixed driving cycle for cities and highways. The distance for one cycle is 11017 (M) and the duration is 1108 (S). Moreover, the average speed is 33.6 (Km/h), and the maximum speed is 120.09 (Km/h) as shown in Figure 5(b). By comparing the proposed Driving Cycle Model (NEDC) with the original (NEDC) Model we notice that they are the same (refer to the typical NDEC specification of the appendices). As shown in Figure 5(c), power capacity is dropping down over time (SoC), and voltage is approximate 330 V and slightly goes down while SoC dropping. From the figure we can see that the battery voltage for the proposed model without load is about 330 V. In addition, from the battery specification of the LG Proton-IRIZ model, it is clear that the battery voltage without load is about 330 V. So, both have similar battery voltage.

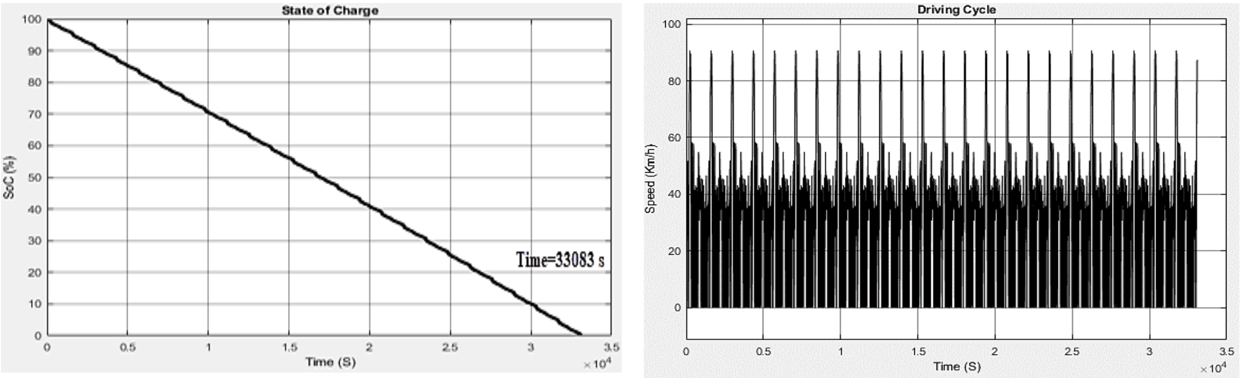


(a) (b)

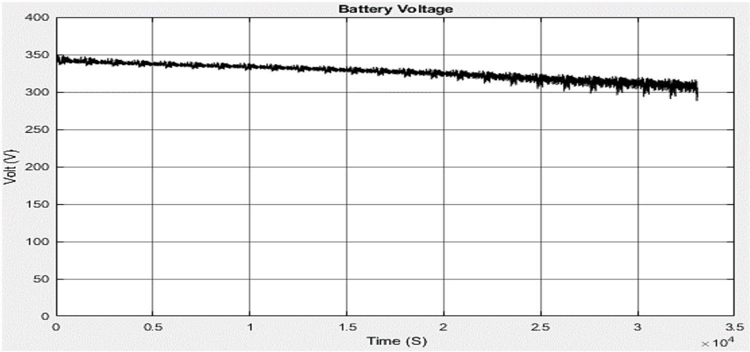
(c)

Figure.5 Testing BEV using NDEC (a) SoC, (b) speed and (c) battery voltage

As seen in Figure 6(a), the basic model using the Urban Dynamometer Driving Schedule (UDDS) has a state of charge scored 33083 seconds, the 100% range for (UDDS) is 314.2 Km, and the 80% range for UDDS is 251.4 Km. It is clear that the UDDS has a better range compared to NDEC because it is only for cities and it has a small average speed. In addition, Figure 6(b) revealed that the distance for one cycle is 17787 (M) and the duration is 1874 (S). Besides, the average speed is 34.2 (Km/h), and the max speed is 91.09 (Km/h). By comparing the proposed Driving Cycle Model (UDDS) with the original (UDDS) model, we notice that they are the same. Finally, Figure 6(c) revealed that the power capacity is dropping down over time (SoC), and voltage is approximately 330V and slightly goes down while SoC is dropping.



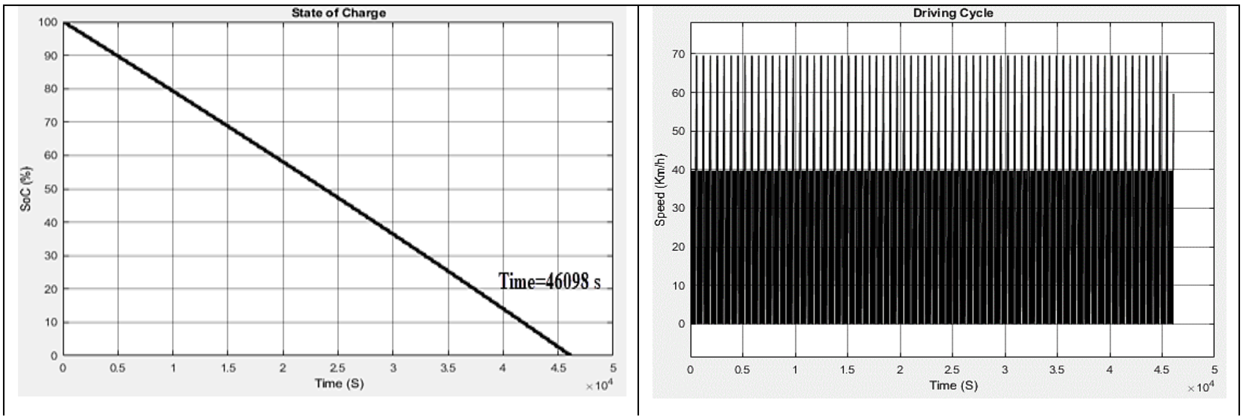
(a) (b)



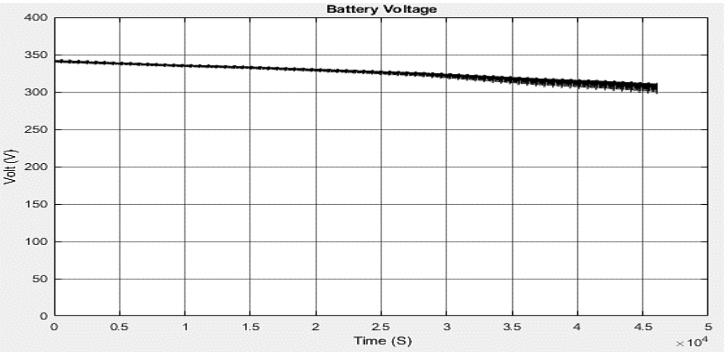
(c)

Figure. 6 Testing BEV using UDDS (a) SoC, (b) speed and (c) battery voltage

Figure 7 show the findings of the basic model using the Japanese 10-15 Driving Cycle mode. Results revealed that the state of charge scored 46098 seconds, which is equals 290.7 Km for the full trip, and the 80% DOD range for (10-15) is 232.5 Km. So, we can notice that UDDS still has a better range compared to NDEC, because it is only for cities and it has a smaller average speed. In addition, the distance for one cycle is 4165 (M) and the duration is 660 (S). Moreover, the average Speed is 22.7 (Km/h), and the maximum speed is 70.09 (Km/h). By comparing the proposed Driving Cycle Model (10-15) with the original (10-15) model we notice that they are the same. Finally, the power Capacity is dropping down over time (SoC), and Voltage is approximate 330V and slightly goes down while SoC is dropping.



(a) (b)



(c)

Figure. 6 Testing BEV using Japan 10-15(a) SoC, (b) speed and (c) battery voltage

8.Conclusion

The basic model of battery electric vehicle (BEV) design is based on the backward-facing model by using the ADVISOR tools in MATLAB. For experimental reliability, the model has been tested based on the LG Proton-IRIZ BEV specifications and also with the different driving cycles to assure that the results from the simulation are similar to the actual results. Good results were shown by using MATLAB when the simulation has been applied and analysed the battery of BEV. When comparing the results of SoC, average speed, maximum speed, and voltage acquired from the proposed design with the typical specifications of the three driving cycles, NDEC, UDDS and Japan 10-15, there are approximately 100% identical measures. The three driving cycle's scenarios shows logical behavior of power capacity is dropping down over time (SOC). The BEV Model using LG-Proton IRIZ BEV technical specifications and NEDC cycle has the best results for the battery; it is about 298 km for full trip.Therefore, the BEV basic design provides a valid result and can be used for testing the desired optimized solutions. Also, a lot of chances still ahead in order to establish better BEV model that will be the basis for further future researches. With the purpose of finding the best voltage, and, state of charge for the battery capacity and the exact component size. In addition, to minimize the use of energy, modeling and simulation are very essential for automotive designers.

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