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SIMULATION AND CRITICAL PERFORMANCE EVALUATION OF A TWO-WHEELER EV SYSTEM UNDER VARYING AERODYNAMIC AND TERRAIN CONDITIONS

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ABSTRACT-
Low tail pipe emissions have increased the global adoption of electric vehicles (EVs) recently. Global utilization of EVs have nearly doubled in the previous decade and continuously increasing with every passing year. Better insights into the EV system will lead to appropriate understanding and working of its components and further refinements in its control and designs. Simulation is a power full tool for complete analysis and evaluation of any physical system. This paper aims to simulate and analyze a two-wheeler EV system under the changing aerodynamic and terrain conditions. The type of terrain where the EV is being driven and the aerodynamic forces affect the range of EVs and also the SOC of the battery. The terrain geography also leads to stresses in the axle of the wheels and vehicle tire. A complete simulation of all the components such as vehicle body, gear system, braking system, drive system etc. has been performed in this paper. The performance of two-wheeler vehicle system with changing aerodynamic conditions and also varying terrain conditions such as up gradient and down gradient performance have been assessed. The performance parameters observed are vehicle speed, range and state of charge (SOC) of the battery. The results obtained corroborate a satisfactory performance of the EV under varying conditions.

Keywords: Electric Vehicle, SOC, Drive cycle, DC drives

Introduction
EVs are now-a-days being globally accepted as the future of transportation due to their quiet, pollution free and grid power regulation capabilities. Though rapid developments and cost depreciations in EV technology have recently been witnessed thereby enhancing their wider acceptability amongst commuters, still plethora of challenges thwart their compatibility with the conventional engine vehicles. The prominent challenges involve higher cost, range anxiety and extended charging time [1]. A broader and deeper research and analysis of different EV designs is therefore necessary to cater these challenges. Precise models of different EV components and simulation of complete EV systems will therefore be beneficial for better analysis of the proposed EV designs. Moreover, EVs are very complex systems containing several components such as battery, power electronics-based drives and transmission systems coupled with wheels working and interacting together. Designing each component precisely and accurately and also understanding the implications of wrong design is an important task before creating an actual experimental model and a prototype [2]. Using simulation as a tool for getting better insights into the working of the actual EV model will therefore facilitate creating better, reliable and affordable EV designs. This paper therefore intends to simulate and assess the performance of a two-wheeler EV under varying aerodynamic and terrain conditions by using the already existing models of different components in Matlab. A comprehensive literature review presented in section 2 on the existing models and simulations of different types of EVs have been carried out with the objective of finding out the existing EV models and simulation-based analysis and the performance of those models. This paper is organized as follows: Introduction in section 1 is followed literature review about the existing EV models and simulation-based analysis. Materials and methods are presented in section 3 describing the general architecture of the two-wheeler EV model and each of its components. Results and discussions of the different case studies are presented in section 4. Conclusions of the research are presented in section 5 and finally the references are presented

in section 6.

Literature Review

In this section the previous works performed by the researchers in the field of modelling and simulation of EV is presented. From the performed literature review, the important facts of those studies have been highlighted and also the research gaps have been identified. Some important modelling and simulation of EVs performed earlier are presented below:

Sharmila B. et. al. (2021) designed and simulated an EV model using the SIMSCAPE components in Matlab. The various components used in creating the EV model were drive cycle source, battery, driver controller, power converter, motor and vehicle sub-system. The regenerative braking in the EV model was also incorporated using H-bridge configuration to recover the power during braking. They also derived the various vehicle parameters such as speed, current, state of charge (SOC), motor RPM and the vehicle range and analysed them for various drive cycles.

Naderi P. et. al. (2013) simulated a hybrid vehicle structure containing fuel cell and an intelligent controller facilitating the regenerative braking and power management. A neuro-fuzzy controller was designed for controlling the fuel-cell power/current based on the demand reference. Different driving and manoeuvring situations were tested and found to be satisfactory in terms of the performance using simulation.

Erik Schaltz, (2011) presented a detailed battery EV (BEV) model. The performance of the BEV was analysed for new European drive cycle (NEDC). Using the simulation, a case study was conducted for a small BEV undergoing 14 driving cycles of NEDC which showed an energy consumption of 148.3 Watt-hr. for travel range of 1 km from the electricity grid. The efficiency from the grid to vehicle wheels was calculated to be 49%.

E. Esmailzadeh et. al. (2010) developed a comprehensive four motor EV model and also implemented various control strategies through this model. Detailed models components were also discussed in their study so as to incorporate the effect of every vehicle component in their analysis. The cases of different driving conditions were simulated for studying the performance of the control laws in handling those driving situations.

Haddoun et. al., (2008) presented the system modelling, analysis, and simulation of an EV with two independent rear-wheel drives. The traction control system was designed to ensure the dynamics and stability of the EV, especially in the absence of differential gears. The use of two in-wheel electric motors allowed for torque and speed control in each wheel, improving overall stability and safety. The traction control system, proposed in the paper, utilized vehicle speed as an input, distinct from wheel speed characterized by slip in the driving mode. To estimate vehicle speed, a generalized neural network algorithm was introduced. The analysis and simulations conducted in the study led to the conclusion that the proposed system was feasible. Simulation results, based on a test vehicle propelled by two 37-kW induction motors, demonstrated the satisfactory operation of the proposed control approach.

Xiaoling He. et. al. (2002) performed a hybrid electric vehicle (HEV) simulation for a parallel hybrid drive train. This was performed with an objective of testing the overall performance of HEV and the various control schemes adopted. The vehicle range performance and acceleration was tested for different drive cycles along with the SOC recovery capability under regenerative braking situations.

D.W Gao et. al., (2007) evaluated the efficacy of many modelling tools such as power train system analysis toolkit (PSAT) PSIM and virtual test bed for modelling and simulation of various components of EVs such as power train etc. Many modelling techniques such as restive companion form technique and bond graph methods were also tested for modelling of power trains and other components. The performance of the modelled vehicle was tested and demonstrated.

Mapelli F.L. et. al. (2010) performed the design and prototype realization of plug-in hybrid electric vehicle (PHEV). The model was created with an objective of analysing the energy flow among the various components of EV and optimizing the power flow among the various components. They also validated the model results using a prototype PHEV. The inverter control techniques such as direct self-control strategy was also tested so as to improve the over-all driving range performance and obtaining the reduced inverter losses.

All the works presented in this section highlights that mostly the simulation of 4-wheeler EV system has been performed. Moreover, the performance of the controllers has been tested during constant speeds, acceleration and braking conditions. These studies have not assessed the vehicle performance during up-climbing and down-climbing situations and also lacks the implementation of the changing aerodynamic drag on the EV body. In this work, therefore a two-wheeler system has been taken as study case and the conditions of changing terrain and aerodynamic drag have been implemented.

Materials & Methods
In this section the use of different components of a two-wheeler system have been described in reference to the figure 1 depicted below. The important parts of an EV two-wheeler are:

(i) Battery: A rechargeable battery is used to store the energy in the form of electrical charge and feed the stored energy to the motor as and when desired according to the need and demand. A wide range of batteries as presented in table 1 are available which can be used for EV applications but now-a-days the application of Li-ion battery is gaining prominence due to their relatively high energy density and less weight and size[3], [4]. In spite of having several advantages the Li-ion batteries are manifested with some difficult issues such as temperature rise and charge equalisation. Therefore, it is required to attach a reliable battery management system (BMS) with the batteries. BMS are electronic circuits used for monitoring the parameters such as battery current, voltage, temperature and SOC thereby estimating the battery state of health (SOH) and performing certain control actions related with temperature control [5].

Table 1: Characteristics of batteries [5], [6]

Battery type	Sp. energy (Wh./kg)	Energy density (Wh./L)	Sp. power(W/kg)
Lead-acid	20-35	54-95	250
Ni-Cd	40-45	70-90	125
Sodium-sulpur	100	150	200
Zebra	100	150	150
Li-ion	90	153	300

(ii) Battery charger: Batteries are not a continuous source of electrical energy. The stored energy in the batteries get used up when they feed a load. Batteries in EV gets drained out of charge when while driving. They possess excellent property of getting charged again with the help of suitable chargers. These chargers are sometimes installed within the body of EV and hence are called on-board chargers. Chargers are also installed at public places and at particular locations out of the body of EV these are called off-board chargers which can handle the charging of many EVs simultaneously due to their high-power requirements. A charger essentially consists of two stages. The first stage is a a.c. to d.c. converter using power factor correction algorithms. The second stage regulates the battery charging current and the battery voltage. The chargers can also be classified as unidirectional and bi-directional depending on the direction of power exchange [6].

(iii) Motor: Motor provides the rotational power to the wheel of the EV required to propel the EV forward or backward. The motors generally used are permanent magnet synchronous motors (PMSM) and brushless dc motors (BLDC). The advantages of using BLDC and PMSM is better and rapid speed control which is required for the EVs where it is required to suddenly accelerate and perform braking actions. BLDCs are normally synchronous motors powered by applying electronically controlled commutation system instead of using mechanical commutation system as in conventional dc motors [6].

(iv) Motor controller: The performances of motors in EVs are controlled using motor controllers. A controller is basically used to either manually or automatically control the motor speed and its rotation in a particular direction or reversing. It not only regulates the motor speed but also protects it against sudden overloads and faults. The controller basically acts as a valve which regulates the input power to the motor according to the drive cycle requirements [7].

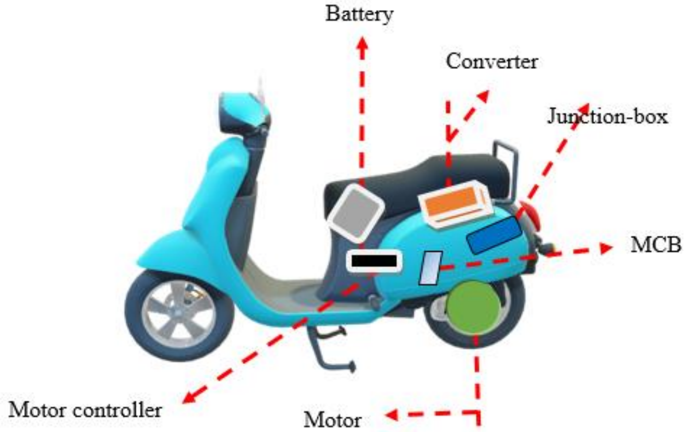

Figure 1: Layout of the important components in a two-wheeler EV.

(v) Converter: The converters used for EV applications mainly are dc-dc converts. The purpose of using these converters is mainly to obtain a changed dc voltage level as compared to the input dc voltage. These converters are necessary for interfacing the battery to dc link. The dc to dc converters can either be unidirectional or bidirectional both depending upon the direction of power flow through them. A bi-directional converter is normally used for implementing the regenerative braking feature. The power through the converters is regulated by changing the duty cycle of the switches connected in the converters. The switching converters however, are manifested with problems such as harmonics and electronic noise[7], [8].

(vi) Miniature circuit breaker (MCB): Miniature circuit breakers are used to isolate the faulty system of a circuit from the from the rest of the circuit for keeping the parts safe. In a two-wheeler EV the MCB protects the battery, controller, motor and other parts from short circuits and the over currents resulting from the short circuits[8], [9].

(vii) Junction box: the battery junction box is used for connecting and disconnecting the battery with other components which require energy from the battery. This component serves as connection point for most of the components in a EV and hence can be called junction box or meeting point for all the components[9].

3.1 Mathematical Modelling of EV components

The mathematical modelling and simulation of each component of the two-wheeler EV considered in this research work is presented in this section. The interconnection of different EV components is depicted in figure 2 below. The simulation of complete two-wheeler EV model and its different components have been performed in MATLAB. A 108 V battery pack module feeds the energy to a dc motor through a converter. The condition of motor acceleration and deacceleration is simulated by changing the duty cycle of the converter. The mechanical power from the motor is transferred to the axle of the vehicle body through a gear system. The braking conditions are simulated using a braking system block. The mathematical equations used for modelling of each block is presented below:

Vehicle body

The vehicle body block is modelled on the basis of forces depicted in figure 2 below representing a vehicle with front and backward axles moving longitudinally. The model assumes single identical wheels on each axle and the centre of gravity (CG) of the vehicle body is considered either at or below the plane of travel. The body model also takes into consideration the effect of vehicle mass (m_v), aerodynamic drag (f_d), road inclination (α), and distribution of vehicle body weight between axles due to acceleration. The variables representing the model are listed in table 2 and the vehicle body is modelled according to equations (1)-(4). The model is based on the equations of motion representing the net effect of all the forces on the vehicle body. The longitudinally acting forces (f_{xf}, f_{xr}) on the tyres provide forward and backward forces on the vehicles. The force of acceleration due to gravity and the vehicle mass ($m_v g_a$) acts through the CG and depending on the angle of inclination (α) the vehicle body is pulled either backward or forward and but the aerodynamic drag force slows down the pull [8]. [10].

$$m_v \dot{V}_x = f_x - f_d - m_v g_a . \sin\alpha \quad (1)$$

$$f_x = n(f_{xf} + f_{xr}) \quad (2)$$

$$f_d = \frac{1}{2} C_d \rho (V_x + V_w)^2 . \mathrm{sgn}(V_x + V_w) \quad (3)$$

The normal forces acting on the front and rear wheels are given by equations (4) and (5)

$$f_{zf} = \frac{-h_{cg}(f_d + m_v g_a . \sin\beta + m_v \dot{V}_x) + b . m_v g_a . \cos\alpha}{n(a+b)} \quad (4)$$

$$f_{zr} = \frac{+h_{cg}(f_d + m_v g_a . \sin\alpha + m_v \dot{V}_x) + a . m_v . g_a . \cos\alpha}{n(a+b)} \quad (5)$$

The normally acting forces on the wheels must also satisfy equation (5)

$$f_{zf} + f_{zr} = m_v g_a \frac{\cos\alpha}{n} \quad (6)$$

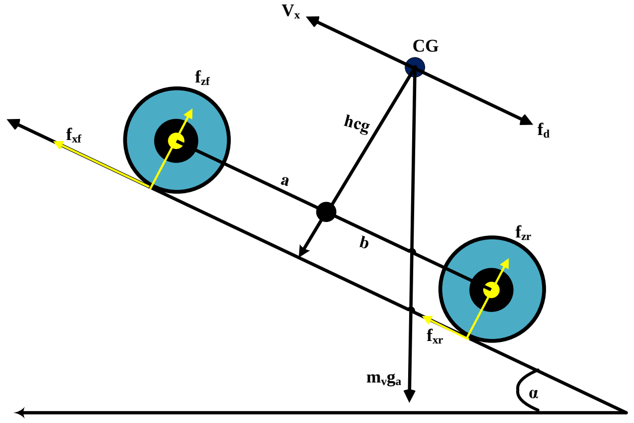

Figure 2: Vehicle body model variables[10], [11].

Variables	Description
g_a	Acceleration due to gravity
A	Inclination of travel
m_v	Vehicle mass
h_{cg}	Vehicle centre of gravity height above ground
a, b	Distance front and rear axle centre points from the normal projection taken from vehicle axle.
V_x	Velocity component of the vehicle in forward and reverse directions.
N	Number of wheels on each axle.
f_{xf} , f_{xr}	Forces on each wheel acting longitudinally at the front and rear ground contact points respectively.
f_{zf}, f_{zr}	Forces on each wheel at the front and rear ground contact points respectively acting normally.
A	Effective frontal cross-sectional area of the vehicle.
c_d	Aerodynamic drag coefficient.
P	Mass-density of air.

f_d	Force due to aerodynamic drag.

Table 2: Variables for model of vehicle body [11].

Battery Pack

Battery pack is modelled as series combination of cells represented by equivalent circuit models (ECM) depicted in figure 3 and modelled according to equation (7). 24 cells each of 4.5 V are connected in series for making a battery pack of 108 V. The voltage requirement of battery pack was kept to meet the requirements of the dc motor driving the EV[9], [11].

$V=V_{oc}-IR_s-V_p$ (7)

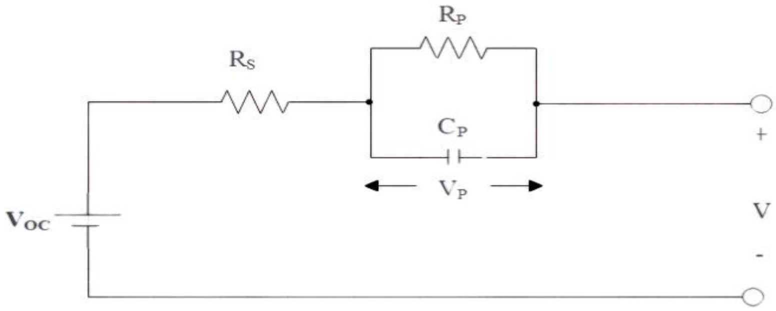

Figure 3: ECM of Li-ion battery

3.1.3. DC motor

The dc motor is modelled according to the equation (8)

$T_m = \frac{k_t}{R}(V - k_v\omega) - j\omega' - \lambda\omega)$ (8)

Where, T_m is the mechanical torque output from the motor, R is the armature resistance, ω is the angular velocity of the armature, V is the armature terminal voltage, J is the inertia of the motor, K_t is the electromagnetic torque constant and λ is the damping [11].

Gear system

The kinematics of the gear system is modelled by the equations (9) and (10)

$R_f\omega_f=R_b\omega_b$ (9)

The gear ratios of follower-base gears are modelled by equation (10).

$G_{fb} = R_f/R_b = n_f/n_b$ (10)

Brake system

The brake system is modelled as friction between two rotating surfaces which are unlocked and their motion is represented by the equation (11).

$\tau = n\mu\, r_{eff}\, \text{sign}(\omega) + \tau_{viscous}$ (11)

where, τ is the transmitted torque, N is the normal force., μ is the friction coefficient, r_{eff} is the effective radius, ω is the relative angular velocity, $\tau_{viscous}$ is the viscous drag torque, μ is the viscous drag torque coefficient[9], [11].

Results and discussion

The results obtained from the simulation of different case studies are presented in this section. In the first case (case-1) the performance of EV is tested when the effect of wind speed opposing the vehicle propulsion is not considered and the road terrain is considered as flat i.e. the vehicle is considered running on a flat surface. In this case as depicted in figures 4(a) the vehicle accelerates from 0 to 40 km/hr. speed in 20 seconds and to 50 km/sec. at 40 seconds. The vehicle runs at a constant speed of 50 km./hr till 75 seconds where brakes are applied to slow down the vehicle to 43 km/hr at 90 seconds and further decelerate the vehicle to 40 km./hr. by braking it at 90 seconds. It can be observed from figure 4 (b) that the total distances travelled by the vehicle is 1.2 Kms. in 100 seconds and the SOC of battery drops from 100% to 98.04%. as depicted in figure 4 (c).

Case-1 Wind speed=0, Terrain=Flat

Vehicle Speed=39.98 Km/hr., Distance travelled= 1.21 Kms., Battery SOC 98.04%.

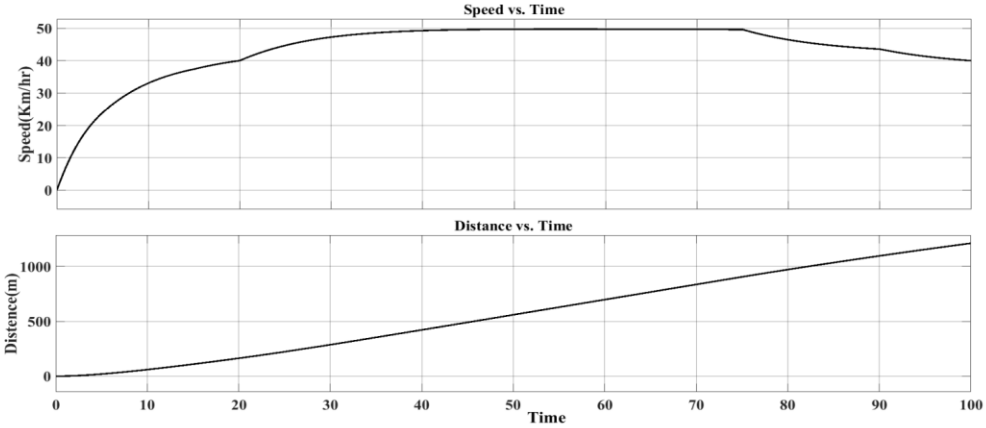

Figure 4(a): Speed vs. time curve & Figure 4(b): Distance vs. time curve.

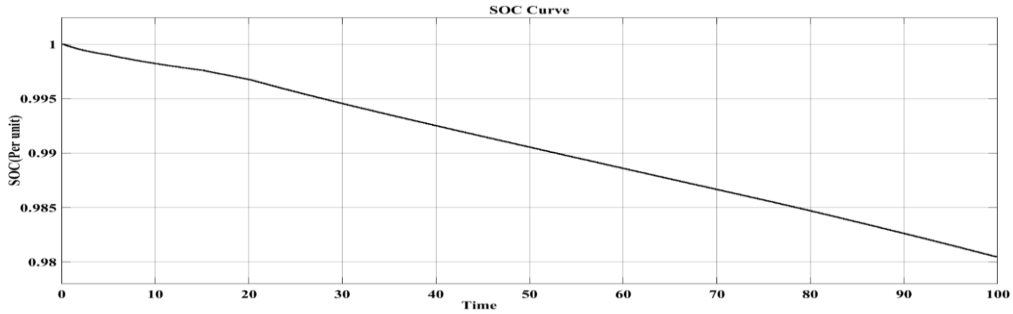

Figure 4c: Battery SOC vs. time curve.

In the second case the effect of aerodynamic wind speed was considered zero and the terrain was taken to be an upward terrain which means the vehicle was climbing an upwards gradient. In this case the vehicle acceleration and braking times were taken same as taken in case 1. From the curve in figure 5(a), it was observed that under same acceleration since the vehicle was climbing upwards, the vehicle speed was reduced to 36.92 kms. /hr. in 100 seconds and also the maximum speed achieved was 38 kms. /hr. at 10 second and further to 45 kms. /hr. till 75 seconds. Hence, the speeds achieved under the similar acceleration conditions were less when the vehicle was travelling upwards as compared to the flat road terrains. The range of vehicle during upward terrain also gets reduced 1.14 kms.as more energy would be required from the battery to overcome the upward gradient as depicted in figure 5 (b) and the battery SOC gets reduced to 97.96% from 100% charged state as shown in figure 5 (c).

Case-2: Wind Speed =0, Terrain= upwards

Speed=36.92 Km/hr., Distance travelled=1.14 Km, SOC=97.96 %**.**

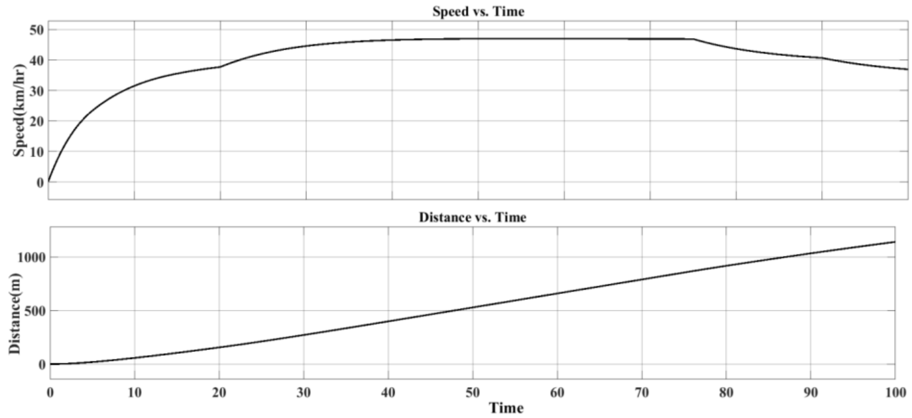

Figure 5(a) Speed vs time curve and Figure 5(b) Distance vs. time curve

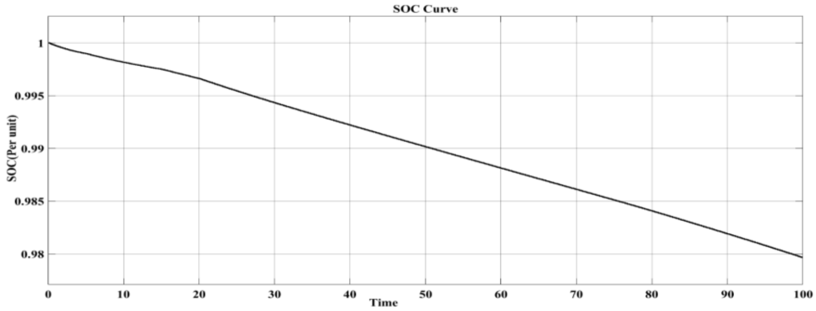

Figure 5(c): Vehicle SOC vs. time curve.

In case 3 all other conditions remains same as above two conditions during simulation but the road terrain is considered downwards. The downward road terrain aids in the vehicle movement hence the vehicle top speed increases to 53km./hr and the speed after braking reaches to 42.91 km./hr. The vehicle range in this case remains highest at 1.28 Km along with battery SOC at 98.12%.

Case-3: Wind Speed=0, Terrain=Downwards

Speed=42.91 Km/hr., Distance=1.28 Km., SOC=98.12 %.

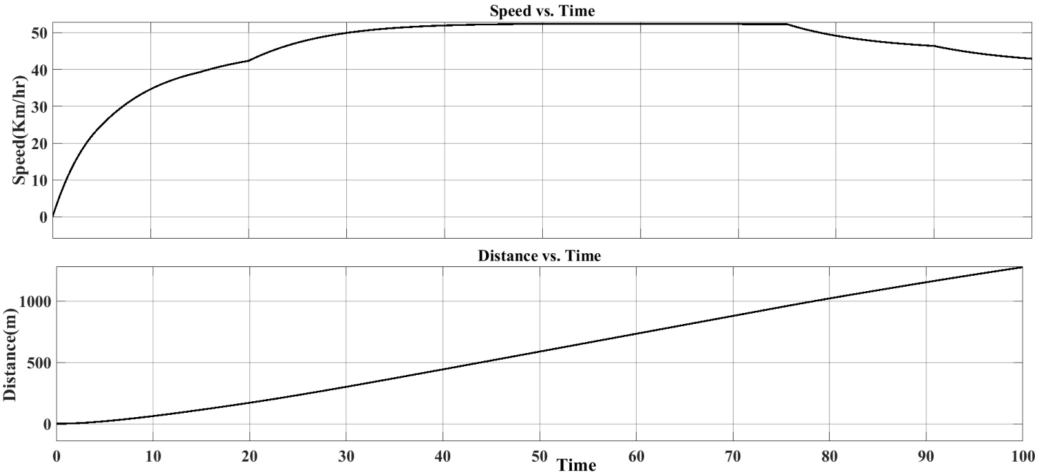

Figure 6 (a) Speed vs. time curve and Figure 6(b) Distance vs. time curve.

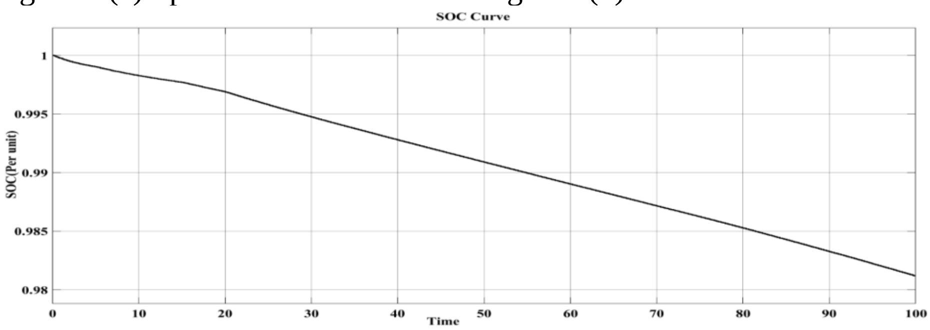

Figure 6(c): Battery SOC vs. time

Cases 4 and 5 are simulated to observe the effect of aerodynamic forces and road inclination together on the performance of EV. Both the cases are simulated under similar vehicle acceleration and braking situations as previous cases. In case 4, when the vehicle experiences aerodynamic force due to wind speed of 2m/s and downward terrain, it can be observed clearly from figure 7(a) that the maximum speed of the vehicle is 48 km/hr. and the speeds achieved after braking at 75 seconds and 90 seconds are respectively 41 km/hr and 37.83 km/hr respectively. Under this condition the total distance travelled by the vehicle is 1.16 km and the battery SOC is 97.99% as depicted in figures 7(b) and 7(c) respectively.

Case-4: Wind Speed=2m/s, Terrain=Downwards
Speed=37.83 Km/hr., Distance Travelled=1.16 Km., SOC=97.99%.

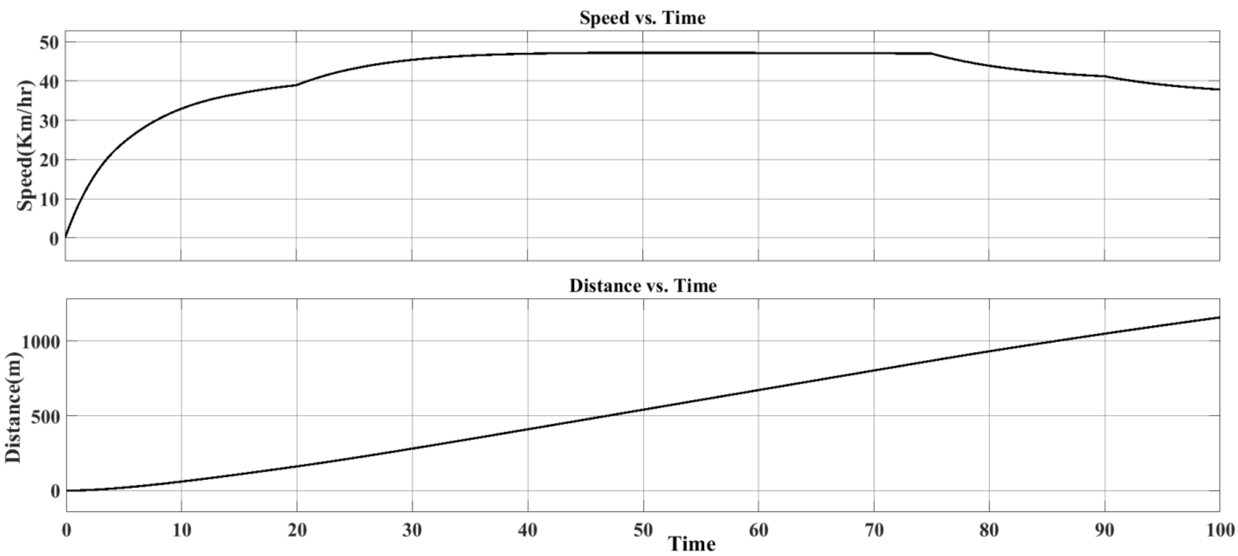

Figure 7 (a) Speed vs. time curve and Figure 7(b) Distance vs. time curve

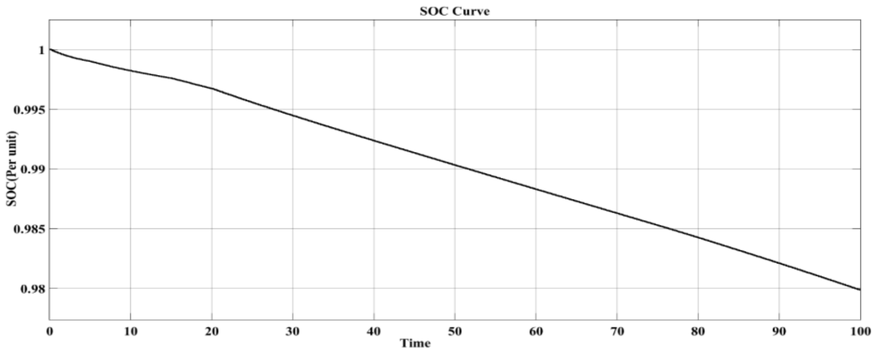

Figure 7(c): Battery SOC vs. time

Case 5 is simulated when the vehicle experiences the aerodynamic forces with wind speed=2m/sec and upward road terrain. The maximum vehicle speed is 41 km/hr and the speeds achieved after braking events are 36.75 km/hr and 32.03 km/hr at 75 and 90 seconds respectively. But the vehicle range in this case reduces to only 1.03 kms. and the battery SOC however, remains at 97.84%.

Case 5: Wind Speed=2m/sec, Terrain=upward
Speed=32.03 Km/hr., Distance=1.03, SOC, 97.84 %.

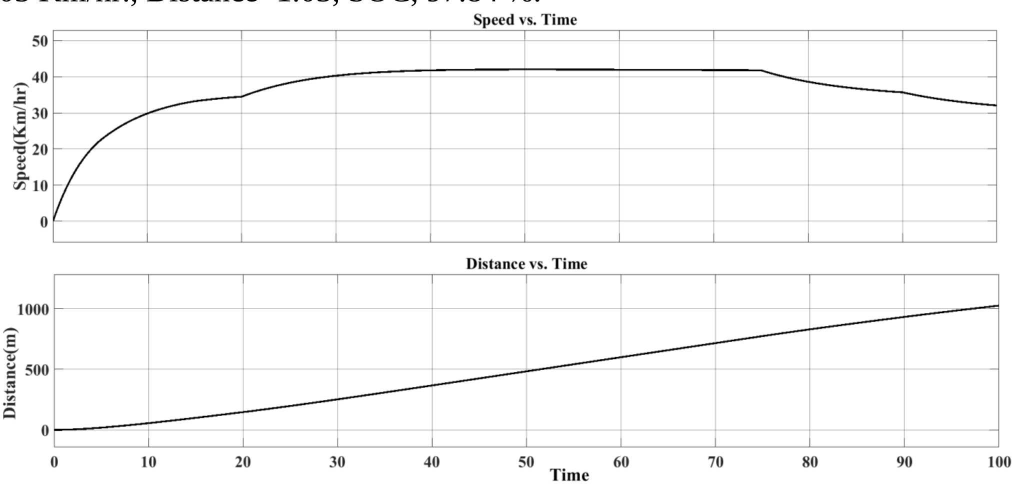

Figure 8 (a) Speed vs. time curve and Figure 8(b) Distance vs. time curve

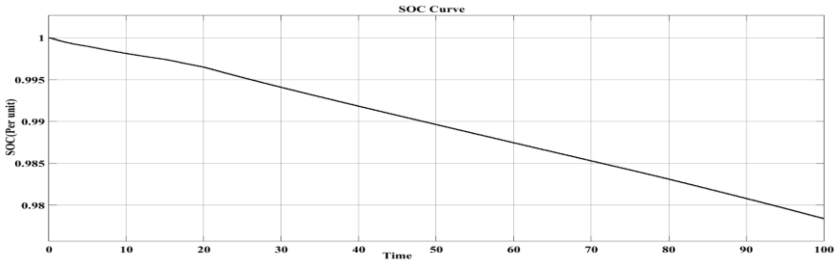

Figure 8(c): Battery SOC vs. time

Conclusions

The performance evaluation of an EV two-wheeler has been performed inn this work through simulations. The performance of the vehicle is tested under different situations by changing the aerodynamic wind speed and the road terrain profile. Interesting results presented in section 4 have been obtained from the study. From the results it can be concluded that under the similar acceleration and braking situations, the vehicle range and the battery SOC are affected by the wind aerodynamics and the road inclination profiles. The wind aerodynamic forces & upward road inclination acting against the forces of vehicle propulsion tends to reduce the vehicle range and the battery SOC however, the downward road inclination increases the vehicle range and also the battery SOC. Hence, the aerodynamic design of EVs must be optimized so that the effect of aerodynamic forces can be minimized and the vehicle range can be extended.

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